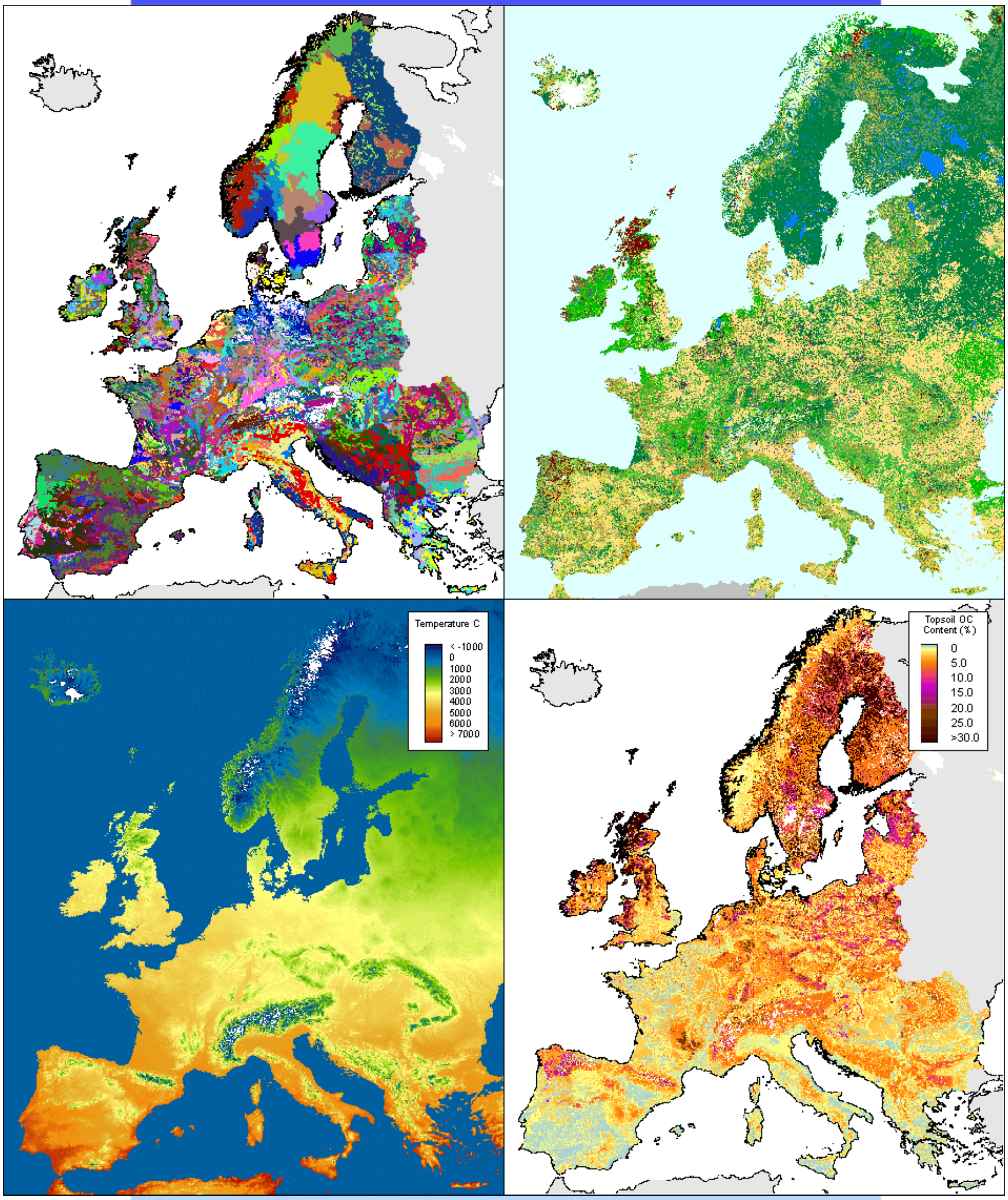
THE MAP OF ORGANIC CARBON IN TOPSOILS IN EUROPE:

VERSION 1.2 - SEPTEMBER 2003

Explanation of:
Special Publication Ispra 2004 No.72
S.P.I.04.72

Robert J.A. Jones, Roland Hiederer
Ezio Rusco, Peter J. Loveland
and Luca Montanarella



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COVER PAGE:

TOP LEFT: SOIL MAPPING UNITS OF EUROPEAN SOIL DATABASE

TOP RIGHT: LAND USE MAP OF EUROPE BASED ON CORINE

BOTTOM LEFT: AVERAGE ANNUAL ACCUMULATED TEMPERATURE

BOTTOM RIGHT: THE MAP OF ORGANIC CARBON IN TOPSOILS IN EUROPE

Corrigendum: The map of organic carbon by country, inset on S.P.I.04.72,
shows carbon stocks calculated in *Giga tonnes* (Gt) **not** *tera tonnes* (Tt) as printed.

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SUMMARY

1. Soil organic carbon, the major component of soil organic matter, is extremely important in all soil processes.
2. Organic material in the soil is essentially derived from residual plant and animal material, synthesised by microbes and decomposed under the influence of temperature, moisture and ambient soil conditions.
3. The annual rate of loss of organic matter can vary greatly, depending on cultivation practices, the type of plant/crop cover, drainage status of the soil and weather conditions.
4. There are two groups of factors that influence inherent organic matter content: natural factors (climate, soil parent material, land cover and/or vegetation and topography), and human-induced factors (land use, management and degradation).
5. Within belts of uniform moisture conditions and comparable vegetation, the mean total soil organic matter content increases from two to three times for each 10 deg. C fall in mean annual temperature.
6. In general, under comparable conditions, organic matter increases as the effective moisture becomes greater.
7. A sandy soil usually contains less organic matter than a soil of finer texture, e.g. heavy loam or clay.
8. Poorly drained soils generally have much greater organic matter content than their better-drained equivalents.
9. Cultivation can have a significant effect on the organic matter content of soil.
10. Experiments conducted in the USA and UK show a decline of up to 30% in organic matter content of soils that have been cropped over a long period.
11. After 50 years of continuous wheat cultivation (from 1843 to 1893) at Rothamsted (UK), a soil on Broadbalk field that received no manure contained 0.89% organic carbon whilst the same type of soil that received 35 t/ha of farmyard manure (FYM) annually, since 1843, contained 2.23% organic carbon.
12. In essentially warm and dry areas like Southern Europe, depletion of organic matter can be rapid because the processes of decomposition are accelerated at high temperatures.
13. At the European level, there is a serious lack of geo-referenced, measured and harmonised data on soil organic carbon available from systematic sampling programmes.
14. The European Soil Database, at a scale of 1:1,000,000, is the only comprehensive source of data on the soils of Europe harmonised according to a standard international classification (FAO).
15. A Soil Profile Database for Europe SPADE (v 1), containing data on organic carbon in the topsoil (0–30cm) for important soil types, is available as part of this database.
16. These data are not comprehensive geographically and have poor replication. An expanded profile database for Europe (SPADE 2) is currently in the advanced stages of compilation and, after 2004, this will provide many more measured values of OC for European soils under different land uses.
17. Organic carbon (OC) data for soils in Europe are available from other sources for example national soil survey archives and the ISRIC-WISE database.
18. It is not possible to produce distribution maps of soil OC from these data sources that would be accurate enough for policy support in Europe.
19. Although not generally available for use outside the country of origin, the national OC data could be used for validating a map of the distribution of OC in European soils.
20. At the present time, the most homogeneous and comprehensive data on the organic carbon/matter content of European soils remain those that can be extracted and/or derived from the European Soil Database in combination with associated databases on land cover, climate and topography.

21. The first attempt to calculate soil OC contents at European level used pedo-transfer concepts, combining the limited measured OC data that are available, the relationship of these OC data to soil type (by texture, structure, classification), land use/land cover, and climatic criteria (temperature).
22. However, the results are not considered to give an accurate picture of the status of soil organic matter in southern Europe.
23. Consequently, a refined pedo-transfer rule, for calculating the OC contents of topsoils in Europe, has been applied recently to a 1km soil data set, derived from the European Soil Database, an extended CORINE land cover dataset, a digital elevation model (DEM) and mean annual temperature data.
24. The resulting map (S.P.I.04.72), accompanying this booklet, and a 1km digital data set covering the whole of Europe, is now available for defining the baseline status of organic carbon in European topsoils.
25. The results from comparing the OC values portrayed on the Map with measured values from >12,000 points on the ground, in the UK (England and Wales) and Italy, are very encouraging and give a coefficient of determination of >0.9.
26. The samples for these ground measurements were collected mostly during 1971-90.
27. In constructing the Map of OC in topsoils in Europe (S.P.I.04.72), errors associated with assigning measured OC data from a small number of points, deemed to be representative of a particular soil type, to polygons delineated on a soil map, that represent much larger areas where no measurements of OC have been made, have been avoided.
28. The OC content, particularly in the topsoil, changes significantly with land use, and thus utilisation of CORINE land cover data (from 1988-92) for producing the OC map of Europe is appropriate to define a 1990-baseline.
29. The use of temperature data, computed for the period 1980-89, is in accordance with the resulting OC distribution being an appropriate baseline for OC in 1990.
30. The map and 1km data set of OC for topsoils in Europe (Figure 3) has been produced to support the forthcoming Thematic Strategy for Soil Protection.
31. By defining the baseline status of organic carbon/matter in 1990, the 1km data should also prove useful for other areas of research, particularly pollutant transfer and global change.
32. In the immediate future, the current version (1.2) of the OC map will be further validated against other national OC data – such as exist in Finland, Scotland, Slovakia, Hungary, Czech Republic, The Netherlands and France.
33. In parts of Europe where OC/OM data are scarce or inadequate, e.g. Greece and Spain, sampling and measuring programmes should be implemented.
34. From the soil protection standpoint, it may be wise to examine land use patterns in areas where OC is estimated to be <2%, with the aim of stabilising or increasing the OC contents.
35. In some areas, for example in Spain and France, low organic carbon contents (<2%) correlate with large rates of soil erosion (>5t/ha/yr) estimated by the PESERA model. In other areas, estimated soil loss is small where there is less organic carbon. These relationships should be subjected to further spatial analysis using GIS.
36. Soils with large amounts of OM are restricted in extent and exist mainly in northern Europe. These soils are a valuable and non-renewable resource and should be protected from development wherever possible.

INTRODUCTION

Following the unprecedented expansion and intensification of agriculture during the 20th century, there is clear evidence of a decline in the organic carbon (OC) contents in many soils as a consequence (Sleutel *et al.*, 2003). This decline in OC contents has important implications for agricultural production systems, because OC is a major component of organic matter (OM) in soil.

The official Communication 'Towards a Thematic Strategy for Soil Protection' (CEC, 2002), adopted in April 2002, identifies eight main threats to soil, and considers declining organic matter (OM) as one of the most serious processes of soil degradation, especially in southern Europe. The benefits of OM are linked closely to the fact that it acts as a storehouse for nutrients, is a source of soil fertility, and contributes to soil aeration, thereby reducing soil compaction.

