Global Change Biology, Volume 14, Issue 10, Date: October 2008, Pages: 2432-2442

Received date: 6/28/2007
Revised date: 1/21/2008
Accept date: 3/19/2008

Will European soil monitoring networks be able to detect changes in topsoil organic carbon content?

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Keywords: Soil; organic carbon; monitoring; network; Kyoto protocol; verification; detection of change; Europe; concentration.

Running title: Detection of changes in soil OC by monitoring

Date of receipt:

Abstract

Within the United Nations Framework Convention on Climate Change articles 3.3 and 3.4 stipulate that some voluntary activities leading to an additional carbon (C) sequestration in soils could be accounted as C sinks in national greenhouse gas inventories. These additional C stocks should be verifiable. In this work, we assess the feasibility of verifying the effects of changes in land use or management practice on soil organic carbon (SOC), by comparing minimum detectable changes in SOC concentration for existing European networks suitable for soil monitoring. Among the tested scenarios the minimum detectable changes differed considerably amongst soil monitoring networks. Considerable effort would be necessary for some member states to reach acceptable levels of minimum detectable change for C sequestration accounting. For SOC, a time interval of about 10 years would enable the detection of some simulated large changes in most European countries. In almost all cases, the minimum detectable change in SOC stocks remains greater than annual greenhouse gases emissions. Therefore, it is unlikely that soil monitoring networks could be used for annual national C accounting. However, the importance of organic C in soil functions, and as an indicator of soil condition and trends, underlines the importance of establishing effective national soil monitoring networks.

1 Introduction

Within the United Nations Framework Convention on Climate Change articles 3.3 and 3.4 stipulate that some voluntary activities leading to an additional carbon (C) sequestration in soils could be accounted as C sinks in national greenhouse gas inventories. Such additions to accounted C stocks would have to be verifiable: their accounting is conditional on meeting a requirement to verify the sequestration claimed. Smith (2004) reviewed possible definitions of the verifiability of C sinks and sources in soils and, at its most stringent, verification would entail such a large number of measurements, that the resources needed would be prohibitively expensive. This is certainly true, if specific regulatory sampling and testing is done.

A recent review of European soil monitoring networks (SMNs) has been carried out within the ENVASSO project - ENVironmental ASsessment of Soil for mOnitoring - (Kibblewhite *et al.* 2005). ENVASSO has been funded under the European Union's 6th Framework Programme for Research and Technical Development and has shown that, in most countries in Europe, official systems for comprehensive soil monitoring exist already, are planned, or are under development. In this context, soil monitoring is defined as 'continuous or repeated observation, measurement, and evaluation of soil and/or related environmental or technical data for defined purposes, according to prearranged schedules in space and time, using standardized methods for data collection and analysis' and a soil monitoring network is defined as 'A spatial arrangement of soil monitoring sites, designed to be representative of soil type, land use and climatic zones; the spatial arrangement maybe random or on a regular grid' (ENVASSO 2007). Most existing national monitoring systems have undertaken a single sampling only, and thus they remain inventories at present. Most of these systems have measured soil organic carbon (SOC) concentrations, in addition to other soil properties, and are geo-referenced with sufficient precision for repeat sampling campaigns.

In relation to climate change, or to changes in land use or cultivation practices, SOC content may increase or decrease and a major issue is to assess whether these changes are detectable by soil monitoring taking, into account the uncertainties caused by spatial heterogeneity, sampling methods and analytical errors. Indeed, the evaluation of the confidence with which changes in SOC content can be detected is important for the implementation of EC Directives, national treaties, emissions trading schemes, and *a posteriori* validation of predicted changes using modelling. The spatial variability of SOC content strongly influences the ability to detect changes (Conant& Paustian 2002a, 2002b, Conant *et al.* 2003). At the field scale, numerous studies have addressed this issue (see for example, (2002b, Conant *et al.* 2003, Conen *et al.* 2003, Garten & Wullscheleger 1999, Saby & Arrouays 2004, Smith 2004). At a regional or national scale, it is necessary to assess the effect of the number of sites and of inherent soil spatial variability on the detection of a change in SOC (see for example Saby & Arrouays 2004 and Bellamy *et al.* 2005). To our knowledge, such an assessment has never been performed at a continental scale.

