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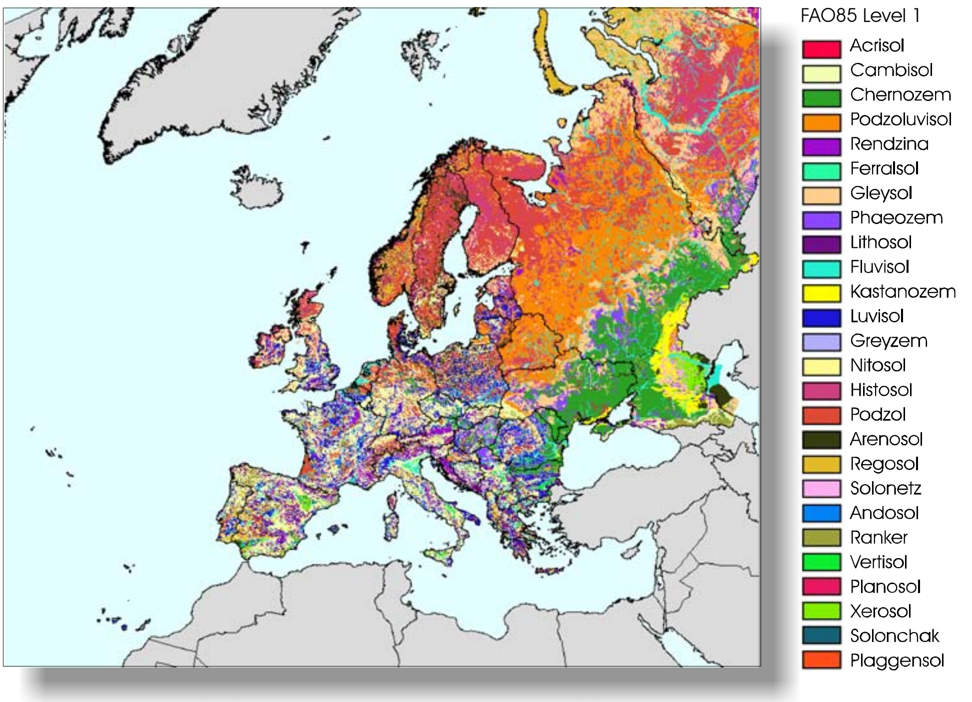
Development of a Spatial European Soil Property Data Set

Roland Hiederer & Robert J.A. Jones



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Contact information

Address: R. Hiederer
E-mail: roland.hiederer@jrc.it

http://ies.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

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[1] European Commission Joint Research Centre
Institute for Environment and Sustainability
TP 261
21027 Ispra (VA)
Italy

[2] National Soil Resources Institute, Cranfield University,
Cranfield
Bedfordshire MK43 0AL
United Kingdom

COVER PAGE:

The cover page shows the distribution of soil classes in Europe according to the FAO 1985 classification scheme mapping the dominant soil typological unit after applying single-criterion land allocation to the spatial layer of Soil Geographic Database of Europe.

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List of Acronyms

Acronym	Full Name
ASCII	American Standard Code for Information Interchange
BS	Base saturation
CEC	Cation Exchange Capacity
DEM	Digital elevation model
DR	Depth to Rock
FAO	Food and Agriculture Organization of the United Nations
ID	Identifier value
JRC	Joint Research Centre of the European Commission
MCA	Multi-Criteria Analysis
OC	Organic carbon
OM	Organic matter
PD	Packing density
PTR	Pedo-transfer Rule
PTRDB	Pedo-Transfer Rules Database
PTRDBt	Pedo-Transfer Rules Database attribute table
SCA	Single Criterion Analysis
SGDBE	Soil Geographic Database of Europe
SGDBt	Soil Geographic Database of Europe attribute table
SLP	Single-criterion Land Parcel
SMU	Soil Mapping Unit
SOC	Soil organic carbon
STR	Soil structure parameter
STU	Soil Typological Unit
UNESCO	United Nations Educational Scientific and Cultural Organization
WRB	World Reference Base for Soil Resources

1 INTRODUCTION

For many applications of modelling environmental conditions or developing scenarios for environmental change analysis information on soil characteristics form a vital component. The conditions to be estimated or modelled very often have a spatial dimension. The spatial dimension is required in the study of processes, which include movements across a surface, like soil erosion, or for which areal statistics are required and where specific features are very unevenly distributed so they do not lend themselves well to spatial interpolation from point observations. Where the results are to be presented in form of maps a method for the spatial illustration of the information estimated or modelled has to be employed. The task is greatly facilitated, or indeed made possible, by having available the main input data in form of spatial representations. Raster data formats are widely used for the modelling of movements through space and the storage of parameters, which change constantly and without a pattern that could be described by a plain mathematical function.

Representing soil attributes in form of a continuous spatial layer is not quite the trivial task it may at first appear due to the variability of the distribution of soil properties but also the methods used to store the information. In a generalization of the methods used to map soil properties one can distinguish three main approaches:

- delineation of areas with largely common assortment of properties;
- interpolation of a surface from soil survey data;
- analysis of surface topography and catena.

A soil database with a common assortment of soil properties does not necessarily signify a homogeneous distribution of a single property across the area. Rather, it refers to a distinct diffusion of typical soil properties within the area of limited extent. The soil properties of an area are defined by a combination of several exemplified soil characteristics. As a consequence, more than one attribute is assigned to the same spatial unit which makes representing the attributes in a single layer a more complex task. For mapping soil properties from point data geo-statistical methods are widely used (Loda, *et al.*, 2008). Depending on the method used ancillary data to support the interpolation process may be incorporated. The analysis of topographical conditions and the use of the catena concept are also referred to as “digital soil mapping” (Carré, *et al*, 2007). The method relies on defining functional links between the position of a soil in the landscape and typical properties associated with those positions.

In this study we use a soil database where the soil properties are stored in tables of generalized combinations of attributes and linked to a spatial layer of delineated mapping units with the aim to investigate

1. the potential of providing a measure of spatial positioning of attributes of a 1-to-many link within spatial mapping units and
2. options of mapping all attributes associated with the mapping unit to a raster layer.

The methods should result in a set of spatial data of soil properties, which avoid the potential bias in the representation of a soil properties when mapping only the characteristics of the dominant typological unit.

2 Source Data

The most detailed and harmonized spatial data set on soil properties in Europe is available in form of the European Soil Database of the European Soil Bureau (*JRC, 2003*). The database is the most detailed source of information available at European level and available to the general public since November, 2006.

2.1 European Soil Database Characteristics

The European Soil Database consists of a compilation of several databases, each addressing very different aspects of soil properties. The main attribute databases used for mapping soil properties are the *Soil Geographic Database of Europe* (SGDBE) and the *Pedo-Transfer Rules Database* (PTRDB). The study only covers the area of Western Europe as used in Version 1.0 of the database. The areas in Eastern Europe introduced in Version 2.0 differ to some extent and crucially in the soil classification scheme used, which is not entirely compatible with the rules of the PTRDB. The SGDBE (King and Tavernier, 1994a) is largely a digital version of the European Soil Map published in 1985 (CEC, 1985). The legend for the map follows the FAO (1974) classification, although the digital database has been updated (FAO, 1990) and subsequently translated to be compatible with the World Reference Base for Soil Resources (WRB, 1998).

