Digital Soil Mapping

as a support to production of functional maps

prepared by

Digital Soil Mapping Working Group of the European Soil Bureau Network

Edited by

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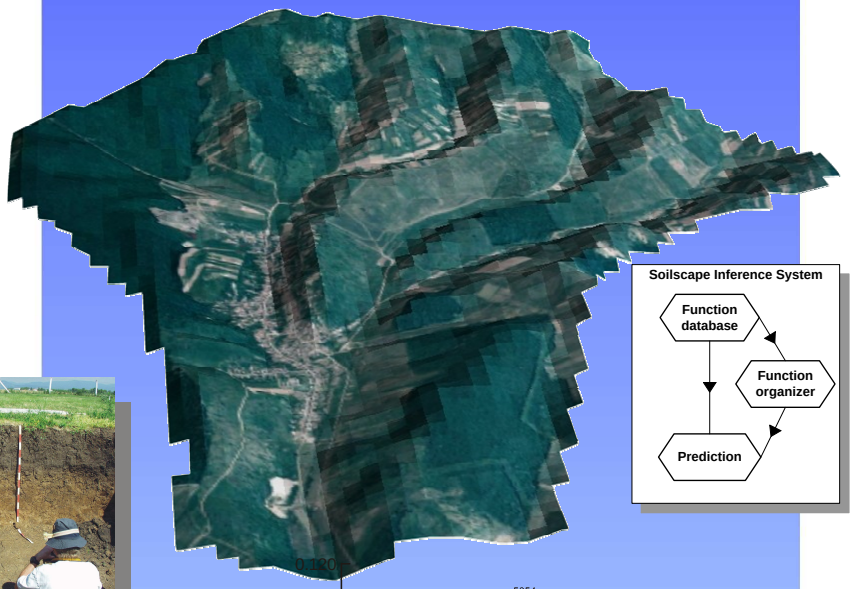

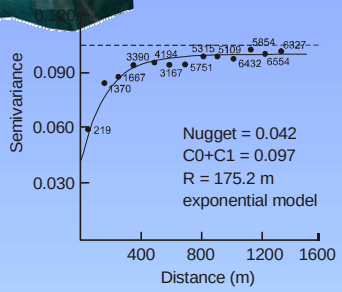

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Institute for Environment and Sustainability

2006

EUR 22123 EN

This document may be cited as follows:

Dobos, E., Carré, F., Hengl, T., Reuter, H.I., Tóth, G., 2006. Digital Soil Mapping as a support to production of functional maps. EUR 22123 EN, 68 pp. Office for Official Publications of the European Communities, Luxemburg.

The DSM Working Group is the advisory board made from researchers and soil mapping experts from EU countries. It has been founded at the last 2004 Plenary of the European Soil Bureau Network (Ispra, Nov 2004) as a support to the Soil Information WG. Its task is to review data, techniques and applications of digital soil mapping and to propose common methodologies for mapping European soils at different scales. Furthermore the WG Activities input to exploitation of potentials to assist the European Commission in policies related to sustainability of soils, namely to inventory and monitor soil functions for the purpose of policy making. For more info, see also http://eusoils.jrc.it

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REPORT OF THE DIGITAL SOIL MAPPING WG:

"Digital Soil Mapping as a support to production of functional maps"

This draft was produced through a joint effort of the members of the Digital Soil Mapping WG, coordinated by E. Dobos (University of Miskolc-Hungary)

The document has been finalized on the World Soil Day, the 5th of December, 2005.

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Table of contents:

1 Introduction

1.1 *Digital Soil Mapping WG*[1]

"Emerging soil protection policies need timely and reliable soil information"

"Soil information is ageing and still not completely available"

Numerous environmental and socio-economic models (risk assessment, scenario testing, etc.) require soil parameters as inputs to estimate and forecast changes in our future life conditions. However, the availability of soil data is limited on both national and European scales. Soil information (i) is either missing at the appropriate scale, (ii) its meaning is not well explained for reliable interpretation, or (iii) the quality of the data is questionable.

Easy-to-interpret-and-use database is needed for the future to support decision making and modelling on the EU scale. The Land Management and Natural Hazards Unit within the EC JRC is the major soil data provider to the potential users, like EEA. However, the available database often fails to provide the necessary soil parameter for the users. In order to fulfill the user requirements, a new generation of soil information, digital soil database has to be initiated that makes use of the state of the art data collection and spatial interpolation techniques. JRC (with the support of ESBN) and EEA have launched a joint work plan on "Digital soil functional mapping" to define the soil data requirement specifications and a route map to implement steps towards a spatial soil database development framework and digital soil functional mapping. In order to support this activity, ESBN has decided to setup a working group.

The WG was founded at the ESBN Plenary meeting held in Ispra, November, 2004, to serve as an advisory board for inventorying and monitoring soil properties and functions needed to support the planned legislative proposal for the protection of soil (*Soil Framework Directive*). The major goals of the working group:

1. **to advise ESBN/JRC** on Digital soil mapping activities
2. **to identify potential data sources**, database formats for the state of the art of soil information systems
3. **to advise on database harmonization** and database building for traditional and DSM needs
4. **to communicate the results and techniques of DSM** towards soil science community and data users
5. **to define the needs for digital soil functional mapping**, its terminology and framework to be setup.

More specific goals were identified later on the WG meetings after the communication with JRC and EEA. The work has been organized into two work meetings. The first meeting was held in April 7-8, 2005 in Miskolc Hungary. The objective of this meeting was:

- **to launch the working group activities,**
- **to specify the concrete tasks, actions,**
- **to define a work plan needed to fulfill the mandate of the WG,**

The road map defined on this meeting is:

1. To create a *state* ***of the art report on digital soil mapping***: its tools, data needs, quality measures and data validation techniques. The first draft of this report was to be ready for the second meeting in Prague for review by the group. The final version was to be presented to EEA and JRC by mid November.

[1] Prepared by E. Dobos.

2. **To develop a technical work plan** with concrete specifications of the data/model availability and needs, estimated output data accuracy, and financial and organizational needs to run the test and the models. Following the conclusions and specifications of the state of the art DSM report and the Soil Information Working Group (SIWG) report. This task depends on the inputs from the SIWG and to be completed in 2006.

The second meeting was held in October 13-14, 2005, Prague. The major goals of the meeting were:

- **to finalize the State of the art DSM book chapters**
- **to conclude the major tasks identified by the subgroups/chapter authors and review**
- **to comment and complement the SIWG report with a proposal of DSM procedure able to support the needs/requirements/specifications identified by the report for the five soil threats**
- **to harmonize the terminology of the major terms with the EEA**

1.2 *Key concepts* (*glossary and the framework*)

In order to introduce the Digital Soil Mapping (DSM) concepts, we first review (Fig. 1.1) the elements which are composing Digital Soil Mapping techniques, the input and output data and the relations between DSM and soil functions and threats.

Digital Soil Mapping can be understood as an advanced technique for:

- **Mapping primary soil properties or soil classes** (1st possibility). In this step a spatial inference model is needed to be established, or
- **Mapping secondary soil properties** (derived from primary properties). In this step, a spatial inference and a property inference are needed, or
- **Mapping functions and/or threats of soil**. For this, the mapper has first to map soil properties (primary and/or secondary) and must have access to external data to soil (like human behavior, land management, climate…)

In order to help stakeholders to protect the soil, some scenario have to be tested and some risks have to be assessed. These applications can be done after Digital Soil Mapping. DSM techniques can be used throughout the framework drawn in Fig. 1.1. The major limitation of this process is the lack of adequate, harmonized data on the European scale for the TIER 1 level (refer to the SIWG report for TIER 1 and TIER2) and the consistent, high spatial resolution, data for comparison and common interpretation for the TIER 2 level. Field surveys are very unlikely to happen in the near future and would be much more expensive. DSM techniques can assist to develop the missing data on a more cost effective basis, while the state of the art requirements of the quality assurance, accuracy assessment, GIS support, reported quantitative data development procedure are more easily fulfilled than in the traditional surveys. These advantages make DSM to be a crucial part of the European soil information system.

The expertise of the DSM WG makes the group capable of providing user-adjusted primary and secondary soil information layers in a functional framework to ensure multifunctional use or define and specify the needs for further research when existing data or method to extrapolate these information is not available. However, the WG is missing the expertise to define the needs of the potential data users. Specifications on the data for EU or regional level use is needed from expert groups, like the Soil Information WG, to define a wish list of optimal parameters and soil variables to manage the soil threats. Similar data specification on soil threats is also needed as major inputs for this work. We recommend setting up a new WG on soil functions and their mapping with the mandate to define soil functions, sub-functions, and the necessary data inputs and specifications to characterize them.

Glossary:

Digital Soil Map – visualization of a georeferenced soil database, which shows spatial distribution of soil types and/or soil properties; digital soil map can also be a digitized existing soil maps.

Digital Soil Mapping – is the computer-assisted production of digital maps of soil type and soil properties. It typically implies use of mathematical and statistical models that combine information from soil observations with information contained in correlated environmental variables and remote sensing images.

Soil observations – measured and observed data available from original soil survey.

Spatially predicted soil properties / classes – interpolated soil properties or classes that are now available at each location in the area of interest. This is the output from the soil spatial inference system.

Secondary soil properties – properties derived from primary soil properties using various inference models (pedo-transfer rules and environmental models).

Soil spatial inference – a procedure or a set of procedures implementing a soil-landscape model also known as the "scorpan" model used to derive soil properties or classes using available soil and auxiliary information.

Soilscape inference system – derivation of secondary soil properties using various inference models (pedo-transfer rules and environmental models).

Soil functions – various ecologic and socio-economic roles of soils, as defined in the COM179(2002) regulation; the most important soil functions are (a) soil biomass productivity, (b) organic carbon fixation, (c) support for raw material, (d) biodiversity and (e) natural heritage.

Soil threats – soil degradation processes coming usually from human activity, as defined in the COM179(2002) regulation; the most important soil threats are (a) soil organic matter decline, (b) erosion, (c) compaction, (d) salinization/sodification and (e) landslides.

Functional maps – visualisation of soil database (a complex document) usable in its current form to any further application, due to its complex description of how it was derived, what accuracy does it have (metadata), how to interpret, what it can be used for; maps easy to use for practical purposes; multifunctional maps.

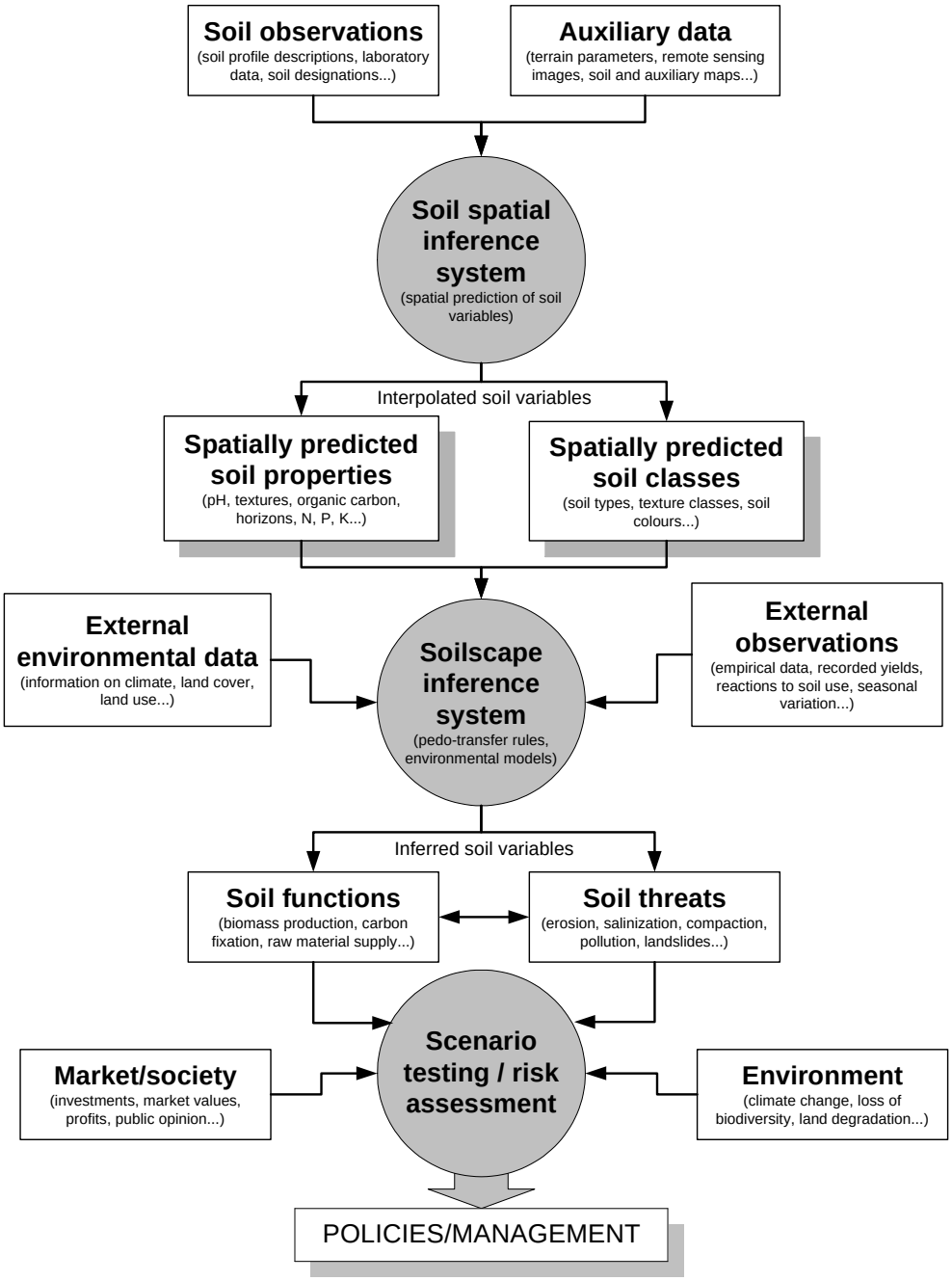

Fig. 1.1. Digital Soil Mapping steps for decision-making and policies management

1.3 *Targeted clients, potential data users, policy relevance*

The concept of "Thematic Strategies" appears in the Commissions proposal on the sixth Environmental Action Programme (6EAP) which the Commission adopted on 24th January 2001. The final text on the 6th EAP, adopted by the European Council and the European Parliament on 22 July 2002 dedicates a specific article on Thematic Strategies and lists a total of 7 strategies to be delivered for the following areas: soil, marine, air, pesticides, urban, waste and resources. In the meantime several other areas of environmental policy are following the staged and participatory approach of the thematic strategies.

Soil Framework Directive (***SFD***)

Five Technical Working Groups were established under the Thematic Strategy for Soil Protection prior to the preparation of the SFD:

- Erosion
- Organic Matter (incl. Biodiversity)
- Contamination and Land Management
- Monitoring
- Research, Sealing and cross-cutting issues

1.3.1 ***Directorate-General Environment*** (***DG ENV***)

Location: Brussels, Luxemburg

Mission statement:

Protecting, preserving and improving the environment for present and future generations, and promoting sustainable development.

Drivers:

- The ***Kyoto protocol*** identifying soil as one of the major sinks for greenhouse gases;
- The ***Water Policy***, particularly for the correct implementation of the ***Nitrates Directive*** (91/676/EEC) and the forthcoming ***Water Framework Directive***;
- The ***Waste management policy t***hrough the relevant soil data needed for the revision of the existing ***Sewage Sludge Directive*** (86/278/EEC);
- The ***Environmental Impact Assessment*** (***EIA*****)** procedure as described in Council Directive 85/337/EEC as amended by Council Directive 87/11/EC;
- The newly established ***European Soil Forum***.

DG ENV has been given the task of drafting a Soil Framework Directive, the objective of which is to identify and control/reduce the threats to soil and to preserve soil functions in Europe. The DG ENV B1. Agriculture and Soil Unit is responsible for completing a first draft Directive by the end September 2005 that is intended for consultation with Member States during November 2005. Initially focussing on five threats – erosion, organic matter decline, compaction, salinization and landslides - the remaining three threats – contamination, sealing and biodiversity – will be either dealt with later or in a different manner. In this context, Member States will be asked to delineate areas at risk of soil erosion, organic matter decline, salinization, compaction and landslides. Therefore, DG ENV will have the strongest and most immediate requirement for Digital Soil Mapping (DSM).

In this content it is important that the following criteria are established:

- the level of detail of soil information maps/data used as the basis for the risk identification
- the modelling approach used for risk identification: (1) models to predict specific parameters, such as organic matter, and (2) models to predict the trend of the different soil threats

Although the Soil Framework Directive will state that at this stage no harmonisation of data collection and monitoring is required, harmonised common criteria for soil characterisation – essentially a harmonised European Soil Database – will be required.

1.3.2 *European Environment Agency* (*EEA*)

Location: Copenhagen, Denmark

Mission statement:

The EEA aims to support sustainable development and to help achieve significant and measurable improvement in Europe's environment through the provision of timely, targeted, relevant and reliable information to policy making agents and the public.

Context: The EEA has a mandate to report on the state of European soils, and consequently has an inherent interest in soil protection. To this end, it has established a Memorandum of Understanding with the DG Joint Research Centre for JRC to provide soil information and scientific assistance. For the Agency, from the eight threats to soil, contaminated sites and contamination will be of most interest. The methodologies for risk assessment have yet to be decided.

EIONET network

EIONET is a collaborative network of the European Environment Agency with members appointed by individual Member State Governments. National Reference Centres, who are normally national data holders, are managed by Member State (MS) National Focal Points. These organisations jointly provide the information that is used for reporting on the state of the European environment and making decisions for improving the state of environment in Europe and making EU policies more effective. EIONET is both a network of organisations and an electronic network (e-EIONET).

1.3.3 *European Soil Bureau*

Location: Institute for Environment and Sustainability, Joint Research Centre, Ispra, Italy

Mission statement:

The mission of the Institute for Environmental and Sustainability is to provide scientific and technical support to EU policies for the protecting of the environment contributing to sustainable development in Europe.

ESBN network (ESBN)

The European Soil Bureau Network (ESBN), with its secretariat located at the Joint Research Centre (JRC), Ispra (I), was created in 1996 as a network of national soil science institutions. Some of these had previously been part of the Computerisation of Land Data Group, from 1982-88, and the Soil and GIS Support Group to the MARS Project, from 1990-96. The main tasks of the ESBN continue to be to collect, harmonise, organise and distribute soil information for Europe (see Table 1).

1.3.4 *Additional interested parties inside the Commission:*

- DG Agriculture (AGRI)
    - The ***Common Agricultural Policy***, particularly for the implementation of the existing (Regulation 2078/92, Regulation 2080/92) and the forthcoming agri-environmental policy, to be further strengthened through the CAP reform under AGENDA 2000,
    - The forthcoming ***GATT*** negotiation round and the need for appropriate soil indicators for agricultural production.

- DG Regional Policy (REGIO)
    - The ***European Spatial Development Perspective*.**
- DG External Relations
    - The forthcoming ***GATT*** negotiation round and the need for appropriate soil indicators for agricultural production.
    - Other ***Internationally binding agreements*** (DG DEVELOPMENT, DG ENVIRONMENT), like the UN Conference on Environment and Development in 1992 in Agenda 21 with Chapter 10 focusing on soils, the European Soil Charter (1972) and Recommendation R (92) 8 (1992) of the Council of Europe, the recent work on Public Policies for the Protection of Soil Resources by the OECD (1994), the Convention on the Protection of the World Cultural and Natural Heritage (1972), the World Soil Charter (1981), the World Charter for Nature (1982), the Convention on Biological Diversity (1992), the Alpine Convention and its protocol on soil protection (Bled, 20/10/98), and the Convention to Combat Desertification (1994).
- DG Development
- EUROSTAT
- MARS crop forecasting
- ENVASSO – environmental assessment of soil for monitoring
- INSPIRE – infrastructure for spatial information in Europe
- GMES – global monitoring for environment and security

1.3.5 *Additional interested parties outside the Commission:*

- FAO
- UNEP
- Member State Institutions

1.3.6 *Related activities*

ENVASSO – Environmental Assessment of Soil for Monitoring. This Framework 6 STREP in currently in the final stages of contract negotiation. There are 37 partners to the project which is being coordinated by Cranfield University, National Soil Resources Institute, UK.