The relatively dense (5 km x 5 km) soil monitoring network of England and Wales, the National Soil Inventory (NSI) described by McGrath and Loveland (1992), has recently been shown to be effective for recording aggregate SOC losses from these countries between 1978 and 2003 (Bellamy *et al.* 2005). However, the density of soil monitoring sites varies considerably between European countries. In this paper, we assess the feasibility of verifying the effects of changes in land use or soil management practice on SOC content, by comparing minimum detectable levels of change in SOC concentrations for existing European networks suitable for soil monitoring, based on the information collected during the ENVASSO project. It is believed that ENVASSO has identified most soil monitoring networks in Europe but some are known to have been excluded because of data confidentiality and problems of national coordination (Morvan *et al.* 2008).

2 Materials and methods

2.1 Theory

We assume that the soil monitoring sites identified within each country will be revisited on a second and subsequent occasions as this is the most efficient way of monitoring change (Lark *et al.* 2006). This means for a monitoring network in which each site is visited at least twice there is a paired sample situation and the change at each site can be calculated. For any particular monitoring network of a variable *x*, *n* sites are sampled at time t_0 and again at time t_1. An estimate of the mean change ($\bar{d}$) in x is

$$\bar{d} = \sum_{i=1}^{n} (x_{i,t_0} - x_{i,t_1}) / n \qquad (1)$$

where $x_{i,t}$ is the measurement at site *i* at time *t* and *n* is the number of sites in the monitoring network. An estimate of the standard error of $\bar{d}$ is $\sqrt{\frac{s_d^2}{n}}$ where s_d^2 is an estimate of the variance of the differences (de Gruijter *et al.* 2006) . However, it is not possible to estimate this variance directly as we know very little about the variation of change in SOC concentrations at European scale, as currently most soil monitoring networks within Europe are inventories. An alternative estimate of the standard error of $\bar{d}$ is $\sqrt{\frac{2s^2}{n}}$, where s^2 is an estimate of the variance of x on the first occasion. This alternative estimate requires us to assume that this variance does not change over time and that the correlation between the two sampling times is small. In this paper the latter assumption is investigated for SOC concentration using data from the NSI of England and Wales. However, this estimate of the standard error of the mean change is conservative and has been calculated in the same way for all countries to compare their monitoring networks.

Assuming a normal distribution for the mean change in SOC concentration (invoking the Central Limit Theorem), estimates of a 100(1-α)% confidence interval for this mean change can be written (Barnett 2002):

$$\bar{d} - z_\alpha s\sqrt{2/n} < \bar{D} < \bar{d} + z_\alpha s\sqrt{2/n} \qquad (2)$$

where z_α is the value of the standardized normal distribution at probability α.

The condition for detection of a mean change y is that

$y - z_\alpha s\sqrt{2/n} > 0$ that is $y > z_\alpha s\sqrt{2/n}$

and hence the minimum detectable change (MDC) is

$$y = z_\alpha s\sqrt{2/n} \qquad (3)$$

With the assumption that the SOC concentration is changing at an estimated rate of change k and that this is constant over the whole time interval t, then

$$t > \frac{z_\alpha s\sqrt{2}}{k\sqrt{n}}$$

and the minimum time to detect a given rate of change k is

$$t = \frac{z_\alpha s\sqrt{2}}{k\sqrt{n}} \qquad (4)$$

Equation 3 can also be used to estimate the number of sites required to detect a certain level of change y i.e.

$$n > \frac{2z_{\alpha}^{2}s^{2}}{y^{2}} \qquad (5)$$

If the assumption made above is valid, (i.e. that the correlation between repeated samplings is small), the variance s^2 described above is the natural heterogeneity of SOC concentration across the landscape, as well as the variation due to the measurement of SOC concentration. It has been found that the best estimate of s^2 is a combination of the estimate of the landscape variation from previous studies $s^2_{landscape}$ and the expected measurement errors (see Ramsey 1998). All these sources of error can be assumed to be independent so that

$$s^{2} = s_{a}^{2} + s_{s}^{2} + s_{landscape}^{2} \qquad (6)$$

where s^2_a is the analytical variance and s^2_s is the sampling variance from the sampling of the soil in the field. $s^2_a + s^2_s$ can be assumed to be the within-site variability. The within-site variability needs to be quantified as it can make a significant contribution to the overall variation.

