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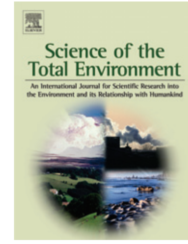

Review

Soil monitoring in Europe: A review of existing systems and requirements for harmonisation

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ABSTRACT

Official frameworks for soil monitoring exist in most member states of the European Union. However, the uniformity of methodologies and the scope of actual monitoring are variable between national systems. This review identifies the differences between existing systems, and describes options for harmonising soil monitoring in the Member States and some neighbouring countries of the European Union. The present geographical coverage is uneven between and within countries. In general, national and regional networks are much denser in northern and eastern regions than in southern Europe. The median coverage in the 50 km×50 km EMEP cells applied all over the European Union, is 300 km^2 for one monitoring site. Achieving such minimum density for the European Union would require 4100 new sites, mainly located in southern countries (Italy, Spain, Greece), parts of Poland, Germany, the Baltic countries, Norway, Finland and France. Options are discussed for harmonisation of site density, considering various risk area and soil quality indicator requirements.

Contents

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1. Introduction

Soil is a vital non-renewable resource providing essential support to ecosystems and to human life and society. Soils deliver valuable ecosystem goods and services (De Groot et al., 2002), e.g. nutrient release from soil organic matter; water storage and transfer (Lavelle and Spain, 2001); water filtering (Morvan et al., 2006, Weber and Miller, 1989); food security (Carvalho, 2006), cultural heritage, etc. Therefore, it is imperative to the environment and society that soil functions (Blum, 1993) and their quality are maintained. A proposal has been made for establishing a directive of the European Commission for a common strategy for the protection and sustainable use of soil (European Commission, 2006a).

Soil monitoring is the systematic determination of soil variables so as to record their temporal and spatial changes (FAO/ECE, 1994). Soil monitoring is essential for the early detection of changes in soil quality. Such early detection enables the design and implementation of policy measures to protect and maintain the sustainable use of soil so that it continues to deliver ecosystem goods and services. A Soil Monitoring Network (SMN) is defined here as a set of sites/areas where changes in soil characteristics are documented through periodic assessment of an extended set of soil parameters. The use of a harmonised methodology is essential to provide data which is comparable among sites and between countries. In this paper, we focus mainly on classical soil analytical measurements. It is appreciated that other approaches have been proposed, such as the use of 'proxy' indicators easily detectable by surveyors in the field. A typical example is the Land Use Land Cover Annual Survey (LUCAS) that includes some direct field observations on more than 1,000,000 observation points over Europe. However, the results from such surveys are crucially dependent on the expertise of the field surveyors and the harmonisation of the results.

The Communication of the European Commission 'Towards a Thematic Strategy for Soil Protection' identifies eight threats to Europe's soils (European Commission, 2002, 2006a,b; Van-Camp et al., 2004): soil erosion, decline in soil organic matter, soil contamination, soil sealing, soil compaction, decline in soil biodiversity, soil salinisation and landslides. We also considered desertification as a threat to soil in our study. Relevant measurable indicators of the threats to soil have been proposed (Table 1, after Huber et al., 2007).

The objective of this paper is to review existing SMNs in the Member States of the European Union (EU) and Norway, and to identify and describe options for harmonising soil monitoring in these countries. Therefore, in this paper, the soil monitoring network in Switzerland is not taken into account, although it is known to exist (Schmid et al., 2005; Bucheli et al., 2004). Considering the need to produce comparable and consistent results between countries, it is important that differences among EU SMNs are highlighted and that ways of overcoming them are identified. Using these data, we studied the representativeness of the spatial coverage of the monitoring sites in Europe. Using data on the extent of some environmental pressures which are relevant to soil threats and measured within the SMNs, we also studied the representativeness of the spatial coverage of sites in relation to these pressures.

Table 1 – Soil threats and their selected indicators

Soil threats	Main relevant indicators for SMN
Soil erosion	Estimated soil loss Measured soil loss
Decline of soil organic matter	Organic matter or organic carbon content Bulk density C:N ratio
Soil contamination	Heavy metal content pH Nutrients content
Soil sealing	*Not relevant for SMN*
Soil compaction	Bulk density Organic matter content Particle size distribution Soil water retention Saturated hydraulic conductivity Observation of soil structure
Decline of soil biodiversity	Earthworm diversity Collembola diversity Microbial respiration
Soil salinisation	Salt profile Electrical conductivity Exchangeable sodium percentage
Landslides	*Not relevant for SMN*
Desertification	Organic matter content Salt content Electrical conductivity

2. Materials and methods

2.1. Soil monitoring networks in Europe

A standard Excel spreadsheet was sent to ENVASSO project (ENVironmental ASsessment of Soil for mOnitoring) partners requesting detailed information on national soil monitoring networks (SMNs), their sampling designs, monitoring site coordinates, measured parameters and analytical methods. A previous attempt to collect this information was made during the period 2002–2004 (Jones et al., 2005a) but the results obtained were incomplete spatially and of a qualitative nature only.

To be recognised as a soil monitoring site, each site had to fulfil the following conditions: i) the georeference of the site is known with an accuracy of less than 10 m, and ii) one or more measuring campaigns have been conducted, or following an initial campaign, future measurements are planned or could be undertaken at the site (excluding sites that are now in built-up areas). These conditions are regarded as the minimum. The quality of a SMN will be enhanced if the following conditions are fulfilled: i) a composite sample or several replicates samples are collected from the site in order to measure the spatial variability of the soil, ii) the accuracy of the georeferencing is less than half of the site area, and iii) each subsample is individually georeferenced.