- ***Soil Geographic Database of Europe***

  The SGDBE consists of several components: a spatial component in form of a digitized soil map, a non-spatial component of related attributes and link information of associating spatial units with attributes. The non-spatial data are stored in form of tables as database files. To avoid confusion with other attribute tables the attribute table of the SGDBE will be referred to as the *Soil Geographic Database Table* (SGDBt). The digitized soil map contains a single layer of spatial units, to which a unique identifier value (ID) is assigned. The layer ID is used to establish a link to the records of the attribute database. The spatial components are referred to as *Soil Mapping Units* (SMUs). The SMUs are stored in the database as polygons in vector format. Although each polygon has a unique identifier, the area belonging to an SMU is not necessarily continuous. Soil characteristics are defined in the database in form of *Soil Typological Units* (STUs). A STU is composed of a typical association of specific soil attributes. Individual soil attributes of the SMU are defined by linking one or more appropriate STU(s) to the spatial unit in form of a one-to-many relationship. The link employed is a non-geographic join and, as a consequence, the location of the STU within a SMU is not defined. Only the relative portion of the appropriate STU(s) within the spatial unit is provided by a separate table.

  A graphical representation of the basic links between the mapping units of the spatial layer and the attributes is given in *Figure 1*.

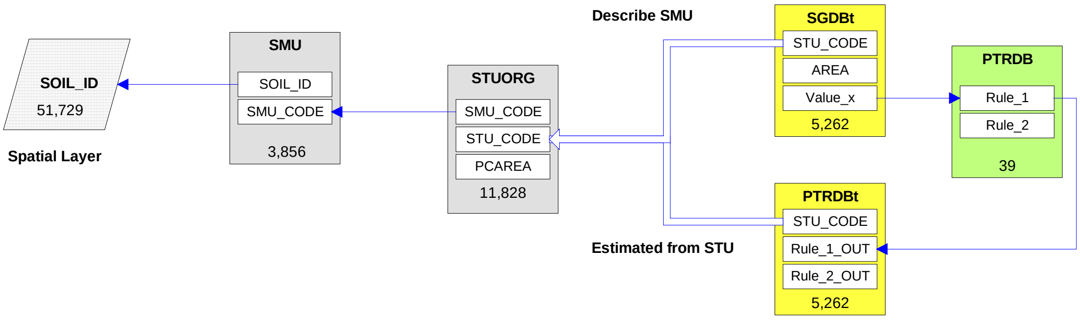


Figure 1: Linking of Soil Attributes to Units of Spatial Layer

The graph illustrates the separation of the spatial units from the attribute databases with the STUORG table defining the links. It also shows that the PTRB forms an independent set of information which when applied to the STUs generates the derived attributes provided by the PTRBt (Lambert, *et al*., 2003)

- ***Pedo-Transfer Database***

The second attribute database table used is provided by the PTRDB. The PTRDB consists of a collection of rules in form of ASCII text files (Van Ranst *et al*., 1995)and a data table containing the results of applying the rules to the SGDBt. A *Pedo-Transfer Rule* (PTR) is designed to extend the range of soil parameters to properties not observed or measured in a soil sample. A PTR condenses the results obtained from field surveys to typical conditions, which were found to be associated with a specific soil property (Daroussin & King, 1997). The main parameters and the principle conditions defining a property and the representative value for that property are identified through expert knowledge. The field survey-based knowledge of typical associations is encoded in form of a series of IF-THEN conditions. The conditions are arranged in order of increasing detail and, as a consequence, the order of the conditions becomes part of the rule (Jones, *et al*., 2005).

The order of the conditions is as important as the parameters themselves. The combination of parameters set in a PTR should arrange general conditions before more specific ones. A more general rule following a specific rule would overwrite the previous assessment and the specific condition would not be recorded as a result in the PTRDBt.

The information stored in the SGDBt describes the specific observable conditions of the SMU, such as soil type, morphology and land use. The information stored in the of PTRDBt comprises the output of the rules of the PTRDB as applied to the STUs. It is therefore only indirectly linked to the units of the spatial layer.

2.2 Consideration for Soil Attribute Mapping

The principle of mapping soil attributes is based on linking parameter values of the typological units to the spatial units. Values of parameters are stored in two main data tables: the SGDBt and the PTRDBt. This structure of the SGDBE allows for efficient data storage: there is only one spatial layer of vector data and attributes are stored in tabular format without replication. However, the storage arrangement is not particularly well suited for spatial analysis, for combining the soil data with external information, or for applying mathematical functions as part of the *rule-based* systems.

One of the main obstacles in mapping attributes is the lack of an exclusive link between the attribute tables and the spatial units. Technically, there is a one-to-many relationship between the spatial SMU and the attributes of the STU(s). As a consequence, an attribute can only be mapped directly, if a single STU is assigned to a spatial unit. Since there are commonly at least 3 STUs linked to an SMU, with a maximum of 10 STUs, attributes cannot be mapped directly to a single layer. In principle, each attribute to be spatially represented requires 10 separate data layers. Even so, the spatial position of an STU within an SMU cannot be improved regardless of the number of linked STUs included.

Despite the simplicity of the data model the relationship between spatial units and attributes of the typological units is to some degree ambiguous. A major source of uncertainty of assigning attributes to a spatial location is the lack of information on the spatial position of soil properties within an SMU, another is the incomplete characterization of the spatial units by typological units. These limitations have lead to some simplification when mapping soil attributes from the databases. Traditionally, when seeking to display soil properties, only the parameter value of the dominant STU within the SMU is displayed. The dominant STU is generally the one with the largest area within an SMU. This method of direct mapping of an attribute by the dominant STU is ambiguous when there is no dominant STU linked to an SMU, i.e. when the largest area value is not unique. Furthermore, the representation of the property of the spatial unit remains incomplete for all cases, where an SMU is made up from more than one STU. A more accurate way of spatially representing soil properties is to use the full information of the STUs comprising an SMU and to calculate attributes as continuous values stored in a single data layer.

Even so, using parameter values from all typological units linked to an SMU does not improve the geographic position of the attributes within a spatial unit. For a better spatial representation of attributes ancillary information has to be integrated into the mapping procedure. One of the methods of improving attribute positioning exploits the additional morphological information found in the SGDBt. By associating the STU records with an ancillary digital elevation model (DEM) the morphological information can be used to improve the location of one or more STUs within the SMU. This method has been applied to generate the European Soil Raster Data Set.

3 METHODOLOGY

The purpose of creating a European Soil Raster Data Set was to provide a standardized set of basic soil properties in form of spatial data layers. The layers should be readily usable as input for spatial models across a wide range of applications. The database should also contain additional thematic data layers, which are not directly included as typological values in the databases, but which are useful as model input parameters, such as bulk density.

In order to achieve the aim of producing a Spatial European Soil Property Data Set a methodology had to be developed to address the main obstacles in creating the spatial data layers identified:

1. improve the spatial positioning of typological attributes within a spatial unit;
2. use information of all typological units linked to a spatial unit for attribute mapping.

On account of the ancillary information used (land cover from satellite images, DEM, etc.) the database spatial layers use a raster in preference to a vector format. The grid size was set to 1km, which is appropriate for the scale used to present SMUs in the SGDBt (scale 1:1mio.). The methodology applied to reach the objectives of improved spatial positioning and representation of attributes is described hereafter.

3.1 Improve Spatial Positioning of Attributes within Spatial Mapping Unit

For an improved spatial positioning of attributes two independent methods were developed. The methods are based on very different approaches to assigning attributes and complement each other. The methods can be separated based on the way attributes are managed as follows:

1. attribute association;
2. attribute replacement.

Both methods operate on spatial layers and require suitable ancillary data to be applied effectively.