2 State of the art of DSM

2.1 *Soil data and auxiliary information*[2]

2.1.1 *Introduction*

Soil mapping in general requires (i) a predefined model of soil formation, (ii) data on soil properties and on other environmental variables that have significant impact on soil formation and thus on the spatial distribution of the soil properties. In this sense, traditional soil mapping and digital soil mapping do not differ much. Both approaches need input data on soil and covariates characterizing the environment where the soil formation takes place. The major difference is the way how the model derives the soil information from the input data. The traditional models are based on empirical studies and qualitatively defined correlation that formulates a mental model in the surveyor's mind used to understand and characterize the soil resources. This approach requires intensive field work. Decisions are made mainly on the field, where all environmental covariates can be directly observed and information on the soil can be deduced. The digital soil mapping approach is quite similar; it is based on hard soil data as well. Like in the traditional approach, profile information is needed to train our models, and to understand the soil resources of the area. The major differences, the strengths and also the limitations are coming from the way how the environmental covariates are represented in the procedure. Digital soil mapping requires digital data sources as input variables for the quantitative models. Jenny's well-known equation (1941) identified 5 major factors in the soil formation, namely the climate, organism, relief, parent material and time:

$$S = f\,(cl, o, r, p, t)$$

The prediction of the soil variables and a successful survey needs good quality, adequate resolution input data. Jenny's approach focuses on the prediction of certain soil chemical, physical or biological characteristics on a given location and did not consider the soil as a continuum, where the soil properties at a given location depend on their geographic position and also on the soil properties at neighbouring locations. This fact is utilized by geostatisticians, who predict soil properties of a given site from known observations neighboring the point. From an applied soil survey point of view, the group of the five soil forming factors needs to be enlarged with the addition of the geographic position.

Some soil properties are difficult or expensive to measure, but can be predicted with acceptable accuracy from other soil parameters of the same location. That we also have to consider, where a full picture has to be painted about the data needs for soil property. This approach was followed and summarized by McBratney *et al.* (2003), who identified 7 factors for soil spatial prediction:

S: Soil properties at the same location

C: Climate

O: Organism

R: Relief

P: Parent material

A: Age, time

N: Geographic position

and formulated the so called SCORPAN equation:

[2] Prepared by T. Hengl and E. Dobos

$$S_a = f(S, C, O, R, P, A, N) \quad \text{and} \quad S_{cl} = f(S, C, O, R, P, A, N)$$

where S_a is the estimated soil attribute value and S_{cl} is the estimated soil property class. This approach is followed here as well to summarize the data needs for digital soil mapping.

2.1.2 *Soil profile observations in Europe*

Existing soil maps and profile databases in EU

European countries are great reservoirs of existing large and medium scale soil maps, many still in paper form (Jones *et al.*, 2005). The major limitation of such kind of data is the lack of exact geographic positioning. In addition only generalized polygons are available with potential inclusions of other soil bodies, which cannot be represented using the nominal scale. These data sources often provide only representative data, giving the most dominant soil information for the area covered by the polygon. In a small scale DSM study, large or medium scale soil maps can be useful for training the model or can be used indirectly to deduce qualitative or quantitative rules and build an expert knowledge based classification scheme. At the moment, there is an ongoing joint project between ISRIC and JRC to collect and digitize all the available soil maps for the five continents. The work is ongoing and the European CD will be issued in the near future.

Another big reservoir of soil information are the profile databases. Soil profile observations is the primary soil information that is collected on the field and represents the most certain information on soils ('ground truth'). Collecting profile data is the most time-consuming and costly part of the surveying procedure. Such data is theoretically unaltered, unprocessed, and thus can be an unbiased input for all type of applications using different processing methods. Soil profile observations are typically **the most valuable part of soil survey and they represent the major input into the soil spatial inference system** (Fig. 1.1). Note that profile data is crucial for DSM work, but the results of interpolation can be often poor when non-representative profiles are used to characterize areas.

In EU, profile data is often collected by national institutions. We estimated that there must be over 500.000 detailed soil profiles described over EU countries in last 20-30 years (Table 2.1). Unfortunately, many responsible national institutions are not willing to give this data out easily; instead only processed, generalized products are marketed. Unlike in USA, the most of environmental data from governmental agencies in EU are 'clouded' with licence agreements, which do not offer much more than simple viewing or interpretation of the data (Rossiter, 2004). Often, it is not easy even to found out who distributes the data and in which format. The fact that soil profile data from the national surveys are not available to public is one of the major constrains for pan-European DSM projects. There are also great differences in both the measurement techniques as well as the storage techniques of existing soil profile data across Europe (Jones *at al.*, 2005). This has to be addressed through metadata definitions as well as by developing appropriate harmonization techniques. In general, national datasets are fairly difficult to harmonize. There are successful initiations as well, like the ECALP project, aimed to harmonize soil databases along the border for the Alpine areas, or the Forest monitoring project, from which an internationally accepted guideline has been set up and being tested to create a harmonized EU wide monitoring site coverage. Another example is the Danube basin project, which now gathers some 8.000 soil profiles (Fig. 2.1) and which will be used for flooding monitoring projects [http://natural-hazards.jrc.it/].

One of the most urgent tasks for the soil science community acting on the European scale is to create common guideline for sampling and characterizing soil profiles incorporating/utilizing the results of the above mentioned projects. Special attention has to be put on the representativity of the profile location (geomorphologic, geological, land-use, land cover point of views) and to sampling techniques (bulk or point samples) to ensure representative values.

Table 2.1. Estimated number of profiles per EU countries.

Country	<1:200K	1:200K - 1:25K	>1:25K	Number of Sampling (Inventory or Monitoring) sites
Albania	100%		28%	
Austria		63-98%	10-63%	5.000 (F) + 2,500 (A) + 26.000 analyses …
Belgium	100%	100%	100%	15.000 soil profiles + analyses
Bosnia & H.		100%		
Bulgaria	100%	100%	90%	50.000 main soil profiles
Croatia		100%		2.200 soil profiles
Cyprus	100%	100%		nitrate monitoring (1:250.000)
Czech Rep.	100%	100%	100%	30.000 soil profiles + 200 permanent plots + 500 forest plots
Denmark	100%	100%	in prep	8.000 soil profiles (7 km grid) + 393 heavy metal samples
Estonia	100%	100%	100%	10.000 soil profiles; various monitoring programmes
Finland	In prep.	30%		28.000 (texture) + 90.000 samples + 2.000 heavy metal samples
France	30%	Incomplete	case studies	ICP Ft (16 km grid, 540 plots) + …
Germany	30%	Incomplete	case studies	over 10.000 profiles per federal state
Greece			case studies	3.000 sites for fertiliser monitoring
Hungary	100%	100%	70%	1.200 points (800 A + 200 F + 200 hot spots)
Iceland	100%	75%		soil erosion database
Ireland	100%	44%		295 soil points (22% of country)
Italy	100%		case studies	
Latvia	100%		100% (A)	2.547 points (5 km grid); various monitoring projects
Lithuania	100%		farm level	7.000 profiles + various monitoring projects
Luxembourg	100%	100%		
Macedonia				
Malta		100%		280 profiles (1km grid) + 350 profiles + 800 soil samples
Netherlands	100%	100%	55%	various monitoring projects
Norway				9 km grid (F)
Poland		district level		2.000 (F) + 5,700 (A) + 1.000 mineral soil samples + 216 plots
Portugal	100%	35%	case studies	800 described + 100 analyzed + erosion monitoring
Romania	100%	80%	20%	4.200 + 942 profiles (16 km grid) + 1.200 pedo-geochemical
Serbia	100%		Case studies	some monitoring
Slovakia	100%		100%	18.000 soil profiles + 330 (A) and 280 (F) monitoring points
Slovenia	100%	100%	100% (A)	1.700 soil profiles + pollution (2 and 4 km grids)
Spain	50%	15%		453 profiles + 2.000 critical loads + 20.000 (erosion) + contamination: 1.200 (pastures) +2.600 (arable land)
Sweden		1% (A)		ICP Forest soil monitoring (no. of sites not known)
Turkey		irrigation		
UK	100%	30%	case studies	6.000 soil profiles + 9.000 national (5km grid) + 2.200 sites…

Correlation of the existing profile databases

Correlation and cross-border **harmonization of the national profile datasets would be the most cost effective approach to create an EU wide profile database**. However, there are serious constrains: due to 'uncorrelatable' variables used in different national systems and also due to varying uncertainty within the dataset (see Table 2.1). A thorough statistical study on the Danube profile database collected for the Flashflood model within JRC would be an ideal pilot study to test the potential of 'bias-corrected' international profile database compilation (Fig. 2.1). In the meantime, bilateral harmonization studies could be initiated as well to test the correlation on the simplest setup, having only two types of data, which can be later compared on a much wider scale. In a mid term view it is necessary to build or buy soil profile database for European use that is available both for correlation and harmonization studies and for deriving thematic soil property layers to Commission use.

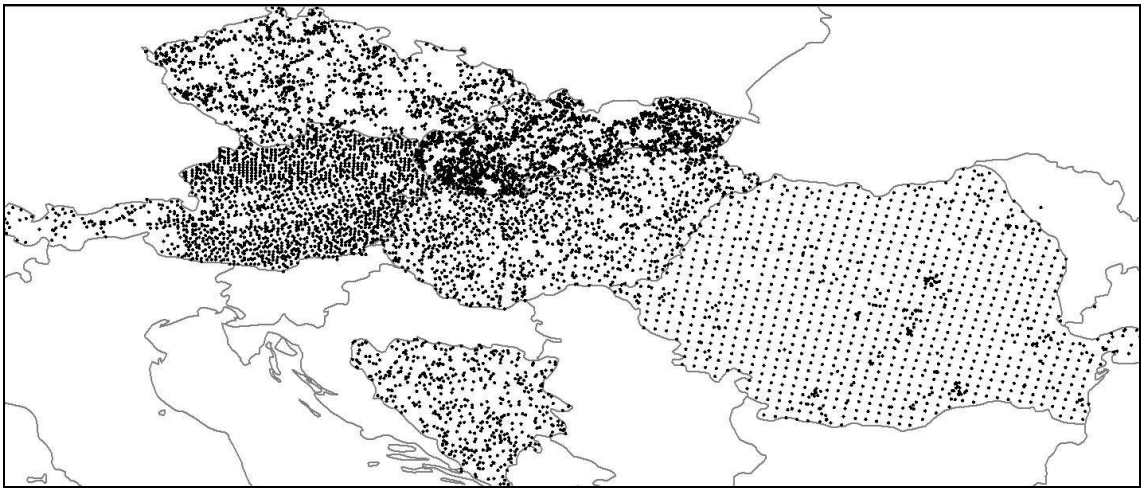

Fig. 2.1. The Danube basin soil profiles with integrated national soil survey profiles. Note how striking are the differences between the sampling densities, sampling designs and representativity of the point samples between the neighbouring countries.

Existing or new surveys?

Although some datasets are already available at JRC (for example SPADE), most of the countries keep their data confidentially, often without a clear distribution policy. In addition, many countries have not translated the local classification systems to the international one (WRB), which might ask for additional efforts. The SPADE project is in that sense a real step forward, however it, at the moment, consists of only 496 profiles sparsely spread around the EU continent. The number of profiles needs to be increased by 3-4 or more time, especially by the data from France, Germany, Spain and Italy. Integration and merging of such a large amount of subsets might be very time and resource consuming. In fact, a serious question is weather the soil data from different EU countries can be integrated and improved at all?

In principle, it would be relatively hard to run reliable interpolations by using point data with less than 2000 profiles[3] and without covering at least 80% of the EU continent. The Australian team (Henderson *et al.*, 2005) has, for example, used over 150.000 profile observations to make the soil atlas of Australia [http://audit.ea.gov.au/anra/]. US Geological Survey works with a Geochemical Survey point database that consists of some 60.000 measurements [http://tin.er.usgs.gov/geochem/] of heavy metals and similar soil attributes. Similarly, the DSM WG stresses the requirement for new data collection. The DG Environment has just started the Forest FOCUS BioSoil project where about 8.000 detailed soil profiles will be collected, regularly spread over all EU countries. Such data will not only have multifunctional use, but it will be highly

[3] This is because each predictor requires at least 10-50 measurements and we also need to diminish impact of outliers and unrepresentative profiles.

usable due to a high consistency of methodology of sampling, description and laboratory analysis. If a similar project would be implemented for the agricultural and urban areas, we would be able to have a consistent soil profile data set with probably more than 20.000 profiles of high quality and ideal consistency. Such datasets would revolutionalize the DSM mapping over EU and reduce the existing data gap between the EU and USA or Australia.

2.1.3 *Auxiliary sources of soil-related information*

Typically, there are four major groups of the auxiliary information: climate, organism, relief, parent material and time. McBratney *et al.* (2003) further added to this list the geographical location of the soil profiles and the available soil properties that show correlation with the ones to be estimated. These are the major inputs of a statistical framework – also known as SCORPAN – used to predict soil variables at each location of the study of interest. SCORPAN is a conceptual model of soil spatial inference. In practice, we work with images or maps that come from different sources, different companies or technologies. A common spatial prediction technique that can be used to apply SCORPAN model is the regression-kriging (Fig. 2.2.), which we use to illustrate the general flow of data through the system to estimate the unknown soil parameters. These models assume that there is a stochastic relationship between various predictors and target soil variables, although it can also be used to improve the deterministic models of soil genesis (Hengl *et al.*, 2006).

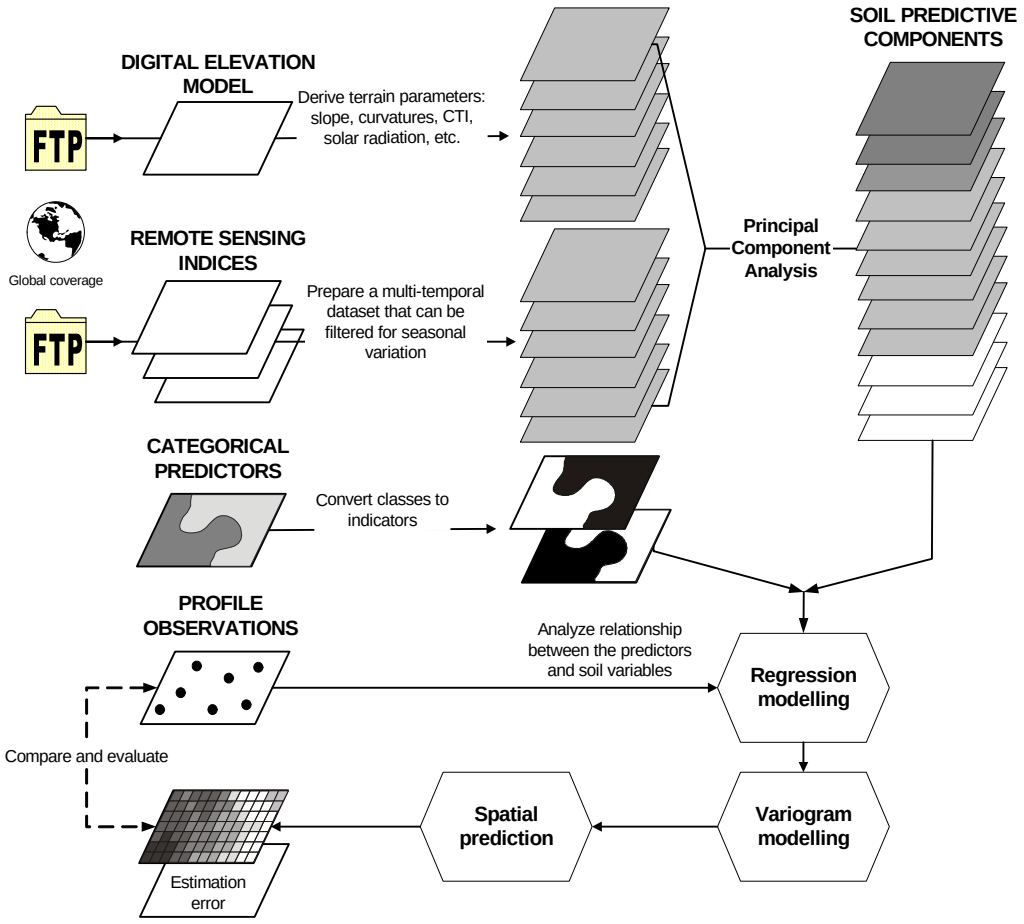

Fig. 2.2. Example of data-flow used to interpolate soil variables from profile observations using auxiliary information (the regression-kriging model).

In practice, we deal with about three types of soil auxiliary information (in statistical terms 'predictors'): (a) remote sensing images; (b) topographic information and (c) thematic maps interesting for soil mapping (Table 2.2). In this case, also (traditional) soil delineations can be considered to be just another layer of auxiliary information. In further text, the three main groups of auxiliary information and its applicability for soil predictive mapping and small and medium scales/resolutions will be described.

Table 2.2. General sources of auxiliary information for DSM applications at EU scales.

Data type	data sub-type	Detailed resolutions (<20 m)	Medium resolutions (20-200 m)	Coarse resolutions (>200 m)
Remote sensing imagery	Multi-spectral imagery	**IKONOS, SPOT**	**LANDSAT, ASTER**	**MODIS, MERIS**
	Hyper-spectral imagery		**AVIRIS**	
	Radar and radiometrics imagery	**Airborn EM LIDAR**		**ASAR, MWR**
Topography	Topographic information	**National mapping agencies**	**SRTM**	**GTOPO**
Auxiliary thematic maps	Climatic variables		**National meteorological agencies**	**MARS**
	Vegetation / land cover maps		**CLC1990 100 m**	**CLC 1990 250 m**
	Geological and parent material maps		**Geological surveys**	**FOREGS**
	Soil delineations	**Regional soil surveys**	**National soil surveys**	**ESBN**

Climate Data

Climate data are usually punctual and provided with a coarse resolution, from 2 km for national scale soil map to 50 km for European data-MARS Data (Genovese, 2001). These data are derived based on the ground measurements coming from more than 6000 stations distributed in 48 countries. Common climatic variables that are regularly observed and mapped over whole EU are: minimum and maximum temperature, cumulated mean temperature, mean temperature, precipitation, potential evapotranspiration, climatic water balance, global radiation, snow depth and similar. The MARS Data provides also information about annual phenological calendar in order to put in relation climate attributes with vegetation cycles. Considering soil properties, climate can explain soil functions and threats of soil like soil particles loss, weathering and erosion of soil, soil fertility.

Remote Sensing images

The literature review (McBratney *et al.*, 2003) indicates the following major soil properties showing relatively high correlation with remote sensing images: iron-oxide content, soil organic matter content, salt content, parent material differences, soil moisture content, and some chemical and physical properties like pH, calcium-carbonate, mineral N, total carbon, total and available phosphorus, clay- silt- and sand contents. Some soil properties are directly related to the surface colour and thus relatively easy to map when the soil is bare and visible spectra is used to detect the colour. Iron-oxide and organic matter content, and partly the soil moisture contents and soil texture are good examples of that. Other soil features, like many of the chemical properties of the deeper horizons, can be detected only indirectly, through the type and the condition of the surface vegetation. These relationships are often indirect and explain less of the total spatial variation than the one for the soil surface properties. Many lab-spectrometer simulations have been carried out to identify the spectral reflectance changes of soils due to certain physical and chemical alteration of the soil. These studies concluded significant

relationships between remote sensing images and soil properties and proved the primary importance of the above mentioned properties in determining the spectral response of soils (Ben-Dor, 2002).

Although it was originally expected that remote sensing would revolutionize soil mapping, as it had done for vegetation mapping, the direct derivation of soil properties from remote sensing data is still limited to areas of low vegetation cover, such as grasslands, semi-deserts or agricultural plots in fallow. Apart from some specific cases, such as using radar images to map soil moisture content, it has not yet proved possible to use images of visible and infrared part of spectra directly to map soils in all parts of the study area. This is due to the complex illumination structure caused by terrain, cloud interference and atmospheric attenuation, or reflectance of vegetation. Until the day, many types of sensors have been used for soil studies. Majority employed high spatial resolution sensors, the Landsat TM with 30 meter, the SPOT with 20 meter resolutions and IRS LISS II with 23 meter resolution. There is no overall agreement in the literature about the selection of Landsat bands for deriving soil information. Some authors mention all bands as significant information sources, while other highlight the outstanding performances of the green, red and especially the thermal infrared bands. The thermal band of the Landsat TM has shown to be significant in contributing to the separability of soil categories through its ability to characterize the clay, organic matter, and iron-oxide content of the soil. Active remote sensing, like radar sensing has been successfully used for surface structure measurement, and also for measuring direct soil properties like surface roughness and soil moisture contents.