2.2. EU-wide databases

The representativeness of spatial coverage by the monitoring sites was assessed by overlaying the map of soil monitoring sites on soil and land cover databases and on spatial coverage of pressure data, for example, estimated soil loss by water erosion and vulnerability to compaction. Representativeness has also been assessed using the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) grid, which has been used in many other studies (Göransson et al., 2006; Hirst and Storvik, 2003). It has several advantages because its resolution is suitable for: the calculation of the density of sites expressed as 1 site per number of km^2, the production of European scale maps, and the overlay of such aggregated maps directly on estimates of emissions or of depositions of air pollutants provided by EMEP.

2.2.1. The European Soil Database

The Soil Geographical Database of Europe at 1:1,000,000 forms the geometric component of the European Soil Database which is part of the European Soil Information System — EUSIS (Le Bas et al., 1998). It is the product of a collaborative project involving all the European Union and neighbouring countries, that has been active for the past 20 years (King et al., 1994, 1995, Heineke et al., 1998), providing simplified representation of the diversity and spatial variability of Europe's soils. A primary component of the database is the Soil Typological Unit (STU), which is described by variables (attributes) that specify the nature and properties of the soils, e.g. texture, parent material, soil water regime, stoniness and depth. It is not feasible to delineate the STUs separately at the 1:1,000,000 scale; so they are grouped into soil associations that can be depicted spatially as Soil Mapping Units (SMU), to illustrate the functioning of soil systems within the landscape.

Because of the considerable variability of soils in Europe, and the small scale to which the database relates, the precision of the variables is low. The paucity of measured data for representative soil profiles at a local scale in Europe has necessitated the estimation of soil properties by expert judgement, even for relatively widespread soils. This expertise was developed during synthesis and generalisation of national or regional maps, already published at more detailed scales, e.g. 1:50,000 or 1:250,000. Delineation of the SMUs on the European Soil Map was undertaken by the same national experts. Quality indices of the information (purity and confidence level) are attached to each soil parameter, to guide interpretation and usage. The latest version of the European Soil Database (v2.0) includes an extended geometric component 'The Soil Geographical Database of Eurasia' (Lambert et al., 2002), which includes the Russian Federation, Belarus, Moldova and the Ukraine, but does not yet cover Cyprus and Malta.

2.2.2. Corine Land Cover 2000

The aim of the Corine Land Cover (CLC) database is to provide an inventory of Earth surface features relevant to environmental management (Heymann et al., 1994). Only features that are relatively stable in time are mapped; for example diurnal changes (e.g. tide), seasonal changes (e.g. vegetation cycle) or short-term changes (e.g. flooding) are specifically excluded. Computer-aided visual interpretation of satellite images has been chosen as the mapping methodology (http://image2000.jrc.it/ last accessed, 12/07/2007). The basic choices of scale (1:100,000), minimum mapping unit of 25 ha and minimum width of linear elements of 100 m represent a trade-off between cost and detail of land cover information (Heymann et al., 1994).

The standard CLC nomenclature includes 44 land cover classes. All national teams had to adapt the nomenclature according to their landscape conditions, following standard criteria. The 44 classes have not changed since the implementation of the first CLC inventory (1986–1998). However, the definition of each nomenclature element was improved (Bossard et al., 2000) to facilitate comparable results in time and space. A special feature of the nomenclature is the class 'Heterogeneous agricultural areas'. It is formed by objects, (e.g. plots of arable land, areas of natural vegetation, etc.) which themselves would be smaller than the minimum mapping unit (25 ha).

2.2.3. Soil erosion risk estimates

Pan European Soil Erosion Risk Assessment — PESERA (Kirkby et al., 2004, S.P.I.04.73, 2004) was developed as a model to handle spatial and temporal data of variable precision and detail and to enable the impacts of agricultural policy, land use and climate changes to be assessed and monitored across Europe. PESERA uses a process-based and spatially distributed model to quantify soil erosion by water and assess its risk across Europe. The published PESERA version (S.P.I.04.73) does not cover Cyprus, Malta, Norway, Sweden and Finland because at the time of implementation (October 2003), Corine land cover data were not available for these countries.

The estimated soil loss (t ha^{-1} yr^{-1}) from water erosion has been calculated by applying the PESERA grid model at 1 km, using the European Soil Database, CORINE land cover (1988–92), climatic data based on the MARS agroclimatic database (Vossen and Meyer-Roux, 1995), interpolated to 1 km, and a 30 second (1 km) EROS digital elevation model (DEM). The PESERA model produces results that depend crucially on land cover as identified by CORINE and on the accuracy of the interpolated climatic data.

An average European soil erosion threshold for mineral soils, set according to average soil formation rates, is considered to be, 1 t ha^{-1} yr^{-1} (Jones et al., 2004). A soil loss exceeding that threshold may not be sustainable in the long-term. Therefore, all the cells with soil loss estimates greater than 1 t ha^{-1} yr^{-1} were considered as soil erosion risk cells. The selected cells were aggregated in the 50 km EMEP grid, (http://www.emep.int/index_data.html), available free of charge on the Internet.

2.2.4. *Peat map*

Jones et al. (2005b) described the methodology for estimating soil organic carbon (SOC) contents (% w w^{-1}) in topsoils across Europe. Processing of the data was performed on harmonised spatial data layers in raster format, with a 1 km × 1 km grid spacing, and these data were used as a basis for the peat map. Montanarella et al. (2006) showed that, using a threshold of SOC ≥25%, the distribution of peat and peat-topped soils is more accurately portrayed by the map of organic carbon in topsoils of Europe (Jones et al., 2005b) than by using a reduced threshold of ≥20% SOC or the organic soil map units on the European Soil Map. The peat areas at 1 km were then aggregated into the 50 km EMEP grid.