The need for accurate information on the OM content in soils at European, national or regional level has been increasing steadily over the past few years. This is a result of increasing concern about environmental problems such as soil degradation, desertification (CEC, 1992; UNEP, 1991; EEA, 1995; Kosmas *et al.*, 1999), erosion and, at the worldwide level, the impact of climate change.

To ensure sustainable management of land, therefore, it is imperative that OM in the soil is maintained and sustained at satisfactory levels. A decrease in OM content is an indicator of a reduction in quality in most soils. This is because soil OM is extremely important in all soil processes.

PURPOSE OF THE MAP

The main objective in producing the Map is to identify and to secure an existing information base for OC and OM contents of European soils at time T_0 i.e. to define a 'baseline (background) or reference level' against which to monitor future trends. The Map, published as S.P.I.04.72 in ISO B1 format, shows the distribution of calculated (modelled) OC contents in topsoils (0-30cm) in Europe. Effectively this means compiling and analysing data on the OC content because in most cases this is the parameter measured. The next objective is to establish the future trend in soil OC (and OM) contents with a view to developing more sustainable systems of land management and to avoid or reduce further losses.

Figure 1: Mineral-organic soil material in (a) Phaeozem (photograph by Peter Schad) (b) Calcisol (photograph by Otto Spaargaren).

To avoid further losses of OM from the soil, the immediate value of the OC map, and associated database, is to provide a 'baseline' for OC contents in European soils in support of the forthcoming Thematic Strategy for Soil Protection (CEC, 2002). For policy-making purposes, it is now vitally important to have an accurate picture of the OM content in European soils and to understand the components of the systems of land management that have the greatest effect.

FUNCTION OF OC/OM IN SOILS

Organic matter is also an important 'building block' for soil structure and for the formation of stable aggregates (Waters and Oades, 1991; Beare *et al.*, 1994). Other benefits are related to the improvement of infiltration rates and the increase in storage capacity for water. Furthermore, OM serves as a buffer against rapid changes in soil reaction (pH) and it acts as an energy source for soil micro-organisms. Without OM, biochemical activity in soil would effectively be negligible.

Soil organic matter is evident to the layman because it makes the surface horizon of most soils darker than the subsoil. Figure 1 shows (a) Phaeozem in the Andes, with a surface horizon much darker than the subsoil because it is rich in organic material, juxtaposed with (b) Calcisol in Italy containing only a small amount of organic material as evidenced by the much lighter coloured surface horizon.

Figure 2: Organic soil material: fibrous peat (photograph by Erika Micheli)

Figure 2 and Figure 3 show organic soil material in the form of peat, with OC contents in excess of 45% (78% OM).

Figure 3: Organic soil material: semi-fibrous peat (photograph by Erika Micheli)

Figure 4 shows a Histosol, which comprises deep peat. More details of the distribution in Europe of peat and soils rich in OM are described by Montanarella *et al.*, In press).

Figure 4: Histosol developed in deep peat (photograph by Erika Micheli)

In mineral soils, OM is concentrated in the topsoil or surface horizon (Figure 1), but a few soil types have significant concentrations of OM in the subsoil, e.g. Ferri-humic Podzol (Figure 5).

Factors Influencing Organic Matter Status of Soils

Formation and behaviour of soil OM is a very complex subject. Organic material in soil is essentially derived from residual plant and animal material, synthesised by microbes and decomposed under the influence of temperature, moisture and ambient soil conditions. In essentially warm and dry areas, like Southern Europe, depletion of OM can be rapid because the processes of decomposition are accelerated at high temperatures.

The factors influencing soil OM may be divided into two groups of:

1. Natural factors;
2. Human-induced factors.

The most important **natural** factors are:

1. Climate: temperate or Mediterranean for example;
2. Soil parent material: acid or alkaline (or even saline);
3. Land cover and/or vegetation type;
4. Topography: slope and aspect.

Human-induced factors can be summarised as follows:

1. Land use and nature of farming systems;
2. Land management;
3. Degradation of soil and land.

Figure 5: Ferri-humic podzol showing the accumulation of organic matter in the surface horizon and also translocation of organic material in the subsoil (photograph by Otto Spargaren)

Identifying the factors influencing soil OM turnover and quality is important for a number of areas of research:

1. Carbon sequestration;
2. Soil fertility;
3. Pollutant transfer;
4. Sustainable crop production;
5. Soil-water relations;
6. Soil-groundwater relationships.

Of considerable concern at continental and global scale now are carbon emissions that influence global warming and climate change. Continuously high temperatures during the summer in the Mediterranean lead to a rapid decline in the OM content in cultivated soils. This decline is further exacerbated by the removal or burning of crop residues. Unless sufficient OC is returned to the soil to offset the loss occurring during mineralization, the content of OM will decline. When OC stocks in the soil are in decline, the process is called 'soil nutrient mining' (Zdruli *et al.*, 1998).

In examining data on OM content of representative mineral soils, it is clear that there are differences between soils of different physiographic provinces, but also within particular localities. Heterogeneity is the rule and is generally expected by most soil and earth scientists. However, there are some broad relationships that are helpful in predicting the distribution of soil OM (Zdruli *et al.*, 2004).

Effect of Climate

Climatic conditions, especially temperature and rainfall, exert a dominant influence on the amounts OM found in soils. When moving from a warmer to a cooler climate, the OM content of comparable soils tends to increase (Figure 6). This is because the overall trend in the decomposition of OM is accelerated in warm climates, while a lower rate of decomposition is the case for cool regions.

In summary, within belts of uniform moisture conditions and comparable vegetation, the average total OM contents increases from two to three times for each 10 degree C fall in mean annual temperature (Buckman and Brady, 1960, p152).

Effective soil moisture also exerts a very positive control upon the accumulation of OM in soils. In general, under comparable conditions, OM content increases as the effective moisture becomes greater. This is explained by the fact that microbes are more active, and the humification of OM more rapid in areas of moderate to low rainfall (Figure 6:), which tend to have scantier vegetation than wetter areas.

In Europe, temperature and precipitation tend to change in opposing directions. Thus, as rainfall increases, temperature decreases. Because water supply is not limiting this encourages the growth of plant species, many of which have more lignin-rich components than their lowland neighbours, but microbial activity decreases at these lower temperatures.

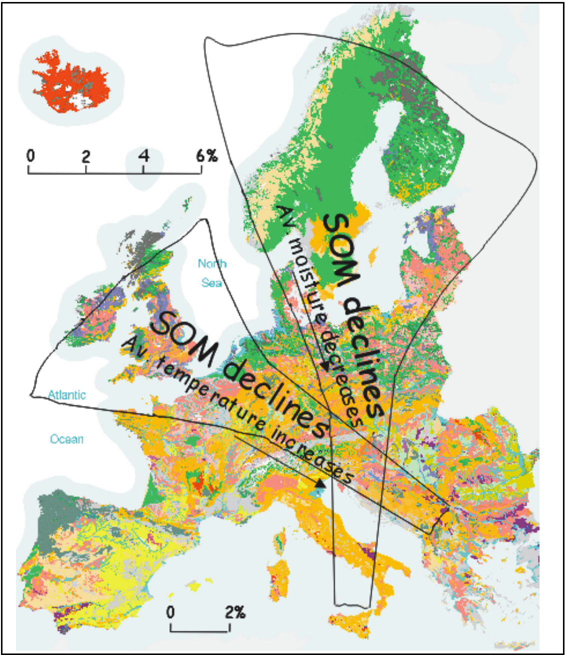


Figure 6: Influence of temperature and moisture on soil organic matter(SOM) in Europe (adapted from Buckman and Brady, 1960, p152)

Thus OM accumulates, e.g. in peat soils, or peat layers at the surface of the mineral soil. High rainfall also leads to acidification due to leaching and microbial activity is lessened at more acid pH. Conversely, at lower altitudes and warmer latitudes, production of OM can be limited by water stress, but microbial processes are faster. Thus, OM content tends to decrease.

Effect of Soil Properties

Provided other factors are constant, the texture of the soil influences the amount of OM and nitrogen present. A sandy soil usually contains less OM than a soil of finer texture – heavy loam or clay. This is because the generally lower moisture content and greater aeration in sandy soils result in more rapid oxidation of OM compared with heavier soils. Generally, poorly drained soils have high moisture contents and low aeration. This results in generally much larger OM contents in these soils than in their better-drained equivalents.

Microbial activity, as mentioned above is strongly influenced by soil pH. Where soil pH is raised by the presence of base-rich material, e.g. limestones, or by an adequate supply of base cations such as calcium, then these processes will be more rapid than where more acid soil conditions prevail, and OM will thus be mineralised to a greater extent.

Effect of Erosion and Vegetation

Water and wind erosion can be responsible for physically removing OM from soils, because OM is concentrated in the top 30cm and this is the layer that is normally removed first. Conversely, vegetation is an important source for replenishment of OM, but where plant cover is scant OM is usually deficient.

Effect of Cultivation

Cultivation can have a significant effect on the content and quality of soil OM. During field operations such as ploughing, drilling, harrowing etc. soil aggregates are repeatedly disturbed and broken, thus exposing fresh surfaces, many of which will have coatings or particles of OM associated with them.

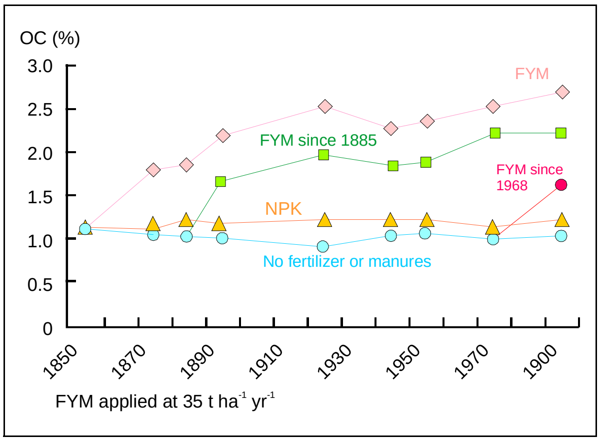
In the undisturbed state, much of this OM is relatively protected from mineralization because it is in equilibrium with soil conditions on a very local, often microbiologically-controlled, scale. Continual disturbance will change these conditions repeatedly, and this generally leads to a greater degree of decomposition of the OM, especially of the labile forms (sugars, gums, amino-acids etc.), which play a major role in stabilising soil physical structures.

The so-called residual OM, left when the more labile forms have been mineralized, is less effective at stabilising soil structure. Unless OM is quickly replenished, the system is in a state of degradation, leading eventually to a non-sustainable situation (World Bank, 1993).

Contrary to the situation in northern Europe, agriculture in the Mediterranean is dominated by fruit-trees, citrus, olives, vines, vegetables, and cereal crops, such as wheat, barley and maize. Grasslands and associated stock rearing are of limited extent and the accumulation of OM associated with these uses is, therefore, severely restricted.