2.2 Data

The following sources of data were used to estimate the minimum detectable changes in SOC concentration across Europe:

2.2.1 Soil monitoring networks in Europe

A metadata collection was conducted by means of a questionnaire completed by ENVASSO partners from 25 European countries, providing information on national soil monitoring networks (SMNs), their site sampling designs, the geo-reference of the monitoring sites, the parameters measured at each site and the number of sampling campaigns (Morvan *et al.* 2007). Where possible, descriptive statistics (mean, median, standard deviation) were also collected for each parameter within each country, categorised by three land use classes (arable, forest, pasture) and peat soils.

2.2.2 Metadata of within-site variation

To obtain estimates of the sampling variance (s^2_s) and the analytical variance (s^2_a), we conducted a meta-analysis of published and some unpublished data. The following relevant factors were included in the compilation: area of the site (ranging from 1 m^2 to 20 ha), number of samples, mean values of soil parameters, indication of within-site variability (i.e. variance, or standard deviation, or coefficient of variation). We also extracted data on analytical variability when available. Literature searches were performed using the electronic database "Web of Science". Some unpublished data were also supplied by ENVASSO partners (mainly from France and Slovakia) and we excluded references to tropical soils. One hundred and twenty sites were retained. The data were used to derive quantitative estimates of the mean values, variances, standard deviations and coefficients of variation for all available parameters. We examined the possible relationships between within-site variability and site area and/or mean values. From these relationships we derived estimates of the coefficient of variations for all the sites for which the area was known.

2.2.3 Digital map of organic carbon in top soils across Europe

Jones *et al.* (2005) developed a methodology for estimating organic carbon concentrations (%) in topsoils (OCTOP) across Europe. The information presented in map form (Jones *et al.* 2004) is also available as a database which can be downloaded from the EU-soils web site (http://eusoils.jrc.it) hosted by the Joint Research Centre, Ispra (I). The OCTOP map and database provide policy-makers with estimates of current topsoil OC concentrations when developing strategies for soil protection at regional level. Although the methodology used to compile OCTOP is based on pedotransfer functions, the results have been validated using SOC concentrations from more than 12,000 sites in England and Wales (from the NSI), and Italy. Statistical analysis showed that 95% of the variation in the estimated SOC concentrations, aggregated on the basis of European soil map units (SMU), was accounted for by the measured SOC concentration from the detailed inventories conducted in these countries (Jones *et al.* 2005). Therefore, these baseline data were used to estimate national distributions of soil organic carbon (SOC). Processing of data was performed on harmonized spatial data layers in raster format with a 1 km × 1 km grid spacing. Using SOC concentration values on this 1km grid, the variances were calculated for each country. We set the initial SOC concentration value for each monitoring site identified in the ENVASSO project, to the topsoil OC (OCTOP) predicted by Jones *et al*. (2005) because the data from the individual sites were not available for reasons of confidentiality.

3 Results

3.1 Investigation into assumptions made in the methodology

One of the main findings of the ENVASSO survey of SMN's across Europe was that very few had actually been resampled (Morvan *et al.* 2007, Morvan *et al.*). This meant that it was impossible to estimate s_d^2 (the standard error of mean change) directly. Only the NSI for England and Wales, has been resampled for SOC concentration and, thus the assumption that the correlation of SOC concentrations between sampling times is small, could be examined. Table 1 shows the standard deviations of the original NSI sample of SOC concentrations; the resampled SOC concentrations, standardised to cover the same interval at all sites; and the difference at each site. It can be seen that under arable agriculture the assumption is reasonable (an over-estimation of 15%), but the standard deviation is over-estimated by 30% for grassland and by more than 100% under forest. Since these are all over-estimations, the estimate of minimum detectable change will also be an over-estimate and, as long as the same methodology is applied across Europe, the results will be comparable.