2.2.5. *Compaction risk*

The compaction risk map (Jones et al., 2003) is based on the European Soil Map at the scale 1:1,000,000. The map is classified into 4 compaction risk classes: low, medium, high, and very high and the current version excludes Cyprus and Malta. The representativeness study was performed in the high and very high compaction risk areas, aggregated according to the 50 km EMEP grid.

2.2.6. *Heavy metals deposition data*

Deposition of heavy metals can cause soil contamination. The EMEP programme notably focuses on providing monitored and modelled data on concentrations, depositions and transboundary fluxes of heavy metals (Ilyin et al., 2006) and Persistent Organic Pollutants (Gusev et al., 2006) in Europe. It relies on three main elements: the collection of emission data, the measurements of air and precipitation quality and the modelling of atmospheric transport and deposition of air pollution. In this work, we only used the heavy metals data because most of the SMNs do not monitor organic pollutants or air and precipitation quality.

The EMEP programme provides data on annual averages of lead, cadmium and mercury concentrations in air and annual averages of lead, cadmium and mercury depositions. For this study, we use deposition data for the year 2004, at a spatial resolution of 50 km × 50 km for Europe (EMEP, http://www.msceast.org/ Section 'EMEP Countries'), except Cyprus and Malta.

2.2.7. *Population density*

Soil contamination is often associated with areas of high population density, defined in this study as areas with more than 200 inhabitants per km^2. In these areas there may be a pressure on soil from the emission and subsequent deposition of pollutants (Saby et al., 2006), or by other mechanisms such as urban waste spreading, soil sealing or landscape fragmentation. The population density database is part of the GISCO (Geographic Information System for the European Commission) database (http://eusoils.jrc.it/gisco_dbm/dbm/p1ch3.htm, last accessed 08/10/2007). This database contains population numbers and population density within the regional subdivisions based on NUTS5 units (Nomenclature of Territorial Units for Statistics, level 5) defined by RISE (Infra-Regional Information System; Eurostat).

This database raises some problems. First, it covers mainly the western part of Europe but does not include data for Scotland, Norway and Malta, or the countries of eastern Europe. Secondly, there are large differences in the size of the NUTS5 polygons in the different countries. A typical NUTS5 area may be 20,000 km^2 in Sweden, but less than 1 km^2 in another country. Moreover, if we consider population density as a pressure indicator, monitoring sites may fall within a small area of low population density as defined by the database, but actually be in a densely populated area and so represent soil that is subject to population pressure. To take this problem into account, we aggregated the NUTS5 data by calculating an area-weighted mean for 50 km cells in the EMEP grid.

2.2.8. *Livestock*

More intensive livestock production may also cause soil contamination by zinc or copper, e.g. by spreading of concentrated animal manures (slurry and sludge). We obtained pig and cattle population densities from the Eurostat database (http://epp.eurostat.ec.europa.eu/portal/page?_pageid=0,1136162,0_45572076&_dad=portal&_schema=PORTAL, last accessed 08/10/2007). This database contains several animal categories and is based on the NUTS2 nomenclature. The NUTS2 polygons represent the highest resolution of European-wide information on livestock but there is no information in the databases for Norway and Malta. The data used for this study are the mean livestock values between 1997 and 2005. The densities of pigs and cattle in Europe were aggregated separately on the 50 × 50 km grid, to take account of the different NUTS2 polygon areas. Grid cells were mapped that exceeded 70 pigs and 55 cattle per km^2.

2.2.9. *Desertification map*

Desertification is mapped on a 1 km grid, based on the PESERA climatic data. A climate index, based on precipitation/evapotranspiration, developed for the MEDALUS Project by Kosmas et al. (1999) was calculated for each cell. As this map is based on PESERA climatic data, it does not cover Cyprus, Malta, Norway, Sweden and Finland. For the representativeness study, arid and semi-arid areas were considered as either desertified or under risk of desertification. These areas were then aggregated according to the 50 km EMEP grid.

2.3. Analysis of representativeness

Using the ArcGIS™ spatial analysis software, the different databases characterising the monitoring sites coverage were overlaid to produce maps showing the coverage of soil monitoring sites (SMN) for parameter categories. For each mapping unit (SMU, land cover or EMEP cells), we calculated a coverage per site expressed as site per number of km^2. The median value of this coverage of the SMN sites in the whole of Europe was used as a reference to estimate the number of new sites or new measurements that would be needed in each country to reach an acceptable common coverage for the whole of Europe. In order to map representative areas for each pressure data, only EMEP cells with an area under threat that is greater than this median value were retained.

3. Results and discussion

3.1. Spatial coverage of the monitoring sites

The geographical distribution of the soil monitoring sites in Europe is not uniform (Fig. 1). Some countries have rather dense networks (e.g. England and Wales, Northern Ireland, Austria, Denmark, Malta), whereas other large countries have relatively few monitoring sites (Spain, Italy, Greece).

The coverage of sites, expressed as the number of km^2 represented by each site in the EMEP cells (50×50 km), is highly variable over Europe. Some EMEP cells have no site at all, and the coverage within a country can be either homogeneous (with completed systematic grids, e.g. England and Wales, Scotland, Northern Ireland, Ireland, Denmark) or heterogeneous and based on a spatially irregular selection of sampling locations using expert judgement (e.g. Germany, Hungary, Poland). Some countries have several different networks (e.g. Belgium, Spain) that are not coordinated, while others have a systematic grid for which initial sampling has not been completed yet (e.g. France). For some countries, participants did not provide information for all the SMNs that exist. For example, we did not receive detailed information on some monitoring projects that have been described by Ibáñez et al. (2005) for Spain, and by Filippi (2005) for Italy; in some cases participants only had access to georeferenced sampling positions for forest (mainly ICP Forest, International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) monitoring sites. For example, non-forest soil monitoring sites were not reported for Sweden although these do exist. Our experience suggests it is probably not feasible to obtain a better level of overall information about national SMNs without a considerable amount of extra effort. Although most SMNs use a database and GIS to store and process the monitored data, and are able to deliver them in various formats without major technical problems, the external access to data is often limited and restricted to the metadata that describe the nature and the origin of the information. It is noteworthy that some national SMNs have not yet defined clear rules for data availability and, unless clarification is forthcoming, this will be a barrier to effective reporting on the status of soil conditions at the European level. Notwithstanding some incomplete information, the results of this study represent the most exhaustive collection to date of metadata on soil monitoring activities in Europe. Also, this information is judged to be sufficient to provide a meaningful Pan-European analysis of the adequacy of current SMNs and the extension of these which would be required to provide a harmonised and sufficient coverage, based on an analysis of representativeness, while considering the limitations outlined above.