Nonetheless, the fact that crop yields in areas long under cultivation have been maintained or raised does not mean that OM contents are being maintained at satisfactory levels.

Experiments conducted at Rothamsted (Figure 7) have demonstrated that very different forms of manure application and crop rotations have had a very large influence on the carbon and nitrogen contents in the soil but only a small influence on the C/N ratio (Russell, 1961, p.277).



[FYM – Farmyard Manure; NPK – nitrogen, phosphate, potassium fertilizer]

Figure 7: General influence of cultivation and soil management on OC contents at Rothamsted during the past 150 years (after Poulton, 1995).

Jenkinson (1990) and Johnston (1991) describe more details of Rothamsted's research into soil carbon and Goulding *et al.* (2003) report more recently on trends in OC that can be traced from the experimental field data up to 1990 (Figure 7).

Sources of Soil Organic Matter

Major sources of OM elsewhere in agricultural areas are derived from plant material, crop residues and animal manure, for example from rearing cattle, sheep, pigs and poultry. However, the distribution of agricultural activities at national level is not uniform, thus in some areas the concentration of organic materials is much larger than in others.

Transportation of animal manures can be expensive because the bulk volume to be removed is considerable. Rarely are intensive livestock enterprises juxtaposed with extensive arable systems that would benefit from applications of the large quantities of the animal manures produced.

Other potential sources of organic materials in soils under agricultural use are sewage sludge, urban waste, and litter from forest trees. The use of these materials for fertilising soils requires special technologies for processing the raw material. Collection of plant litter can be very labour-intensive involving considerable costs, but is useful to replenish OM.

The vast majority of sewage sludge is produced distant from areas that could profit from their application. There is a risk of contaminating soil through the application of industrial wastes and sewage sludge. Therefore the use of these wastes, to replenish OM, must be carefully controlled and only adopted when the food processing and distribution industries are ready to accept produce from agricultural systems receiving such recycled organic waste.

Decline in Soil Organic Matter

There are many factors responsible for the decline in soil OM and many of them stem from human activity.

1. Conversion of grassland, forests and natural vegetation to arable land;
2. Deep ploughing of arable soils causing rapid mineralization of labile components of OM;
3. Overgrazing, with high stocking rates;
4. Soil erosion, by water and wind;
5. Leaching;
6. Forest fires.

The ‘drivers’ 1-3 above probably lead to the most rapid decline in OM contents. Two other important processes, erosion and leaching, are important contributors.

When natural or semi-natural habitats are cultivated, new and usually smaller quantities of OM are established. It is, therefore, normal to find much less OM (by 30 to 60%) in cultivated soils compared to their undisturbed (or virgin) equivalents.

Generally, plant roots, root exudates and plant residues are not generated in sufficient amounts in cultivated soils to replace the OM that is lost following repeated soil disturbance during the cultivation cycle. Thus, the OM content of the soil will drop until some relatively small equilibrium value is reached which might be too small to support all soil functions at some desired level.

Erosion causes removal of soil particles, particularly from the topsoil. This can have a devastating impact on overall soil OM contents, because organic materials are concentrated in the surface layer of the soil. Erosion can also remove considerable quantities of nutrients, as well as sediments. Where erosion is severe, more fertiliser and organic manure are needed on agricultural land to counteract the losses, compared to the requirements in non-eroded areas.

Leaching of soil nutrients and organic compounds to the groundwater is a problem in some areas. Heavy winter rainfall or excess irrigation water may exacerbate the problem. Salinity and acidity also have devastating effects on the quality and quantity of OM.

ASSESSING ORGANIC MATTER CONTENT OF EUROPEAN SOILS

This report focuses on mapping of OC content in European topsoils. In most cases, organic matter in soil is measured as OC, and, if necessary, the values converted to OM content using a standard conversion ratio OC:OM of 1:1.72. This conversion is considered to be satisfactory for providing data on OM, given OC measurements, for input to broad scale modelling and the policy-making process. Sometimes the more approximate ratio 1:1.7 is used – Buckman and Brady (1960, p.149). However, care is needed when inverting the ratio and converting OM to OC, because determining OM by loss on ignition can lead to an overestimation of OC. Therefore, a standard procedure for determining OC should be adopted for future sampling programmes.

Previous Studies

There have been several attempts to estimate carbon stocks at regional level in Europe (Howard *et al.,* 1995; Batjes, 1996; Smith *et al*., 2000a, b; Arrouays *et al*., 2001; Leifeld *et al*., 2003, In press). The primary aim in these studies was to estimate the carbon sequestration potential of soils in global change research.

Batjes (1996, 1997) used the WISE database and calculated OC contents for the major soil groups of the FAO classification. Howard *et al.* (1995) estimated soil organic stocks in land under arable agriculture, using OC measurements made during the National Soil Inventories in England & Wales and Scotland (1979-83). Smith *et al.* (2000b) revised the estimates of Howard *et al.* (1995) for the UK using data compiled by Batjes (1996) and a relationship that assumes a quadratic decline in soil OC contents with depth.

Arrouays *et al.* (2001) calculated OC in the soils of France using the CORINE land cover data, the 1:1,000,000 scale soil geographical database of France and a database containing point measurements of OC mainly from agricultural areas. More recently, Lettens *et al.* (2004) have used national soil profile databases in Belgium to plot the distribution of carbon stocks in soil in the country.

Contents of OC have been measured systematically in some countries, for example in UK (McGrath and Loveland, 1992; Bullock and Burton, 1996), Denmark (Krogh *et al*., In press), Belgium (Sleutel *et al*., 2003; Lettens *et al*., 2004), Slovakia (Landscape Atlas of the Slovak Republic, 2002) and The Netherlands (Kuikman *et al*., 2003).

Other countries, for example France (Arrouays *et al*., 2002; Walter *et al.,* 1996) and Italy (Rusco, In prep.), have large if not systematically collected national data sets on OC, whereas some countries have only limited data (Rodrigues-Murillo, 2001). Regrettably, many sample data from field surveys are either insufficiently geo-referenced or not accessible outside the country of origin, which poses a serious obstacle to using them for defining baseline OC status at European level.

Therefore, an extrapolation procedure based on sample data from national data sets is impractical for an improved determination of the distribution of OC in European soils at this time.

ESB Approach

The European Soil Bureau (ESB), based at the Joint Research Centre, Ispra (Italy), has been sponsoring the collection of soil information throughout Europe for more than fifteen years (Montanarella and Jones, 1999).

The result is the construction of a European Soil Database v.1.0 (King *et al*., 1994, 1995a, 1995b; Le Bas *et al*., 1998; Heineke *et al*., 1998) from source material prepared and published at a scale of 1:1,000,000 (CEC, 1985), augmented by data from national soil survey archives. The resulting soil data are harmonised for the whole of Europe according to a standard international soil classification (FAO-UNESCO, 1974; FAO-UNESCO-ISRIC, 1990), together with a Soil Profile Analytical Database for Europe, SPADE 1 (Madsen and Jones, 1995).

European Soil Database

SPADE 1, a component of the European Soil Database v1.0, contains data on OC in the topsoil (0–30cm) for important soil types, as well as data for other soil properties. Unfortunately, because of the difficulties of collecting geo-referenced data at European level, the data currently stored in SPADE I are not comprehensive geographically and have poor replication.

Therefore, applying an extrapolation procedure, linking the analytical data to polygons representing Soil Mapping Units (SMUs), was deemed unsuitable to build an accurate distribution of soil OC for Europe as a whole. Many thousands of OC measurements would be needed, thus the soil type and texture, as defined in the database, provide the main input parameters for soil in the current studies.

Direct Mapping Approach

In the first attempt directed at guiding policy-makers at European level with respect to OC in European soils, Rusco *et al.* (2001) made a study based on the European Soil Database. The results obtained, from mapping the topsoil OC data generated by a pedo-transfer rule (PTR), are shown in Figure 8. The estimates are approximate, appropriate only for use at continental level. Furthermore, because the results are expressed as classes of OC it is difficult to establish the true OC content for some European soils.

For example, peat soils contain much more OC (15-60%) than the lower limit of 6% of the highest class ‘H’. Consequently, this analysis does not separate peat soils from soils with less OC, which fall into the same class.

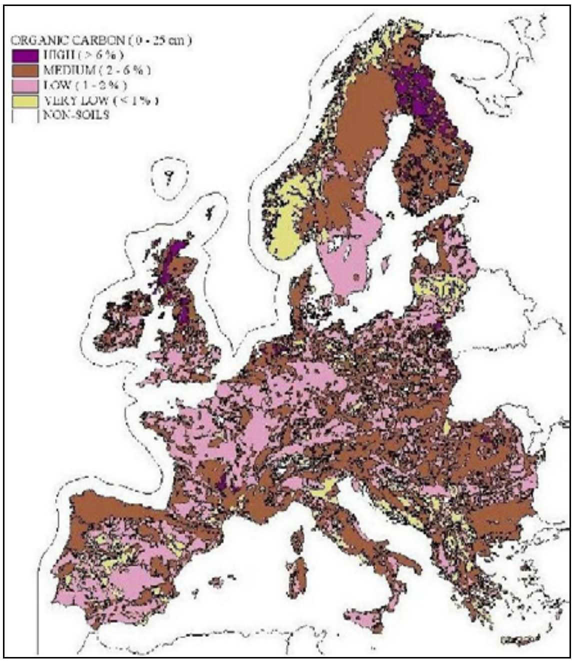


Figure 8: Distribution of topsoil organic carbon through application of the original pedo-transfer rule 21 of Van Ranst et al. (1995) after Rusco et al. (2001)

Validation of the distribution of the estimated OC contents, portrayed in Figure 8, proved impossible because, at the European level, there is a serious lack of measured geo-referenced data on soil organic carbon (Bullock *et al*., 1999). Such data are more readily accessible at national level.

Revised Pedo-Transfer Approach for Europe

For a meaningful spatial representation of topsoil OC (OC_TOP), an alternative methodology to using sample data, in combination with an extrapolation algorithm, was developed. The approach is based on processing a revised PTR and the European Soil Database (Jones *et al*., 2003). The conditions in the revised PTR for OC_TOP were translated into processing commands, which operated directly on spatial data layers in a Geographic Information System (GIS).

Description of Pedo-Transfer Rules

Measured soil properties are extended in the database to a range of soil parameters, which are not observed or measured in a soil survey by using a system of PTRs defined by Van Ranst *et al.* (1995). Technically, a PTR condenses the results obtained from sample surveys of typical conditions, which were found to be associated with a specific soil property. The principal parameters defining a property and the representative value for that property are identified through expert knowledge (Jones and Hollis, 1996). In detail, a PTR is defined as a series of structured 'if-then' conditions, applied sequentially from general to more specific situations and using a variety of related environmental parameters (Daroussin and King, 1997).