The data collected from the ENVASSO survey was comprehensive regarding the number and geographical location of monitoring sites, but few countries supplied summary statistics of their data. Therefore, the variation of SOC concentrations at the landscape scale had to be estimated from the digital map of topsoil OC across Europe. To examine the effect of using this methodology on the results, the data from the few countries supplying summary statistics were used to estimate the minimum detectable change (MDC) within land use classes and this was compared with the MDC calculated using the SOC map. Figure 1 shows the results for England & Wales (treated as one country), Hungary, Romania, France, Belgium, and Austria. The MDC is not well estimated for soils under forest in those countries with large areas of forest, however, the estimate using the European OCTOP map falls between those for arable and grassland for all countries, except Belgium where it is slightly smaller. The original assumption that there is a weak correlation between sample values led to estimates derived using the summary statistics for each country being over estimates, particularly for forest soils. The estimation of variation from OCTOP is not affected by extreme values because it is derived from a combination of soil, climate and land use data on a 1 km x 1 km grid rather than from point samples (monitoring sites) and as such is a more robust estimator. The MDC for the only country for which information on the variation of change was available, England & Wales, is also shown in Figure 1 (as E & W_res), where the MDC is estimated using the directly estimated variance of differences at individual sites. It is impossible to draw conclusions from one dataset but this result does indicate that the estimate of MDC, using the estimate of variance from OCTOP, gives a reasonable estimate of MDC for OC concentration of soil under grassland and arable land use.

3.2 Within-site variability

We found a strong relationship between the within-site variability of SOC concentration and the site area. Figure 2 shows the relationship between the coefficients of variation of SOC concentration and the area of sites, grouped into area classes. The analytical value (1) corresponds to the coefficient of variation obtained by re-analysing the same sample several times.

3.3 National variances

National variances of values of topsoil SOC concentration predicted across Europe using OCTOP show a marked effect of latitude (Figure 3). The northern countries have very high standard deviations, which can be related to the existence of soils with very high SOC concentration (peat soils) and very low SOC concentrations in some intensively cropped areas. By contrast, soils in Mediterranean countries are generally characterised by lower and more uniform SOC concentrations with smaller standard deviations.

3.4 Number of monitoring sites

Figure 4 and Table 1 show the heterogeneous distribution of the monitoring sites for SOC concentration for each country reported by an ENVASSO partner. Some countries have relatively dense networks (e.g. England and Wales, Northern Ireland, Austria, Denmark, Malta), whereas in other countries soil monitoring sites are relatively scarce (Spain, Italy, Greece). Some ENVASSO partners reported forest sites only, generally belonging to the International Co-operative Programme (ICP) on Forest Soil Condition Survey in Europe (Vanmechelen *et al.* 1997), although the countries represented are known to have implemented SMNs more widely than just on forest land. For example, detailed information was not obtainable for some SMNs such as those described by Ibáñez *et al* (2005) for Spain, and by Filippi (2005) for Italy, whereas information on site coordinates is also lacking for agricultural areas in Sweden or Belgium (Van Orshoven *et al.* 1993). Topsoil OC concentration was measured at 33,334 monitoring sites, representing 92 % of the monitoring sites identified by ENVASSO, making the topsoil OC indicator one of the most widely available indicators of soil status in Europe. Only SMNs in Austria, Estonia, Finland, Germany and Slovenia reported that topsoil OC was not measured at all monitoring sites.

3.5 Minimum detectable change

The minimum detectable change (MDC) using α equal to 0.05 was highly variable amongst SMNs (see Figure 5). As expected, the highest values of MDC for SOC concentration were observed in countries having very organic soils and/or having very few sites measuring this indicator. Six countries show a MDC larger than 10 $gC.kg^{-1}$. The large MDC observed for both Estonia and Slovenia would be reduced if SOC concentrations were measured at all the existing monitoring sites.

3.6 Number of sites required

The policy process requires the number of sites, by country necessary to achieve a given MDC. We estimated the number of sites (n_1) required to detect a relative change of 5 % in the national mean of topsoil OC concentration, which was chosen because it is the requirement for monitoring soil in the UK (Environment Agency 2007). Table 2 shows that n_1 mainly depends on country area and on the variability of SOC concentrations within the country, such that a total of 57,628 sites would be required for the EU-27 countries. If we compare this estimate to the actual number of sites, n, where measurements of SOC concentration are undertaken currently, we can deduce an estimate of the additional number of sites, n_2 that would be needed in each country to achieve this level of detectable of change. Except for some countries where relatively dense SMNs exist already, most of the countries would have to make considerable efforts to be in a position to detect a 5 % relative change in SOC concentration.