Compound remote sensing indices such as NDVI, which generally reflects biomass status, have been shown to correlate well with the distribution of the organic matter or epipedon thickness (McKenzie & Ryan, 1999). Even the coarse (1×1 km) AVHRR data have shown to be useful for mapping the clay content, CEC, EC or pH (McBratney *et al.*, 2003). A logical further development was to combine DEM-derived and remote sensing data to improve prediction models (Dobos *et al*., 2000). The use of combined terrain data and remote sensing imagery has been especially interesting for medium scale-surveys (grid resolutions from 20–200 m), although there have also been an increasing number of field-site (precision agriculture) studies. It is also important to use the multi-temporal data sources to cover the temporal changes of the environment and increase the separability between soil types based on the temporal changes occurring in the soil forming environment. Although, individual images often show tremendous amount of spatial detail, the use of multi-temporal RS databases complemented with terrain information is concluded to be essential for deriving reliable soil classification categories (McBratney *et al*., 2003).

In the last few years a new era of very high spatial and spectral resolution remote sensing has become available. Sensors, like AVIRIS [http://aviris.jpl.nasa.gov], are already used for soil characterization (Palacios-Orueta *et al.*,1999). In addition, we have now a possibility to make images not only of surface cover, but also of the sub-surface and even deeper sub-surface. This is possible with the use **of gamma radiometrics and electromagnetic sensors**. Many successful studies with such sensors have been carried out world-wide, mostly in Australia. This data was also used recently in Finland for the 1:250.000 scale soil map of Finland. A good model how should be the new soil/geological survey done is, for example, the TELLUS project [http://www.tellus.detini.gov.uk], which is the Geophysical/geochemical survey project for the Northern Ireland. TELLUS consists of two parts: (a) ground survey – collection of soils samples, waters and stream sediments at 1-4 sites per km^2; and (b) airborne survey – an aircraft equipped with magnetic field gradiometer, 256 channel gamma-ray spectrometer and 4 frequency electromagnetic (EM) system. The large amount of images showing not only surface but also the subsurface features will be correlated with the field measurements to produce accurate maps of soil texture, parent material, mineralogy and current and paleo-hydrological soil properties. Note that collaboration between the soil mappers and geologist could also be extended to vegetation mappers and similar environmental sciences – the cost of the survey can be seriously reduced if joint projects are conducted (one aircraft – multiple sensors, one field survey – multiple analyses).

One of the most interesting data sources of remote sensing data for pan-European mapping is the MODIS imagery that has relatively coarse spatial details (250 m), but excellent temporal coverage (images available every 15 days). In addition, this data is freely distributed via the NASA's Distributed Active Archive Centre [ftp://e0dps01u.ecs.nasa.gov]. The original MODIS data are prepared in the Sinusoidal projection system with WGS84 ellipsoid. The true advantage of using multi-temporal EVI set is that different vegetation types and land

farming practices can be incorporated in the modelling of soils. Assuming that vegetation and organism are an important soil forming factor, such information can supplement pure terrain parameters for spatial prediction of soil variables.

Digital elevation models and terrain parameters

Relief or topography can be characterized with the use of digital elevation models (DEM). DEM is used to derive quantitative measures of soil forming processes, also called terrain parameterization. This is a process of quantitative description of terrain by terrain parameters. These can be derived using various algorithms that quantify morphological, hydrological, ecological and other aspects of a terrain. In simple terms, terrain parameterization is extraction of terrain parameters using input digital elevation models and terrain parameterization software. Extracted terrain parameters can then be used, for example, to improve mapping and modelling of soils, vegetation, land use, geomorphologic and geological features and similar. There are relatively simple and easy to derive terrain parameters (the slope gradient, aspect, curvature) and there are some more complex ones which are derived with the combined use of the primary terrain parameters. The primary features are direct descriptors of the terrain features, like the slope, curvature or aspect, while secondary features describe more complex characteristics of the landform, which are linked to certain terrain-regulated processes, like stream power index or the compound topographic index (CTI). These features can be used to estimate potential soil loss or sedimentation and also for calculating "terrain-adjusted" climatic variables, like temperature, solar irradiation, long wave surface radiation, reflected radiation, which are important factors in the energy balance of the surface and thus in the soil formation. A thorough summary of these secondary variables and programs that calculates them can be found in the book of Wilson and Galant (2000). The terrain features, like slope or aspect, which are recognized as leading-forces of the soil formation within a relatively small area, show significant relationship with soil attributes, but often represent low predictive value when used individually. However, when these terrain variables are combined in one model, the predictive value can raise relatively high. The use of digital terrain parameters as soil predictors is certainly not only the way of organizing our soil-landscape knowledge, but one of the most powerful ways certainly.

The most common terrain parameters:
Absolute elevation
Relative elevation (surface roughness)
Slope / aspect
Curvatures
Specific catchment area
Length of slope
Distance from the waterway
Height above the closest waterway
Potential drainage density
Generic landform shapes
Wetness index or CTI
Stream Power Index (SPI)
Drainage Proximity Index (DPI)
Accumulated Flow Index (AFI)
Sediment Transport Capacity Index (STCI)
Incoming solar radiation
Solar radiation hours
Relative wind exposition

The terrain defines the way how the water moves through the landscape and transport soil materials in solid or soluted forms. Thus, the variables, which controls the way of water flow have the greatest significance in explaining the spatial distribution of numerous soil properties. The majority of the studies use slope gradient, curvature and CTI variables among others, which are proved to describe these water-movement–controlled material transport through the landscape. Many of the soil landscape elements, variables have been translated to DEM-derivable format. There is a good and commonly accepted toolkit of digital terrain variables, but the need to develop new variables and approaches to improve our capability of soil-landscape modelling and decrease the unexplained portion of the soil-landscape relationship is still evident.

One of the most limiting factors of the use of the DEM is its accuracy and spatial resolution. Different DEM resolutions and DEM derivatives were investigated and evaluated for use in soil studies. McBratney *et al.* (2003) suggested a way to relate resolutions and the corresponding cartographic scale and extent of the study area. Predictive relationships developed at one scale might not be useful for prediction at different scales. That may limit the use of terrain variables developed for large scale in small-scale studies. The majority of the studies were carried out in the field or small watershed scale. Ten out of the nineteen cited “DEM-papers” used an original grid spacing of less than 20 meters, 7 of

them used 20-50 meter resolution, while only three used coarser resolution DEM (100-1000 meter spatial resolution) and carried out regional or continental scale studies. Many of the papers stayed with relatively high resolution DEM to keep the study area small enough to ensure its lithological and climatic homogeneity and to minimize the noise or error of the prediction model generated from the non-terrain origin variability of the soil forming environment. With increasing study size, the prediction error for pure digital terrain variable containing model is always increasing.

At JRC, a Digital elevation model (DEM) of the EU has already been prepared from the SRTM at 90 m resolution and topographic survey data (for Scandinavian countries above 60º N latitude). Although STRM DEM defines a surface[4] rather than a terrain model, this is one of the most consistent and most detailed sources of topographic information. Further improvements to the SRTM data are expected over the next couple of years. There is an ongoing work within JRC to create a filtered and adjusted 100 m resolution DEM for the whole area of Europe. A coarse spatial resolution DEM with 1 km grid size is also available. Note that there is also the higher resolution SRTM DEM, i.e. the original, processed Shuttle DEM with a 30 m resolution. However, the access to these data is still limited for the EU continent. Certainly the integration of the DEMs derived from the national topographic surveys (contour lines from the 1:25K topo-maps) and RS-based DEMs is the step that needs to be undertaken before actual extraction of terrain parameters.

2.1.4 *Conclusions*

A large amount of both soil and auxiliary data is today available at pan-European scales. In the case of soil data (soil profiles), a serious effort needs to be done to integrate all existing national surveys to produce a coherent soil profile database for the EU. A relevant question is whether the soil data from different EU countries can be integrated and improved at all? We definitively hope to find some kind of compromise between the data quality, accessibility and coverage. If this does not prove to be successful, we should also consider using data from new surveys (see for example BioSoils) with well described and harmonized/consistent soil mapping methodology – from sampling designs to laboratory analysis and interpretation of results. If a similar project would be implemented for the agricultural and urban areas, we would be able to have a consistent pan-European soil profile data set with probably more than 20.000 profiles of high quality and consistency. This could then be used to produce images of key primary and secondary soil properties at fine resolutions of 250 m or better. The biggest cumbersome to run interpolation on the 250 m grid[5] would be the computational complexity. Running, for example, regression-kriging on the 1 million pixels can easily last over 12 hours, not to mention the 100 million pixel grids. Still, Australian teams have shown that it is possible to work with so extensive data and produce usable products (Henderson *et al.*, 2005).

There are three main sources of auxiliary information that can be used to improve the spatial and thematic detail of existing maps: (a) remote sensing images, (b) topographic images and (c) auxiliary thematic maps. The terrain parameters are DEM-derived products that can be used to quantify the (geo)morphology of the terrain (soilscape or soil-landscape), i.e. accumulation and deposition potential, or to adjust the influence of climatic factors on the local terrain. The remote sensing images reflect the overall environmental conditions,

The most important data sources for pan-European DSM are:

- **National soil profile databases; Forect FOCUS BioSoil profile database and similar;**
- **(SRTM-based) Digital elevation model of Europe at resolution of 90 m;**
- **MARS meteorological database of Europe;**
- **MODIS multi-temporal 15 days composites (250 m resolution);**
- **Soil-type, geological and land cover maps and images produces at similar resolutions**

[4] SRTM DEM shows the surface of all objects scanned, so that forest and urban areas are shown as topographic features, which means that such areas need to filtered out.

[5] The 250 m grid is about 18514×18294 pixels (33-336 MB); in the case of 1 km grid resolution there are 4628×4573 pixel (2-21 MB).

type and conditions of the vegetation influenced by the soil properties, surface roughness, colour, moisture content and other surface characteristics of soils. Unlike the soil profile data, auxiliary data are already available and ready to use without a need for calibration and harmonization. Many remote sensing images of the considered scale are today available even at no cost. Especially SRTM DEMs (Farr and Kobrick, 2000) and (MODIS) vegetation indices are rich sources of auxiliary data, which can be downloaded at no cost via NASA's Distributed Active Archive Centre.

2.2 *DSM models*[9]

Digital soil Models are the set of inferences - and their combination - that aims to predict secondary soil properties from sets of soil data and auxiliary spatial variable describing the variations of the soil forming factors over the mapped zone. A lot of research has been done on these models since the early 1990's and exhaustive reviews of these models are now available (McBratney *et al.*, 2003; Scull, 2003; Walter *et al.*, in press). We are now moving toward the use of these models for the effective production of digital soil information over regions, nations and continent (Henderson and Bui, 2005). In the perspective of such an operational production, i.e. "soil functional mapping", for Europe and for its state members we shortly describe in this chapter the different types of available soil models and their possible integration in a future spatial soil inference system that could progressively replace the geo-referenced soil databases currently in use in Europe. In view of reaching this perspective, some preliminary tasks that could be included in a next research program are finally presented.

2.2.1 *The different types of DSM models*

Fig. 2.3 shows the different types of DSM models that are used in Digital Soil Mapping. A first distinction between DSM models is made according to the nature of the inference they concern. It is thus distinguished (1) Spatial inference models or scorpan models that produces soil class maps and maps of soil properties from soil observations and auxiliary spatial variables and (2) soilscape inference models or attribute models which derives new properties from these previously produced outputs. These two types are briefly examined in the following.

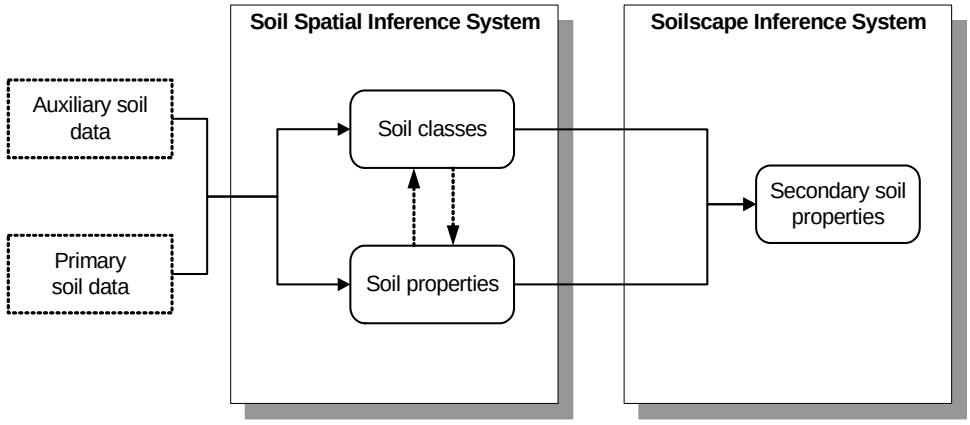

Fig. 2.3. The different types of DSM models (after Lagacherie & McBratney, in press).

Spatial Inference models

A detailed inventory of these type of models ("scorpan functions") has been recently presented by McBratney *et al.* (2003). They propose a general formulation of these models through the equation $S = f(Q) + e$ where S stands for soil class or soil attribute, Q is the scorpan predictor variables included in the auxiliary database (see §3.1), and e is the prediction error. The general approach for establishing these functions is to take m observations of S in the field at known locations $[x, y]$ and relate them with some kind of function to a set of

[9] Prepared by P. Lagacherie.

pedologically meaningful predictor variables *Q* which will generally be a set of variables or data layers of size *M* at locations [*X*, *Y*] from the auxiliary database with the [*x*, *y*] ⊂ [*X*, *Y*]. Once the model is fitted at the *m* observation points, the predictions can be extended to the *M* points or cells in the raster layer thereby giving a digital map. The efficiency of the method relies on the fact that hopefully m << *M* and because *S* is much more difficult and expensive to measure than the *Q*. A number of possible soil models have been proposed for predicting either soil classes (the *class Scorpan Function*) or soil properties (*Property Scorpan Functions*). Three great ways of building such models can be roughly distinguished:

- **the "data-mining way"** – that consists in discovering from a training set of data the unknown relationships between the predictor variables *Q* and the predicted variable *S*. The hypothesis made by this approach is that all the required knowledge to establish soil predictions is contained in the data and can be extracted if a sufficient amount of training data can be collected. The most frequently data mining models used in soil science are multiple regression (e.g. Moore *et al.*, 1993; Odeh *et al.*, 1994), classification trees (Bell *et al.*, 1992), and neural network (McBratney *et al.*, 2000; Zhu, 2000; Behrens, 2005). Because they are fully generic, such models are well documented, largely implemented in statistical software and possibly coupled with GIS.
- **the "geostatistical way"** – initially proposed in soil science for interpolating soil properties from dense sets of soil observations collected over small areas, geostatistical models have been further extended to larger areas where spatial variations may exhibits trends. To deal with these more complex situations, more sophisticated models such as regression kriging (Odeh *et al.*, 1994) or Kriging with external Drift (Bourennanne *et al.*, 2000) using layers of predictor variables *Q* have been tested. Their theoretical advantage over the data mining models is that their soil predictions integrate not only the correlations with *Q* but also the spatial correlations between the soil observations.
- **the "soil surveyor way"** – consist of building the relations $S = f(Q) + e$ from the knowledge of soil surveyors having substantial experience in a given region. Several methodologies for capturing this knowledge have been experimented (see a review in Walter *et al.*, in press): narrative models translated into a set of rules "if conditions on Q then prediction on S" (McKenzie *et al.*, 1999, Cole *et al.*, 2004), Bayesian belief networks (Skidmore, 1991), Fuzzy inference systems (Zhu *et al.*, 1996), conditional probabilities derived from existing soil maps (Lagacherie *et al.*, 1995). Some hybrid approaches have also been tested, which consist in embedding soil surveyor knowledge in data mining models (Lagacherie & Holmes, 1997, Bui *et al.*, 2003) or geostatistical models (e.g. Voltz & Webster, 1990) through the use of existing soil digitised soil maps as input data.

Soilscape inference models

This section only addresses the pedotransfer functions, i.e. the soilscape inference models that are currently used in Digital Soil Mapping. The uses of more specialised environmental models that are included above in the definition of soilscape inference models goes far beyond the topic of this review and thus are not described here. The following summary is an excerpt of a previous paper written by Lagacherie and McBratney (in press). Pedotransfer functions (Bouma, 1989) aim to predict hard-to measure soil properties, that are required by the soil data user, from primary soil properties. They have become a 'white-hot' topic in the area of soil science and environmental research. Reviews on the development and the use of pedotransfer functions, particularly for predicting soil hydraulic properties have been given by Rawls *et al.* (1991), Wösten (1997), Pachepsky *et al.* (1999), Wösten *et al.* (2001) and McBratney *et al.* (2002). Wösten *et al.* (1997) recognized two types of PTF based on the amount of available information, namely, class and continuous PTFs. Class PTFs predict certain soil properties based on the class (textural, horizon, etc.) to which the soil sample belongs. Continuous PTFs predict certain soil properties as a continuous function of one or more measured variables. McBratney *et al.* (2002) proposed a more detailed classification that accounts for the crisp/fuzzy nature of the inputs and outputs.

Beside pedotransfer functions, other non spatial inference models have to be considered too:

- The *Class-to-Primary Properties Functions* (*cppF*) aim to describe the content of pre-defined soil classes with respect to the primary soil properties, i.e. those determined classically by soil observations. They can be considered as a makeshift solution for describing unmapped soil patterns.
- The *Soil Allocation Functions* (*saF*) aim to allocate soil individuals to pre-existing soil classes using a set of soil properties that can be provided either by field observation or by a scorpan estimate. This is useful in situations where the soil map that would provide the soil class is lacking and where the soil class is required to apply class-to-secondary property pedotransfer functions

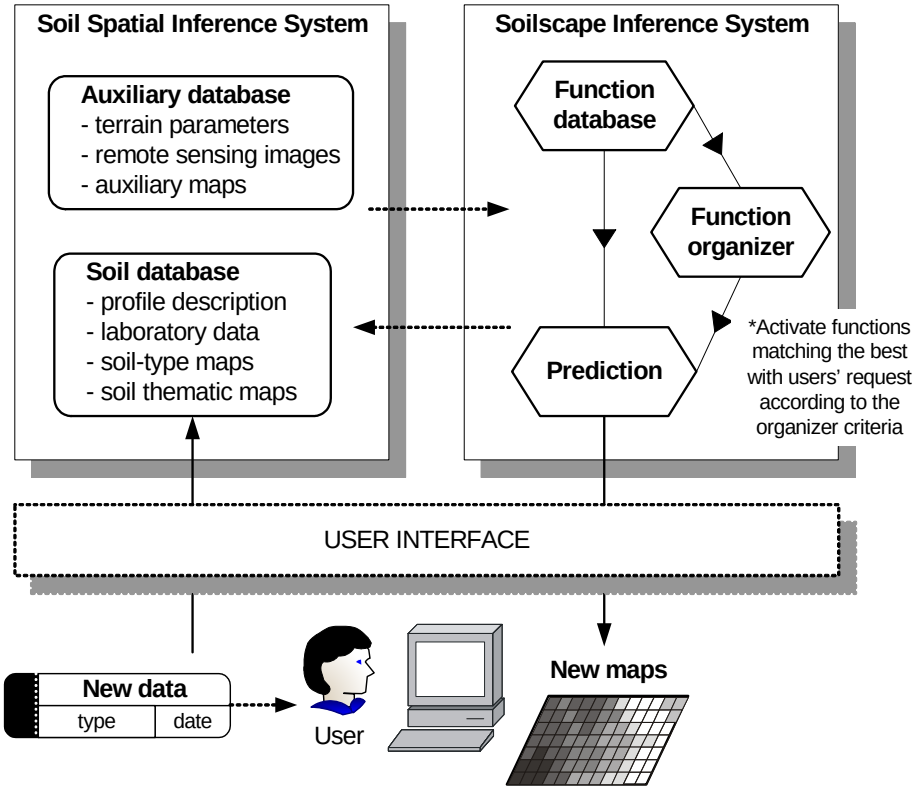

Fig. 2.4. Spatial Soil Inference System as output of Digital Soil Mapping (after Lagacherie & McBratney, in press).

2.2.2 *Spatial Soil Inference System and Digital Soil Mapper*

As seen from Fig. 2.3, many pathways are possible to predict secondary soil properties from soil observations and auxiliary data. Furthermore each pathway can be performed diversely since each type of models including itself several alternatives. It seems very unrealistic to select among this diversity a kind of best DSM models that would run properly whatever the study area and the data configuration across the whole European territory. Therefore, our alternative proposal is to move toward a Spatial Soil Inference System (Lagacherie & McBratney in press) that makes the DSM models cooperate to produce the best possible soil map according to the available input data and to the soil-user request. In this section we set the principles of this

Spatial soil Inference System, seen as the adding of a Digital Soil Mapper to the Georeference soil data bases currently used in Europe and elsewhere in the world.