The PTR21 defined by Van Ranst *et al.* (1995), used to estimate OC in the topsoil horizon (OC_TOP), uses 6 input parameters – three for soil, one each for texture, land use and temperature. Table 1 shows some examples of the 'if-then' conditions that comprise this rule, a total of 150 conditions being defined.

Table 1: Selected conditions from PTR21 for topsoil organic carbon (OC_TOP)

Co	SN1	SN2	SN3	TEXT	USE	ATC	OC
35	L	g	*	*	SN	M	M
37	L	c	*	2	C	M	L
85	J	t	*	2	SN	*	H
117	O	*	*	*	*	*	H

Co – condition number; * – 'wild card'
SN1 – FAO soil group code (e.g. L Luvisol)
SN2 – FAO soil subgroup code (e.g. g gleyic)
SN3 – FAO soil subgroup (2nd) code (e.g. s stagnic in Lgs)
TEXT – FAO texture class (1 coarse – 5 very fine)
USE – Land use class (C cultivated, SN semi-natural
ATC – Accumulated temperature (L low, M medium, H high)
OC – OC_TOP class (L, M, H - see below for limits)

The results for OC_TOP are output by Rule21 in four classes:

V(ery) L(ow): < 1.0%
L(ow): 1.1-2.0%
M(edium): 2.1-6.0%
H(igh): > 6.0%

Conditions 37 and 85 can be translated into program code as follows:

```
:
37 IF (SN1=L) AND (SN2=c) AND (TEXT=2) AND
   (USE=C) AND (ACT=M) THEN LET OC_TOP=L
:
85 IF (SN1=J) AND (SN2=t) AND (TEXT=2) AND
   (USE=SN) THEN LET OC_TOP=H
:
```

The revised PTR for OC_TOP uses 5 input parameters instead of the 6 parameters in the original PTR21, temperature being removed from the conditions because it is taken into account through the correction coefficient ($TEMP_{cor}$).

Data Sources

The methodology applied in the study uses soil, land use and climate data to calculate a continuous spatial thematic layer of quantitative OC content in topsoils in Europe. The methodology is explained in more detail in Jones *et al.*, In press).

Soil

The European Soil Database provided the main input for soil. The spatial component of this database comprises polygons, which represent Soil Mapping Units (SMUs). These spatial elements are linked to a database of Soil Typological Units (STUs) in the form of a one-to-many relationship. Attribute data exist for STUs, so these data can be related to SMUs and consequently to areas on a map.

Until a better soil profile database has been compiled (a SPADE 2 database is in preparation – Hollis, *pers comm*), and many more (standardised) analytical data for soil properties become available, OC is calculated, at the European level, by a pedo-transfer rule combining the limited measured OC data that are available, the relationship of these OC data to soil type (by texture, structure, classification), land use/land cover, and climatic criteria (particularly temperature).

Land Use/Cover

The land cover information was derived from a data set covering Europe with information according to the CORINE Land Cover classification codes. For areas where CORINE data are absent (e.g. Sweden), land cover was taken from specifically adapted Eurasian land cover data, derived from a US Geological Survey (USGS) database. To achieve comparable thematic coverage between the CORINE and USGS data, a series of crossclassifications was carried out, using various USGS data layers and re-assigning or merging classes where appropriate. The final layer corresponds to the CORINE level 3 classification codes.

Climate

Variations in soil OC with different climatic conditions were taken into account by using the average annual accumulated temperature (AAAT), expressed in day degrees C. The data used were derived from station observations available through the Global Historical Climatology Network – GHCN – (Easterling *et al.*, 1996). The influence of station altitude on temperature observations was adjusted for by applying an adapted moist adiabatic lapse rate. This period used in the study covered the years 1970-79. The period was chosen because it precedes the collection of ground samples, in UK and Italy, used for determining OC and to provide data for verifying the calculated OC contents.

Moisture status was not included as a separate parameter in the PTR, because the influence of this soil-forming factor is implicitly taken into account with the inclusion of the soil type (parameter SOIL) in the PTR. We believe that this implicit consideration of moisture is sufficient to satisfy the aims of the study, which is to produce baseline data, i.e. a data layer of estimated OC content, rather than to model soil development and carbon stocks. Using external datasets to model the influence of soil moisture could make the model unnecessarily complex and, given the paucity of OC data from ground measurements, of little value to the current exercise.

Temperature Effect

The influence of temperature on OC_TOP content was taken into account through the development of a mathematical function designed in accordance with the established principle that, within belts of uniform moisture conditions and comparable vegetation, the average total OM in soils increases by two to three times for each 10 degree C fall in mean annual temperature (Buckman and Brady, 1960, p152).

This is only a very general relationship but it is considered to be suitable for this basic pan-European study. The function parameters used to calculate a correction coefficient were determined by analysing changes in OC in the ground data in relation to AAAT. Due to the characteristics of the area covered by the ground measurements, the range of temperature at sites with ground OC data was restricted to AAAT > 2000 day degrees C.

The relationship between AAAT (t_{AAAT}) and temperature correction coefficient ($TEMP_{cor}$) was defined by a sigmoidal function of the type:

$$TEMP_{cor} = f \times \cos\left(t_{AAAT}\right)^{n} + c$$

where: t is temperature as AAAT
f, n and c are constants

Figure 9 shows, for the range of values found from the available sampling points, the weighted averages for ground measurements and the values used by the function.

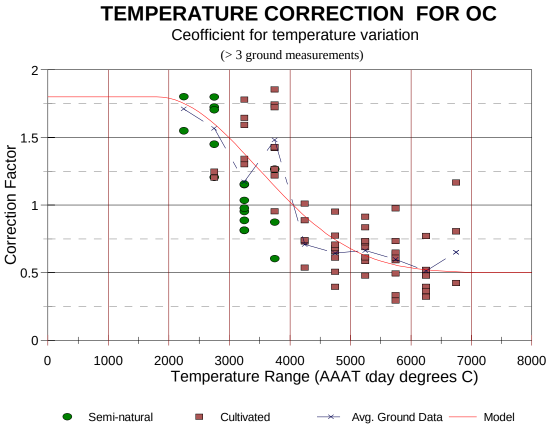


Figure 9: Correction coefficient for organic carbon content by temperature variations

According to the land use in the PTR, data points were determined separately for 'semi-natural' and 'cultivated' areas. The best fit of the modelled data gave a coefficient of determination (R^2) of 0.6.

Based on the ground data the function inflection point was found at 4000 day degrees C. In practice, AAAT values of this magnitude occur in southern England, northern France and southern Germany The lower limit of $TEMP_{cor}$ was set to 0.5, which corresponds to AAAT values in the range 6500 to 7000 day degrees C, that are found in southern Europe.

The upper limit of $TEMP_{cor}$ was set to a value of 1.8, found in areas with AAAT of 1800 day degrees C. These temperatures are characteristic of northern Europe and in Alpine regions. This upper limit was defined in consideration of the fact that the OM content of a soil cannot exceed 100%, which approximates to an OC_TOP value of 60%. Thus compatibility with the relatively stable OC:OM ratio of 1:1.72 is maintained.

Limiting the maximum correction factor to 1.8 is also in accordance with the analysis of the ground data that reveals an average of 1.7 at 2250 day degrees C. Areas where $0<AAAT<2000$ day degrees C are too cold for biomass production to be sufficient to increase OC and, at these low temperatures, mineralization is too slow to cause a decline in OC. Thus, $TEMP_{cor}$ remains stable at 1.8 down to AAAT= 0.

Processing Environment

All processing was performed using spatial data layers. The conditions were converted into processing code of IDRISI 32 Release 2 (IDRISI, 2003) GIS and applied to the spatial data layers. The layers for soil and texture originate from a rasterized version of the European Soil Database (Hiederer *et al.*, In press), while the land use layer comprises re-classified extended CORINE data.

All data – soil, land cover, climate and topography – were compiled as standard 1km x 1km raster data sets for processing as spatial layers. The projection and spatial frame used conform to the Lambert Azimuthal Equal Area projection of the Eurostat GISCO database. All raster data were geometrically and thematically harmonised according to the standards developed by the Catchment Information System (Hiederer, 2001).

The output from this stage is a ‘baseline’ map of OC_TOP for Europe, derived from the revised PTR applied to the European Soil Database, using spatially detailed and complete land cover and temperature data Figure 10.

VERIFICATION OF CALCULATED OC

To justify the use of the modelled (calculated) OC contents in the surface horizon of European soils for policy support, the data were compared with measured OC contents from sampling surveys on the ground, in UK and Italy. The verification was performed for two different types of reference items:

1. *Soil-related reference items:* Ground and modelled (calculated) data are compared following aggregation at the level of FAO soil subgroup (STU) codes and SMU units.
2. *Soil-independent spatial item:* Ground and modelled data are compared following aggregation based on Catchments and NUTS units.

Measured data from Ground Surveys

The data from England and Wales originate from the National Soil Inventory (NSI) made during the period 1979-1983 (McGrath and Loveland, 1992). The OC content was determined by a wet dichromate acid digestion method (Avery and Bascomb, 1982). The OC data for Italy were compiled by Rusco (In prep.) and analysed by a similar method.

England & Wales

The sampling procedure for England and Wales was a systematic scheme, using a 5km x 5km grid (McGrath and Loveland, 1992). Sites under all land cover types were sampled, with the exception of some built-up areas, and the data exist for >5500 points. The systematic nature of the ground samples allows comparison of point and aggregated estimates with measured data over a wide range of soil types, environmental conditions and OC values (Jones *et al.*, In press).

Italy

The ground data from Italy were sampled selectively mainly from agricultural land. Furthermore, the sample locations (approximately 6800) were strongly clustered in some areas (see Jones *et al.*, In press). The sampling scheme and the limitations in the location of the sample sites render the Italian ground data unsuitable for the compilation of general statistics for aggregated units. However, the data are valuable for verifying OC estimates for southern European conditions on agricultural land.