3.1.1 Attribute Association of Spatial Parameters

A promising method for improving the spatial representation of attributes exploits the exemplified typological combinations stored in the attribute tables of typological units. As mentioned, an STU is defined through a typical combination of soil characteristics, which separate one STU from another. By associating ancillary spatial information on the location of one or more of the defining characteristics the STU may be positioned according to the distribution of the characteristic in the ancillary data. The spatial assignment of STUs within spatial units can be achieved by using the information of defining STU characteristics in a *multi-criteria analysis* (MCA) (Eastman, *et al.*, 1993). The association of parameters describing the SMU with equivalent spatial layers to improve the position of the STUs within an SMU is presented in *Figure 2*.

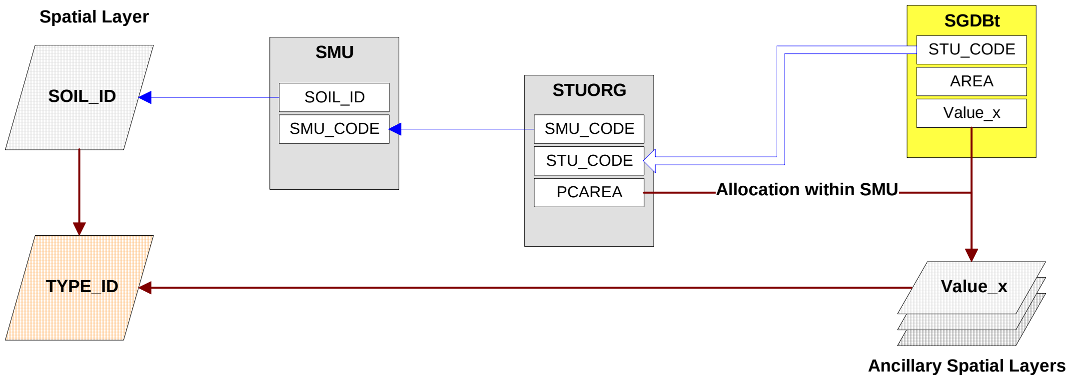
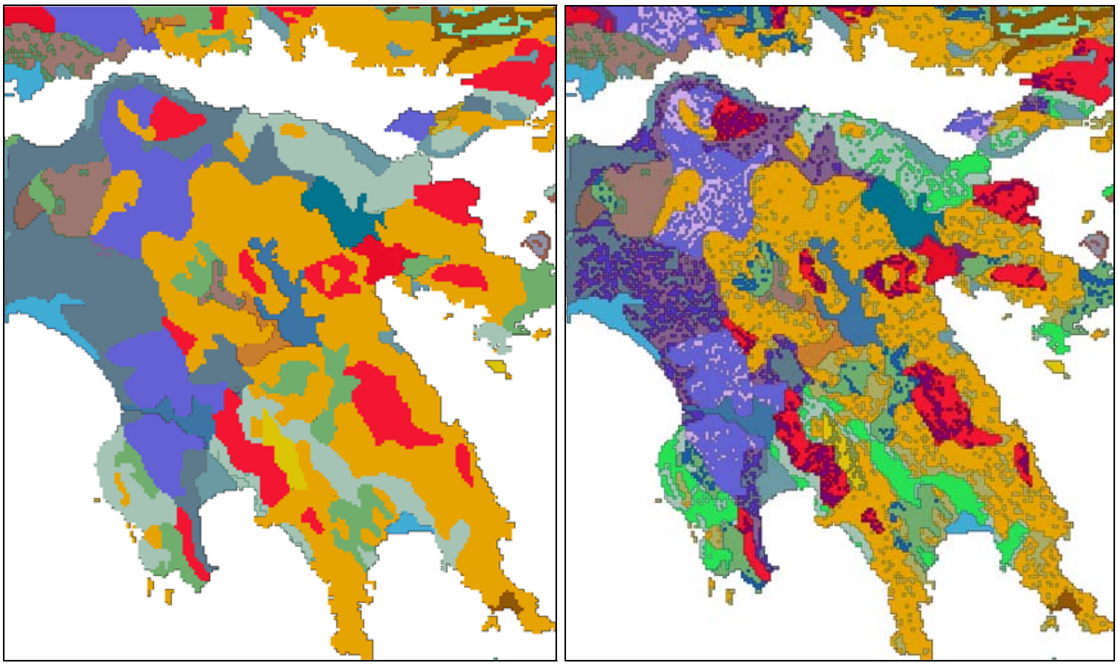


Figure 2: Schematic Configuration of Data for Attribute Association

Requirements for the ancillary information are a thematic equivalence with the criteria used in the analysis and spatial representation at a scale at least comparable to the resolution of the spatial unit of the SGDBt. Thematic equivalence could also include temporal correspondence. For example, the SGDBt contains information on land use for the STUs. However, land use varies over time and it would only be useful in the MCA, if both the soil data and the land cover map were surveyed at the same time or when applied to areas without land use changes.

For the generation of more detailed spatial units it was decided to use stable topographic information as an ancillary data source in the analysis. The ancillary data were provided in form of a DEM at 1km grid spacing. The parameters easily derived from the DEM are elevation and slope, which are also used to characterize an STU. In the study only the slope parameter was used to position typological units within the linked geographic units. The analysis is thus restricted to a rank procedure of a single criterion. An example of the results of processing the attribute information on slope in the spatial domain provided by the DEM is given in *Figure 3*.



Soil Mapping Units (SMUs) Single-Criterion Land Parcels (SLPs)

Figure 3: Distribution of Soil Mapping Units as compared to Single-criterion Land Parcels after Association of Slope Parameter (Example: Peloponnese)

For Western Europe using slope alone increased the number of spatial units from 1,657 in the SGDBt to 2,539 Single-criterion Land Parcels (SLPs) in the processed spatial unit layer. The improvements obtained vary with the method used to link STUs to SMUs in the source database. In general the degree of sub-division is largest in areas, where morphology was used as a defining parameter for an STU and where the spatial units were comparatively large, as is the case in Sweden. In other areas, e.g. Italy, the original spatial units could not be sub-divided.

The study found that despite the increase of about 50% in the number of spatial units the data model for new spatial sub-units is basically no different from the one used for SMUs. As a consequence, the resulting spatial units are still not sufficiently differentiated to allow the definition of an exclusive one-to-one link of STUs to the spatial units and consequently, soil attributes cannot be directly mapped to a single spatial layer.

3.1.2 Attribute Substitution of Typological Parameters

While the observed values of attributes of the STU tables can be associated with equivalent ancillary spatial data to improve the positioning of the STUs within the SMUs the PTRDBt contain projected attributes, which are defined through conditional reasoning. The parameters and the conditions of a rule are parametric and not directly associated with a spatial unit. Instead, the particular parameters of the STUs are evaluated to link the results of the PTRDB to the spatial units. Some of the input data used in the PTRs may be more consistently represented in ancillary spatial databases. By substituting the conditions defined for the STUs by ancillary spatial data and processing the PTR in the spatial domain the results of the PTR can directly represented as spatial layers.

Compared to the method of attribute association, the demands of data used to substitute an attribute are less stringent. Because the output of the PTR is a projected value based on exemplified conditions the PTRs can also be used to model changes in the input parameters. As a consequence, the values of an attribute of the soil database can be substituted by a more accurate ancillary data source. This procedure can be an option to improve the results of a PTR and to adapt the results to varying conditions represented by one or more of the input parameters.

An overview of the methodology applied to substitute parameters by equivalent spatial layers for the PTR data is given in *Figure 4*.