A Spatial Soil Inference System would incorporate two basic entities within a common user interface: A Spatial Soil Information System and a Digital Soil Mapper (Fig. 2.4).

Spatial Soil information System (***SSINFOS***)

A Spatial Information System includes two components.

a) **A Geo-referenced soil database** with various types of soil information: soil profile description and laboratory analysis (preferably at georeferenced sites), digitised soil maps, images of primary soil properties, e.g. clay content, pH, etc., and images of secondary soil properties, e.g. infiltration parameters, field capacity, lime requirement etc. A number of such soil databases now exist as reviewed by Rossiter (2004). The European Soil Database is an example of these soil databases.

b) **An auxiliary database of predictive co-variables** (i.e. soil forming factors) that are available over the area of interest. McBratney *et al.* (2003, §4) provided a detailed inventory of these variables, -i.e. "the seven scorpan factors"- and of their sources: information on soil themselves by remote and proximal sensing (s) and data layers of environmental variables, i.e. climate variables (c), vegetation and land use (o), relief (r), parent material (p), age or elapsed time (a) and spatial coordinate alone (n).

Digital Soil Mapper (***DSMAP***)

A Digital Soil Mapper includes a numerical form of the knowledge required to infer new soil data from the one already available in the current SSINFOS. Three components are identified (Fig. 2.4):

- **A function database** that consists in a set of spatial and a spatial functions for predicting soil types and soil properties.
- **A function organiser** that collects arranges and categorizes the functions with respect to different criteria (nature of input, nature of output, validity area, expected uncertainty of prediction….)
- **A predictor** which consists of an inference engine that successively selects and activates the soil prediction functions according to a user request and to the criteria attached to each function. This can be an interactive tool in which users play an active role in selecting themselves ad-hoc prediction functions from their own knowledge. Different available functions that are able perform the same task can with this tool be compared on the basis of their known performance on a per prediction basis.

The association of these three components forms the Digital Soil Mapper that provides the possibility of exploiting any new data which are added to the Spatial Soil Information system in a given study area of interest, i.e. a new scorpan layer, or a set of soil observations provided by a user or by the spatial data infrastructure. As these new data are integrated in SSINFO, DSMAP adds progressively to SSINFO more precise digitised soil maps and images of soil properties that will progressively update the former ones.

2.2.3 ***Research Agenda:***

The spatial soil inference system described above is a perspective that cannot be considered as the goal of a three year research program. However, some preliminary research tasks can be defined that would help to move toward this goal. These tasks are defined hereafter:

1. Building the **DSM library** – This library will contain the most current and promising DSM models that have been tested within this past 15 years. These DSM models will be accessible through an appropriate user interface and will be fully documented so that they can be handled by a large panel of potential users. A list of metadata that describe each models have to be fixed. Items may include the nature of input and output of the models, their forms, indicators of quality of their outputs. The DSM library will be coupled with GIS to ensure the data input/output

2. **Setting pilot areas** across Europe with harmonised datasets - The pilot areas are regions of Europe in which Digital Soil Mapping will be tested to assess its feasibility. They will have to be representative of the diversity of situations that can be encountered in Europe, both in terms of pedology and in terms of data configuration. They will be preferably located in areas where there is already a sufficient amount of soil data in order to ensure the application of a large number of DSM models as well as their validations while limiting the experimental costs. Furthermore, they will be preferably located in regions where a functional soil mapping is needed, and ideally, has been already undertaken, so that the usability of the DSM models could be evaluated too.
3. **Testing DSM models** and combination of DSM models - The goal is to identify generic rules for selecting the more appropriate DSM model combinations with respect to the nature of the variations of the soil cover to be mapped and to the data configuration of the study region. This expertise will be further integrated in the digital soil mapper. Combination of DSM models able to deal with the multi-scale nature of the soil variability at regional scale will be particularly considered. The test will be performed over the whole set of pilot areas in view of modulating the evaluation with consideration of the pilot areas characteristics.

2.3 *Accuracy assessment*[10]

Soil mapping, be it conventional or digital, cannot do without a proper accuracy assessment. There is no use in producing a soil map without providing information to the user about the associated map quality. If the map accuracy is not specified, then users may be tempted to use a map for purposes for which it was not developed and may take wrong decisions. In the past, users have come to appreciate the quality of a soil map from acknowledging the reputation of the institute that produced the map or from a general description contained in the legend to the map, but at the present time there is a need for more detailed and precise communication of the accuracy of soil maps. This is particularly true in the case of digital soil mapping, because digital soil maps are used for many more purposes than just a visual presentation of the soils in a region. Digital soil maps are used as input to a variety of models and analyses to evaluate the status of the environment, such as for predicting erosion and groundwater contamination, or for assessing ecodiversity. Errors in the soil map will propagate to the results of these analyses and can potentially do much harm. If soil maps are used in decision making, then the errors can lead to erroneous political decisions (INSPIRE, 2002, p. 17).

Digital soil mapping (DSM) also needs accuracy assessment for two other reasons. First, DSM is a relatively new approach to soil mapping that is rapidly developing but that yet needs to demonstrate that it works in a variety of situations. It needs to show that it can produce maps of the soil that are equally good or better than conventional soil maps, at the same or cheaper expense. This can only be done convincingly if the accuracy of the DSM products is assessed and communicated in a verifiable and transparent way. Second, as was pointed out in the previous chapter on DSM models, DSM involves selecting for each application the best DSM model among a large set of possible ones. In order to make a justified choice, the accuracy associated with each of the candidate models for a given application must be known. Thus, accuracy assessment is a prerequisite for proper evaluation and comparison of different modelling approaches and for striking the balance between costs and accuracy.

The purpose of this chapter is to present a methodology for accuracy assessment of DSM products. The methodology will be largely based on the existing spatial accuracy assessment literature, which has been developed in GIS research over the last decades (e.g., Goodchild and Gopal, 1989; Guptill and Morrison, 1995; Heuvelink, 1998; Heuvelink and Lemmens, 2000; Foody and Atkinson, 2002; Heuvelink and Burrough, 2002; Hunter and Lowell, 2002; Shi *et al.*, 2002; Longley *et al.*, 2005; Heuvelink and Brown, 2005). Also, it draws on the pioneering work by Marsman and De Gruijter (1986) and a recent paper by Finke (2005), which address the same issue. In this chapter, we first define the DSM products for which an accuracy assessment is to be derived. Next we present accuracy measures for these products and discuss ways to estimate them. We also discuss stochastic DSM methods which quantify the accuracy associated with the resulting maps by means of a predicted accuracy, and discuss spatial error propagation techniques that allow analysing how uncertainties in digital soil maps propagate to policy-relevant products that use the soil information as input (i.e., maps of soil functions and soil threats). We conclude the chapter with a research agenda.

2.3.1 *DSM products*

The main DSM products and all that we consider in this chapter are static, two-dimensional maps of soil types and soil properties. These maps can be represented in two fundamentally different ways, namely either as maps of *objects* or as *fields* (Goodchild, 1992). In the object approach, the map is populated by simple objects - points, lines and areas - that are characterised by their geometrical and topological properties and by their non-spatial attribute values. In the field approach there are just fields of attribute data, without defining abstract geographical objects. The attributes of the objects and fields can be numerical as well as categorical. The distinction between objects and fields is important because fields can only have attribute uncertainty (notwithstanding that positional uncertainty can be the source of attribute uncertainty in fields); whereas objects can have both have positional as well as attribute uncertainty (see next section).

[10] Prepared by G.B.M. Heuvelink.

It is important to acknowledge that attributes of objects and fields always have a so-called *support* associated with them. Here, the support refers to the size, shape and orientation of the entities that are represented in the map (Webster and Oliver, 1990, p. 29). For example, a raster map of the organic matter content of the topsoil (0-30 cm) must specify whether the values represented in the map refer to the organic matter content at the centre 'points' of the grid cell (e.g., a soil sample of 200 gram) or to the average organic matter content within the grid cell (or to the average over a smaller or larger area than the grid cell, for that matter). Likewise, a polygon map of soil types must specify whether it represents the dominant soil type per polygon or the soil type at each and every point within the polygon. These are principal differences that can affect greatly the accuracy assessment. If, for example, over 50 per cent of the points in all polygons of a soil map have the specified soil type then the 'dominant soil type map' is error-free, while up to 50 per cent of the locations in the map may have the wrong soil type.

2.3.2 *Accuracy measures for DSM products*

In this section we present measures that characterise the accuracy of DSM products, as seen from a DSM producer's perspective (Finke, 2005). These measures are useful not only because they quantify the accuracy of DSM products, but also because they provide necessary information to decision makers who wish to analyse how the uncertainty in DSM products propagates to derived products, on which decisions and policy measures are based.

Positional accuracy

Positional accuracy in a soil map needs to be considered only then when the map takes an object representation of the real world. In most practical cases these objects are the soil mapping units, i.e., closed polygons delineating areas of the same soil type. Assuming that these objects indeed exist and can in principle be identified in the real world, the boundaries of the object will have a positional accuracy that can be measured and quantified in various ways, notably through frequency distributions of observed errors in the x- and y-coordinates of the boundary or through confidence intervals such as the 'epsilon-band' (see Shi *et al.* 2002 and Longley *et al.* 2005 for introductions). In practice, the frequency distributions associated with all boundary points in the map are unknown and need to be estimated from a sample of independent validation data.

In characterising positional accuracy we have assumed that the real world is populated by crisp objects. However, in reality soil units are rarely separated by crisp boundaries but gradually transform from one type into another. Such objects may be modelled by a vague (fuzzy) representation (Lagacherie *et al.*, 1996; Finke, 2005). The degree to which a location is part of an object then depends on its membership value, which can be any number between 0 and 1. Fisher (1999) makes a case for distinguishing between fuzziness and uncertainty. In case of vague or 'fuzzy' objects with gradual boundaries, the associated positional uncertainty may be characterised by associating uncertainty with the position of the isolines of equal membership value for each object. However, a much simpler solution in situations where there are no clearly distinguishable spatial objects (i.e., soil mapping units) might be to put aside the object representation of the real world and replace it by a field representation.

Attribute accuracy for numerical attributes

When an attribute is measured on a (continuous) numerical scale, the attribute accuracy of a spatial object such as a soil mapping unit can be expressed by the difference between the true attribute value of the object and that of the mapped representation of it. The same definition of attribute accuracy can be used for fields of numerical attributes. For example, if the soil depth at some location equals 1.20 m while the mapped value is 0.95 m, then the difference of 0.25 m is a suitable measure for the attribute accuracy of the soil map at that particular location. This measure can in principle be computed for all objects or all locations in the field, which may be summarised by a cumulative frequency distribution of the differences or the parameters of it (e.g., the mean and standard deviation). If the geographic coordinates of the observed differences is noted as well, then their spatial correlation structure may be quantified as well, such as by means of a semivariogram. This is frequently done in accuracy assessment of Digital Elevation Models by comparison with control points (e.g.,

Holmes *et al.*, 2000), but it can easily be done for numerical soil properties as well. Quantification of the spatial correlation in the error is important for error propagation analyses with spatially distributed models.

Attribute accuracy for categorical attributes

Attribute accuracy for categorical variables for an object or location is done by a simple comparison of the 'true' attribute values of the validation set and the corresponding values represented in the soil map. This presumes that the validation data are error-free, which need not be the case in practice. If the comparison is done for all objects or all points in the field or for a sample from it then the result of the comparison can be summarised in a so-called error matrix or contingency table (Stehman, 1992). These matrices can be further summarised by a kappa coefficient and by consumer and producer accuracies (for an overview see Finke (2005)).

Other accuracy measures

Above we have concentrated on positional and attribute accuracy measures. However, the spatial data quality literature identifies three more accuracy measures, which are completeness, logical consistency, and lineage (DCDSTF, 1988).

The quality of a soil database is, from the perspective of a user, often determined by its ***completeness***, which is the degree to which the necessary data are present. Many soil databases suffer from unsatisfactory completeness, both geographically (data density relative to the map scale) and thematically (attribute completeness).

Logical consistency of a soil map refers to the degree to which the soil map or soil database satisfies internal logical rules. For example, course textures in a soil mapping unit that is classified as a clay soil point to a logical inconsistency. Logical inconsistency may result from interpretative mistakes or human blunders made in the mapping process. Logical inconsistencies may also occur when results of several mapping projects are combined (Finke, 2005). In fact, logical inconsistency primarily conveys that the soil database suffers from positional and/or attribute uncertainties and arguably is not a separate accuracy measure. However, logical inconsistencies can have immense negative effects on subsequent analyses and it is therefore sensible to consider it as a separate accuracy measure. Logical inconsistencies can also be fairly easily checked and may thus be used to repair attribute and positional errors.

Lineage refers to the degree to which information is retained about the history and development of the soil map. Lineage specifies when the map was constructed, in what way and by whom. Lineage provides important information that can be used to estimate positional and attribute accuracy (e.g., an old map representing a fairly dynamic soil property is likely to have a poor positional and/or attribute accuracy).

2.3.3 *Accuracy estimation from DSM models*

Accuracy measures for digital soil maps have been defined in the previous section. In this section and the next we examine how these measures may be computed in practice, either by means of the DSM model (this section) or using independent validation data (next section). Many DSM models can provide as a by-product accuracy estimates associated with the predicted soil maps. These DSM models can be classified into two main groups, depending on the theoretical framework that is used to represent uncertainty.

Stochastic DSM models treat the soil as having both a deterministic and stochastic component. The stochastic component characterises the unknown spatial variability, the magnitude of which is described with a variance. The aim of mapping is to make predictions that are as close as possible to the true value, but the model recognises that some of the spatial variation cannot be explained and will yield a non-zero error variance attached to the predictions. Kriging (Webster and Oliver, 1990) is a typical example of a stochastic DSM model. Geographical information science provides generic probabilistic models both for positional as well as attribute accuracy (Longley *et al.*, 2005; Heuvelink and Brown, 2005).

Alternatively, one may also use ***fuzzy logic models*** to predict the soil and quantify the associated mapping accuracy. Fuzzy logic models do not work with variances or standard deviations but use possibility distributions or membership values instead. The fuzzy logic framework is particularly useful if part of DSM model input data

is derived from expert knowledge such as odds of occurrence of a given soil type (Zhu *et al.*, 1996) or intervals of values of a soil property (Cazemier *et al.*, 2001). It is also appropriate if the DSM model has to be validated from qualitative soil observation or traditional detailed soil maps (Lagacherie, 2005). It can be used both for quantifying positional as well as attribute uncertainty. Fuzzy logic literature provides generic tools to handle uncertainty (Dubois and Prade, 1988).

Since stochastic and fuzzy DSM models quantify the accuracy of their products, one might be tempted to conclude that validation is no longer required. However, it is important to realise that the 'predicted accuracies' or 'precisions' (Finke, 2005) produced by these models are based on assumptions that may not hold in reality. Independent validation is therefore recommended. Furthermore, DSM models generally provide too optimistic accuracy estimates since these estimates are calculated from the data that have been used to construct the soil map. This is why, although they can provide useful information to the user about inaccuracies and especially their spatial variations, they have to be themselves validated from independent data.

2.3.4 *Estimation of accuracy measures from independent validation data*

Arguably the best method to quantify the accuracy of DSM products is by means of comparison with independent validation data. Here, a number of issues need attention. These issues should be taken into account when working out a generic 'validation protocol' or 'accuracy assessment framework'.

First, it is important to guarantee that the validation data are truly independent from the data used to construct the soil map. If this would not be the case then the validation would render a too optimistic assessment of the map accuracy.

Second, it will rarely be the case that validation data are available for all locations in the map. Thus, in practice one works with a sample. Purposive and convenience sampling have the disadvantage that the sampling error cannot be determined, but they have practical advantages and sometimes there is no control over how validation data are obtained. If probabilistic sampling is employed, remaining questions are how large the sample should be and what design should be used (e.g., simple random sampling, stratified sampling, systematic sampling). These issues are discuses at length in Marsman and De Gruijter (1986).

Third, the validation data themselves are also rarely error-free. They involve measurement errors or interpretation errors. This is particularly true if the validation data are not 'hard' measurements but qualitative soil interpretations or more detailed conventional soil maps. Thus, the discrepancy between the digital soil product and the validation data must partly be attributed to errors in the validation data, but in order to make the distinction one must be able to quantify the error in the validation data.

Fourth, it should be noted that in many cases the validation data are not at the same support as the soil map predictions. This means that either the soil predictions or the validation data have to be scaled up or down prior to the comparison (Leopold *et al.*, 2006). Typically, the predictions are at a larger support than the validation point observations. A solution may be to replace the point observations by bulk samples or to aggregate the point observations to a larger support using block kriging. These are viable approaches but one should be aware that kriging introduces an interpolation error in the aggregated validation data.

Fifth, the validation must not only concern the estimated value of the soil attribute but also the predicted accuracy provided by the DSM model (see previous section). For this, a specific protocol has to be defined as well.

2.3.5 *Error propagation*

Accuracy measures of DSM products quantify the accuracy or uncertainty associated with these products. Such measures are potentially very useful to analyse the accuracy of analyses and procedures that use these soil maps as input. For example, soil functional maps provide estimates of the state of the environment, which are needed by the decision maker. These soil functional maps are the result of an analysis or operation on various inputs, among others soil maps. Clearly, the error in the soil map will propagate to the soil functional map. Error propagation techniques such as Monte Carlo simulation (Heuvelink, 1998; Longley *et al.*, 2005) can be used to

analyse the propagation of errors. However, in order to implement this one must first know how large the error in the input to the analysis is. Accuracy assessment of digital soil maps provides the necessary information.

Error propagation techniques are extremely useful not only because they make it possible to compute the accuracy of end-products such as soil functional maps and maps of soil threats, but they also provide a means to analyse how much each of the error sources contributes to the final error. This is potentially very useful information because it tells where the weakest link is and where improvements must be sought to improve the accuracy of the final product (Heuvelink, 1998).

Error propagation techniques are not only useful to analyse how errors in digital soil maps propagate to the results of analyses that use the DSM product as input, but they can also be used by DSM models to analyse how errors in the inputs to the DSM model propagate to the DSM map.

2.3.6 *Research agenda*

This chapter has briefly reviewed approaches for spatial accuracy assessment as these have been developed and applied in geographic information science, geostatistics and pedometrics. Adaptation of the general methodology to accuracy assessment of digital soil maps raises many questions that deserve attention. They make up a research agenda for accuracy assessment of digital soil maps. The most important of these are listed below.

- What accuracy measures should be used to assess the positional accuracy of digital soil maps?
- What accuracy measures should be used to assess the attribute accuracy of digital soil maps?
- Are completeness, logical consistency and lineage important accuracy measures for characterising the quality of digital soil maps? How to measure and store them?
- What sampling designs can be used to estimate the accuracy measures? How large should the validation sample be? How should the sampling locations be chosen?
- How can accuracy assessment with independent validation be done if the validation data are not free of error or have been collected using convenience sampling?
- How can accuracy assessment be done in a situation where the predictions are at another spatial scale (support) than the independent observations?
- Is it sensible and feasible to standardise the accuracy assessment of digital soil maps by means of the introduction of a ‘validation protocol’ or ‘quality framework’, and if yes, how should such a protocol or framework be developed and its use enforced?
- How should accuracy measures associated with digital soil maps be stored? Can we develop a soil information system that explicitly stores detailed information about the accuracy of the data?
- How can minimum accuracy requirements of digital soil maps be defined? Can a rating system for digital soil maps be developed?
- What actions should be undertaken when accuracy assessment of digital soil maps shows that the accuracy is below the prescribed standard?
- What techniques can be used to analyse how uncertainty in digital soil maps propagates to soil functional maps and other data products used in policy decision making. How should these techniques be implemented?
- How can the accuracy of digital soil maps best be communicated and visualised to end-users?

2.4 *Visualization possibilities*[11]

Some examples of different visualization techniques to present soil maps were presented at the first conference of the on Digital Soil Mapping held in Montpellier September 2004. The further discussion included the eternal raster vs. vector debate; the discussion was also extended to 3D, animation and other new technologies. Making user-friendly or popular animations needs time, skill, expensive software and money. In further section different visualization technologies and possibilities will be introduced and discussed.

2.4.1 *Scientific Visualization / Virtual Reality / GIS*

In principle, there are three main groups of advanced visualization techniques used to visualize the soils in the landscapes: (a) scientific visualization technologies, (b) virtual reality systems and (c) standard GIS systems. All these typically require digital elevation model (skeleton) and some soil thematic information on soils (content).