Using the data available, it is possible to do the same calculation for any desired relative change we might wish to detect. Table 3 shows that except for Malta, the number of sites needed to detect a 1 % relative change would exceed 20,000 in all national cases, and more than 170,000 in Norway, which would be prohibitive under current circumstances. At the European scale, the number of sites needed would be close to 1,000,000.

3.7 Time required to detect a given change

With the following assumptions: (i) that a variable is changing at an estimated rate of change *k*; (ii) that this is constant over the whole time interval between samplings and over the whole of Europe; and (iii) if we assume a given number of sites and α equal to 0.05, it is possible to calculate the time necessary to detect a given change. Equation 4 was used to develop an example based on a study from Bellamy *et al* (2005). This showed very large changes in SOC concentrations across England and Wales, from 1978 to 2003. They used data from the National Soil Inventory of England and Wales obtained during two sampling campaigns, the first during the period 1978-83 (McGrath *et al.* 1992) and the second 1995-2003. Bellamy *et al* (2005) demonstrated that OC has been lost from soils across England and Wales at a mean rate of 0.6% yr^{-1} (relative to the existing SOC concentration), over the period 1979-2003. They also found that the relationship between rate of C loss and initial OC concentration was independent of land use, suggesting a link to environmental change. By supposing that such a change is occurring throughout Europe, it is possible to calculate the time interval needed to allow detection of this change, either by using existing SMNs, or as described previously by simulating the existence of additional sites.

For most countries with relatively dense SMNs, the time necessary to detect such a change is below or close to 10 yr (Figure 6). This result supports the idea that, at least for these more dense SMNs, and assuming a relatively large change in this parameter, a time interval of 10 yr would be efficient. The cases of Estonia and Slovenia give a good example of the importance of archiving samples. Analysing organic C on archived samples for all sites would reduce the number of years needed from about 30 years to about 10 years.

4 Discussion

All the calculations described rely on several assumptions regarding the variation of SOC concentration and its change: (1) a normal distribution of the mean change in SOC concentration, (2) repeated sampling is carried out by the same method, (3) that the variance of SOC concentration remains the same on successive sampling occasions, (4) the correlation between the repeat and original samples is small so that the variation in SOC at a single sample can be used to estimate the variance of change and (5) the variation of OC within a country can estimated using the European map of topsoil organic carbon (OCTOP). These assumptions have been investigated as far as possible using the available data and it has been shown that a reasonable estimate of the MDC for soils under arable and grassland, in each country, can be made. They are also essential to enable estimates to be made from the available data that are comparable across Europe.

It was also assumed that within-site variability is only dependant on site area and the mean value of SOC concentration, and that these relationships hold throughout Europe. This is likely to be false, as it is well known that numerous other factors may control OC variability at site level (e.g. climate effects on soil drainage status, land-use, soil type, management practices, etc.). However, using literature values for estimating a within-site variance should not greatly affect the results obtained, as the measured within-site variation is much smaller than the between-site national variation.

Although Bellamy *et al.* (2005) explored how their results for England and Wales, showing a relatively rapid rate of change in SOC concentration, might be extrapolated to similar soils and climates, there is no quantitative evidence that such changes are widespread across the soils of Europe. Our study shows the magnitude of change in SOC concentration that might be detectable at continental and regional scales. Policy makers might be interested in knowing the changes in OC stocks and associated fluxes represented by this change, for example in the context of a Soil Framework Directive (COM 2006). An estimate of topsoil OC stocks across Europe can be obtained from the database of Jones *et al.* (2005) and application of pedotransfer functions of the type proposed by Adams (1973) and pedotransfer rules of the type defined by Van Ranst *et al*. (1995) to estimate bulk densities. If the calculated MDC by country is added to the estimate of topsoil OC concentration and the estimation of soil bulk density is repeated, the difference between these estimated stocks represents the magnitude of change that is detectable in the European stocks of topsoil OC. Table 3 shows that for most of the countries, detectable changes range from 1 to 10% in the base estimate of stock. These changes are very similar to the projected changes (about 6%) simulated by Smith *et al.* (2007) in mineral soil C of European Russia and Ukraine's croplands and grasslands over the last ten years of their simulation (2060-2069), under the business as usual scenario. This suggests that over about 10 years most of the existing SMNs could be used to verify such changes. However, it would be important to measure bulk density wherever possible during monitoring to allow better estimates of carbon stock to be made. It was found in the ENVASSO survey that bulk density was measured at less than 10% of the monitoring sites so future soil monitoring programmes need to address this. Over shorter timescales, most of these networks could only detect changes of more than the total national *annual* greenhouse gas emissions. For example, Arrouays *et al.* (2002) estimated that the potential of additional C storage in soil in France is about 5 Tg yr^{-1}. Assuming this rate of change, its statistical assessment using the present French SMN would take about 45 years.