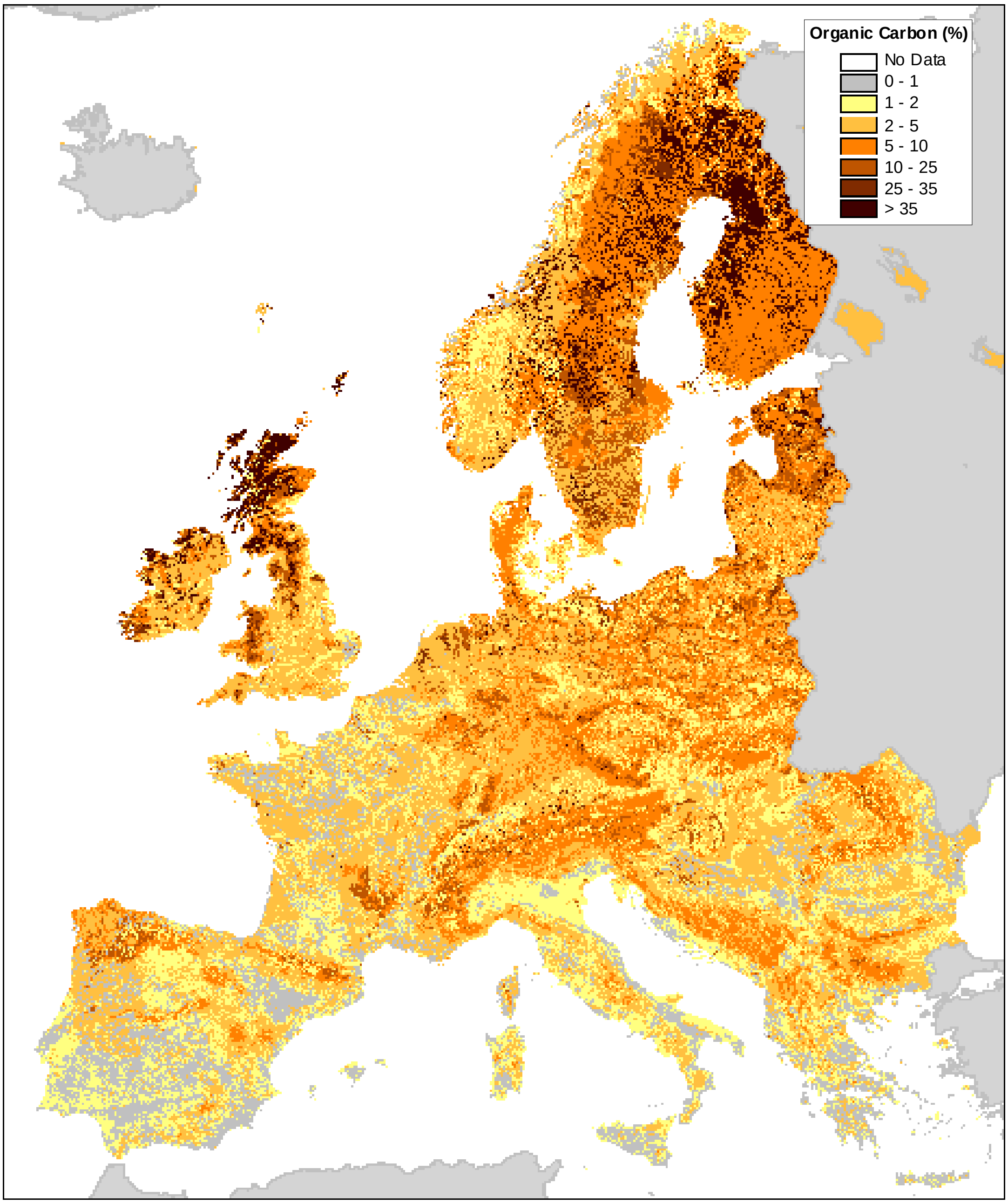


Figure 10: Organic carbon content (%) in the surface horizon of soils in Europe (S.P.I.04.72)

Aggregation

The use of the FAO (FAO-UNESCO, 1974) soil subgroup codes for aggregating the data allows an evaluation of any variation between modelled (calculated) and observed values using parameters that are also included in the PTR. Data were also aggregated to SMU level, i.e. for the actual spatial units in the soil geographic database.

However, for maximum benefit to policy-makers, the information provided must be presented at the level at which protection measures are likely to be implemented. This can be assumed to be administrative units, for example one of the NUTS (nomenclature of territorial units for statistics) levels in Europe as used by Eurostat. European statistical information covering a very wide range of thematic areas is also linked to NUTS units.

Environmental protection measures linked to water quality and quantity relate to the management of catchments and river basins. River basin districts are the management units for the implementation of ‘Directive

2000/60/EC of the European Parliament and the Council of 23 October 2000 establishing a framework for Community action in the field of water policy', often referred to as the 'Water Framework Directive' (WFD).

FAO Soil Subgroup Codes

Soil type is an attribute of an STU in the European Soil Database. Because of the nature of the SMU-STU relationship (one-to-many) it is not possible to generate a definitive OC value for a specific SMU. However, using the dominant STU in an SMU, it is possible to calculate an approximate mean value for OC for the STU, effectively an FAO soil subgroup. The SMUs are identified by the FAO subgroup code of the dominant STU. For England and Wales, there are 32 different subgroup codes for the dominant soils stored in the database, whereas the Italian ground data cover 22 different subgroup codes.

Soil Mapping Units (SMU)

There is a total of 1,657 SMUs in the European Soil Database. England and Wales are covered by 75 SMUs, of which 4 do not contain any ground sample points because of their small extent. It was decided not to calculate an OC value for SMUs in Italy because this would not be meaningful in view of the selective and clustered sampling scheme used.

Catchment Layer

The catchment units used in the study comprise the primary data layer of the Catchment Information System (CIS) of the Joint Research Centre (Hiederer and de Roo, 2003). Primary catchments of the CIS are defined by the flow of surface water to a single point, which is the outlet of the catchment to the sea. Complete coverage is achieved by combining coastal areas with logical catchment units.

For England and Wales 15,979 catchment units are defined in the CIS. The size ranges from 1km^2 to 10,969km^2. The size of the spatial units are of importance, because small units have few or even no ground survey points and are coastal areas by circumstance. For that reason, the study concentrated on catchments larger than 1000km^2.

Administrative Layer

The administrative units used to aggregate the OC data are those of NUTS Level 2 territorial units, as found in the Eurostat databases. This level corresponds to the more detailed areas of the two regional levels. For England and Wales, 32 units are defined at this level, ranging from 322km^2 (Inner London) to 13,122km^2 (West Wales and The Valleys) in the GIS layer.

Results: Ground vs. Modelled Data

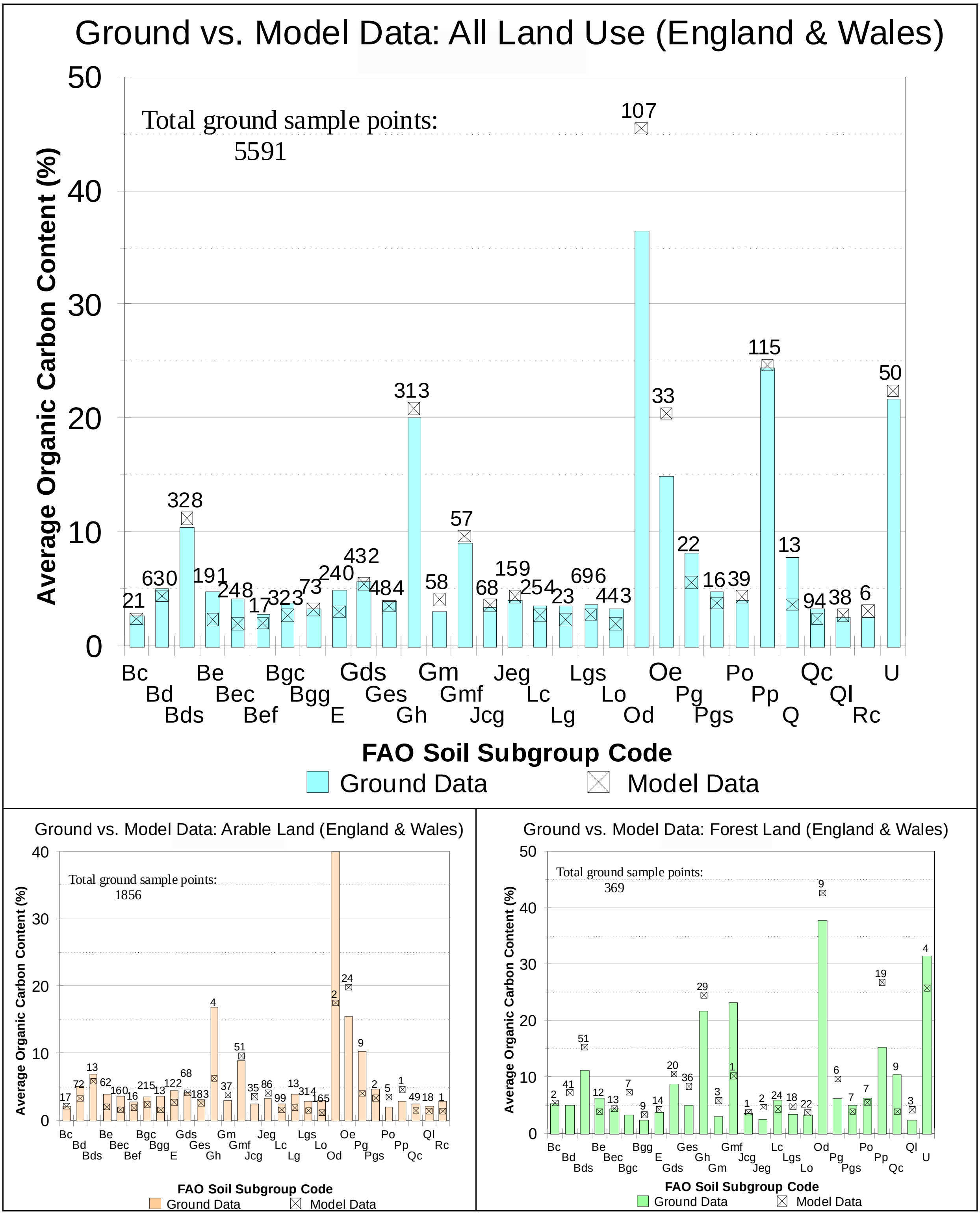
The average OC_TOP content in the ground data was calculated using the arithmetic mean of the observed values of all points within the spatial unit. The spatial data can be aggregated using two different approaches: either the average value for a spatial unit is calculated from modelled data at the location of ground samples (point aggregation) or the average is compiled from all data within the spatial unit (area aggregation).

The method used depends on the question to be answered. The first approach should be used when relating modelled to measured data, because it reduces the influence of a lack of representativity of the sample for the population, for example because the sample is small.

The second method would be applied when deriving regional estimates from spatial data, because it integrates information from the area as a whole and not from a sample. Hence, for the purpose of validating the modelled data, a regression analysis using the point aggregation method was used. Conversely, regional estimates of OC_TOP content by spatial units were calculated using area aggregation, thus taking the full range of information into account.

England & Wales

A graphical presentation of the mean OC content in England and Wales by FAO-UNESCO (1974) soil subgroup is given in Figure 11. A total of 5591 points were used in this aggregation and the number of observations per FAO soil subgroup ranges from 6 for *Rc (Calcaric Regosols*) to 696 for *Lgs (Stagno-gleyic Luvisols*). There is generally an extremely close relationship between the mean OC_TOP content for ground and modelled data.