Scientific visualization (SciVis) transforms numerical symbolic data into geometric computer-generated images. According to Barraclough and Guymer (1998) it is one of the most powerful communicators of spatial information. Advanced visualization techniques better communicate spatial information between people of different backgrounds such as scientists, administrators, educators and the public. Just as maps can visually enhance the spatial and temporal understanding of phenomena, 3D representations can enhance our understanding of soil patterns. Interactivity enhances the perception and interpretation of soil-landscapes.

Virtual reality (VR) has different meanings. Full or immersive virtual reality requires the participant to be subject to stimuli affecting many senses, including vision, hearing, balance and touch. Such systems require head-mounted displays, audio speakers, moving platforms, and tactile gloves. Immersive VR systems are expensive and access is limited (Grunwald, 2000). One option is to use cave-like screens on which anaglyphic imagery is projected (this requires special glasses for 3D impression). Another option is to work with 3D holographic displays, 3D printers and real-time 3D tablets such as XenoVision Mark III. Desktop virtual reality is the most commonly used form of VR systems, due to the fact that it can be presented on standard computer monitors. Here, conventional PC software is used to create and view artificial worlds in the office and over the internet. The World Wide Web (www) provides a desktop-based virtual environment (VE) where users can interactively navigate though VEs, they can interact in real time with objects, and have feelings of presence. Desktop VR is useful for representations of environmental systems, because it provides 3D capabilities, interactivity, and assists making extremely complex system transparent and supporting scientific interpretation and analysis of the natural environments.

Geographic information systems (GIS) are still the most common tools to store, analyze, and visualize digital soil and landscape data. Usually soil-landscape representations use a 2½D design, where soil or land use data are draped over a digital elevation model (DEM) to produce a 3D view. Since this technique describes patterns on 2D landscape surfaces rather than the spatial distribution of subsurface attributes (e.g., soil texture, soil horizons) it fails to address three-dimensional soil-landscape reality. Numerous 3D sketches of soil-landscapes can be found in Soil Survey Manuals. However, these mental models do not utilize field data nor do they utilize a geostatistical method (Grunwald, 2000).

[11] Prepared by H. Lilja.

2.4.2 3D and human brain

The most important advantage of using 3D displays is the way they appeal to our brains and eyes. A 2D plot of individual elevations on a surface does not spark much of an image when we look at it; a contoured surface is a little better, but the viewer is required to build the image in his mind. A wireframe perspective display in colour makes the surface come alive. All of details, as well as the generated trends, are immediately visible. 3D displays portray data, which are a sample of a real world, in a way they how they actually appear in the real world (Raper, 1989).

Hillshading or Reflectance is a method which uses information about the illumination source. Regions from there the source are not visible are in shadow. ***Perspective displays*** are effective methods of portraying the shape and texture of surfaces. In a perspective view, the size of an object varies with distance from the viewer. Graphic displays often create perspective views with a "wireframe of reflectance" model of a surface. The wire frame is a series of profiles parallel to the rows and columns of the original ***grid*** (for a raster case), viewed by a perspective transformation. The effect is for parallel lines to converge with increasing distance, an important depth of cue for human perception. Additional realism can be added by removing the edges and surfaces that would be hidden from the observer by the solid surface. ***Triangular meshes***, as produced by Delaunay, Voronoi or simple triangulation for example, can also be viewed as wire frames. Still further realism can be added by adding surface colour, reflectivity and texture, simulating an illumination source, smoothing the geometrical artefacts of the wire frame geometry, and creating further depth cues such as the variation in haze due to the atmospheric conditions. Effective graphical overlays can be produced by ***draping*** one surface over the wire frame or another surface. For example a soil map can be draped over a topographic surface (Kraak 1993; Bonham-Carter 1994).

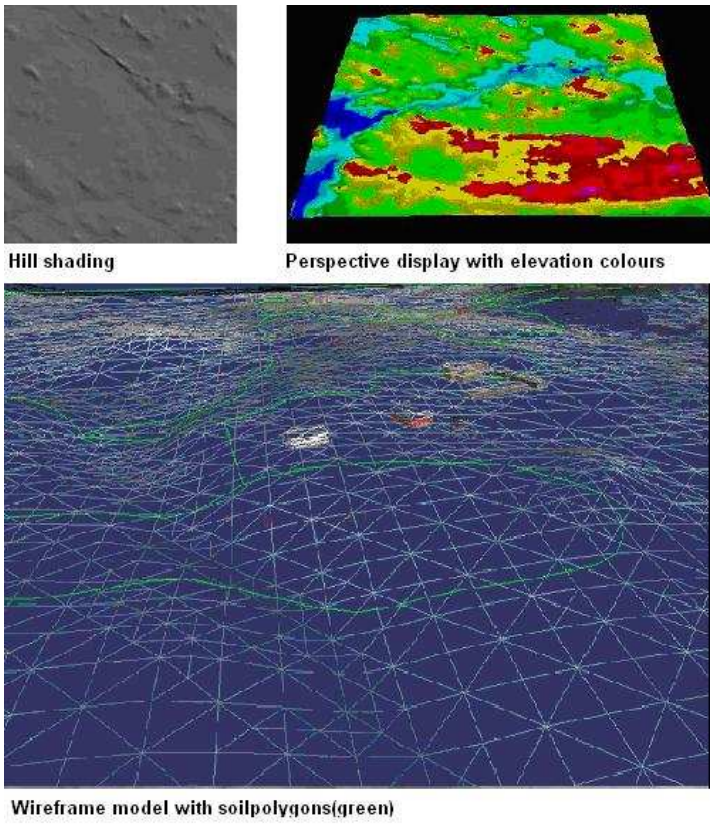

Fig. 2.5. Examples of visualisation techniques.

2.4.2 ***Visualisation products*** (***outputs***)

In all visualisation projects we have to determine what kind of output we want. What comes to visualisation in soil mapping, we don't have a lot of experience what kind of output would be successful in different situations. From my own experience as a 3D-modeller, common people mostly wanted to watch virtual models with real colourful aerial image. They wanted to go to their home yard and watch from there, how the new planned infrastructure will affect their everyday life. If their house was in wrong colour, they had difficulties to recognise it from "helicopter perspective" even everything else would have been right. In visualisation a little detail can really make the difference. Determinations below are taken from website of my

former employer "Northvisions" [http://www.northvisions.com]. When making of this Work-package, I made **virtual models**, when created some **still images** and **animations**.

Still images

Still images are rendered from any kind of model. The model content defines the detail level in a still image. Still images can be very realistic, almost photo looking, and contain realistic materials and lighting with shadows and reflections. Still images can also be done in very high resolution so they can be used in slideshows, magazines, television and large format prints. Wirerfame model in Fig. 2.5 is a still image.

Photo montages

Photo montage is an advanced version of a still image where the 3d-model and a real photo are combined in a correct perspective. The perspective can be calculated automatically. Typically a 3d-model is inside the photo so that elements like trees from the photo are masked in front of the model and at the same time background is behind the model.

Panorama

Panorama images are images that kind of surround the viewer. The viewer can look around from the place the panorama image was taken from. Panorama images are small but still give some additional feeling of being inside a real virtual model. Panorama images are good for Internet presentations [http://www.virtualparks.org].

Animation

Animation is film making. First we make a script, and then we shoot our camera moves and finally edit the film in a video-editing studio. The only difference from real world filmmaking is that all this is done inside a 3d-model. In virtual models we can record animations while moving in the model. For better cinematographic camera moves and visual quality it is possible to use special animation software that has real camera, lighting and material properties. Rendering animations can take time. Final animation can be a multimedia CD-ROM, DVD, VHS video, AVI file or a video file for Internet. You can download and watch animations at [http://www.mtt.fi], [http://serc.carleton.edu] and [http://www.nodvin.net]

Video montage

Video montage is a very demanding task similar to photomontage where 3d-model is cut into a moving video. Video montage technology is used in Hollywood-productions where computer generated characters are added to the filmed video. In the same way a 3d-model of a design can be added to a video taken from a helicopter above the design area. The advantages of video montage technology are the presentation of change - change from the current situation to a designed situation, lesser need for modelling - no need to model the existing environment and of course the realism because most of the image is real video.

Virtual model

Virtual model is a real time 3d-model of the existing environment and a proposed design. In a virtual model it is possible to move freely around the model like in computer games. This makes it is a very interactive presentation tool that allows people to investigate the model freely. There has been a research in Finland that shows that people find virtual models a better way of presenting designs than traditional maps and drawings and people find virtual models also reliable which is important especially in decision making.

VRML

Virtual models can be put on the Internet in a standard format called VRML. This allows people to look and walk inside the model at their homes with ordinary home PC's. A future format MPEG-4 will replace VRML soon with ten times smaller file sizes and advanced streaming capabilities that makes virtual models even more suitable for Internet. Grunwald prepared a gallery of VRML presentations connected to soil at: [http://grunwald.ifas.ufl.edu]. Note that, in order to watch these models, you will have to install a plug-in, like Cortona Player, into your browser.

1.4.3 Conclusions

The group suggests to proceed by addressing the following research topics:

- Visualisation of uncertainty/fuzziness in VR
- Visualisation of soil threats in VR
- Use of 3D prints, Caves, costs of using these techniques
- Use of “Conceptual model of soils” in VR

3 Mapping soil functions and threats: some case studies

3.1 *Definition of soil functions and threats*[12]

At the first meeting of the Digital Soil Mapping Working Group at Miskolc, Hungary (07-09 April, 2005) the following issues were raised:

- The origin of the phrase "digital soil function mapping" is unclear and a clear definition is also missing. However, in the meeting agreed, that the aim of “digital soil mapping” should be to develop methodologies and techniques for production digital soil maps with the assistance of computer tools, using also auxiliary information. These maps are created to display basic soil properties in their spatial context. “Function mapping” should be the next phase in creating soil information, when the primary soil map information (of digital format) can be processed for specific requirements e.g. modelling, characterization of soil functions etc.
- Secondly, it was proposed that "soil functions" should be first defined and described, than proceed towards the "digital soil function mapping". This approach would have the major benefit of having well defined targets, upon which the mapping procedure can focus. Participants mentioned also that, within the frame of the activities of this working group, techniques and procedures of digital mapping of basic soil properties should be first summarized. Having the guidance of expertise on soil information, the DSM working group can than proceed forward to digital soil function mapping

In the last decade, there has been a trend to complement traditional soil classification with an appraisal of the different functions which different soils can perform in ecosystems and landscapes (Blum, 1993; Karlen *et al.*, 1997). By so doing, the emphasis shifts from the properties of different soils, towards the functions of different soils, based on those properties. It is argued that such an approach will allow soils to be more widely recognised by society (Karlen *et al.*, 1997), to provide society and governing institutions with options and trade-offs in land use decision making (Miller *et al.*, 1995) and to help clarify the role of soil science in the land use decision making process (Bouma, 2001).

Table 3.1. Functions of soil after Blum (1993).

Soil Function	
Biomass production	Food, fibre and timber production
Filtering, buffering and transforming action; ‘environmental interaction’	For example: buffering of atmospheric inputs; biodegradation of toxic compounds; gaseous emissions from soils
Biological habitat and gene reserve	Microbial diversity *within* the soil; basis for valued semi-natural habitats and associated fauna
Physical medium	Base for built development and other human activities such as recreation
Source of raw materials	Supplying raw material such as sand, gravel and peat.
Cultural heritage	Concealing and protecting archaeological remains; as a record of land use and settlement patterns

Blum (1993) and CEC (2002) provides a succinct summary of the six main soil functions. Three of these are ecological in character whereas the other three are more directly related to man’s direct intervention. They are summarized in table 3.1. These have been used to provide the overall context for specific suggested actions in MAFF/DETR’s draft soil strategy published in 2001 (DETR, 2001). The European Commission published the Strategy for Soil Protection in 2002 where soil functions are explicitly mentioned and five different functions are defined. In some EU countries soil functions have already been defined within the framework of existing legislation. In Germany, for example, within the Federal Soil Protection Act (BBodSchG) natural functions,

[12] Prepared by T. Mayr.

functions as an archive of natural and cultural history and functions useful to man are described (Article 2, pages 3 and 4).

3.1.1 Biomass production

As a result of the increase in world population, there is mounting pressure on the amount of world biomass production that is required to meet this need. This includes not only food production, but also that of fibre and timber. However, it is vital that such an increase in productivity is managed carefully to ensure that the resource itself, along with the wider environment, is sustained to continue meeting this need.

The products of food, agriculture and forestry industries are therefore essential for human survival and are totally dependent on soil (Tzilivakis *et al.*, 2005; Doran, 2002). The functioning of soil as a medium for biomass production provides the following functions:

1. To supply water and nutrients to vegetation
2. To provide stability of roots
3. To provide the basis for livestock production
4. To interact with the climate and determine the type of crops cultivated

To ensure the longevity of biomass production, care needs to be taken to protect the soil as any degradation of the soil will reduce its overall potential to perform the functions listed above. Pressures on the soil to carry out these functions come from a variety of sources. For example, the intensification and mechanisation of farming in general can lead to the compaction and ultimately the erosion of the soil, as well as reducing biodiversity and reducing the amount of organic matter within the soil. Other threats to the soil structure come as a result of poor timing of cultivation, overworking of soils or overstocking (Environment Agency, 2004).

3.1.2 Environmental interaction

Soil, water and air interact chemically, physically and biologically, therefore it is essential that they are considered as one ecosystem (EA, 2004). The role that soil plays in performing functions related to the interaction of the environment can be split into four sub-functions – storage, buffering, filtering and transforming. The roles that soil plays within these subfunctions include:

- To link the atmosphere, geology water resources and land use
- To filter substances from water – natural filter for groundwater/drinking water
- To receive and transform particles (e.g. pollutants) deposited from the atmosphere
- To emit and absorb atmospheric gases – releases CO2, methane and other gases in atmosphere
- To act as a reservoir for carbon (greenhouse gases)
- To regulate the flow of water in the water cycle
- To store and degrade organic matter
- To breakdown toxic compounds present in the soil

The importance of these functions has been highlighted by international organizations who warn that the loss of these functions can have detrimental effects. For example the Commission of the European Communities suggest that the ability of certain contaminants to exceed irreversibility thresholds for storage and buffering capacity requires monitoring and early warning systems to prevent environmental damage and risks to public health (CEC, 2002).

3.1.3 Biological habitat and gene reserve

Soil provides an important habitat for organisms, spending whole or part life cycles in the soil. For example, the CEC (2002) estimate that in a pasture, for each 1 to 1.5 tons of biomass living on the soil (from grass to livestock), approximately 25 tons of biomass (such as bacteria, earthworms, etc) are present in first 30

cm of soil. These organisms are vital for maintaining soil functions. Biological activity within the soil provides the following functions:

- To ensure the maintenance and functioning of specific ecosystems or habitats
- To drive processes such as soil formation, nutrient cycling and nitrogen fixation,
- To assist in the maintenance of soil structure
- To provide a source of symbiotic soil fungi on which many plants depend
- To generate and stabilise soil structure
- To contribute to the structure and fertility of soils
- To strengthen erosion resistance
- To provide resilience to and counteract the effects of environmental stresses through the breakdown of chemical contaminants and pathogens

These functions provided by the presence of biological organisms in turn enable the soil in general to maintain valued semi-natural habitats and to define landscape character. This also assists the soil in regulating habitat quality, such as those suffering or at risk from changes in land use, agricultural nutrient runoff or soil erosion (Environment Agency, 2004). Römbke *et al.* (2006) highlight the importance of protecting the biodiversity of soil at a National and International level, as well as addressing the legal issues surrounding the protection of soil as a biological function.

3.1.4 Physical medium

Pressure on the natural environment from human activity such as building houses and transport links inevitably puts a significant amount of pressure on the ability of soil to perform the necessary functions to be able to support these activities. For example:

- To form the foundation for the built environment
- To influence land use and shape the landscape
- To act as an essential component in many waste treatment systems for built land-uses
- To ensure performance and safety of all domestic and commercial electricity systems through soil conductivity potential for earthling
- To act as an aquifer recharge
- To control flash runoff from built areas and hard surfaces
- To provide recreational space in urban and urban-fringes (e.g. gardens, parks, public open space, allotments etc)
- To provide a means of transport for sediment and nutrients

These functions are profoundly affected by the physical and chemical properties of the upper layers of the soil. Wood *et al.* (2005) identify that natural variations in soil texture and chemical properties have a significant effect on the functionality of soil in the built environment. For example, any change in the pore volume and distribution in the soil profile (e.g. as a result of compaction) determines the rate of water transfer to groundwater as well as the movement of air to and from the soil surface.

Loveland and Thompson (2001) highlight the fact that any damage to the soil surface, or risk of damage to soils in a vulnerable state, will reduce the ability of the soil to perform the functions listed above. An additional risk to the ability of soils to provide a solid foundation for the built environment comes from the threat of climate change. For example, Bradley *et al.* (2005) suggest that increased droughts will enhance the risk of shrink-swell in clay soils. This has the potential to increase disturbance to building foundations and may therefore result in the need for underpinning or repair. Other effects of climate change include potentially increased chemical attacks on foundations as a result of increased soil temperature.

3.1.5 Source of raw materials

Historically, and up to the present day, soil has been seen as a storage and source of raw materials to support human activity. These functions of soil and the effects of such activities on the physical and chemical properties of the soil are often overlooked but are important aspects of planning and restoration projects. Such functions include:

- To provides raw materials such as clay, sands, minerals, peat, topsoil
- To act as a storage-site for raw materials
- To act as a natural reservoir for water

In considering soil functionality in terms of providing raw materials, there are two issues to take into account. Firstly, there are the requirements of a site to actually provide the raw materials from the upper layers of the soil, such as topsoil, peat and Brick Earth clays). For example, Van Seters and Price (2001) show that the extraction of peat has a long-term effect on the hydrological function of the Cacouna peatland in Quebec. Secondly, the requirements of a site where minerals have been extracted from below the solum itself (e.g. coal sands and gravels) need to be taken into consideration, particularly in reference to the restoration of the site to its original land use. Both of these situations ultimately lead to considerable soil disturbance, through the removal of soil to allow extraction, the storage of removed soil on top of another at an alternative site, and the disposal of material generated during extraction onto soil at another site (Loveland and Thompson, 2001).

3.1.6 Cultural heritage

Despite early research into the importance of using soil survey information for recording and mapping archaeological finds (Dekker, 1973), the interaction between soil and archaeological remains has received little attention, despite it's overwhelming importance for understanding past uses of the landscape and providing an insight into historical cultural activities. The Defra Soil Action Plan (2004) highlights this fact by stating that there is currently a *"poor awareness of the importance of soils and their heterogeneity in heritage and landscape, partly because of the concealed nature of the archaeological resource and partly because of a lack of relevant soil quality indicators"*.

The main functions that soil provides in terms of cultural heritage can be summarised as follows:

- To conceal and protect archaeological remains
- To provide an historical record of land use and settlement patterns
- To inform current knowledge and investigation of archaeological sites
- To influence the deterioration of archaeological remains (through contamination and modern day agricultural practices)
- To provide an historical record of climate change

3.1.7 Summary

Increasingly, however, soil functions are seen only as part of the wider environment and there is a tendency towards the definition of environmental services, which include all the components of the environment, including air, water, and vegetation as well as the man-made environment. In addition to the potential customers identified at the European level, an even wider range of customers exists at the national level. There are increasing demands from central, regional and local government as well as government agencies, particularly for environmental protection. In addition, commercial interests come from the utility companies (electricity, water, etc), the insurance sector (subsidence/flooding) as well as civil engineering (electrical properties).

3.2 *Assessing and displaying land suitability*[13]

3.2.1 *Introduction*

Present work illustrates a complex research of land suitability evaluation and IT development, which integrates different requirements (expression of management and climate factors, crop specific evaluation) to a modern land evaluation system, on the bases of digital information, including digital maps. A new land information system is developed in Hungary to assist land productivity based land use planning and cropland information management. The core of the system is a quantitative land evaluation system that is applying high-resolution (vectorized 1:10000 scale) digital soil maps and data on nutrient status of soils. Digital cadastral maps are used to assist land use planning tasks. The system operates as web-based application, providing easy communication interface (functional maps and supporting information) between farmers, extension experts and administrative agencies. Main goal of the so-called D-*e*-Meter project was to develop an information system that fulfils the following objectives:

- displaying soil quality by means of digital functional maps using on-line GIS tools,
- plant production modelling on the basis of soil quality and other criteria (e.g. optimal fertilizer use),
- assistance for farmers to fulfil their obligations to provide information on the use of arable land, and providing means for direct communication with administration agencies, extension services, etc.
- Thus, the system described above can achieve the following:
- The relationship between the yields of the agricultural land use and the natural resources becomes analyzable.
- Land use information is displayed with digital functional maps.
- It makes possible to keep up-to-date records of information on plant production and environment management, and the exchange of information between farmers, extensionists and the administration of the sector becomes simpler and faster.