Conclusion

The important role of carbon in soil functions and as an indicator of soil condition and trends underlines the importance of effective national soil monitoring networks that could contribute to developing an overall European picture of long term trends in soil organic carbon. Our results suggest that the minimum detectable changes in SOC concentration differ considerably amongst soil monitoring networks in Europe. Considerable effort would be necessary for some countries to reach acceptable levels of minimum detectable changes in C concentration. A time interval of about 10 years would enable the detection, in most European countries, of some large simulated changes in topsoil OC concentration. National soil monitoring networks are not suitable to detect *annual* changes in soil carbon stocks but would allow longer term assessments.

Acknowledgements

This work has been conducted under the European 6th Framework Programme of Research ENVASSO Project Contract no 022713. The financial support of the European Commission is gratefully acknowledged. The following participants in the ENVASSO Project provided the data and information on existing soil monitoring networks without which it would not have been possible to prepare this publication:, P. Strauss, H. Spiegel, E. Goidts, G. Colinet, S. Sleutel, T. Sishkov, N. Kolev, V.

Penizek, J. Kozak, T. Ballström, P. Penu, T. Köster, H. Lilja, C. Jolivet, R. Baritz, C. Kosmas, G. Becher, J.P. Renaud, A.H. Arnoldussen, P. Pavlenda, P. Neville, P. Michopoulos, E. Herzberger, P. Simoncic, D. Fay, V.V. Buivydaite, A. Karklins, S. Camilleri, S. Sammut, A. Higgins, J. Crawford, M. Rutgers, J. Niedzwiecki, T. Stuczynski, M. Da Conceição Goncalves, R. Dias Mano, A. Lilly, G. Hudson, M. Zupan, J. Kobza, I. Simo Josa, M. Olsson

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Table 1 Estimates of standard deviations of SOC concentrations using data from the National Soil Inventory of England and Wales.

Landuse	Arable (n=658)	Grassland (n=996)	Forest (n=210)
Mean initial SOC(g/kg)	29.49	46.66	81.89
Standard deviation of original sampling of SOC(g/kg)	28.23	36.28	91.43
Standard deviation of resampled SOC(g/kg)	19.40	21.02	66.39
Estimated s.d. of difference under assumption of no covariance	34.25	41.93	113.0
Directly estimated s.d. of difference (g/kg)	29.81	32.65	54.5

Table 2: Number (n) of sites where SOC concentration is measured; theoretical number (n_1) of sites needed to detect a relative change of 5 % from the national mean of topsoil SOC concentrations according to national statistics on variances; number (n_2) of additional sites needed in comparison with n,

Country	**n**	**n_1**	**n_2**
Austria	3,313	1,073	0
Belgium	2,546	2,105	0
Bulgaria	432	866	434
Czech Repubic	738	1,933	1,195
Denmark	848	1,323	475
England&Wales	6,018	3,853	0
Estonia	128	2,314	2,186
Finland	1,446	2,153	707
France	1,532	2,182	650
Germany	1,254	2,079	825
Greece	146	1,230	1,084
Hungary	1,328	1,680	352
Ireland	1,317	3,121	1,804
Italy	341	1,331	990
Latvia	127	2,513	2,386
Lithuania	146	2,849	2,703
Luxembourg	6	850	844
Malta	271	34	0
Netherlands	531	2,086	1,555
Northern Ireland	582	3,116	2,534
Norway	1,057	6,988	5,931
Poland	894	1,580	686
Portugal	290	1,540	1,250
Romania	948	1,286	338
Scotland	721	1,255	534
Slovakia	424	1,374	950
Slovenia	56	850	794
Spain	1,009	2,304	1,295
Sweden	4,885	1,764	0
Total	**33,334**	**57,628**	**32,498**