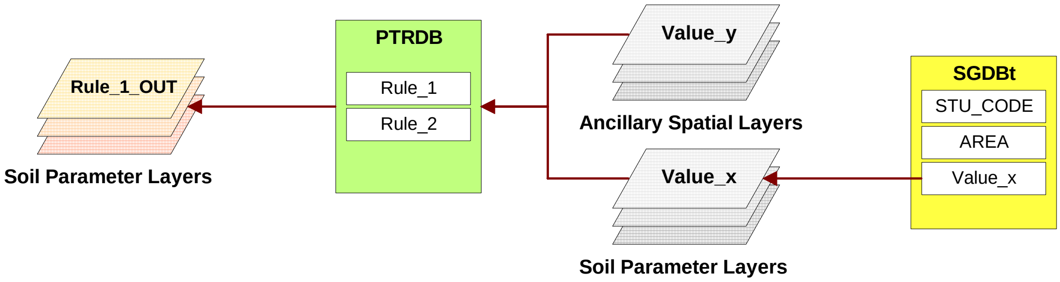


Figure 4: Schematic Configuration of Data for Attribute Substitution

For the study of mapping soil attributes ancillary PTR input parameters substituting the STU values were land cover and temperature. Geo-morphological parameters could have been substituted by the DEM, but were not part of the PTRs investigated.

The land cover information was supplied by a data set of pan-European coverage. The main source of information was provides by the CORINE Land Cover (LC) dataset. Since CORINE LC covers only part of the area of interest, the areas not included were covered with a specifically adapted Eurasian land cover data. The data were derived from a US Geological Survey (USGS) database. To achieve comparable thematic coverage between the CORINE and USGS data, a series of cross-classifications was carried out, using various USGS data layers and re-assigning or merging classes where appropriate. The final layer corresponds to CORINE Level 3 classification codes.

A direct substitution of the land use parameter in the ESDB by the European land cover map is hampered by the different spatial units, to which the information refers. The map information relates to the size of a grid element (1km), while the soil database assigns values to STUs. However, STUs cannot be accurately positioned and assigning a map land use to an STU is a non-trivial task. Various approaches to resolve the lack of compatibility between the spatial and the typological units could be considered, such as assigning the dominant land cover class to a spatial unit in the soil database or using a class- matrix for each spatial unit in the soil database. The first option was considered too simplistic, leaving a large part of the information unexploited, while the second option would have led to a very complex analysis and processing system. The option adopted for substituting typological attributes was to process the rules in the spatial domain, thus avoiding the inconveniences of using a simplistic or overly complex system.

3.2 Mapping Attributes of the STU Database

The development of a methodology of mapping attributes of the typological databases was performed under the objectives of

a) using all information linked to a spatial unit in the typological database, not only the dominant STU and

b) expressing physical parameters in form of continuous values instead of class values or ranges.

Using all information of an attribute associated with a spatial unit is achieved by processing all linked STUs. The information provided by an STU in the link group is weighted according to the aerial portion of the STU within the spatial unit. In cases where a spatial unit is not fully defined by STUs the value is scaled to cover the whole area concerned. The general approach is mathematically formulated in the following equation:

$$P_{SMU} = \sum_{i=1}^{n} P_{STU(SMU)_i} * A_{STU(SMU)_i}$$

where

P: Property value of STU
A: Relative portion of area covered by STU within SMU
i: number of STUs linked to an SMU

Where possible, continuous values are obtained from classes by using an appropriate physical value for a class code. For classes covering ranges the central value is most often used. Values for open ranges at the lower and upper ends were estimated according to expert knowledge, taking into consideration the distribution of a value in the range to be covered. The values are then weighted according to the aerial portion of the STU within the spatial unit.

In cases where the calculation of a continuous value is not appropriate, e.g. where an attribute is not expressed in form of a physical unit but as a qualitative property, the above mentioned method cannot be applied. In those cases separate layers are calculated for each parameter class, containing as values the portion of the class within the spatial unit. It is then up to the user to decide on how to employ the data in a model, which could be using a single layer defined by the dominant class or using the information provide by all layers.

3.3 Mapping Attributes of the PTR Database

As far as the basic database concept of spatial unit and linked attribute table is concerned the PTRDBt structure is no different from arrangement of attributes of the SGDBt. The same links between spatial and typological units apply and the same STU codes are used in both databases. However, the databases differ with respect to the parameters available and in particular the method, through which the parameters are determined. The SGDBt mainly contains a record of parameters measured for soil samples and other observations made in the field. The PTRDBt parameters, on the other hand, are derived from one or more measured or other parameters of the database through a system of rules.

In the SGDBE these rules are applied to the individual STUs of the SGDBt. There is thus a 1:1 relationship between the records of the two tables and, as a consequence, a 1:n relationship between the spatial units and the typological data of the PTRDBt. The same procedure used for mapping observed attributes could be used to map the derived attributes. However, when using ancillary spatial data in the mapping process of the attributes of the SGDBt situations may arise where the conditions defined in the STUs are no longer valid in the spatial data. The combination of some parameters defined in the STU may not be found in the spatial domain and the combinations found in the spatial layers may not be represented in the STUs. Therefore, when associating ancillary spatial data layers with the observed typological attributes the rules of the PTR should be processed in the spatial domain. This step requires the transfer of all input data of the PTRs to spatial data layers and coding of the rules in a GIS environment.

4 IMPLEMENTATION

4.1 Processing Environment

The study used the "European Soil Database, Version 1.0", which includes the Soil Geographic Database of Europe in Version 3.2.8.0, 19/07/1999 and the Pedo-Transfer Rule Database in Version 2.0 (files from 22.07.1999). The spatial units of the SGDBt were processed using the Idrisi[1] GIS. Tabular data were analysed and processed in Paradox, Version 7.0. The processing environment consisted of a desktop computer with one or two Intel Xeon processors with clock rate of 2.4GHz and hard disk with SCSII interface. The use of a RAM-disk is very much recommended to accelerate data processing.

Processing was carried out using Idrisi Macro Language (IML). The language is in principal a script of sequential commands in parametric text format. It has no built-in control procedures and only a single level of sub-routines can be addressed. Despite conceptual shortcoming all processing was done using IML, because the format stores the scripts in ASCII text format, the commands used are evident to any operator vaguely familiar with the software and procedures developed manually can be copied and pasted from the processing log file into the IML script.

All data – soil, land cover, climate and topography – were compiled as standard 1km x 1km raster data sets for processing as spatial layers. The projection and spatial frame used conform to the Lambert Azimuthal Equal Area (LAEA) projection of the Eurostat GISCO database. All raster data were geometrically and thematically harmonized according to the standards developed by the Catchment-based Information System.

4.2 Attribute Mapping Procedure

The attributes transferred to the spatial data set cover the major soil characteristics from both, the SGDBt and the PTRDBt. In general, attributes are calculated by the procedure described in the methodological section. Depending on the attribute mapped, the use of external data to substitute values of an internal attribute and the type of attribute values the resulting layers can be grouped into four classes, which are determined by type of attribute value and spatial allocation. The link between input and output data is graphically presented in *Figure 5*.