The information system is based on a land evaluation system that also entails environmental aspects, and which:

- determine the production potential of agricultural lands in a quantitative way,
- allow evaluations by major cultivated plants or groups of plants,
- include the possibility of expressing any decrease in productivity and production risks that originate from climatic effects and are realized through pedological and geological factors (drought, inland water),
- describe the conditions of production also on various intensity levels of cultivation

3.2.2 *Land evaluation methods and results*

Database requirements of the land evaluation analyses

The basis of the land evaluation work was the soil fertility analysis of the databases available from various sources. The analysis meant statistical processing of pedological, climatic, plant production, soil analysis and fertilizer application data. The following databases were available for this task:

a) National plot-level soil, fertilization and yield databases. 5 years, 80000 cultivated fields each year, containing yield, fertilization and soil information for each plot. The data of the database can be classified in three major groups:
   1. Basic data (location, size, sloping, exposure, meteorological area etc.)
   2. Soil analysis data (SA) (pH, texture, humus, N, P, K)
   3. Plot registry data (plant, succession, yields, fertilizer application)

[13] Prepared by G. Toth.

b) Database of National Long Term Field Experiment network. Information on yields of 30 consecutive years, with soil nutrient dynamics and fertilizer response data of 9 field trial station. The experiment network representing differing ecological conditions, in which the fertilizer application experiments are carried out in 9 different geographical regions among differing soil conditions.

c) Database of a 10 sample farms of different characteristic agro-ecologic site, 1-5 thousand hectares area each, containing farming records and soil analysis data as well as a 1:10000-scale digital genetic soil maps (these case study areas were also used during the IT development).

Land evaluation analyses

Land suitability indices have been worked out on the basis of soil taxonomic classification, which provides basis for soil mapping information as well. Soil varieties of the classification system are characterized by their relative fertility (related to the fertility of all other soils in the classification system) regarding major cultivated crops, and group of crops. Regional climatic conditions, hydrologic and terrain factors are also taken into account. Meteorological variability and cultivation intensity are also expressed in the land evaluation system.

Above all, the land evaluation work has been based on the computerized statistical processing of available soil and plant cultivation information. In the first phase of the statistical analyses the fertility limit values of the soil types and sub-types (of soil classification) have been determined, in the context of the water management regime of their units. The effect of the water regime and moisture circulation of the soil has been incorporated to the land evaluation system. In the course of this work the effects of the elements of the soil water balance (precipitation, evaporation, surface runoff, infiltration, fluctuation of inland water etc.) on the production capacity have been examined in interaction with the soil characteristics.

That was followed by exploration of the fertility conditions of soil varieties of the lower taxonomic levels. The initial phase of the land evaluation work was followed by the definition of the fertilizer responses of the soils. This was meant to explore the causes of changes in the production potential resulting from fertilizer application of various intensities and to express the extent of such changes.

Validation and visualization of the land evaluation model in case study areas

The creation of GIS databases for the sample areas in the various agro-ecological regions of the country served several goals. The land evaluation model is developed on the basis of archive farming data and the results of experiments were used to calibrate the model also among real conditions of farming. At the same time, sample areas are also needed for the integrated visualization of the land evaluation supported by GIS modelling. The results of the land evaluation research and the information technology development have been united in the sample areas.

3.2.3 *IT development methods and results*

Planning of the data-model

Database planning has been carried out according to common practice of relational database development, starting from generalized approach to specific solutions, to widen the functionality of the system. As a basis, the system applies fine resolution (digitized 1:10000 scaled) soil maps, field data on soil nutrient status, vectorized cadastral maps (and includes land evaluation algorithms to asses the production potential of agricultural parcels).

- Object used in the system:
- Cadastral unit
- Land use unit
- Agricultural field

- Parcel (agricultural plot)
- Soil mapping unit

Calculation of land capability indices (***the land evaluation process***)

Soil and terrain data and spatial information are used to calculate the land capability index of any given field. Each soil variety (in the corresponding agro meteorological region) is evaluated according to its fertility regarding the given crop. Calculations are carried out both under extensive and intensive cultivation conditions. The land information system stores data on different indices:

- Crop-specific capability index for extensive conditions
- Crop-specific capability index for intensive conditions
- General capability index (index calculated by weighting of crop-specific indices according to crop ratio of the cultivated land)

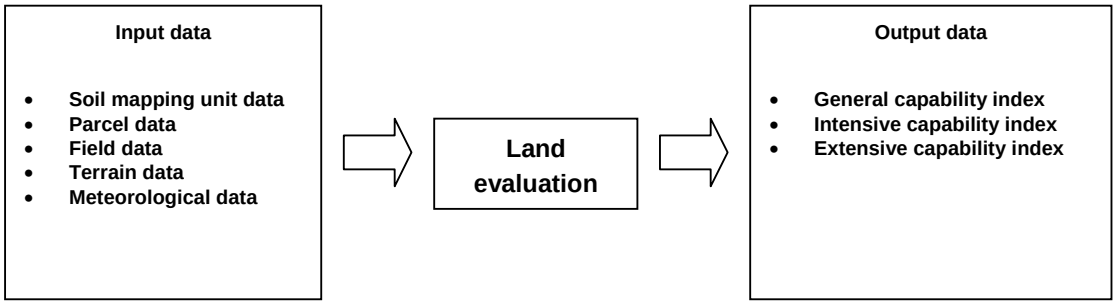

Fig. 3.1. Land evaluation calculation input and output data.

Java development environment has been used in order to keep platform independency. To secure the system's accessibility to other information systems, connecting interfaces has been designed by using national and international standards. XML application was applied for system communication, creating specific protocol for the system. Database server and WEB server is operating in different physical locations (giving possibility for regional services in the future).

Interface design and system operation

Since the web-linked monitor is the meeting point of the system and its user, it was especially important to give clear user-friendly design with full functionality to the interface. Digital ortho-photos assist the users to locate interested areas, where vectorized digital cadastral maps are used for building farm spatial database on-line. Maps of agricultural fields can be created and edited on the selected areas. During land use planning parcels can be delineated by taking land capability into account. As further function of the land information system, different farming and management data (on cultivation, amelioration, pest management, fertilization, harvest etc.) can be also registered in the system.

3.2.4 *Conclusions*

With the application of the above described decision support system the relationship between the yields of agricultural land use and natural resources becomes analyzable. The results of the analyses are displayed on digital maps and they can be applicable for land use, land management and crop production related planning (or further analysis) to support decision-making from plot to national levels. Digital soil map information is used to produce digital soil functional (easy, user-friendly) map to display parameters of a selected soil function

(productivity). In similar way, other soil functions can be displayed as well, so to provide information to land users and decision makers on soil and land qualities and utilization options.

3.3 *Modelling soil-environment*[14]

3.3.1 *Introduction*

In the last decade, there has been a trend to complement traditional soil classification with appraisal of the range of functions that individual soils perform in ecosystems and landscapes (Blum, 1993; Karlen *et al.*, 1997). By so doing, the emphasis shifts from the **properties** of different soils, towards their **functions which are based on the** properties. Blum (1993) provides an excellent summary of the six main soil functions listed in Table 3.1. The first three are ecological in character and the others are related to man's direct intervention in soil/land management. This paper describes preliminary results of a continuing project predicting key soil functions in diverse landscapes.

3.3.2 *Methodology*

The approach

Most functions are sufficiently diverse that a single model cannot describe them all adequately. Environmental interactions, for example, encompass a variety of different components including buffering, filtering, storage and transformation. The way that a soil performs most functions can be assessed using a combination of appropriate models, each addressing a component or sub-component of the function.

The project was designed to investigate the value of existing models that are readily available to researchers. An attempt was made to identify models for as many components and sub-components of the functions as possible, although there is wide variation in the number and type of models describing the functions. Most of the assembled models are based on a capacity-type approach, i.e. the capacity of the soil to sustain a particular component of a soil function. All modelling was spatially explicit using a 250 m grid resolution. All models were implemented using Structured Query Language (SQL) in order to make the approach as portable as possible.

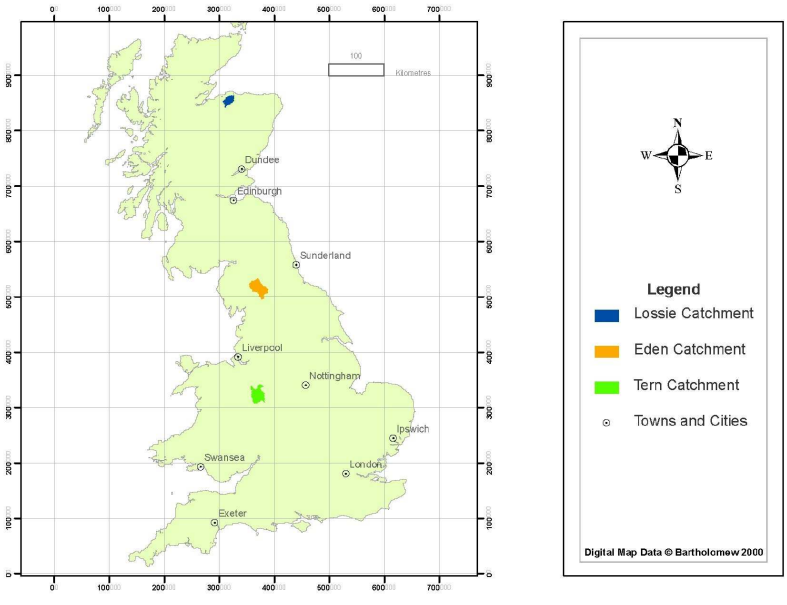

Fig. 3.2. Location of study sites.

Study sites

The methodology was tested in three very diverse catchments located: in the Lossie (Scotland), the upper Eden (north-west England) and the Tern valley (central England) (Fig. 3.2). The Lossie covers 270 km^2 (4379 grid cells), has an elevation range from 2.5 to 521.7 m, annual rainfall of 957 mm at Torwinny and the land-use is predominantly semi-natural and commercial forestry. The Eden covers 689 km^2 (10723 gird cells), has an elevation range of 89.9 to 892.7 m and an annual rainfall of 1483 mm at Kirby Stephen. Grassland is the dominant land-use in the Eden. In contrast, the Tern covers 593 km^2 (9301 grid cells),

[14] Prepared by T. Mayr.

has an elevation range of 48 to 376 m, an annual rainfall of 694 mm at Walcot and has a predominantly arable land-use.

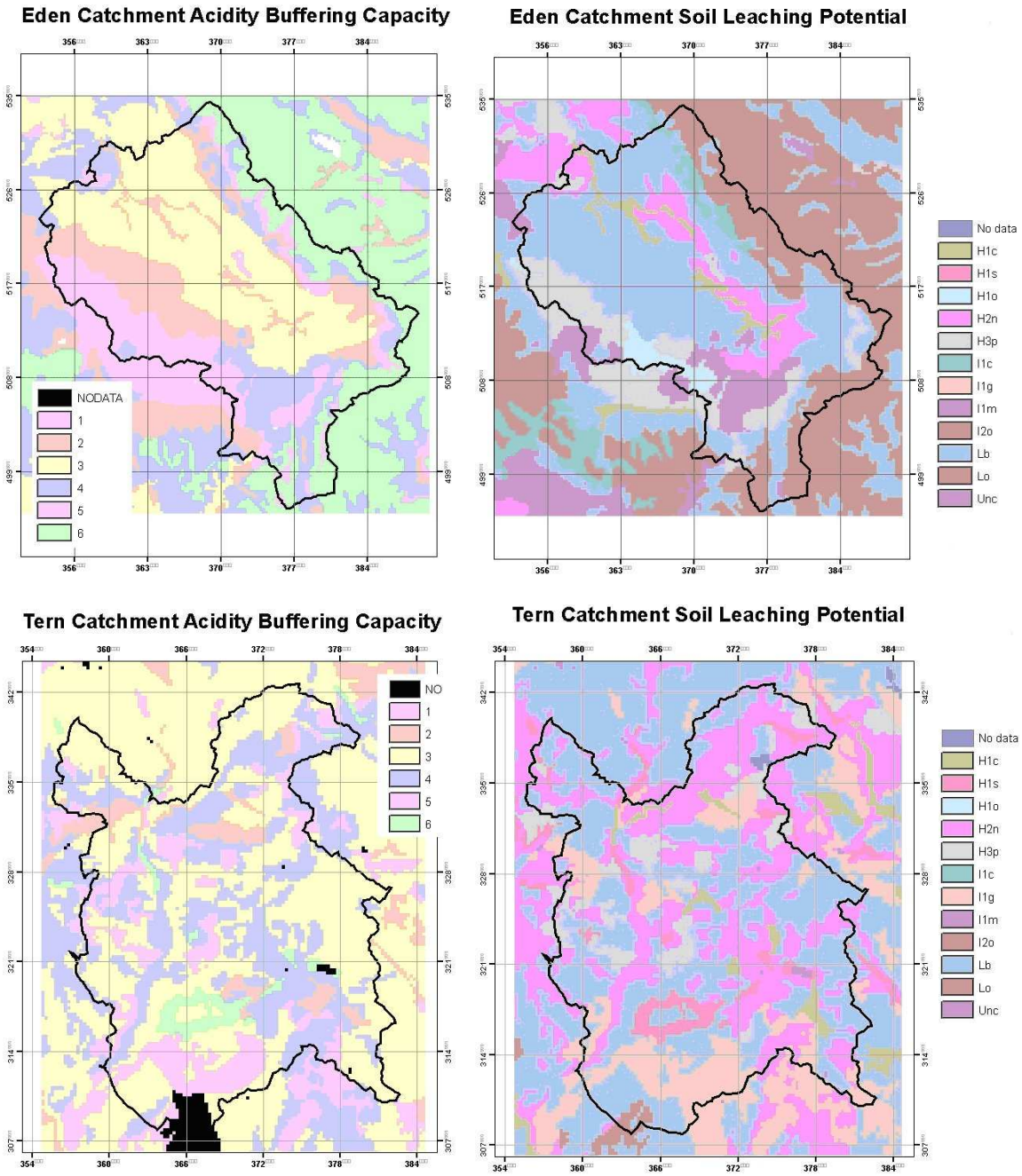

Fig. 3.3. Distributions of buffering capacity and pesticide leaching risk for the Eden and Tern catchments.

Data and models

In addition to soil data (maps and associated properties), a range of environmental data is required for some of the models, demonstrating that in may cases 'soil functions' are also driven by external factors such as terrain (fixed), climatic data (gradual change) and land use (constantly changing). Twenty three different models were used in total to describe the six functions. They ranged in complexity from those driven by simple look-up

tables to relatively complex mechanistic models. However, the use of more advanced and complex models is often restricted by their need for extensive and wide ranging data, some of which may not be readily available.

3.3.3 *Results*

The main output from the project so far is 69 suitability/capacity maps derived by running each of the 23 models in each of the three catchments. Fig. 3.3 provides examples of the distributions of acidity buffering capacity and pesticide soil leaching potential for two of the catchments.

Acid buffering - The lowland and western parts of the Eden catchment provide reasonable buffering capacity for acidity (Classes 1-3) with limestone soils in the west providing most potential for buffering (Class 1). The acid upland peats have negligible buffering capacity (Class 6). The Tern is dominated by soils with intermediate buffering capacity (Classes 3 and 4). Areas of low buffering capacity (Classes 5 and 6) are represented by the acid peat soils of the Weald Moor and the acid sandy podzols developed over Bunter Sandstone.

Soil leaching potential - The Eden is dominated by soils with slowly permeable subsoils and low leaching potential (L) and hence provide natural protection to groundwater. Small areas of coarse-textured high (H2) leaching potential soils are found close to the river Eden where it flows across the Triassic sandstone aquifer. The Tern has an intricate pattern of low (L) and High (H2) leaching potential soils. The slowly permeable boulder clay soils have low leaching potential and provide protection to groundwater. However, the well drained coarse-textured soils over Triassic sandstone have High (H2) leaching potential.

3.3.4 *Conclusions*

There are a number of limitations which need to be recognized in this type of assessment of the relative functioning of soils using simple suitability/capacity models. Foremost, there is no spatial connectivity between individual grid cells as this would require more complex mechanistic modelling. Secondly, there are no interactions between individual components or sub-components of soil functions, i.e. the multi-functionality of the system is not accounted for. In a few cases, the spatial resolution of the ancillary data (particularly climate) proved to be the main limiting factor.

Models have been identified that describe the main components of all soil functions. Many were developed 20-30 years ago and are based on simple modelling approaches. These simplistic models often provide a qualitative rather than quantitative ranking of soils and the results are not suitable for assessing the changes in the way that a soil might function following land use change or climate change. What can be achieved, however, is the ability to map the functional capacity of soils within a catchment.

Acknowledgements

This research is undertaken in collaboration with the Centre for Ecology and Hydrology (CEH) and the Macaulay Institute. Funding is provided by the Department of the Environment, Food and Rural Affairs (DEFRA) and the Scottish Executive Environment & Rural Affairs Department (SEERAD).

3.4 *Assessing soil pollution by heavy metals*[15]

3.4.1 *Introduction*

A problem of soil pollution by different anthropogenic inputs of heavy metals, but also of other potentially toxic substances, has received global dimensions in the last decades. In Europe, decision makers and spatial planners more often require information on soil quality for different purposes: to locate areas suitable for organic (ecologically clean) farming and agro-tourism; to select sites suitable for conversion of agricultural to non-agricultural land, particularly for urbanization, setting up protection zones for groundwater pumped for drinking water; to estimate costs of remediation of contaminated areas, etc.

In practice, soil pollution by heavy metals is commonly assessed by interpolating concentrations of heavy metals sampled at point locations (Webster and Oliver, 2001). Resulting maps indicate areas with pollution risks and can provide decision-makers or local authorities with critical information to delineate and isolate polluted areas. The first problem of working with maps of **heavy metal concentrations** (HMC) is that the limiting values for polluted soils are commonly set as crisp boundaries. For example, a soil is polluted by zinc and not suitable for organic agriculture if the measured values are larger than 300 mg kg^{-1} (1986/278/EEC directive). This means that a soil with zinc concentration of 299 mg kg^{-1} and a soil with a concentration of 301 mg kg^{-1} will be classified differently although the difference may be due to the measurement or interpolation error. The second problem with HMCs is that different elements come in different ranges of values. This makes it fairly difficult to get the compound picture about the soil quality. For example the threshold value for zinc is 300 mg kg^{-1} and for cadmium 3 mg kg^{-1}. If we measure, at a point, values Zn=230 (suitable) and Cd=3.2 (not suitable), does this means that this location is polluted or not polluted? Now imagine a case with tens of HMCs – how to sum these values to get the compound picture about the quality of soil? What is obviously needed is a more sophisticated, more continuous approach that will: (a) be able to depict areas of overall high HMCs and (b) resemble the financial losses more realistically.

3.4.2 *Methodology*

Traditionally, suitability maps are derived as Boolean maps (**yes** or **no**), where none of the dangerous HMCs does not exceed a threshold value (Table 3.2). This means that only the areas that do not exceed ANY of the given thresholds can be considered as being suitable for agricultural production. Here the problem is obviously that the intensity of pollution within the polluted areas is unknown. Our approach is somewhat different in a sense that we also want to spatially quantify the overall soil pollution. For this we use the concept of limitation scores.

Table 3.2. Transformation coefficients calculated for given threshold concentrations. X_1 – maximum concentration of contaminant to maintain multifunctionality, X_2 – serious soil pollution. Official threshold levels used in Croatia.