The mean coverage of sites across the European Union is about 133 km^2 per monitoring site, the median value being

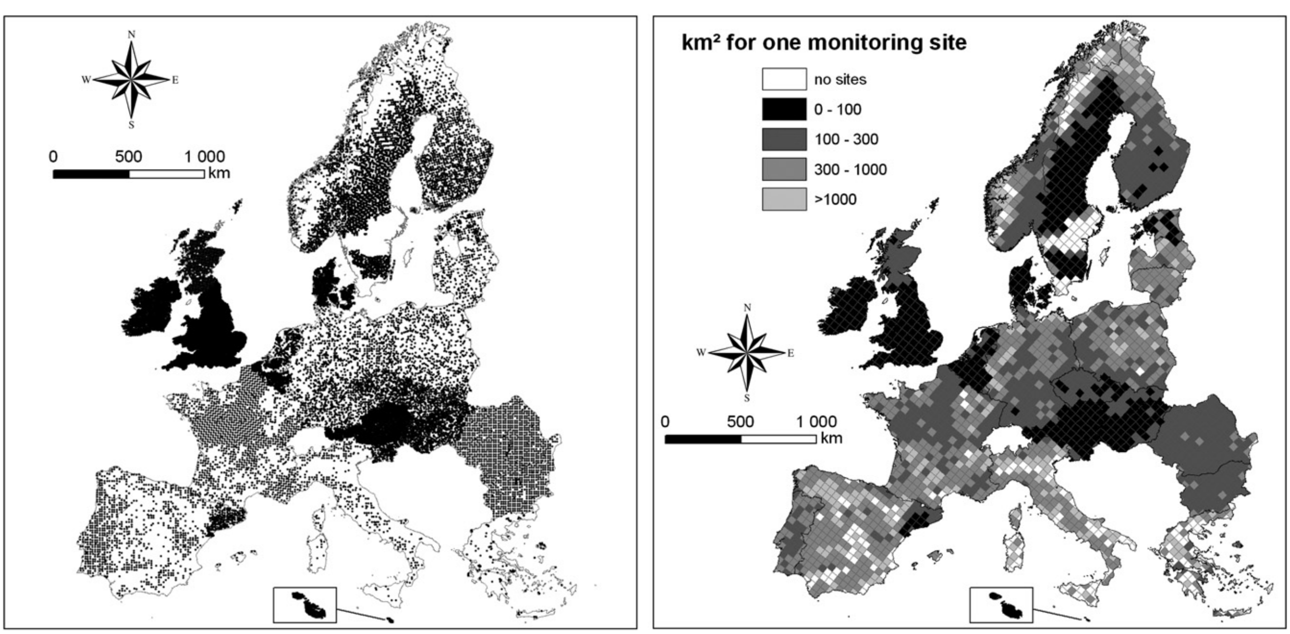

Fig. 1 – Repartition (right) and density (km^2 for one monitoring site in the 50 km × 50 km EMEP cells, left) of the soil monitoring sites in Europe.

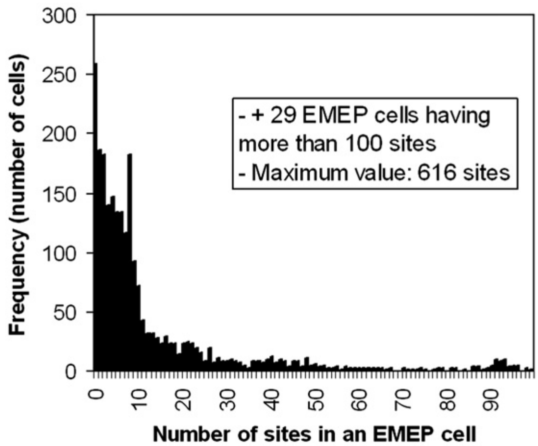

Fig. 2 – Distribution of the number of soil monitoring sites in the EMEP cells.

around 300 km^2. The distribution of the number of sites in the EMEP cells is shown in the Fig. 2. This median coverage would also arise from a 17 km×17 km systematic grid. To populate 50 km×50 km cells with this median coverage, 4100 new sites would be required, mainly located in southern countries (Italy, Spain, Greece), and parts of France, Poland, Germany, the Baltic States, Norway, Finland and Sweden (Table 2). This number is probably a slight overestimate, considering that some metadata were not available for Italy and Spain, and that some SMNs are currently being implemented (France). The results illustrate the large differences in SMNs between countries, and the significant effort that would be required to achieve harmonisation. However, it is relevant to note that a 16 km×16 km grid has already been established for forest soils (ICP, 2004), and that if extended this would closely match the median coverage emerging from the analysis of existing SMNs described in this paper.