For explanation of FAO soil subgroup codes, see table on page 26

Figure 11: Topsoil organic carbon content in England and Wales by FAO soil subgroup (all land cover, forest and arable)

Notable however, is an over-estimation by the model for *Histosols* (organic soils): *Od (Dystric Histosol*) 36.4% for ground data vs. 45.5% for modelled data and *Oe (Eutric Histosols)* 14.8% for ground data vs. 20.4% for modelled data.

The OC data for the soil subgroup units were further aggregated according to land cover. The graphs for forest and arable land are also included in Figure 12. These land cover types were selected in preference to the land use parameters 'semi-natural' and 'cultivated' identified in the PTR, because they correspond better to the needs of policy-makers.

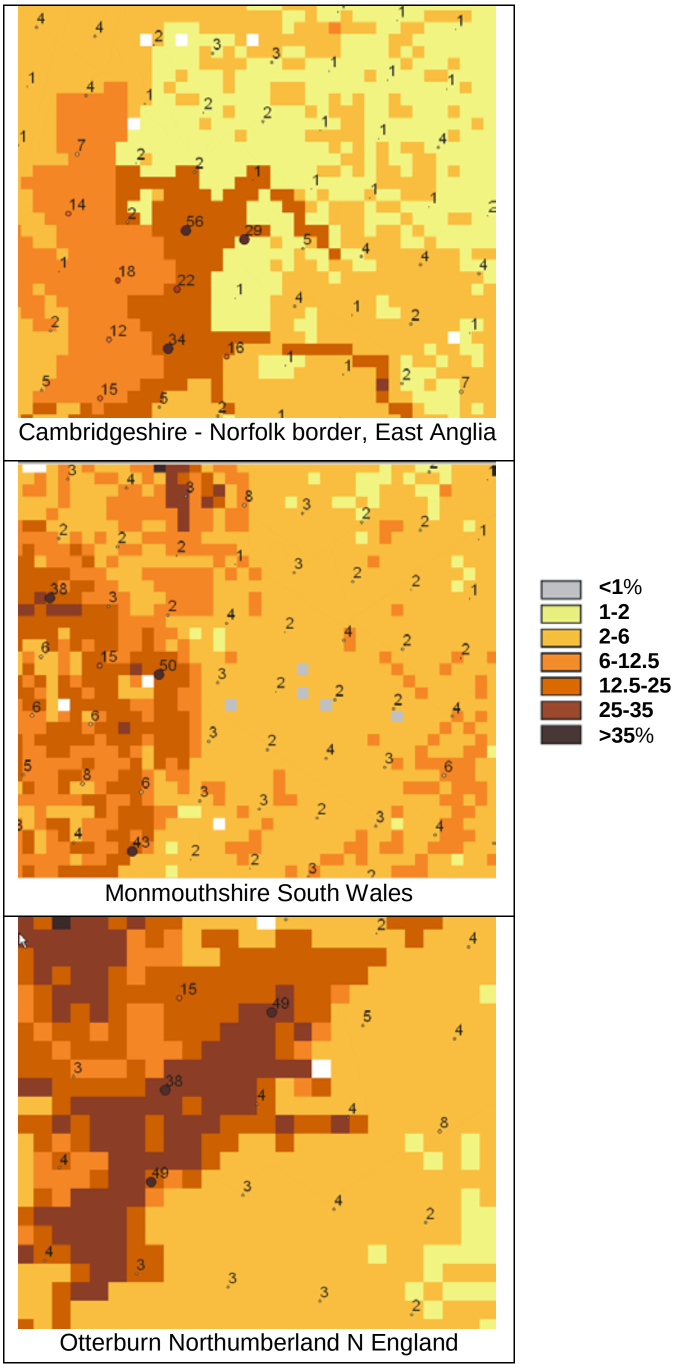
A total of 1,856 points fell on arable land in the land cover layer. The most obvious discrepancy between ground and modelled data occurs for *Dystric Histosols Od* (OC=39.9% for ground data compared to 17.5% for modelled data), for which there are only 2 ground sample points in an SMU and in which the dominant STU covers 70% of the area (with 30% covered by *Oe*). For *Oe (Eutric Histosols)*, the model over-estimates the mean OC_TOP content by about 4% (15.5% for ground data, from 24 ground sample points) vs. 19.8% for modelled data. By contrast, the model underestimates OC for *Gh (Humic Gleysols)* on arable land by 10.6%, albeit there are only 4 ground observations.

In forested areas, 369 ground-sample points are located within the area. Notable deviations from the generally good agreement between ground and modelled data were found only for *Pp (Placic Podzols),* 15.3% for ground data vs. 26.8% for modelled data and *Qc (Cambic Arenosols),* 10.3% for ground data vs. 3.9% for modelled data. Other variations are more likely to be caused by the small number of samples, for example *Gmf (Molli-fluvic Gleysols)* 1 point, *U (Rankers)* 4 points.

Using SMUs as the aggregation unit, the mean OC_TOP for all land uses is 6.5% for the ground data and 6.4% for the modelled data at the locations of the ground samples. The results of aggregating OC_TOP content by SMU can be characterized by a linear correlation:

$$OC\_TOP_{GRD} = 0.82\ OC\_TOP_{MODEL} + 1.45$$

The coefficient of determination (r^2) for the relationship is 0.95, indicating that the model closely represents the situation within the SMUs of England and Wales.


Cambridgeshire - Norfolk border, East Anglia

Monmouthshire South Wales

Otterburn Northumberland N England

Figure 12: Ground data plotted in relation to modelled OC values for three areas in UK

The OC measurements from the ground survey (NSI) are shown, in Figure 12, plotted on the modelled values on the OC Map for three areas in England and Wales. These plots show the very good spatial agreement between the two data sets across the whole range of OC.

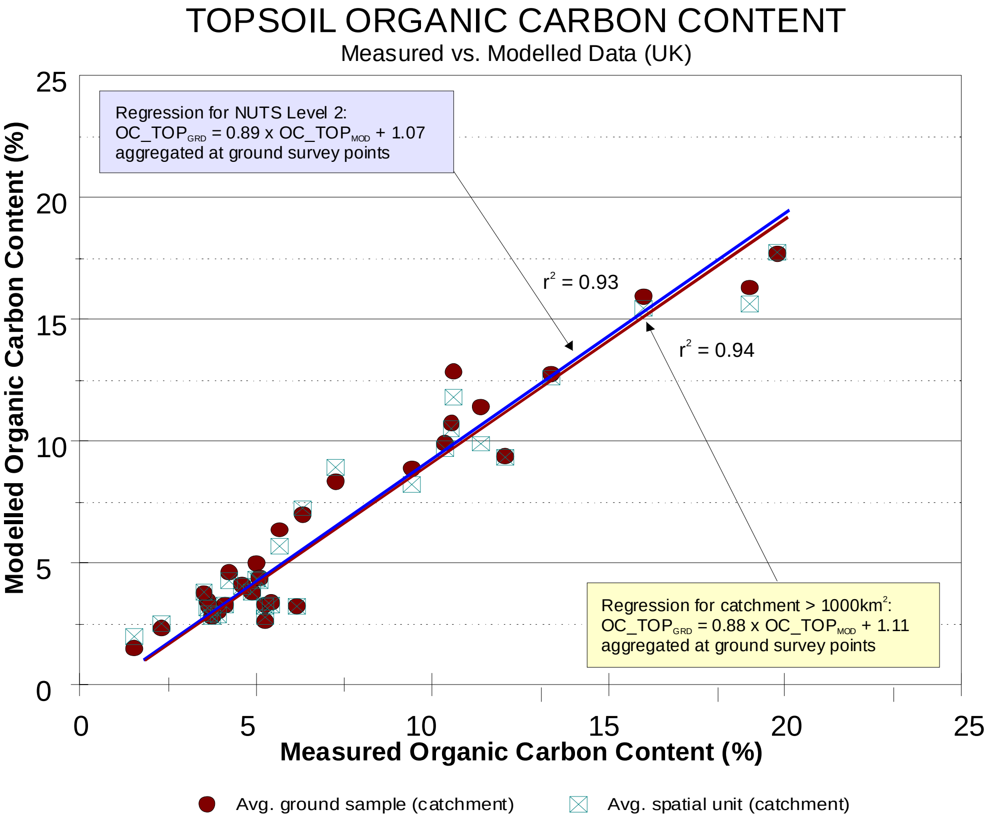
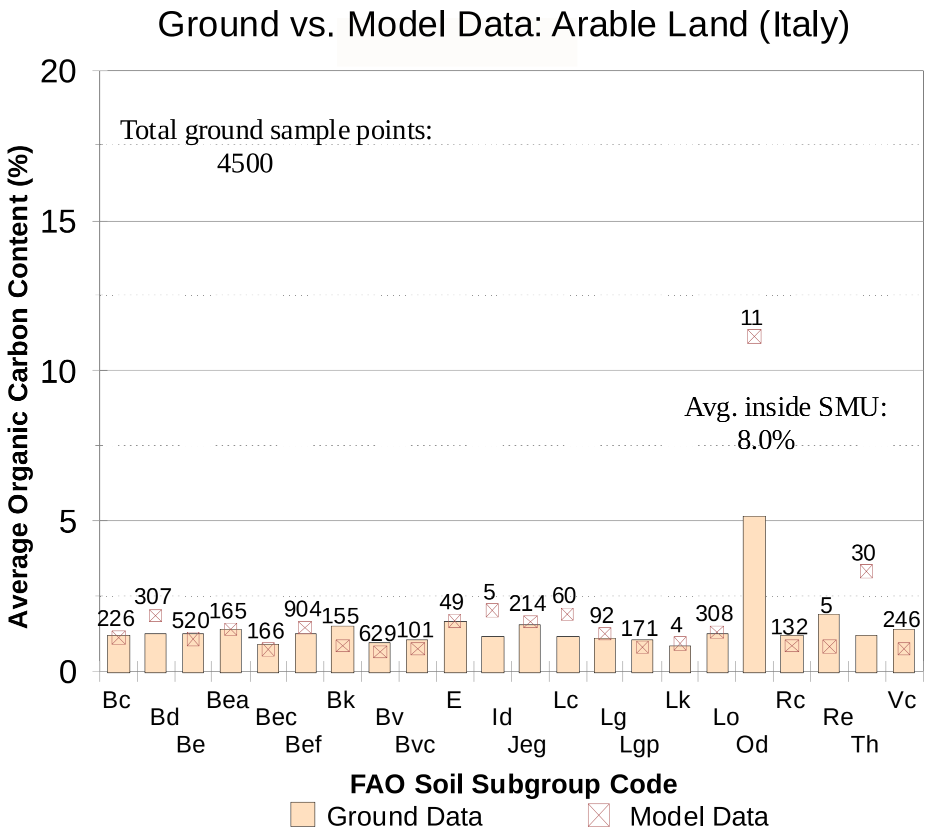


Figure 13: Relationship between ground and modelled data for topsoil organic carbon content in England and Wales, for CIS primary catchments (>1000km^2) and NUTS Level 2.