[1] Clark Labs, Clark University 950 Main Street, Worcester MA 01610-1477 USA. http://www.clarklabs.org/

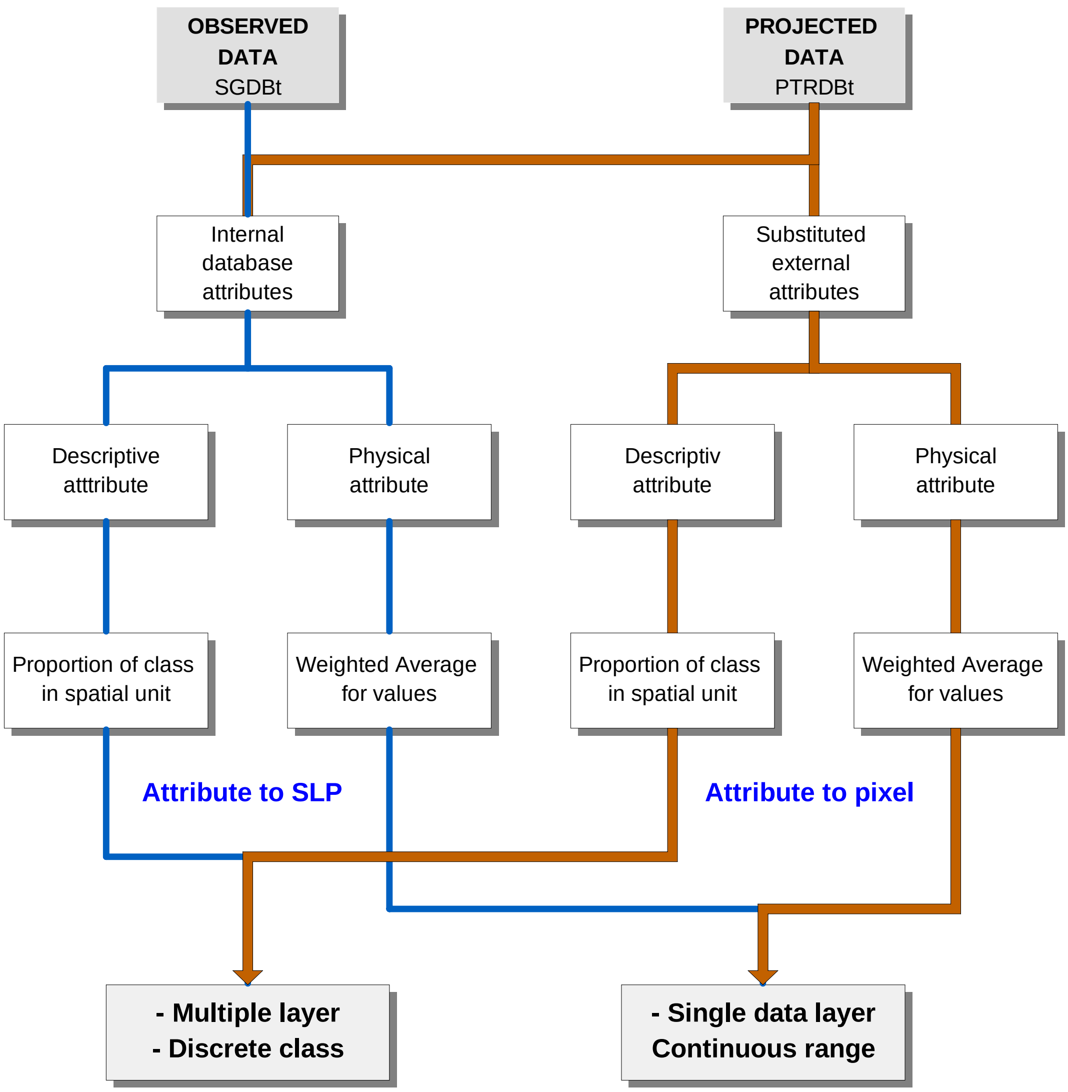


Figure 5: Output Classes of Attribute Mapping Procedure

Although, according to the parameters used to define the groups, the output of the mapping process produces four different types of data, i.e. attribute to either SLP or pixel, they all use the same spatial representation. The attribute data type is maintained, discrete classes are not altered, only their presentation and allocation, while physical parameters can be expressed as a continuous range in a single layer. The spatial unit, to which an attribute is assigned, should be of secondary importance to users of the data, because a single format for data representation is used.

The attributes mapped and the type of output class, to which the attributes belong, are summarized in *Table 1*.

Table 1: Spatial Attribute Data Layers by Output Class

DISCRETE CLASS Multiple Layers		CONTINUOUS RANGE Single Layers	
Attribute to SLP	*Attribute to Pixel*	*Attribute to SLP*	*Attribute to Pixel*
STRSUB_CLS1	STRTOP_CLS1	CLAY_TOP	PD_TOP
STRSUB_CLS2	STRTOP_CLS2	CLAY_SUB	BD_TOP
STRSUB_CLS3	STRTOP_CLS4	CLAY_TDN	BS_TOP
STRSUB_CLS4		SAND_TOP	CEC_TOP
		SAND_TDN	
		SAND_SUB	OC_TOP
		SILT_TOP	OM_TOP
		SILT_SUB	
		SILT_TDN	PEAT_TOP
		NOTEXT_TOP	
		NOTEXT_SUB	
		NOTEXT_TDN	
		TEXT_NODATA_TOP	
		TEXT_NODATA_SUB	
		TEXT_NODATA_TDN	
		DR	
		VS	
		PD_SUB	
		BS_SUB	
		CEC_SUB	
		PEAT_AREAP	

The general methods described for mapping attributes are applicable under standard conditions, where a spatial unit is completely defined. Yet, in reality this is not always the case and the general procedures have to be adapted to allow for specific conditions in the data.

One of the main problem encountered stems from missing data. Instances of missing data can be separated into those of defining the spatial unit and those defining an attribute in the database:

1. **Incomplete description of spatial unit**
   The area of the typological units linked to a spatial unit does not completely cover the spatial unit. Under these conditions the attribute values are computed from the linked typological data and the value is then scaled to the whole spatial unit.

2. **Missing attribute values in database**
   In many cases the absence of any data for an attribute is coded in the data legend. This is not always the case and an attribute field contains an empty entry. These entries are usually treated as missing values and processed as such.

3. **Use of default value in PTR**
   The presence of missing data can be hidden behind the definition of a default value in the PTR. The first condition in a PTR usually defines a value for any combination of input data values. This condition allows provision of a value for combinations not dealt

with in a condition in the rule. However, it does not distinguish between any valid value and missing data. As a result a value is assigned to all STUs, even those for which no input data are available.

Another problem encountered is composite-coding of attributes. Composite-coding in this context refers to the type of value used in the coding legend. For some attributes the coding mixes a discrete class-type attribute with a range attribute. For example, the texture legend contains ranges of texture and a discrete class of “no texture”. Whenever composite-coding was encountered for mapping an attribute the codes were first separated by type into discrete class or continuous range and then processed separately.

4.3 Particulars on Mapping Procedure by Attribute

The conditions are not always as unambiguous as described above. The specific steps taken to resolve incomplete or incompatible data depend on the specific conditions of defining and recording attributes. They are therefore described separately for each of the attributes mapped.

4.3.1 Texture

The first attribute transferred to spatial layers is soil texture. The attribute is recorded in the SGDBt and, as most other attributes the database, distinguishes between soil texture in topsoil and subsoil. The coding legend contains seven classes to describe the attribute, which are given in *Table 2*.

The information presented in *Table 2* may seem confusing, but it illustrates the attributes found in the texture layers and why there are 5 layers for topsoil and subsoil. The coding system used for texture appears simple enough, but it contains an assortment of continuous ranges with discrete classes and missing data. Cases of missing data (“no information”, Class 0) are actually present in the database (129 occurrences). This leads to a situation, where a spatial unit is completely described by STUs, but where the actual attribute in not available. Under those conditions the STU with “missing data” is treated as an incomplete description of the spatial unit by typological data.

“No texture” (Class 9) poses a specific problem: no texture value is given, but the absence of a texture value has to be treated differently from missing data. Essentially, it is not of the same type as the texture classes, but a discrete class in itself. As a consequence, a layer of “No texture” is calculated containing the portion of the class within the spatial unit. In addition, it is not clear, if Code 0 has always been used to signify “no information”, or whether at times it has been used instead of the Code 9 for “no texture”; some samples of *histosols*, which do not have a texture class but have been identified, are assigned the Code 0 (50 cases).