Discussions are still ongoing in Europe about the effectiveness of stratified sampling compared to grid design. Previous simulations have shown that a 16 km×16 km grid is representative of most soil type/land cover combinations at European and national scales (Van-Camp et al., 2004; Arrouays et al., 2001). However, the design of a sampling scheme is determined by the indicator to be monitored and the output and precision required for that indicator. For

Table 2 – Additional monitoring sites needed (per country) based on different pressure indicators

	Total	High soil loss estimates	Peat area	Compaction risk	High population density	High cattle density	High pig density	Cadmium deposition	Mercury deposition	Lead deposition	Desertification risk
Austria	0	0	–	0	0	0	0	–	–	–	0
Belgium	0	0	–	1	0	1	1	1	0	1	–
Bulgaria	12	2	–	2	x	–	–	5	3	0	2
Czech Republic	0	3	–	1	x	–	–	0	0	0	0
Denmark	2	0	–	0	0	0	0	–	–	–	–
England and Wales	2	0	0	1	0	0	0	–	0	–	–
Estonia	21	–	2	8	x	–	–	–	–	–	–
Finland	209	x	81	203	0	–	–	–	–	–	–
France	452	107	–	124	30	61	29	15	3	28	1
Germany	205	66	0	51	61	63	86	19	1	12	–
Greece	330	105	–	16	9	–	–	13	59	33	34
Hungary	0	0	–	0	x	–	0	0	0	0	0
Ireland	0	–	0	0	0	0	–	–	–	–	–
Italy	656	201	–	115	213	52	91	–	5	5	163
Latvia	89	–	2	29	x	–	–	–	–	–	–
Lithuania	79	3	–	63	–	–	–	–	–	–	–
Luxemburg	0	–	–	–	0	2	–	–	–	–	–
Malta	0	x	–	x	x	x	x	x	0	0	0
Netherlands	2	–	0	0	2	1	1	1	0	0	–
Northern Ireland	0	–	–	0	0	0	–	–	–	–	–
Norway	417	x	4	313	x	–	x	x	–	–	–
Poland	247	81	3	97	x	–	72	175	69	4	–
Portugal	38	13	–	23	5	–	–	1	3	10	9
Romania	14	7	–	3	x	–	–	0	0	0	14
Scotland	4	0	0	0	x	–	–	–	–	–	–
Slovakia	0	0	–	0	x	–	–	0	0	0	0
Slovenia	0	–	–	–	x	–	–	0	0	–	–
Spain	914	232	–	109	67	4	118	15	11	4	566
Sweden	407	x	24	2	14	–	–	–	–	–	–
TOTAL	4100	820	116	1161	401	184	398	245	154	97	789

–: country not concern by the pressure indicator.
x: no pressure data information in this country.

example, if maps are required, a systematic grid would be appropriate for monitoring threats such as decline of organic matter (Bellamy et al., 2005) and diffuse contamination (Saby et al., 2006). For specific threats occurring only in certain areas, a stratified approach based on risk area delineation would be more appropriate (Van-Camp et al., 2004; EC, 2006b).

3.2. Spatial coverage based on soil mapping units and land cover

Approximately 90% of the soils and the land cover classes of Europe have at least one monitoring site. However, the density of sites in the soil mapping units (SMU) of the European Soil Database is highly variable. About 7% of the area covered by these SMUs does not have any monitoring site. The greatest density of sites falls in pasture land. The density of sites in arable land and forests is less but comparable. Permanent crops (e.g. vineyards, orchards) and open spaces with little or no vegetation are under-sampled in comparison to other land cover classes.

3.3. Spatial coverage based on pressure data

There is little monitoring of erosion at sites in areas for which high rates of soil loss by water erosion are estimated using PESERA (Fig. 3); indeed in many of the relevant EMEP cells there are no soil monitoring sites at all. In Spain, Italy, Greece, France, Germany and Poland, such areas are poorly and inadequately monitored. A total of 820 new sites would be needed to achieve one monitoring site per 300 km^2 for these areas. Furthermore, actual soil loss is not measured nor estimated at virtually all the monitoring sites.

The monitoring of peat areas in Northern Europe is quite dense in the United Kingdom and in parts of Sweden (Fig. 3). Reaching the median coverage would require 116 new sites, mostly located in Finland and Sweden (Table 2).

The areas of high or very high compaction risk, irrespective of land cover, occupy significant areas in Europe. Thus, 1161 new sites would have to be established to reach the median coverage. Of these 74% are located in Finland, Norway, France, Italy and Spain (Fig. 3, Table 2).

Areas of high population density are well monitored in the United Kingdom and in the Benelux, but in some densely populated areas of France, Spain, Italy and Greece there are no monitoring sites. To reach the median coverage, 401 new sites would be needed, of which more than half would be in Italy (Table 2).

Areas with high livestock densities are covered relatively well by the SMN sites, except for cattle in the north of Italy, small regions of Spain and parts of Germany, and for pigs in Brittany in France, regions of Poland, Spain and Germany. The western and the central parts of France are also under-represented although this will change in the next two years as SMN implementation is ongoing. In addition, some data are missing for Italy and Spain and these may be better represented than the data analysis has indicated. In order to reach the coverage of one site per 300 km^2, 184 and 398 monitoring sites would have to be established to monitor areas with high livestock density of cattle and pigs respectively (Table 2).

Areas with higher levels of cadmium deposition to soil are mainly located in eastern Europe: Poland, Slovakia, and parts of Romania and Bulgaria. Some high concentrations are also observed in the Benelux and in the Ruhr region. About half of the areas with higher concentrations have a monitoring site coverage of less than one site per 300 km^2, and 245 new sites would be needed to reach the median coverage (Table 2). For mercury and lead, the same coverage would require 154 and 97 new monitoring sites.

Areas subject to soil desertification risk are located mainly in southern Europe. A coverage of 1 site for 300 km^2 in all the selected EMEP cells, would require 789 new monitoring sites, with 72% and 21% of them located in Spain and Italy respectively (Table 2). This might be an overestimation because some information on SMNs was not available for these two countries.