For explanation of FAO soil subgroup codes, see table on page 26

Figure 14: Topsoil organic carbon content in Italy by FAO soil subgroup (arable land only)

For catchments and administrative units the mean OC_TOP derived from the ground sample data is 6.7%. The mean value calculated from the modelled data at the locations of the ground survey is 6.3% for both units.

For the ground data the mean OC_TOP values for catchments range from 1.5% to 19.8% (2.7% to 13.9% for NUTS). The range of values for the modelled data for catchments spans from 1.5% to 19.8% (2.4% to 14.3% for NUTS). The range of values in catchments is larger than in the NUTS units because the catchments are smaller in size compared to NUTS units, i.e. some local conditions are better represented in the smaller spatial units.

A graphical representation of the linear relation between ground observations and modelled data for England and Wales for catchments and NUTS units is given in Figure 13.

The graph depicts for each primary catchment the data pair of mean OC_TOP content derived from ground data and from modelled data. Filled symbols (●) represent means from the point aggregation, boxes (☒) relate to values derived from area aggregation.

The regression lines show the linear relationship between ground (OC_TOP_{GRD}) and modelled data (OC_TOP_{MOD}) aggregated over catchments >1000km^2 and NUTS Level 2 territorial units using point aggregation for all sample points.

The mathematical expressions for the relationships are:

Catchments:

$$OC\_TOP_{GRD} = 0.88\ OC\_TOP_{MOD} + 1.11$$

NUTS Level 2 units:

$$OC\_TOP_{GRD} = 0.89\ OC\_TOP_{MOD} + 1.07$$

The R^2 value of the relationship is 0.94 for catchments and 0.93 for NUTS units (see Figure 13).

Italy

The Italian data set contains 6779 measurements of topsoil OC content for Italy. The range of values, mainly 1-2% OC, is too small and the sampling too restricted (only agricultural land) to permit calculating a meaningful correlation coefficient between ground observations and modelled values. Yet, the data are very useful for calibrating the AAAT correction function for areas where OC contents are small, such as southern Europe.

A total of 4500 points were used to relate ground to modelled data for Italy (Figure 14). Generally values for OC content are much smaller in Italy than those found for arable land in England and Wales. Noticeable is the over-estimation (6%) by the model for *Od (Dystric Histosols)* (5.1% ground, 11.1% model). This corresponds to the results for England and Wales for the same soil type. The mean for *Od* was calculated from the data for 11 points.

The most likely explanation for this discrepancy is the scale: the boundaries for the SMUs dominated by *Od* are derived from the European Soil Map at 1:1,000,000 scale whereas the ground sampling was geo-referenced to +/-10m. The analysis of administrative units was restricted to NUTS units since the use of catchments did not change the results.

The OC measurements from the ground sampling of agricultural land in Italy are shown (Figure 15) plotted for three areas on the OC Map, in the north and the south of the country. These plots again show the very good agreement between the measured and modelled data sets, even for small OC contents.

The mean topsoil OC content of 1.2% for the ground measurements equates with the mean (1.2%) calculated for the modelled data. This value of OC content is small, but is to be expected for agricultural land in a Mediterranean country because the dry conditions and high temperatures, especially in summer, favour rapid mineralization of OM.

Although the OC values in the Italian data set are derived from sampling a restricted land use, these findings indicate that the modelled data are reliable estimates of topsoil OC content for agricultural land in Southern Europe, when aggregated at the NUTS Level.

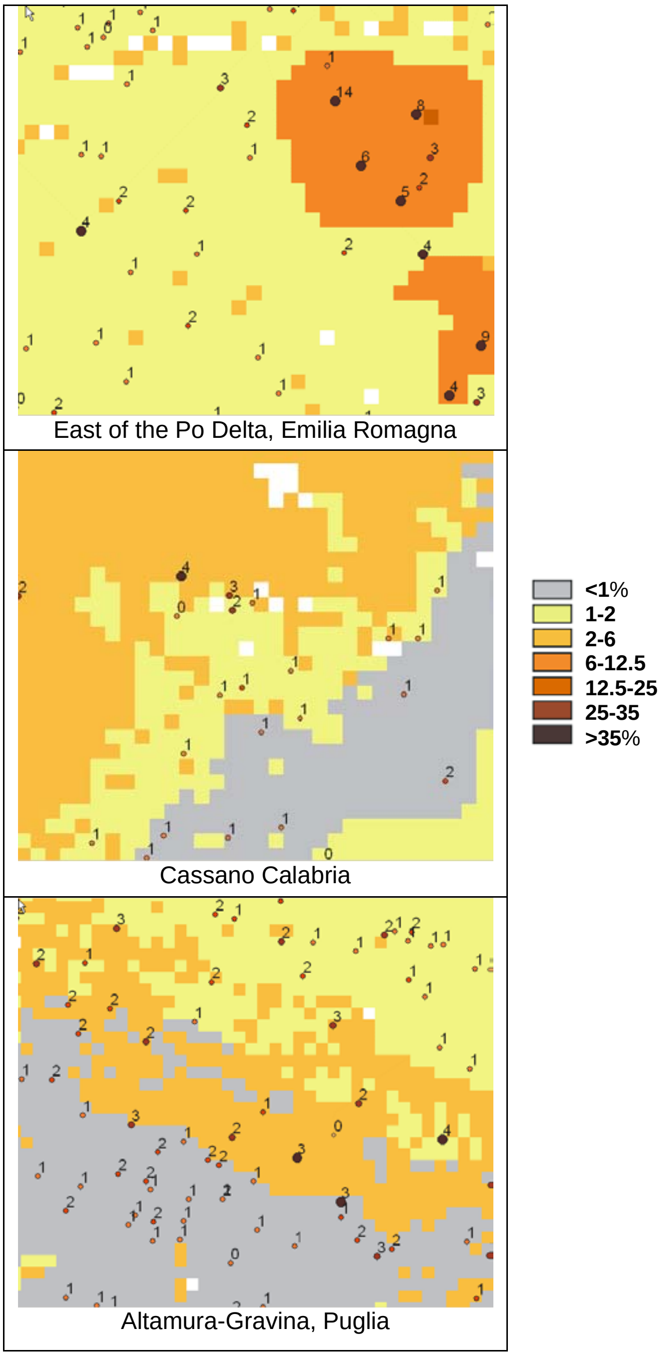
SOIL DEGRADATION

Very low OC (and OM) contents are generally an indicator of soil degradation, though the exact OC (or OM) content of degraded soil is still a subject for debate. Loss of topsoil through erosion is a process causing severe degradation in Europe, thus comparing OC contents with estimates of soil loss could highlight areas under particular stress.

Soil erosion losses have been estimated for Europe, at a resolution of 1km, using the Pan-European Soil Erosion Risk Assessment (PESERA) model (Gobin *et al.*, 1999). A map summarising the results of PESERA has been published (S.P.I.04.73) by Kirkby *et al.* (2004) in the same format as the Map of OC in topsoils in Europe (S.P.I.04.72).

The PESERA erosion estimates provide a measure, at 1km resolution, of the state of degradation of the soil through erosion in Europe. For example, sediment losses of >2 t/ha/yr are considered unsustainable in human timescales. It is also reasonable to assume that OC<1% is a sign of poor soil quality, particularly in Mediterranean areas.

Therefore by comparing the coincidence of high rates of soil erosion with low OC contents, areas with degraded soils could be highlighted. Figure 16 shows maps of the PESERA soil erosion estimates juxtaposed with the OC in topsoils for Spain. This shows that some areas of low OC content (OC<1%) also have large estimated soil loss by water erosion.


East of the Po Delta, Emilia Romagna

Cassano Calabria

Altamura-Gravina, Puglia

Figure 15: Ground data plotted on modelled OC values (rounded) for three areas in Italy (0 indicates a positive OC<0.5)

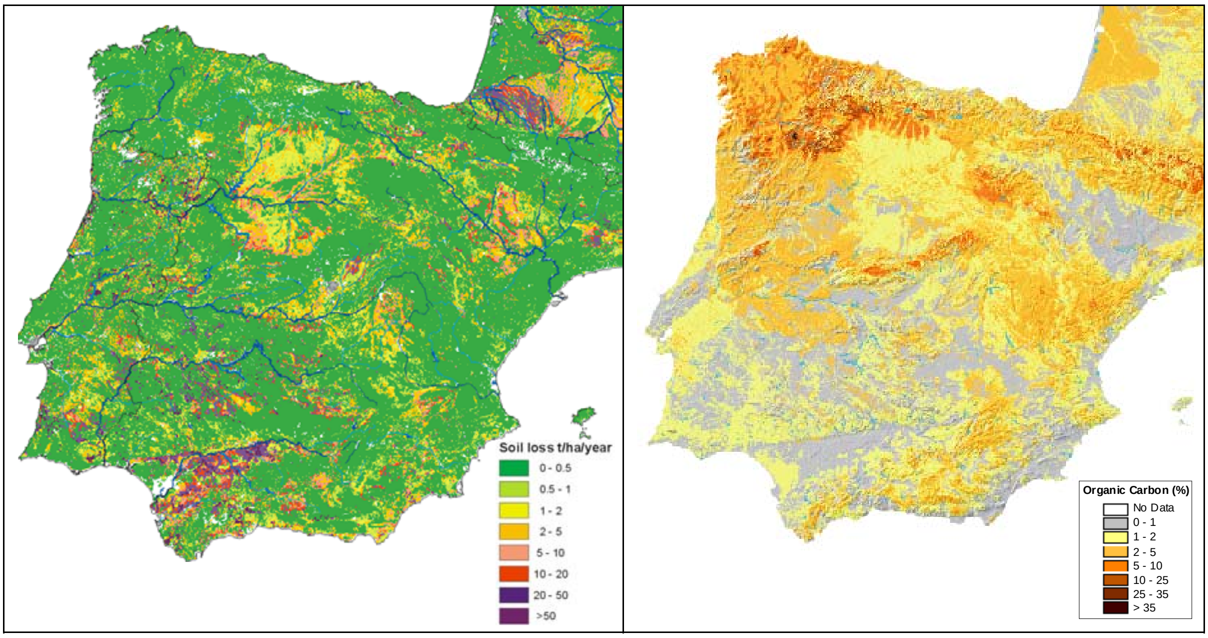


Figure 16: Soil erosion estimates from PESERA (S.P.I.04.73), compared with topsoil organic carbon content in Spain