Table 2: Coding System of Texture Classes in SGDBt

Texture			Type Grouping for Processing	
Class Code	*Class Comment*	*Class Type*	*Class*	
0	No information	Missing data	Class 1	
1	Coarse (clay <18% and sand >65%)	Range of continuous values	Class 2	Class 2.1
2	Medium (18% < clay < 35% and sand > 15%, or clay <18% and 15% < sand < 65%)			
3	Medium fine (clay < 35% and sand < 15%)			
4	Fine (35% < clay < 6 %)			
5	Very fine (clay > 60%)			
9	No texture (histosols, ...)	Discrete category		Class 2.2

In order to allow meaningful processing of the data the coding system had to be analysed using a step-wise rearrangement of the legend entries. First, the entries were divided into two classes of “data” and “no data”. The separation allows computing a scaling factor for extrapolating the results obtained from processing typological units with data to the whole spatial unit. In a second step the texture entries were separated into sub-classes of “texture” and “no texture”. The “texture” classes were translated into components of sand, silt and clay. The texture components and the information on no texture are expressed as the relative portion of area of the attribute calculated over the area of the spatial unit with texture data. Those values are then assigned to the whole spatial unit. As a consequence, the texture mapped to a spatial unit ($Texture_{SU}$) is composed of four attributes according to the following equation:

$$Texture_{SU}(\%) = \left[Clay(\%) + Sand(\%) + Silt(\%) + No\_Texture(\%)\right]_{SU\_Data} = 100(\%)$$

This structure of representing texture in the spatial layers was preferred to a proportional representation of just the texture elements (clay (%) + sand (%) + silt (%) = 100), because it provides a direct measure of the existing texture within a spatial unit. For information purposes the area of no texture and the portion of missing data within a spatial unit are provided as separate layers.

The procedure described above could be used as presented for computing texture estimates for topsoils. Mapping subsoil texture attributes had to rely on information from more than the subsoil texture field. Subsoil texture is available in the SGDBt under fields TD1 (dominant) and TD2 (sub-dominant). Unlike topsoil texture measured textures of subsoil are much less widely available for the area covered by the database (1,872 STU have “no data” entries in the TD1 field). Estimates of subsoil texture are available for a slightly larger geographic area through the attribute for the field TD of the PTRDBt.

The values for subsoil texture mapped to the raster data layers were derived from combining the values of the various subsoil texture fields. Where measured values (TD1 or TD2) were available, they were used. Inferred values of TD of the PTRDBt were used in cases, when no measured values were recorded. Using this approach subsoil texture values could be estimated for an additional 1,254 STUs. Still, some areas remain without data on subsoil texture.

4.3.2 Peat

In the PTRDBt the attribute “Peat” is defined through rule PTR 22 (see King *et al*., 1994b). The field is of type binary, i.e. the attribute of an STU is either Y or N. No code is considered for “missing data”. In the raster layer for peat the value given is the portion of the spatial unit covered by peat.

Because the rule defines the attribute “PEAT” by the parameter “SOIL” alone and an entry exists for all STUs, a value is inferred by the PTR also for those STUs, where the entry for texture indicates missing data. Consequently, the area mapped for “PEAT” is not the area provided in the data layer on “no texture”.

4.3.3 Volume of Stones

The attribute “Volume of Stones” (*VS*) can be found in the PTRDBt. It is inferred by PTR 412. Results of applying the rule are recorded in four classes with values of 0%, 10%, 15% and 20%. The transfer figures use the class values. The default value is 0% and all STUs are coded, i.e. no provision was made for missing input data. Since none of the input data attributes are substituted by a spatial layer the value computed for the raster data layer simply comprises of the weighted class values for the typological units linked to a spatial unit. No distinction is made between topsoil and subsoil properties.

4.3.4 Depth to Rock

The attribute “Depth to Rock” (*DR*) is defined through PTR 411 and recorded in the PTRDBt. The rule is highly structured, using eight parameters to define a value. The rule outputs data into one of four classes of ranges. The ranges of the PTR are given in *Table 3*, together with the values used in the transfer to the spatial layer.

Table 3: Class Codes and Transfer Values for "Depth to Rock" Attribute

Depth to Rock		Range	Transfer Value
Class Code	*Class Name*	*cm*	*cm*
S	Shallow	< 40	20
M	Moderate	40 - 80	60
D	Deep	80 - 120	100
V	Very deep	> 120	150

In general, the transfer values for mapping the attribute correspond to the central range value. The lowest value was set to 150cm, which is considered adequate for when using the data in calculations of water storage capacity. The PTR for “Depth to Rock” uses as input data only non-substituted attributes and the spatial attribute layer is computed using the simple weighted average of the values of the typological units, which are linked to a spatial unit.

4.3.5 Structure

The soil structure property (*STR*) is defined through PTR 422 (topsoil) and PTR 423 (subsoil). Topsoil structure uses as input data the FAO soil name and land use, while subsoil structure is defined by the FAO soil name alone. The PTRs assign a structure parameter to the typological unit according to one of four qualitative values. The class codes and descriptions are given in *Table 4*.

Table 4: Class codes and Descriptions for “Structure” Attribute

Topsoil Structure		**Subsoil Structure**	
Class Code	*Class Name*	*Class Code*	*Class Name*
G	Good	G	Good
N	Normal	N	Normal
P*	Poor	P	Poor
H	Humic or peaty	O	Peaty

** Not used in PTR 422*

The class codes for topsoil and subsoil structure are almost identical with the exception of the description of a soil high in organic carbon. Since the classes are qualitative no meaningful transitional values can be computed when integrating typological units belonging to a spatial unit. The parameter is therefore mapped to four spatial layers, each representing the portion of the class in the spatial unit to which they are linked.

For the mapping of topsoil structure the land use input data of the SGDBt was substituted by the European land cover data. As a consequence, the resulting structure classes are computed for all grid points instead of aggregated spatial units. For the transfer of the subsoil structure the single input factor (FAO soil name) could not be substituted and the class portions were computed as area-weighted attributes to the spatial units.

It should be noted that the PTR for topsoil structure does not define a condition for a poor structure. Hence, there are only three spatial layers for topsoil. For subsoil structure conditions for all four classes are defined and, consequently, four spatial layers are computed.

4.3.6 Cation Exchange Capacity

The parameter "cation exchange capacity" (*CEC*) is set through the application of PTR 321 (topsoil) and PTR 322 (subsoil). The PTR topsoil *CEC* uses four parameters of input data, while two input parameters are used to define subsoil *CEC*. The input parameters used for topsoil and subsoil CEC differ considerably, as do the specific procedures applied, for which reason they are presented separately.

- ***Topsoil CEC***

  Two of the topsoil *CEC* parameters are available as spatial layers from earlier processing steps, which are topsoil organic carbon and topsoil texture. However, the continuous representation of the attributes in the data layers have to be adapted to correspond to the discrete values used in the PTR conditions. For organic carbon this is achieved by re-classifying the values according to the ranges of the four classes used in the classification system. The texture classification is a more complex system, containing four defining factors (no information, no texture, clay, sand). Using the mapped texture attributes as input elements in the PTR would require re-classifying the spatial layers according to the definition of the 7 texture classes. Given that the texture spatial layers were computed without any attribute substitution a re-combination of the spatial layers would not provide any enhancement over using the attribute data of the PTRDBt. For that reason, the attribute texture data was used in the conditions to map topsoil CEC data.

- ***Subsoil CEC***

  The input data for defining subsoil *CEC* are subsoil mineralogy and subsoil texture. Subsoil mineralogy is a parameter derived from two preceding stages of PTR implementations. All input data are derived from typological units without attribute substitution. Hence, the mapping procedure operates on the attribute values of the PTRDBt.