3.4. Indicators of soil threats

The coverage of indicators, notably for soil compaction indicators, is very heterogeneous (Fig. 4): soil organic matter content is monitored almost everywhere, only 4147 new measurements would be required to reach a coverage of one site per 300 km^2, whereas 14,483 new measurements of soil water retention should be made to reach that median coverage (Table 3). Bulk density is not measured in about half of the countries.

The coverage of the soil contamination indicators is also heterogeneous: pH is measured in almost all the monitoring sites, some trace elements are measured in almost all the countries, for instance lead content for which 4775 new measurements are needed, whereas for mercury content, 12,590 new measurements are required. Quite a large number of peri-urban areas are not monitored for contaminants, especially in southern countries. In general, those areas of soil identified as having the highest heavy metal contents appear not to be sampled with sufficient sites, especially for mercury. Areas with high livestock pressures are covered unequally by related indicator measurements: only 191 new measurements of zinc and copper would be required whereas 994 new measurements of bulk density would be needed to monitor the soil organic carbon stocks.

Indicators related to the soil biodiversity threat are measured very rarely: 14,790 new observations of earthworm diversity (almost everywhere in Europe) would be needed to achieve the median coverage.

3.5. Harmonisation of soil monitoring networks

To establish the median site coverage in each EMEP cell, 4100 new monitoring sites would be required. Although this assessment may be a slight overestimate (see above), a considerable effort would be needed to reach a commonly accepted coverage. Furthermore, methodology for sampling and testing protocols is far from uniform even amongst national systems. Indeed, sampling area, number of subsamples, depth of sampling, measured parameters, and analytical techniques used to measure these parameters are often different from one SMN

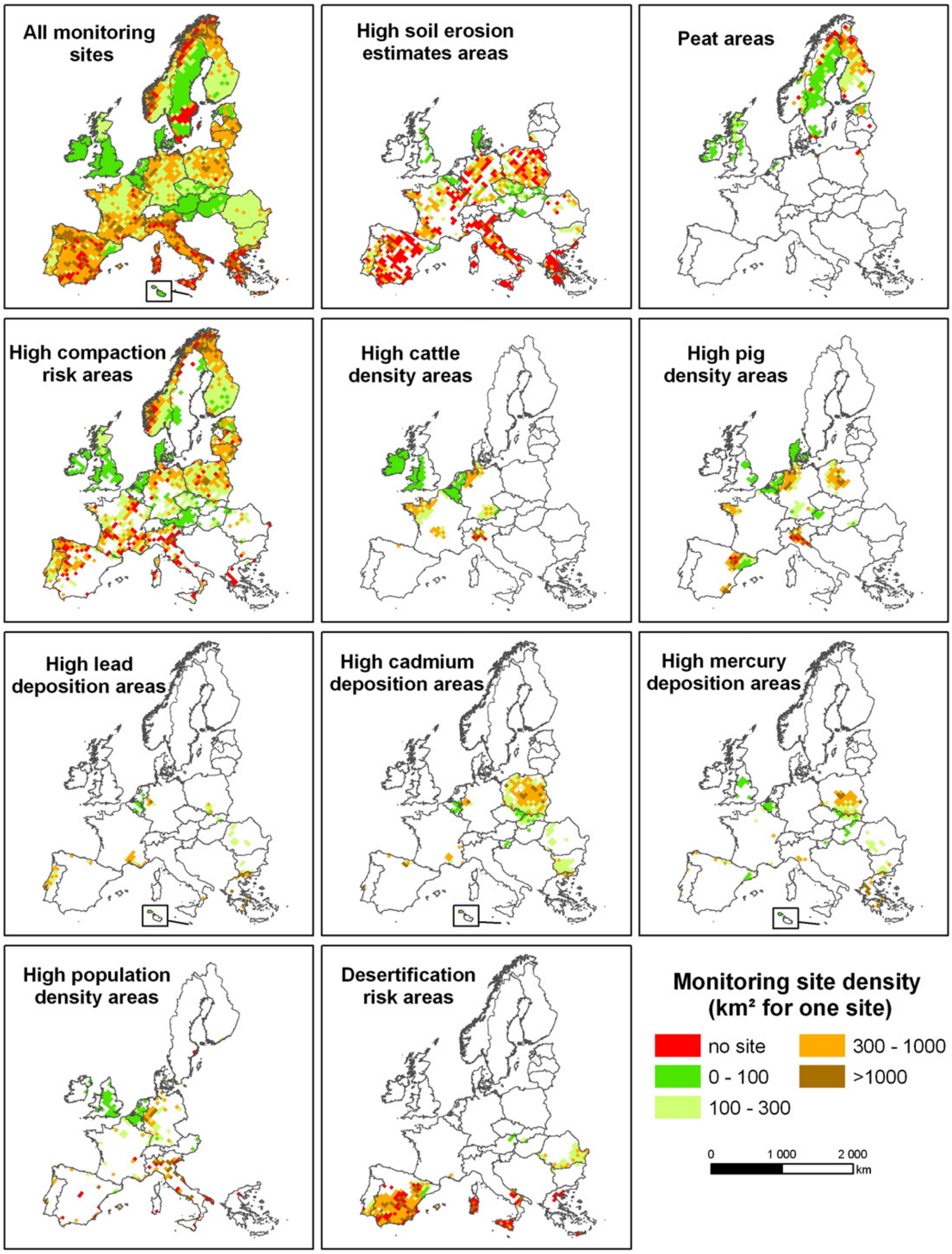

Fig. 3 – Density of monitoring sites depending on different pressure data.

to another (Morvan et al., 2007). Collecting harmonised information on changes in soil quality in Europe implies the adoption of a common methodology for sampling and testing. This task is difficult as most countries have established, at least in part, national soil monitoring schemes. Therefore, changing their protocols to different ones will impede comparison with previous data. One way forward could be to recommend a programme of cross-method validation allowing continued comparisons both within and between countries.