	X_1 mg kg^{-1}	X_2 mg kg^{-1}	$\ln(b_0)$	b_1
Cd	0.8	2	0.392	1.756
Cr	50	100	-9.083	2.322
Cu	50	100	-9.083	2.322
Ni	30	60	-7.897	2.322
Pb	50	150	-5.731	1.465
Zn	150	300	-11.634	2.322

After the HMCs have been interpolated, they can be converted to limitation scores, which will then allow us to sum different maps of HMCs. Such scoring system is often use, for example in land evaluation studies (Triantafilis *et al.*, 2001). For each evaluation parameter, thresholds and limitation scores are predefined and then can be implemented for the whole area. For example, slope map is typically used to give suitability scores

[15] Based on a research paper Romić M., Hengl T., Romić D., Mapping soil pollution by heavy metals using continuous limitation scores. Computers and Geosciences, in review.

to a certain area: 0 for 0-2% slope class, 1 for 2-8%, 3 for 9-16%, 9 for 17-25% and 27 for slopes >25%. Note that in this case the negative scores increase exponentially with the increase of slope. Although the slope difference between the second and third class is only two and half times, the third class gets three times more negative points. Instead of making classes of HMCs, we can also use a simple transfer function to convert HMCs directly to limitation scores (LS). A flexible transfer function, also used in this paper, is the exponential:

$$LS = \begin{cases} b_0 \cdot HMC^{b_1} & \text{if} \quad HMC \geq X_1 \\ 0 & \text{if} \quad HMC \leq X_1 \end{cases}$$

where LS are the limitation scores, b_0 and b_1 are the coefficients, HMC are heavy metal concentration and X_1 is the permissible or baseline concentration. An example of how are HMCs transformed to limitation scores can be seen in Fig. 3.4.

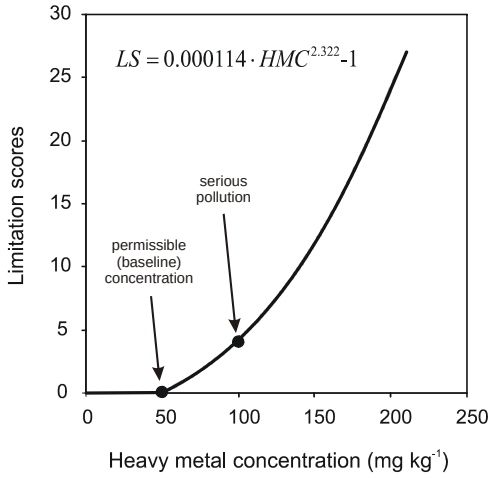

Fig. 3.4. Transforming HMCs to limitation scores.

3.4.3 *Case study: Heavy metals in the Zagreb city region*

The methodology was illustrated using the 784 soil samples analyzed for Cd, Cr, Cu, Ni, Pb and Zn in central region of Croatia. The samples were taken at 1×1 and 2×2 km grids and at fixed depths of 20 cm. Heavy metal concentrations in soil were determined by ICP-OES after microwave assisted aqua regia digestion. The sampled concentrations were interpolated using the regression-kriging (Hengl *et al.*, 2004) with geological, land cover maps, terrain parameters and industrialization parameters as auxiliary predictors. The results showed that the best auxiliary predictors are the geological map, ground water depth, NDVI and slope map and distance to urban areas. The spatial prediction was especially successful for Cd, Ni, Pb and Zn, and somewhat less successful for Cu and Cr. The final map of cumulative limitation scores showed that 33.5% of the total agricultural area is suitable for organic agriculture and 7.2% of the total area is seriously polluted by one or more heavy metals (Fig. 3.5). The developed procedure for geostatistical analysis of HMC data enabled us to identify a number of contamination hotspots and to map the cumulative contamination by heavy metals. Regression-kriging proved to be a flexible interpolation technique because what was not explained by auxiliary predictors was later on interpolated using kriging (Pebesma, 2004).

3.4.4 *Conclusions*

An advantage of using limitation scores is that the map of cumulative limitation scores can be directly be interpreted as the map overall soil pollution, hence, it can serve better decision makers who require a single and simple map showing where the soils are polluted and where not. Note that the formulas used can easily adopt any model between the cost and concentration. The most important thing about the limitation scores is that they are standardized and can be summed for different HMCs. Note that we did not evaluate the acidity of soils, which is also an important factor for the pollution of soils. Mol *et al.* (2003) showed that the mobility of heavy metals in soil will increase as the soils become more acid, which happens because the acid soils usually have low binding capacity. In areas where the soil acidity is much serious problem, it would be also important to map pH

in soils and then convert this variable to limitation scores or use this information to calculate weighted limitation scores from the input concentration values.

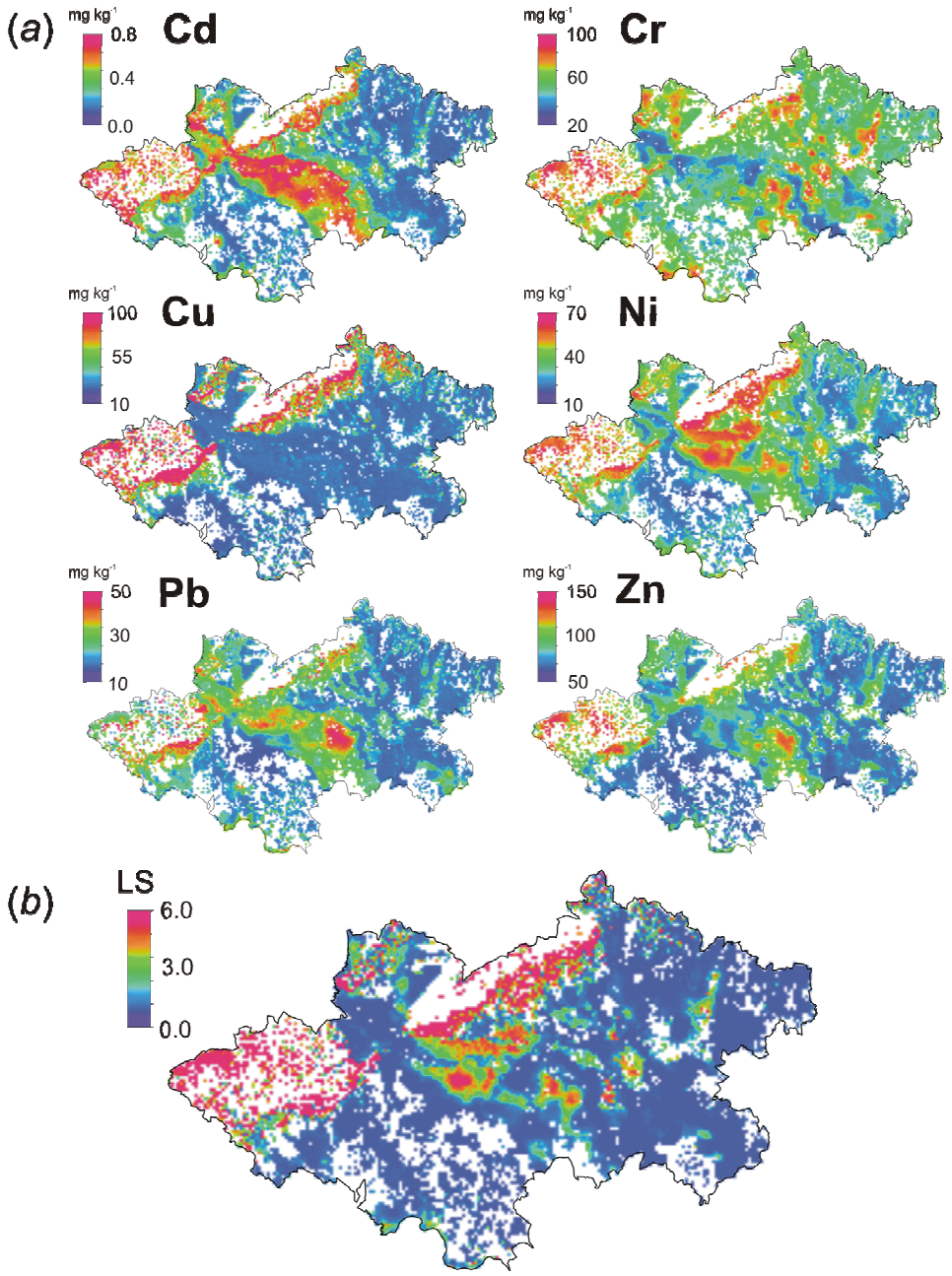

Fig. 3.5. Interpolated maps for Cd, Cr, Cu, Ni, Pb and Zn. Masked areas (white) are forests and water bodies (a). Map of cumulative limitation scores showing overall soil pollution (b).

Our hope is that this methodological framework will open several perspectives. Next step will be to think of methods to relate the cumulative limitation scores directly with the remediation costs (Broos *et al.*, 1999). Different ratios could have been used for different HMCs. A more objective approach would be to work with real figures from real-life projects and then adjust the coefficients statistically.

3.5 *Modelling soil erosion*[16]

3.5.1 *Introduction*

Wind erosion occurs over a wide variety of climatic and land surface conditions. For example, wind erosion induced dust emissions of desert surfaces are well known to influence the radiative forcing of the climate (IPCC, 2001). For more human influenced areas, like agricultural areas under cultivation, wind erosion decreases the soil fertility by removal of the most fertile parts of the soil, which are bounded to the organic matter and the finest mineral fractions (EEA, 2003). However, to what extent agricultural soils of the middle altitudes contribute to the atmospheric dust load is still vague. In the middle altitudes the wind erosion process is highly variable in time and space and depends on the area of bare soil and the climatic conditions at that given time. For the part of that report section we will focus on the wind erosion aspect.

3.5.2 *Method*

A physically based single field wind erosion model was integrated into a GIS. We used the "Stand alone erosion part" of the Wind Erosion Prediction System (WEPS) to calculate wind erosion and dust emission from agricultural used fields in Europe. The dust emission can be divided into the amount of total suspended particles (TSP ~50µm) and the PM10 part (particles <10µm). Some of the required input data has been summarized in Table 3.2. Meteorological data were assimilated from the ERA40 data sets [http://www.ecmwf.int/research/era/], which contains 40 years of 6 hourly data on a spatial resolution of almost a one-degree grid for the whole earth. Field size and field orientation are both major influencing parameters in wind erosion and thus for dust emission. Information for such parameters is available only at selected locations and a consistent, large-scale dataset is missing. ETM, TM and MSS-Satellite Data were obtained from the Global Land Cover Facility at the University of Maryland for the area of Europe. In total, 130 images were selected for the analysis. First, multi resolution image segmentation was performed using Ecognition 3.0 software, which separates consistent units of the image. Each separated unit can be characterized by size, width, length, and main direction. Secondly, using manual sample identification (n = 30 for each image) a fuzzy land use classification was performed to identify agricultural used fields in each image. Up to 10 land use classes were identified, depending on the type of landscape. Area weighted result of field size and other parameters were analyzed geo-statistically and maps created. Databases from FAO and other sources were used to determine changes in agricultural land use. Unknown locations were estimated using literature values or expert interviews. Soil input data were used from the WISE database (Batjes, 2003). Further parameters as the aggregate geometric mean diameter and aggregate geometric standard deviation, minimum and maximum aggregate size have been computed using regression equations. They are closely related to other soil parameters, like soil texture and organic matter content.

Table 3.3. Selected Requirements of Parameters for the WEPS model

Parameter group	Parameters
Field Size	Size, Length, Width, Orientation to North,
Soil	Texture, OM content, Soil water content, roughness,
Climate	Wind speed, precipitation, Temperature, Snow depth
Management	Soil cover, Roughness, Plant height

After completion of all needed input parameter the "Stand alone erosion part" of the WEPS was used to calculate wind erosion and emission of dust and PM10 for each cell. Calculations are based on the averages of

[16] Prepared by H.I. Reuter and R.Funk.

field size, field orientation, soil texture and the total agricultural used area in a grid of 0.5° × 0.5°. Results are the summarized amounts of PM10 emissions per month and square metre in the grid cells. In Fig. 3.6 for example the sum of all modelled emissions of PM10 for March 1992 by considering a bare surface are shown.

3.5.3 *Conclusions*

The amount of dust emission varies significantly time. We identified three major factors influencing the results at that scale of modelling. The observed field size varies significantly in space over the entire region which has an influence on the different transport modes, as the growing crop areas vary significantly with time and the meteorological condition from year to year. Still, other parameters like the change in management practice might influence these results as well, however data to identify these have to be obtained and tested. An evaluation for conditions occurring in the state of Brandenburg (Germany) does show good agreements of the temporal variations between simulated erosion events and measured events, but the simulated dust emissions are still overestimated.

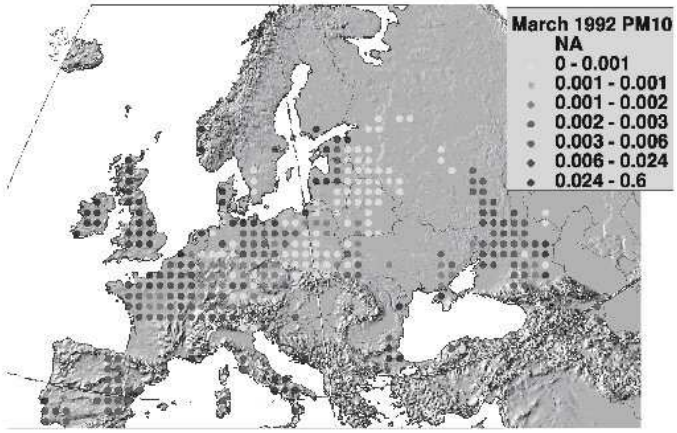

Fig. 3.6. PM10 emission in kg/m² for bare soil in the grid cell (example March 1992).

3.6 *Implementing soil functional mapping in Germany*[17]

In 1998 the Federal Soil Protection Act (BGBl 1998) was adopted by the German parliament. Beside some general targets main functions of the soil are defined within the act (Table 3.4). Natural functions relate to the following three subjects: 1) The role of soils as a habitat for people, animals, plants and soil organisms (basis for life and biomass production potential), 2) their importance as part of the ecosystem (regulation potential within the water and nutrient cycle) and 3) their ability to decompose and retard solutes and to regulate bioavailability, as a result of its filtering, buffering and substance-converting properties.

If soil functions as defined by the Soil Protection Act of Germany are compared to soil functions as described by the EU Soil Communication "Towards a Thematic Strategy for Soil Protection" (EU Commission 2002), many parallels, but also some differences can be recognized (Table 3.4). One example is the regulation potential within the water and nutrient cycle on the left which is not matched by an equivalent term on the right.

Table 3.4. Soil functions according to the German Soil Protection Act (BBodSchG) and the EU Soil Communication.

German Soil Protection Act (BBodSchG)	EU Thematic Strategy for Soil Protection
1. Natural functions	
- as a basis for life and a habitat for people,	Biomass production
animals, plants and soil organisms,	Biological habitat and gene reserve
- as part of natural systems, especially	
by means of its water and nutrient cycles,	
- as a medium for decomposition, balance	
and restoration as a result of its filtering,	Filtering, buffering
buffering and substance-converting properties,	and transforming action
and especially groundwater protection	
2. Functions as an archive of natural	
and cultural history	Cultural heritage
3. Functions useful to man as	
- a medium that holds deposits of raw materials,	Source of raw materials
- land for settlement and recreation,	Physical medium
- land for agricultural and silvicultural use,	
- land for other economic and public uses,	
for transport, and for supply, provision	
and disposal	

The compilation of soil functional maps to implement the Federal Soil Protection Act of Germany is currently under way. The methodologies applied may serve as an example when similar goals are pursued at the European level. For a successful integration of information on soil functions into planning processes, five preliminary steps are necessary:

- Identification of land quality criteria that allow a classification of soil functions and soil functional aspects;
- Compilation of selected pedotransfer rules from existing databases;
- Evaluation of all land quality criteria according to threshold values;

[17] Prepared by V. Hennings.

- All land quality criteria associated with a soil function have to be given a weight as part of a matching procedure;
- Interpretation of results for the implementation soil protection measures. This fifth step is not subject of this paper.

The term "land quality criteria" used in the first step complies with the land evaluation nomenclature. A land quality criterion corresponds with one or more of the various aspects that make up a soil function. The goal is to identify all land qualities needed to comprehensively describe the respective soil function. For Germany this was done by an expert group (Ad-hoc-AG Boden 2003). Their results are shown in Table 3.5.

Table 3.5. Allocation of land quality criteria to soil functional aspects and soil functions.

Soil function	Soil functional aspect	Land quality criteria
1. Basis for life	1.1 Habitat for people	- Exceeding of contaminant threshold values according to the Federal Soil Protection Act
	1.2 Habitat for animals and plants	- (Degree of) pristineness of biotopes
	1.3 Habitat for plants	- Biomass production potential
	1.4 Habitat for soil organisms	- Suitability of the site for soil organisms
2. Part of natural systems	2.1 Function of the soil by means of its water cycles	- Regulation potential for surface runoff - Mean annual percolation rate from the soil as part of the groundwater recharge rate - Overall evaluation of the soil water balance
	2.2 Function of the soil by means of its nutrient cycles	- Potential and availability for nutrients in terms of basic cations
3. Medium for decomposition, balance and restoration	3.1 Filtering and buffering properties for inorganic reactive contaminants	- Retention capacity for heavy metals
	3.2 Filtering and buffering properties for organic reactive contaminants	- Retention capacity for organic contaminants
	3.3 Buffering properties for acidic input	- Buffering capacity for acidifiers
	3.4 Filtering properties for non-reactive contaminants	- Risk of nitrate leaching
4. Archive of natural and cultural history	4.1 Archive of natural history	
	4.2 Archive of cultural history	

For the soil function relating to the soils ability to decompose and retard solutes and to regulate bioavailability the allocation of land quality criteria to soil functional aspects can be described by 1:1 relationships (functional aspects no. 3.1 – 3.4). In other cases several land quality criteria are needed to cover one soil functional aspect, e.g. functional aspect no. 2.1. When the function of the soil as a habitat for plants is considered, there may be a contradiction between agricultural and nature conservancy demands (functional aspects no. 1.2 / no. 1.3).

The main task of the expert group (Ad-hoc-AG Boden 2003) was not only to find land quality criteria fitting to soil functions according to the Federal Soil Protection Act, but to look for appropriate models to derive these land quality criteria from basic soil characteristics. For this purpose, the inventories of existing pedotransfer rules databases had to be compiled and evaluated. Starting in 1991, the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover established the first elements of a German soil

information system (FISBo BGR) (Eckelmann *et al.* 1995) at the national scale. FISBo BGR's detailed objectives are to:

- extend and provide a database of soil information in co-operation with the German federal states according to the needs of politics at national and EU level, of research areas and for data users e.g. from agriculture and all other affected disciplines;
- analyse this database to answer requests for information from the federal government (e.g. for preparing reports on the current situation);
- allow the compilation of basic and thematic maps and draft guidelines at administrative level;
- provide a basis for answering questions submitted by European Union agencies or international bodies;
- provide a basis for co-operation with other research institutions (e.g. for nationwide analyses).

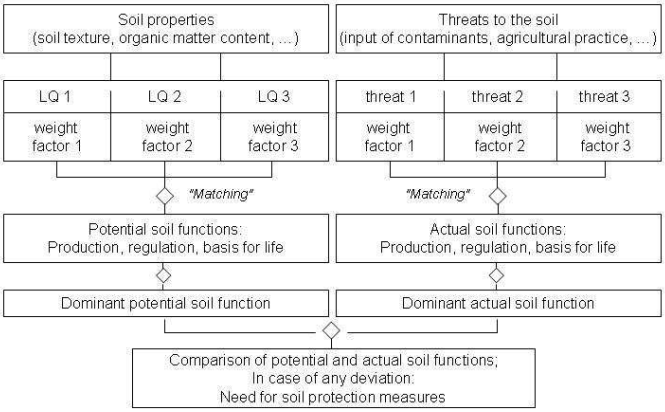

Fig. 3.7. Flow chart for the balancing of land qualities ("matching") and final interpretation of soil functions.

The following main structural components are in continuous development at the BGR in analogy to the information systems of the individual German states:

- Spatial database that maintains a number of already existing soil and related maps including the geometric-topographical data;
- Soil profile and laboratory database that contains both observation data from soil surveys as well as the results of all soil chemical and physical analyses;
- Method database ("function database", "pedotransfer rules database") for estimating the groundwater recharge rate, the retention capacity for pollutants or the susceptibility of the soil to erosion.

All of the methods in the method database are non-mechanistic, functional models based on simple empirical relationships and can be classified as "pedotransfer rules". They consist of pedotransfer functions in modular form. Examples for this kind of algorithms are the pedotransfer rule to assess the potential leaching risk of inorganic reactive contaminants such as heavy metals (DVWK 1988) or the pedotransfer rule to assess the potential leaching risk of non-reactive contaminants such as nitrate (Renger *et al.* 1990). When the inventory of the pedotransfer rules database is compared to the list of required land qualities from Table 3.5, some general remarks can be concluded: pedotransfer rules to derive all kinds of filtering and buffering properties are available and can be applied in a routine manner, while models to derive aspects of the "basis for life" function still have to be developed or are restricted to regional applications.