  The subsoil texture data used by PTR 322 is based on the field *TD1* in the SGDBt. As described in Section 4.3.1 on mapping subsoil texture, the parameter is not particularly presented in the database. It was subsequently replaced by the combined value of observed and derived subsoil texture, which was used to map the subsoil texture property.

The conditions of the PTRs for *CEC* output a value according to a class system of three items. The classes, respective descriptive comments and the transfer values are provided in *Table 5*.

Table 5: Classes and Transfer Values for Cation Exchange Capacity

Cation Exchange Capacity		Range	Transfer Value
Class Code	*Class Name*	*cmol(+)/kg*	*15cmol(+)/kg*
L	Low	< 15	8.0
M	Medium	15-40	27.5
H	High	> 40	60.0

A single set of transfer values was defined for topsoil and subsoil *CEC*. The PTRs define a value for all typological units with the default value set to class M (27.5 cmol(+)/kg).

4.3.7 Base Saturation

Topsoil Base Saturation (*BS*) is defined in PTR 331, while subsoil Base Saturation in PTR 332. The input data for topsoil *BS* consists of the FAO soil name and land use. The conditions for subsoil *BS* use the FAO soil name and subsoil mineralogy as input parameters. For computing topsoil *BS* the land use values of the database are substituted by the European land cover data. For subsoil *BS* none of the input data were substituted and the database attribute values were used to map the parameter.

The rules for BS result in one of three (topsoil) or two (subsoil) classes. The classes, a class description and the transfer values are given in *Table 6*.

Table 6: Class Codes and Transfer Values for "Base Saturation" Attribute

Base Saturation		Topsoil Range	Subsoil Range	Transfer Value
Class Code	*Class Name*	*%*	*%*	*%*
L	Low	< 50%	< 50%	30%
M	Medium	50% – 75%	-	62.5%
H	High	> 75%	> 50%	80%

The PTR for topsoil *BS* was amended in 2004 by adding a condition (No. 58), bringing the total number of conditions to 86. The default value of the PTR is set to class “H” (high). The 41 conditions in the PTR for subsoil BS were not modified. As transfer values for the two subsoil BS classes the values of the low and high classes of the topsoil classification were applied.

4.3.8 Packing Density

The measure indicating the density of particles in the soil used in the soil database is Packing Density (*PD*). It is an inferred parameter rather than an observed property (Benecke, 1966; Renger, 1970; Hodgson 1997). Topsoil I is defined through PTR 431, while PTR 432 defines subsoil I. Input data for topsoil I are topsoil structure, topsoil texture and land use. As topsoil structure input parameter the previously mapped data layer was used, which was computed using substituted values of the database land use information by the European spatial land cover layer. Evidently, the same attribute substitution was applied to the land use input data for the topsoil *PD* PTR. The texture classes were taken from the soil database for reasons described.

The PTR for subsoil *PD* used subsoil structure, subsoil texture and FAO name as input data. No attribute substitution was performed when mapping those parameters. However, the subsoil texture data used in the process was the combined data from observed and inferred subsoil texture properties.

The conditions of the PTRs define topsoil and subsoil *PD* as belonging to on of three classes. The unit for PD is [$g\ cm^{-3}$], but no values or ranges are assigned to the output classes. The transfer values had to be set according to the judgement of experienced soil scientists. The *PD* classes, descriptive names and transfer values are given in *Table 7*.

Table 7: Class Codes and Transfer Values for "Packing Density" Attribute

Packing Density		Transfer Value
Class Code	*Class Name*	$g\ cm^{-3}$
L	Low	1.10
M	Medium	1.55
H	High	1.85

Topsoil *PD* is defined by 8 conditions. The default output class is “M”, i.e. medium. Only the low and the medium classes are set in the conditions, the class “H” is not defined. All three classes are used in the 11 conditions for defining subsoil PD, which also uses a default output value of class “M”.

4.3.9 Bulk Density

Bulk Density (ρ_d) is not directly part of the soil database. It is generally a soil property, which is measured from samples. ρ_d is linked to *PD* by a simple formula (after Jones, *et al*., 2003a):

$$\rho_d = PD + 0.009 \times C \ \ (g\ cm^{-3})$$

where

ρ_d: Dry bulk density (g cm^{-3})
C: Clay content (% by weight)

In the absence of any information of observed ρ_d the property has to be estimated from the inferred *PD* through an inversion of the equation. The procedure can be applied for soils with an *OC* content of approximately up to 6%. For soils with higher *OC* the equation overestimates ρ_d significantly. Using an empirical relationship between ρ_d and *OC* allows extending the estimations of ρ_d to organic soils.

The relationship between ρ_d and *OC* observed in ground sample data from the UK could be modelled as expressed by the following equation:

$$\rho_d\_TOP = \frac{1}{3} * \ln\left(\frac{90}{0.1 + OC\_TOP}\right) \text{ (g cm}^{-3}\text{)}$$

where

ρ_d_TOP: Dry bulk density of topsoil (g cm^{-3})
OC_TOP: Organic carbon content of topsoil (% by volume)

The relationship was defined based on data covering a very wide range of measured topsoil *OC* contents (0.1 to 53%) and ρ_d values (0.15 to 2.01 g cm^{-3}) and provides a very good fit to the data with a highly significant coefficient of correlation of 0.9. Still, it was concluded that using a PTR was a more subtle approach to estimating the variations in ρ_d for soils with *OC* contents below 6%.

Consequently, the procedure applied to map topsoil BD was a combination of the two methods, where the PTR was employed to estimate BD for soils with topsoil OC content of less than 6% and the function was invoked for organic soils. A fuzzy function was used to provide a change between the two systems. Subsoil BD could not be estimated due to a lack of input data.

4.3.10 Organic Carbon Content

The spatial layer on topsoil organic carbon content (*OC*) was developed through a study not directly related to the rasterization of the soil database. *OC* estimates are part of the soil database as an inferred parameter according to PTR 21. The output classes of the rule are given in *Table 8*.

Table 8: Class Codes and Transfer Values for "Organic Carbon Content" Attribute

Organic Carbon Content		Range	Transfer Value
Class Code	*Class Name*	*%*	*%*
VL	Very Low	< 1.0	0.5
L	Low	1.1 – 2.0	1.6
M	Medium	2.1 – 6.0	4.0
H	High	> 6.0	-

With only one class covering soils high in soil OC (*SOC*), organic soils or peat the rule is not very suitable to define those soils and subsequently the areas where the soils can be found. The corresponding *SOC* content ranges from 6.0 – 60%. It would have been impractical to assign a single value to this class. Therefore, to map *SOC* content a modified and more elaborate procedure to map the attribute has been developed. Detail of the procedure are given elsewhere (Jones *et al*., 2003b; Jones, *et al*., 2005).

The data included in the raster database is processed using

- SLP spatial assignment layer
- FAO Soil sub-type
- Soil texture
- Corine Land Cover substituting the land use parameter of the PTR
- Pedo-transfer function to substitute temperature parameter of PTR

The resulting map of topsoil SOC content is presented in *Figure 6*.