For several parameters, combining several techniques, on all samples or on a subset of samples, could be the best option to allow comparisons with data from previous campaigns and to establish pedotransfer functions linking results obtained using different methods. As the main cost in soil monitoring is field sampling, adding new determinations might not greatly affect the total cost. Lark et al. (2006) have discussed the use of multivariate geostatistics to enable the combination of data from different sources and give an example of where it has been used in eastern England. Concerning the sampling depth, one way to harmonise reporting at the EU level could be to report the results on the basis of a same equivalent mineral mass (Ellert and Bettany, 1995). However,

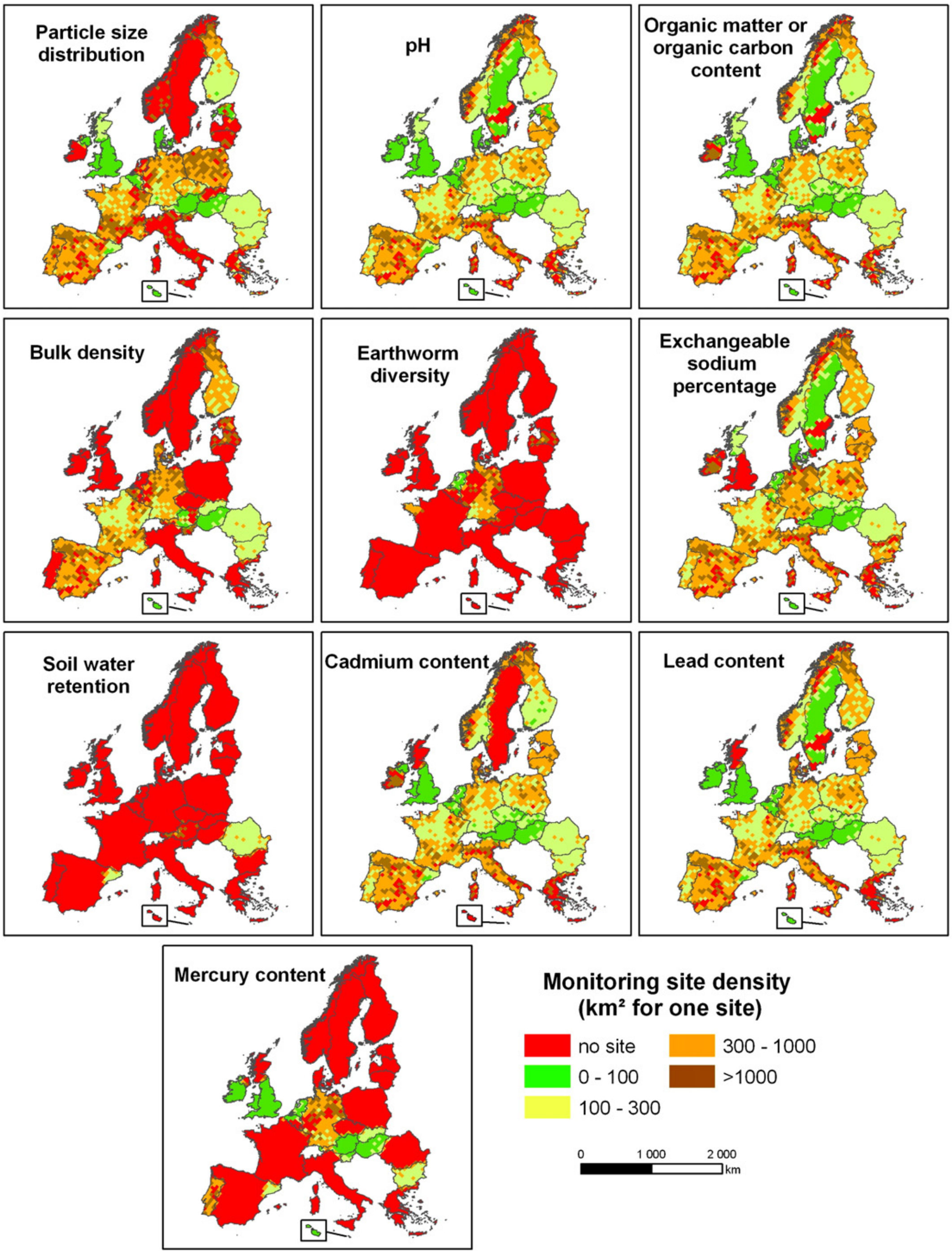

Fig. 4 – Spatial density of some selected indicators.

this would require determination of bulk density at all sites and at each sampling date. The costs of doing this could be prohibitive.

A pan-European transnational soil monitoring scheme was established for forest soils in the 1990s (Vanmechelen et al., 1997), and revitalised under the forest FOCUS regulation (http://www.inbo.be/content/page.asp?pid=EN_MON_FSCC_BIOSOIL_supporting_stuties, last accessed, 05/10/2007). Results from the first trial (Vanmechelen et al., 1997) have clearly shown discrepancies between national results, even using standardised and harmonised methodologies. Most of these discrepancies are likely to be attributable to inter-laboratory differences (Cools et al., 2004). Presently, the ongoing Biosoil monitoring exercise is collecting samples from all over Europe that will be analysed at a single analytical laboratory, to establish the effects of inter-laboratory discrepancies on effective comparison of national results.