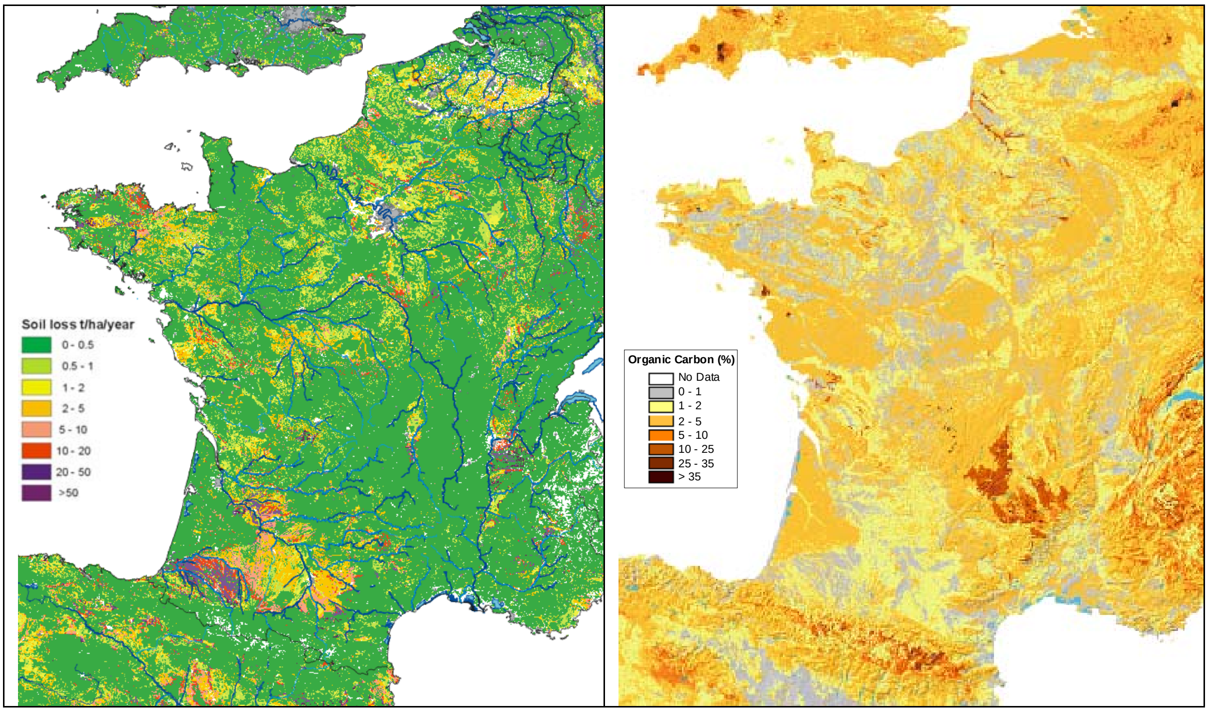


Figure 17: Soil erosion estimates from PESERA (S.P.I.04.73), compared with topsoil organic carbon content in France

From a similar comparison, there appears to be a better correlation between low OC contents and large estimated soil loss by water erosion in France (Figure 17) than for Spain. These relationships are only presented visually here but are being examined quantitatively using GIS, as part of an on-going research programme under-pinning the soil protection strategy.

CONCLUSIONS

Our approach to mapping OC contents is quite different from other methods developed for the purpose and is a genuine attempt to accurately portray the geographical distribution of OC in topsoils in Europe. The other studies on OC referred to here (Howard *et al.,* 1995); Arrouays *et al.,* 2001); Lettens *et al*., 2004) have attempted to estimate carbon stocks not contents. Carbon stocks can easily be calculated from the OC contents using soil depth and bulk density. Unfortunately, bulk density measurements are scarcer than data on OC, with the result that potential errors in calculating carbon stocks can be large.

Furthermore, the research reported here has avoided extrapolating OC data from a small number of sample points, deemed to be representative of a particular soil type, to polygons delineated on a soil map that represent much larger areas with no measured values. This procedure is not suitable in view of the well-known fact that OC contents can vary significantly within pedologically defined units, that can be portrayed on a soil map.

This is clear from the data computed by Batjes (1996, 1997), which show a coefficient of variation (CV) in topsoil OC contents of between 50 and 150% for the same pedological soil group. This variation is undoubtedly due to differences in land use and vegetation within the specific pedological soil group.

The tendency for large variations in OC, within seemingly uniform areas, makes it difficult to estimate OC contents, and consequently C stocks, accurately in soils using only the data from field surveys.

The results from comparing the measurements of OC from ground surveys with the calculated (modelled) values on the OC Map (S.P.I.04.72) are very encouraging (see also Figure 12 and Figure 15), not only because of the detailed quantification of soil OC at European scale obtained, but also for demonstrating the viability of using comprehensive spatial databases to generate standardised data layers that can be calibrated by actual measurements where these are available. The statistical relationships are highly significant and proven for two diverse regions – north western and southern Europe. Furthermore, the pedo-transfer approach developed in the course of the project provides a sound basis for extrapolation and potential for scenario analysis.

There are several other sources of variation that could result in calculated OC values deviating from the measured data from ground surveys. Firstly, topsoil OC contents are known to vary considerably from place to place because of differing land use history, timing of sampling and small variations in soil drainage conditions. Secondly, the land use at the time of sampling may have been different from that defined by the CORINE-based land cover data set (valid for the period 1988-92). This could be a result of land use change or merely the effect of scale.

Major differences in this study, compared to those made hitherto, are the development of a sophisticated PTR, which was applied to the most detailed (1:1,000,000 scale) harmonised spatial soil data that currently exist for Europe and processing directly in the spatial domain, which was made possible by technological advances in computer hardware and software.

Further validation of the *Map of Organic Carbon in Topsoils in Europe* should be performed, in the near future, using measured data from other areas in Europe and on the whole range of land cover types. There may be scope for further refining the definition of parameters used for the temperature correction, which were mainly set empirically and are based only on a general relationship of long standing.

The research could also be extended to incorporate changes in climatic conditions over longer and different periods, for example 1961-2000 and in decades, for example 1961-70, 1971-80 and 1981-90, thus providing valuable input data for climate change modelling. For modelling purposes there may also be some merit in adding a correction, based on precipitation and evapo-transpiration, to account for the effect moisture status may have on OC content.

The status of soil OC (and OM) is known locally in many European countries. However, existing national data must be harmonized and new data collected for regions where soil OC (and OM) data are scarce before a new European map can be produced.

It is clear from the OC Map that the soils in northern countries contain proportionately much larger contents of OC (and OM) than southern Europe. Furthermore, areas where calculated OC contents in the topsoil are less than 1% should be regarded as particularly vulnerable to further degradation by other means and should be managed very carefully in future.

RECOMMENDATIONS

In the light of these conclusions, the following recommendations are identified for future action:

1. Currently, the *Map of Organic Carbon in Topsoils in Europe* (S.P.I.04.72) provides the best basis for underpinning policy making with respect to soil OM.
2. Those EU Member States with adequate national data sets on soil OC and OM should release/make available national records for validating and improving the current OC map of Europe (as already has been done by UK, Italy and Finland).
3. Those Member States with inadequate national data sets on soil OC and/or OM should implement sampling programmes immediately to define the existing status.
4. OM status depends on soil type, climate, land use and human activities. Hence land-use patterns in areas where the OC Map of Europe identifies soil OC<2% (OM<3.4%) should be critically examined, with a view to proposing changes in land management to stabilise or increase soil OC (OM) levels.
5. The relationship between soil sealing and soil OM should be carefully examined, using terrestrial databases and remote sensing, for example with the aim where economically possible of protecting soils with large OM contents from further urban and industrial development.
6. Monitoring: organic carbon/organic matter should be measured in the soils of EU Member States, for example by sampling on a grid, followed periodically (approximately every 10 years) by a resampling at a statistically significant subset of points on the original inventory grid.

Acknowledgements

We thank all our colleagues in European Soil Bureau Network for their past and continuing collaboration in providing soil data and expertise for construction of the European Soil Database. We also express our gratitude to: the National Soil Resources Institute (NSRI), Cranfield University and the UK Department of Environment, Fisheries and Rural Affairs (DEFRA), for access to the data from the National Soil Inventory in UK; the Ministero di Ambiente, Italy for access to the organic carbon data for Italy; and finally to the Institute of Environment and Sustainability, Joint Research Centre, Ispra, Italy, for the support and encouragement in conducting this study.

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Soil Subgroup Codes and Soil Names (FAO-UNESCO, 1974)

for comparing modelled OC values with ground data
in England & Wales, and Italy (see Figure 11 and Figure 14)

Code	Soil subgroup name (FAO, 1974)	WRB Reference Group & Subgroup (FAO,1998)
Bc	Chromic Cambisol	Chromic Cambisol
Bd	Dystric Cambisol	Dystric Cambisol
Bds	Spodo-Dystric Cambisol	Endo-skeletic Umbrisol
Be	Eutric Cambisol	Eutric Cambisol
Bea	Ando-Eutric Cambisol	Eutri-andic Cambisol
Bec	Calcaro-Eutric Cambisol	Calcaric Cambisol
Bef	Fluvi-Eutric Cambisol	Eutri-fluvic Cambisol
Bk	Calcic Cambisol	Haplic Calcisol
Bv	Vertic Cambisol	Vertic Cambisol
Bvc	Calcaro-Vertic Cambisol	Calcari-vertic Cambisol
Bgc	Calcaro-Gleyic Cambisol	Calcari-gleyic Cambisol
Bgg	Stagno-Gleyic Cambisol	Stagnic Cambisol
E	Rendzina	Leptosol
Id	Dystric Lithosol	Dystric Leptosol
Gds	Stagno-Dystric Gleysol	Dystri-stagnic Gleysol
Ges	Stagno-Eutric Gleysol	Eustri-stagnic Gleysol
Gh	Humic Gleysol	Humic Gleysol
Gm	Mollic Gleysol	Mollic Gleysol
Gmf	Molli-Fluvic Gleysol	Fluvi-mollic Gleysol
Jcg	Gleyo-Calcaric Fluvisol	Calcari-gleyic Fluvisol
Jeg	Gleyo-Eutric Fluvisol	Eutri-gleyic Fluvisol
Lc	Chromic Luvisol	Chromic Luvisol
Lg	Gleyic Luvisol	Gleyic Luvisol
Lgp	Plano- Gleyic Luvisol	Gleyic Luvisol
Lk	Calcic Luvisol	Calcic Luvisol
Lgs	Stagno-Gleyic Luvisol	Stagnic Luvisol
Lo	Orthic Luvisol	Haplic Luvisol
Od	Dystric Histosol	Dystric Histosol
Oe	Eutric Histosol	Eutric Histosol
Pg	Gleyic Podzol	Gleyic Podzol
Pgs	Stagno-Gleyic Podzol	Stagnic Podzol
Po	Orthic Podzol	Haplic Podzol
Pp	Placic Podzol	Placic Podzol
Q	Arenosol	Arenosol
Qc	Cambic Arenosol	Haplic Arenosol
Ql	Luvic Arenosol	Lamellic Arenosol
Rc	Calcaric Regosol	Calcaric Regosol
Re	Eutric Regosol	Eutric Regosol
Th	Humic Andosol	Umbric Andosol
Vc	Chromic Vertisol	Chromic Vertisol
U	Ranker	Leptosol

The FAO soil subgroup code is as used on the The Soil Map of the European Communities (CEC 1985).

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