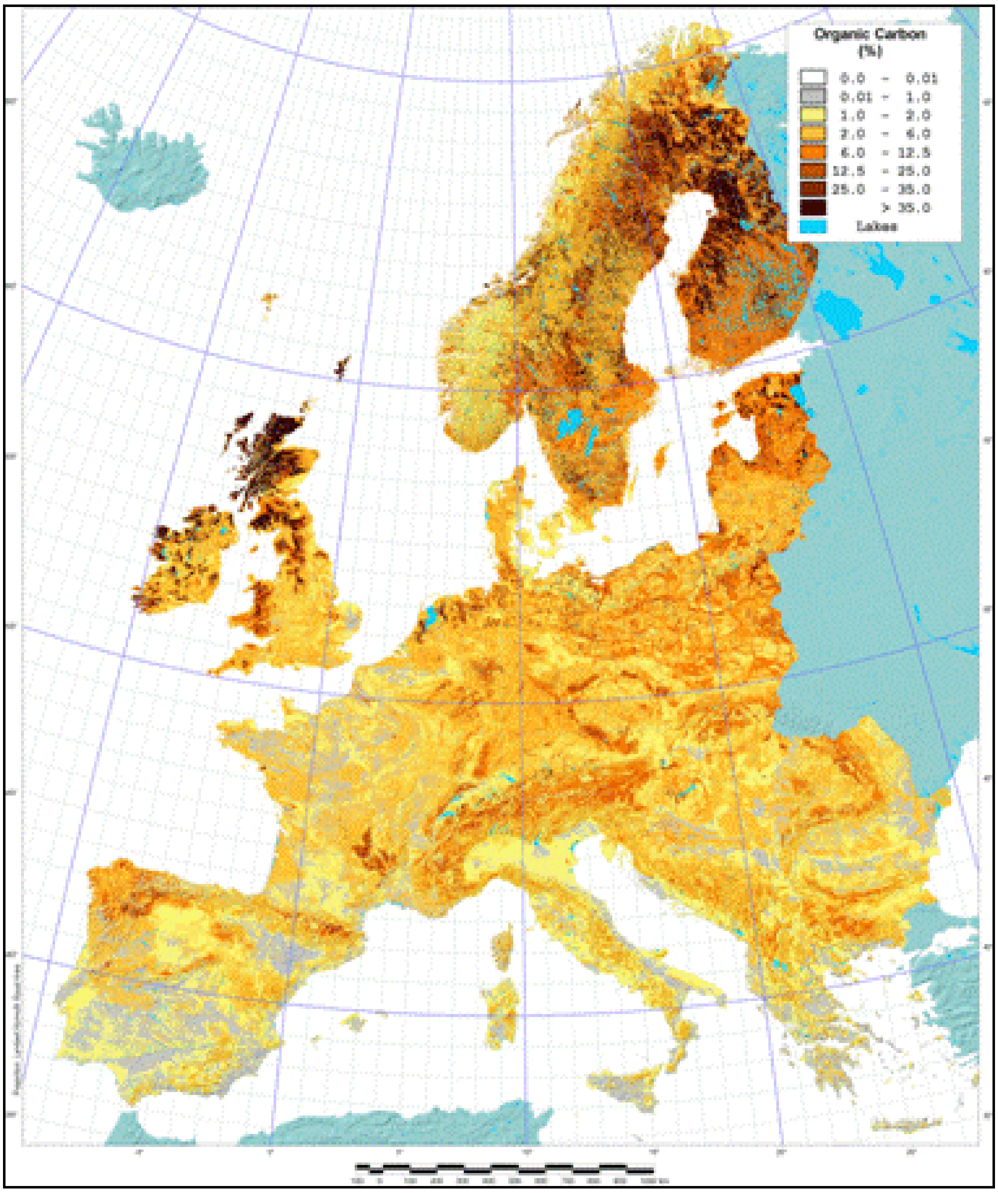


Figure 6: Spatial Data Layer of Topsoil SOC Content

The combination of *SOC* content with bulk density could result in estimates of *SOC* density or *SOC* stock. Estimates of *SOC* stock were computed as average figures at country level as a study exercise. It was found that this approach could be overly simplistic and tends to overestimate *SOC* stock. The main reason for the tendency to overestimate *SOC* stock is the transfer of a relative quantity (mass per area, kg m^{-2}) to a density (mass per volume, $kg\ m^{-3}$). *SOC* density is a function not only of bulk density, but also of layer depth and volume of stones. The SGDBt does not provide an indication of layer depths within the topsoil layer (0-30cm). Also, the information on the volume of stones is rather sketchy and indistinct. For example, no records are given for the volume of stones for Scotland. The absence of such information would lead to a bias towards higher *SOC* densities in an area which is of prominent importance to potential changes in *SOC* content in Europe.

4.3.11 Organic Matter Content

As for the bulk density property the spatial layer of "Organic Matter" (*OM*) was not estimated using the method developed under this study. Instead, it is estimated from the data of topsoil *OC* by the following relationship:

$$OM = OC\ (\%) * 1.72\ (\%)$$

where

OM: Organic matter content (% by volume)
OC: Organic carbon content (% by volume)

The attribute layer can thus be obtained from the *OC* layer by using a simple scalar operation. It is included in the raster database to complete the range of attributes provided.

5 SUMMARY AND CONCLUSIONS

The study demonstrated that information from the soil attribute databases of the SGDBE can be used to improve the geographic positioning of typological parameters in the spatial data layer. It could also be demonstrated that for soil parameters, measured or observed in units of continuous values data from all typological units pertaining to a spatial unit could be integrated into a single spatial layer by using weighted means. Furthermore, applying the conditions of the PTRs directly to spatial layers could be performed and should improve the consistency of the soil parameters with ancillary data for modelling applications.

The study also identified limitations in the extent to which typological parameters can be mapped and to the integration of all soil parameters associated with a spatial unit into a single layer. Using a single morphological criterion to guide the geographic positioning of soil attributes, it was possible to retain some indistinct spatial units with multiple links to STUs. The reason could be that soil typology is only loosely related to morphology, but also that the parameter was only vaguely observed or recorded in the database. The integration of parameters from all levels of soil typological units to spatial layers is very much linked to the success of geographically positioning STUs. Without mapping STUs directly, parameters expressed in discrete values have to be stored in separate data layers.

The transfer of the STU tables to the spatial domain has some clear advantages. It allows substituting a more uniform representation of the output parameters in the spatial layer when integrating ancillary spatial data, such as land use or slope, in the subsequent analysis. Yet, associating soil parameters with ancillary spatial data ties the resulting spatial layers to the ancillary data used. Different layers of land use or morphology could affect the distribution of soil properties within the mapping units.

The potential for substituting parameters of the PTR by ancillary spatial data and processing the rules in the spatial domain could be demonstrated by estimating topsoil SOC content. The study identified limitations in the definition of some soil parameters in the database for the topsoil layer. For estimating soil properties also in the subsoil layer, the database was found to be quite restrictive.

To further advance the development on a spatial soil parameter database it is recommended to

- Provide a method of mapping individual STUs
- Improve the conversion of values measured in continuous units from ranges to distinct values
- Complement parameters of the database with more detailed ancillary

These measures would improve the consistency of the soil parameters when integrating the data with other data sets and enhance the value of the data for surface modelling.

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Abstract

For many applications of modelling environmental conditions or developing scenarios for environmental change analysis soil property data in form of spatial layers are needed. Raster data formats are widely used for the modelling of movements through space and the storage of parameters, which change constantly and without a pattern that could be described by a plain mathematical function. This study into providing spatial soil property layers uses a soil database where the soil properties are stored in tables of generalized combinations of attributes and linked to a spatial layer of delineated mapping units with the aim to investigate the potential of providing a measure of spatial positioning of attributes within spatial mapping units and options of mapping all attributes associated with the mapping unit to a raster layer.

The method developed in the course of the study resulted in a set of spatial data of major soil properties. It also indicates that linking soil morphological data with ancillary spatial information by a multi-criteria analysis could largely improve the mapping of typological soil properties.

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