Table 3 – New analyses required in each country to reach the median density in the EMEP cells, for selected variables

	Particle size distribution		pH		Organic matter or organic carbon content		Bulk density or topsoil organic carbon stocks		Earthworm diversity		Exchangeable sodium percentage		Soil water retention		Cadmium content		Lead content		Mercury content	
	m	a	m	a	m	a	m	a	m	a	m	a	m	a	m	a	m	a	m	a
Austria	2832	4	3531	0	3313	0	696	139	2	277	2859	7	21	259	3815	0	3815	0	2742	20
Belgium	1863	3	2546	0	2546	0	10	92	0	102	752	28	0	102	1110	3	1618	1	833	52
Bulgaria	432	16	432	16	432	16	432	16	0	370	176	195	0	370	432	16	432	16	432	16
Czech Republic	222	52	738	0	738	0	0	263	0	263	531	5	0	263	738	0	531	5	0	263
Denmark	848	2	848	2	848	2	47	107	0	149	848	2	0	149	47	107	47	107	0	149
England & Wales	6018	2	6018	2	6018	2	0	507	0	507	0	507	0	507	6018	2	6018	2	6018	2
Estonia	1488	56	1588	21	128	35	21	130	0	151	107	49	0	151	107	49	107	49	0	151
Finland	1446	209	1446	209	1446	209	746	407	0	1117	746	407	0	1117	1563	209	863	363	0	1117
France	1009	872	1532	452	1532	452	1532	452	59	1769	1532	452	0	1829	1532	452	1532	452	0	1829
Germany	853	456	1317	210	1254	217	719	546	449	779	551	621	0	1189	1374	209	1318	211	553	660
Greece	120	352	141	337	146	333	0	441	0	441	79	377	0	441	29	418	29	420	0	441
Hungary	1249	0	1328	0	1328	0	1328	0	0	310	1328	0	0	310	1328	0	1328	0	1234	0
Ireland	0	232	1317	0	1317	0	0	232	0	232	22	210	0	232	22	210	1317	0	1295	0
Italy	28	969	341	656	341	656	0	1006	0	1006	341	656	0	1006	341	656	341	656	0	1006
Latvia	5	204	127	89	127	89	22	193	20	195	106	109	0	215	107	108	105	110	0	215
Lithuania	9	208	146	79	146	79	0	216	0	216	83	134	0	216	146	79	146	79	0	216
Luxemburg	2	6	6	0	6	0	0	9	0	9	6	0	0	9	6	0	6	0	0	9
Malta	271	0	271	0	271	0	271	0	0	1	271	0	0	1	0	1	345	0	30	0
Netherlands	14	94	531	2	531	2	0	117	503	2	531	2	0	117	531	2	531	2	503	2
Northern Ireland	498	0	582	0	582	0	0	47	0	47	0	47	0	47	582	0	582	0	0	47
Norway	19	1055	1057	417	1057	417	0	1074	0	1074	1057	417	0	1074	1057	417	1057	417	0	1074
Poland	366	674	894	248	894	248	0	1039	0	1039	678	397	0	1039	894	248	894	248	0	1039
Portugal	119	178	290	38	290	38	0	296	0	296	290	38	0	296	290	38	290	38	110	187
Romania	948	14	948	14	948	14	948	14	0	793	948	14	948	14	948	14	948	14	0	793
Scotland	721	4	721	4	721	4	0	261	0	261	721	4	0	261	721	4	721	4	0	261
Slovakia	4	144	428	0	424	0	313	1	0	163	428	0	0	163	424	0	420	0	309	1
Slovenia	11	51	56	11	56	11	11	51	0	68	56	11	0	68	56	11	259	0	203	1
Spain	928	916	1009	914	1009	914	733	956	0	1663	733	956	200	1549	928	916	928	916	195	1549
Sweden	0	1491	4885	407	4885	407	0	1491	0	1491	4885	407	0	1491	0	1491	4885	407	0	1491
TOTAL	22,323	8262	35,074	4128	33,334	4147	7829	10,101	1033	14,790	20,665	6054	1169	14,483	24,425	5917	30,692	4775	14,457	12,590

m: analyses which are done, a: new analyses needed to reach the median density of one result per 300 km^2.

4. Conclusion

This study describes the majority of existing soil monitoring networks in Europe, and identifies differences in their spatial coverage and scope. The present spatial coverage is heterogeneous. National and regional networks are denser in northern and eastern parts of Europe than in southern countries. The median coverage of sites in the EMEP cells applied all over Europe is around 1 site per 300 km^2. This is close to the coverage of the current ICP Forest grid (Haussmann and Lorenz, 2004). If all 50 km×50 km cells were to have a site density equal to this median coverage, 4100 new sites would be required, mainly located in Italy, Spain, Greece, parts of Poland, Germany, the Baltic countries, Norway, Finland and France. This number of new sites may be slightly overestimated because some metadata were not available for Italy and Spain, and some SMNs are currently under implementation (e.g. France), but provides a reasonable estimate.

Most European soil mapping units as well as land cover classes are represented by at least one monitoring site. The number of sites required to reach the median coverage in the EMEP cells depends on the pressure data: 116 new sites are needed for peat areas, whereas 1161 and 789 new sites are required for areas at risk of soil compaction and desertification, respectively.

The coverage is very heterogeneous among indicators. Indicators related to decline of soil biodiversity and soil erosion are measured very rarely, whereas those related to soil compaction, decline of soil organic matter (e.g. soil organic carbon content) and soil contamination (e.g. pH), are measured at almost all sites. Considering that soil is one of the three environmental components supporting life on Earth, the implementation of new soil monitoring sites and the harmonisation of sampling strategies across Europe to create a minimum coverage of one site per 300 km^2, is the least that should be accepted for what is now the third largest population grouping in the world. The work to establish these new monitoring sites should begin immediately, together with an intensive programme of cross-method validation to permit valid spatial and temporal comparisons both within and between countries.

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