The third step, the classification of land qualities according to threshold values, has be done for some land qualities such as mean annual soil loss rates by water erosion. For other land qualities similar classification schemes are still missing.

Finally, all land quality criteria have to be evaluated to classify a soil function and to assess the need for soil protection measures (Fig. 3.7). For every soil function, the evaluation of all associated land quality criteria should be done by summarizing them with an appropriate weighing scheme as part of a matching procedure. This procedure allows the determination of the soils potential for production, its potential as a regulator, or its ability to serve as a basis for life. By using a ranking scheme the dominant potential soil function can be assessed. The whole procedure is repeated for threats to the soil, e.g. input of contaminants, agricultural practice

etc. Finally, potential and actual soil functions are compared; in case of any deviation there is a need for soil protection measures. The whole procedure has neither been standardized nor used for routine applications. Fig. 3.7 shows just one of many possible solutions.

For soil functional mapping at the European scale, the same operations as in Germany have to be executed. Land quality criteria have to be allocated to soil functions and the inventory of the European pedotransfer rules database has to be investigated and evaluated. Results of these first two steps are shown in Table 3.6.

Table 3.6. Investigation of the inventory of the European pedotransfer rules database in order to derive soil functions as described by the EU Soil Communication.

Soil function	Land quality	Existing approaches of the European pedotransfer rules database
1. Food and other biomass production	☞ Biomass production potential, agricultural yield potential	
2. Storing, filtering and transformation	☞ Retention capacity for heavy metals	
	☞ Retention capacity for organic contaminants	← HOLLIS (1990, 1991)
	☞ Buffering capacity for acidifiers	← LOVELAND (1990)
	☞ Risk of nitrate leaching	
3. Habitat and gene pool	? Degree of pristineness of biotopes	
	? Suitability of the site for soil organisms	
4. Physical and cultural environment for mankind	? Importance as an archive of cultural history	
5. Source of raw materials	?	

For the first two functions according to the EU Soil Communication (food and other biomass production, storing, filtering and transformation) associated land quality criteria can easily be found. When the role of the soil as a habitat and gene pool is considered, the derivation of land quality criteria is less clear. The present inventory of the European pedotransfer rules database is documented on the European Soil Bureau's homepage (ESB 2005). According to these citations (King *et al.* 1994, van Ranst *et al.* 1995), only two pedotransfer approaches to estimate retention and buffering properties of the soil are available (Table 3.6). This means that for implementing the EU Thematic Strategy for Soil Protection there is still some future work ahead of us.

When the present situation in Germany and Europe is compared, some general conclusions can be drawn:

(1) The first steps to determine soil functions according to the German Soil Protection Act have been realized in Germany; two further steps are missing: the methodology to weigh soil functions at the different stages of evaluation has yet to be standardized. In addition the final interpretation procedure to derive soil protection measures still has to be developed.

(2) Within the framework of the EU Soil Communication main soil functions have been defined too. For some of them, associated land quality criteria exist, for others this task has not been accomplished yet. At the moment, the European pedotransfer rules database contains only a few appropriate approaches. Filling this gap is an important future task.

3.7 *Soil organic matter*[19]

3.7.1 *The case study*

One of the major stresses on the soil resources is the decline of organic matter content (SOM). In many of the European countries there is no reliable, up-to-date, spatially defined soil OM information. Soil Information and Monitoring Systems were setup in these countries to survey the recent situation and estimate the rate and trend of potential changes of SOM. These Monitoring systems are profile based networks, with regular sampling period, which can provide limited, often insignificant percentage of the country surface. This data needs to be extrapolated to create continuous coverage of the area in question. In the meantime, staying in line with the European mapping standards is also an important requirement.

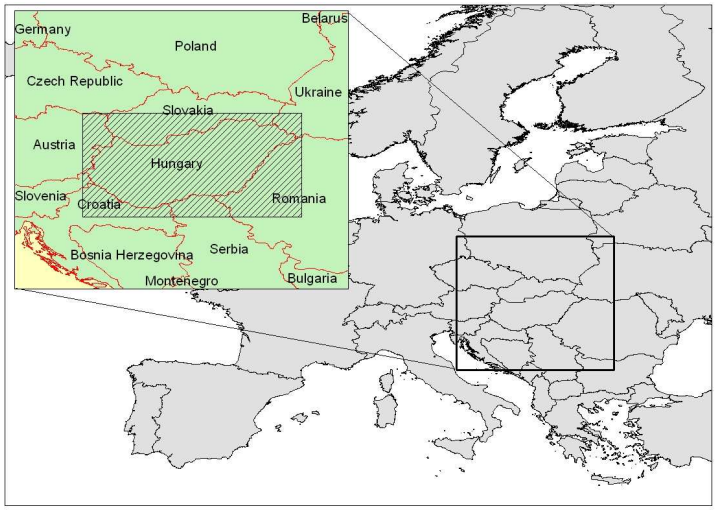

Fig. 3.8. The study area location. The hatched rectangular on the central-European map is the pilot area.

The SOM content of the soil is strongly related to the land use, vegetation, climate and terrain features, which can be modelled with DEM and satellite data. The type and the amount of soil organic matter are strongly related to the presence of water and the lateral redistribution of the surface material by erosion. Both of these phenomena are partially controlled by the terrain. Among others CTI, Wetness index, PDD (Dobos *et al.* 2000), curvature, slope gradient and flow accumulation variables proved to have a significant contribution to the estimation of the depth of A-horizon, soil carbon content (McKenzie & Ryan, 1999; Gessler *et al.*, 2000), soil organic matter content (Moore *et al.*, 1993), and topsoil carbon (Arrouays *et al.*, 1998; Chaplot *et al.*, 2001).

In this case study, a method to extrapolate point information based on an integrated digital elevation and satellite dataset and statistical-geostatistical tools to create a SOM map of Hungary is demonstrated. The overall aim of the study is to develop a methodology, which can be used to derive spatially defined SOM information for the EU policy support.

The study area covers the Carpathian basin (Fig. 3.8). The MODIS sensor data (Salomonson *et al.* 2002) was used for the project. In order to represent different environmental conditions, two dates, May and September of year 2000 were selected. In this study the 1-7 reflective bands, the NDVI, and a thermal infrared band (band 31) were selected. The 1 km layer was later resampled to 500 m.

The 3 arc second resolution SRTM30 database was used as terrain data. Numerous terrain attributes were created and added to the database:

- Altitude
- Specific catchment area (A_s: the ratio of the number of cells contributing flow to a cell and the grid size)
- Profile, planar and complex convexity (see the ArcInfo® online manual)

[19] Prepared by E. Dobos.

- Slope percentage (S)(average maximum technique, Burrough, 1986, see also ArcInfo® online manual)
- Potential drainage density (PDD) (Dobos *et al.* 2005a)
- Aspect
- Flow accumulation (number of cells contributing flow to a cell)
- Relief intensity (difference between the maximum and minimum elevations within a preset sized neighbourhood) (Dobos *et al.* 2005b)
- CTI (Compound Topographic Index: ln A_s /S) (Wilson and Gallant, 2000)

In order to match the 500 m resolution of the MODIS, the terrain data layers were resampled to 500 meter using the bilinear function of Arc/Info. Two artificial layers were created, an easting and a northing one to represent the geographic position. The east-west direction represents the transition between the oceanic and the continental climate, what is – among others - strongly correlated with the rainfall distribution.

***Soil Monitoring System for Hungary* (*TIM*)**

TIM is part of the Hungarian Environmental Monitoring System created and maintained since 1995 (Várallyay *et al.*, 1995). This point-vector database consists of 1236 soil profile descriptions. The locations of these points were selected as representative points of the natural landscape units of Hungary, so the database can be considered a realistic characterization of soil resources of the country. The TIM data served as reference information for the regression and kriging (dependent variable). The SOM contents were calculated on a horizontal basis in t/ha, and the horizon SOM contents were summed up to derive the total SOM content of the area. The variables used to calculate the SOM content were the SOM %, bulk density and horizon depths.

Spatial prediction using regression-kriging

Regression kriging was used to create the SOM content layer for Hungary. The MODIS bands of the two dates provided 18 layers, representing 18 environmental variables. 10 layers of terrain variables were created as well. All together 30 independent variables were derived counting the easting and northing layers as well. In order to achieve normal or normal-like distribution for all the variables, logarithmic and square root data transformations were carried out. Finally 45 layers (variables) were created. These layers complemented with the SOM values derived from the TIM database were used as variables for the regression kriging

3.7.2 *Results*

The forward regression has selected 12 variables into the equation. The variables and the regression coefficients are given in Table 2. The adjusted R^2 was quite low, but significant, 0.238, meaning that there is significant correlation between the SOM content and terrain and spectral variables. The scatterplot of the estimated and original SOM values are shown in Fig. 3.9. The RMSE was 11642,92 in g/m^2 unit.

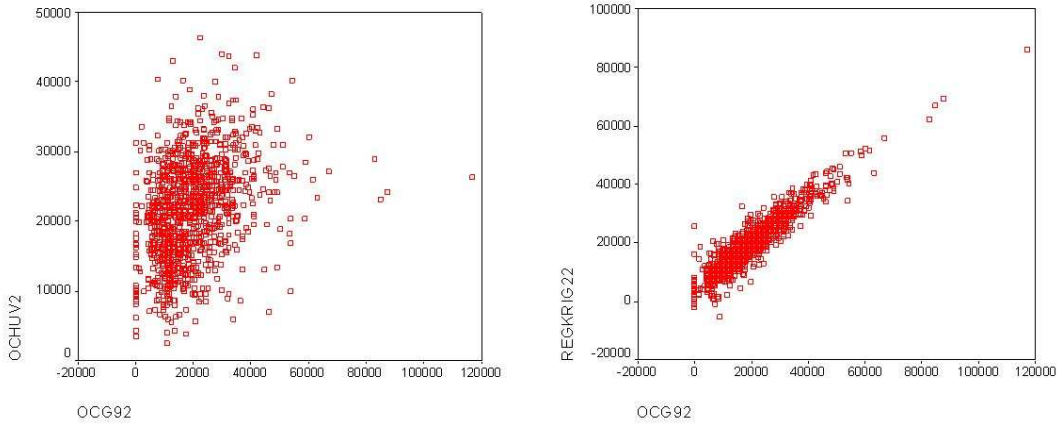

Fig. 3.9. Scatterplots of the original (OCG92) and the predicted SOM values for (a) the regression derived (OCHUV2) and (b) the regression-kriging derived (REGKRIG22) datasets.

Despite of the low statistical correlation, the overall look of the map looks promising. It coincides with our understanding about the spatial distribution of SOM content over Hungary, determined by the climatic, geologic, biotic and human impacts on the soil formation. The low R^2 value and the scatter plot intimate the complex nature of the SOM distribution, determined by important soil forming factors, which are not significantly represented by the satellite images or the terrain variables. Although the major factors regulating the SOM balance in general were present among the variables, the performance of the regression model was disappointing. The authors identified two potential reasons. The first one is coming from the scale issue and the representativity of the training dataset. The independent variables have a 500 meter nominal resolution, what is quite low comparing with the training dataset. The training points were taken as single borehole samples, which do not necessarily characterize well the entire, 500 by 500 m grid cell area. The organic carbon was sampled twice before, first in 1992 and than in 1998. The comparison of the two datasets showed a very high, often unrealistic variation in the SOM content, which is probably due to the sampling design. A block sampling design for the monitoring system would be more appropriate and would result in a much better and consistent SOM database. It would help in the data regionalization as well, which is one of the most important issues at national level. Besides the representativity question, a well defined error trend was identified as well. The organic carbon content (OCC) of the chernozem areas on loess parent materials and on the mountainous areas are well estimated or slightly underestimated or by the regression model, while the OCC of the sandy and clayey regions of the plain area of Hungary are significantly overestimated. This trend was captured by the ordinary kriging of the regression error (Fig. 3.10). The combination of the regression and error kriging steps resulted a refined SOM database, with a much lower RMSE (4382.7) and higher correlation (Fig. 3.9b).

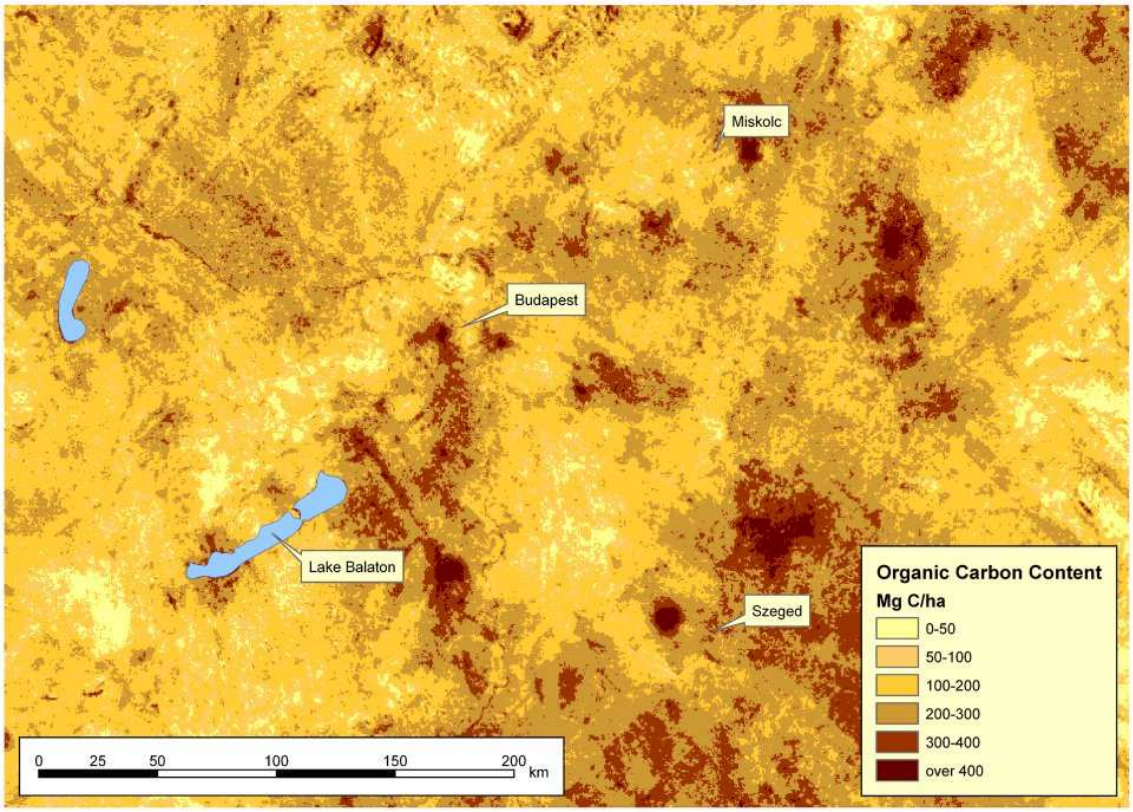

Fig. 3.10. Organic matter content of the soils of Hungary derived from MODIS and SRTM30 data through regression kriging.

3.7.2 Conclusions

A digital soil mapping procedure was tested here to produce a SOM spatial information system for Hungary. The results of the linear regression procedure is quite promising, however, the statistical measures are low. The regression combined with kriging of the residuals, the so called regression –kriging produced a much more accurate result with acceptable statistical measures and realistic spatial distribution of the SOM. The method is based on existing digital data sources with global coverage, thus can be repeated anywhere in the world, where soil profile data is available for training. Digital elevation data and remotely sensed (RS) information are among the best environmental descriptors. However, the correlation between these data layers and certain soil properties depends highly on the data quality and the environmental conditions, when the data was acquired. Stochastic models, like regressing RS data to estimate soil properties are well suited to handle these problems and adapt the function to the information contents of the available predictors. In the frame of a well defined spatial soil inference system, more potential pre-existing input data could be used to run the regression model and refine the procedure to better fit to our needs and exploit the emerging state of the art tools and data of information technology.

Acknowledgements

This study was supported by the European Commission, by the Hungarian National Science Foundation (OTKA, 34210) and by the Bola Foundation.

4 Conclusions[20]

Nowadays, in order to tackle various environmental issues related to soil, like soil degradation due to land management, soil capacities and its sensitivity to threats... Digital Soil Mapping appears to be useful and even, an irreplaceable procedure. However, each DSM system is highly dependent on the purpose and the study area. The input data should be then relevant to the purpose of the study.

4.1 *We need data, we need specifications*

The whole procedure of DSM contains a lot of intermediate steps that are highly data demanding at various phases of its execution. The requirement to fulfil its demand is pre-implicit for successful execution of the procedure. For instance, it is quite difficult to answer the feasibility of precision agriculture with soil data at the regional level. Obviously, the data at higher resolution are more expensive: DEM at 30m resolution can cost about 400 euros/ 100 km whereas a DEM at 90m is free.

Either due to high price or due to the inconsistency on the resolution of the existing data delivered on out by the present techniques exploiting the modern technologies, it is usually difficult to find various adequate auxiliary data. In order to overcome this obstacle, disaggregation and/or aggregation processes must be done as pre-treatments to produce digital soil map at a targeted resolution. Scaling issues are one among the major research topics that must be considered by soil mappers; nevertheless others must also be evaluated.

4.2 *Research needs*

Since Digital Soil Mapping allows for evaluating the accuracy associated to the soil map, this evaluation should also be applied on the input data. The problems ahead to tackle are:

- How to evaluate the quality of the input data, above all soil observations and soil classification from an attribute and geographical point of view?
- How to correlate and harmonize existing data sources with different origin, quality, resolution/scale, and sampling/analysis procedure for a pan European soil database
- If no soil data exists in the study area, how to optimize the sampling/description/analysis procedures of these data according to the purpose resolution?
- How to compute the accuracy in the final functional map?
- In order to assess a risk, is it better, to evaluate the risk only where accuracy is higher than a certain threshold or evaluate the risk whatever the accuracy is?
- How and in what level can the traditional and digital soil mapping techniques be combined to optimize their values in a hybrid system.

The issues raised above are not exhaustive because they will in turn lead to the rise of new problems as research gaps to tackle further.

The main research needs focuses on:

- integration of new covariates and evaluating their relation with soil properties;
- evaluation of data input quality;
- integration of data and model accuracy into function and threat mapping;
- the design of a target-oriented, flexible soil data system for functional data use
- elaboration of DSM toolboxes for an easy to use expert tool

[20] Prepared by F. Carré and S. Selvaradjou.

4.3 *The road towards soil functional mapping*

Almost ten years would be necessary to get better expert knowledge in the field of the application of DSM to match with the appropriate procedure in relevance to the environmental problem in hand, and the object under investigation (study area). On the first step, it is advisable for European soil mappers to better share their expert knowledge and experiences. This can be achieved through establishing a DSM library. Meanwhile, some pilot areas are also need to be set up in order to test the different procedures and to evaluate the best procedure suitable for different cases.

Collecting data, materials and experiences could lead to build up better functional and easy to use tools for all environmental managers and experts.

4.4 *Proposal for new WG on Soil functions*

Digital Soil Mapping is dedicated to map soil types or soil properties that are useful to answer environmental issues through soil function or soil threat mapping. The Soil Information Working Group (SIWG) has initiated focuses on delineation of soil. The SIWG should provide to the DSM WG precise information on the soil properties to map and on the associated scales (Tier I and Tier II). But there is a strong need to acquire useful soil information according to the function to map. That is why the creation of a new Working Group dedicated to delineate various soil functions would be quite useful for Digital Soil Mappers.

In both case, soil attributes provided by the DSM working group are the inputs of the delineation. However, the result of the delineation could provide or underline the strong need of improving the input data. Further, research has to be undertaken to improve the resolution of the soil properties to be mapped. Thus, there is an interlinkage of sharing data information (requirement or task execution) between various working groups (DSM, SI, Function) in order to effectively tackle the environmental issues in hand.

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This report provides an overview of the state-of-the-art digital soil mapping techniques and suggest ways to use these techniques to improve spatial and semantic detail of existing soil data at national and European levels.

The DSM Working Group is the advisory board made from researchers and soil mapping experts from EU countries. It has been founded at the last 2004 Plenary of the European Soil Bureau Network (Ispra, Nov 2004) as a support to the Soil Information WG. Its task is to review data, techniques and applications of digital soil mapping and to propose common methodologies for mapping European soils at different scales. Furthermore the WG Activities input to exploitation of potentials to assist the European Commission in policies related to sustainability of soils, namely to inventory and monitor soil functions for the purpose of policy making. For more info, see also http://eusoils.jrc.it

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