Table 3 Number (n) of sites needed for a level of detectable change corresponding to decreasing percentages of the national means of the topsoil SOC concentration.

country	n to detect a 5 % relative change	n to detect a 2.5 % relative change	n to detect a 1 % relative change
Austria	1,073	4,290	26,813
Belgium	2,105	8,422	52,637
Bulgaria	866	3,464	21,651
Czech Repub	1,933	7,731	48,322
Denmark	1,323	5,290	33,065
England&Wales	3,853	15,412	96,326
Estonia	2,314	9,255	57,843
Finland	2,153	8,612	53,827
France	2,182	8,727	54,542
Germany	2,079	8,314	51,966
Greece	1,230	4,919	30,742
Hungary	1,680	6,720	41,999
Ireland	3,121	12,484	78,026
Italy	1,331	5,325	33,281
Latvia	2,513	10,050	62,813
Lithuania	2,849	11,395	71,216
Luxembourg	850	3,398	21,239
Malta	34	137	855
Netherlands	2,086	8,343	52,143
Northern Ireland	3,116	12,465	77,906
Norway	6,988	27,950	174,689
Poland	1,580	6,320	39,502
Portugal	1,540	6,161	38,507
Romania	1,286	5,144	32,153
Scotland	1,255	5,019	31,368
Slovakia	1,374	5,494	34,338
Slovenia	850	3,399	21,246
Spain	2,304	9,216	57,598
Sweden	1,764	7,054	44,089
Total	57,628	230,512	1,440,702

Table 4: Minimum detectable change (MDC) in SOC stock compared with the national annual anthropogenic emissions of CO_2, CH_4, N_2O, HFC, PFC and SF_6 (including LULUCF).

	SOC Stocks (Tg)	MDC as % of the initial stocks	Gaseous C emissions including LULUCF in 2004 (Tg/yr)	MDC as % of the national annual emissions
Austria	1,135.1	1.9	24.9	86.2
Belgium	313.9	3.4	40.3	26.2
Bulgaria	1,140.3	5.2	18.4	324.4
Czech Republic	1,013.3	5.4	40.1	136.8
Denmark	488.5	4.4	19.0	113.7
England&Wales	2,040.9	2.5	127.0	40.3
Estonia	943.9	9.5	5.8	1,543.4
Finland	7,627.3	2.4	22.2	828.5
France	4,938.8	4.5	153.4	144.1
Germany	4,899.9	4.2	276.9	74.1
Greece	690.0	12.2	37.5	223.6
Hungary	1,012.1	4.1	22.9	180.1
Ireland	1,237.7	3.9	18.7	256.1
Italy	2,159.5	7.8	158.9	105.9
Latvia	1,239.2	11.3	2.9	,776.6
Lithuania	782.1	14.6	5.5	2,078.4
Luxembourg	33.1	37.0	3.5	352.8
Malta	0.7	1.7	-	-
Netherlands	541.5	6.0	59.5	54.3
Northern Ireland	256.3	5.9	4.0	379.7
Norway	3,846.1	7.6	-	-
Poland	4,567.7	4.2	105.8	179.8
Portugal	476.5	9.7	23.1	200.2
Romania	2,395.2	4.3	42.2	244.1
Scotland	2,095.5	2.2	12.0	384.8
Slovakia	615.0	6.1	13.9	268.8
Slovenia	251.8	13.4	5.5	614.9
Spain	3,466.9	5.9	116.7	175.5
Sweden	9,155.3	1.4	19.1	677.9

Figure Legends

Figure 1: Minimum detectable changes in SOC concentrations estimated using summary statistics from National monitoring networks (solid symbols), and European top soil SOC map (Jones *et al* 2005) (stars) for six European countries and also using actual resampled data for England and Wales (E&W_res)

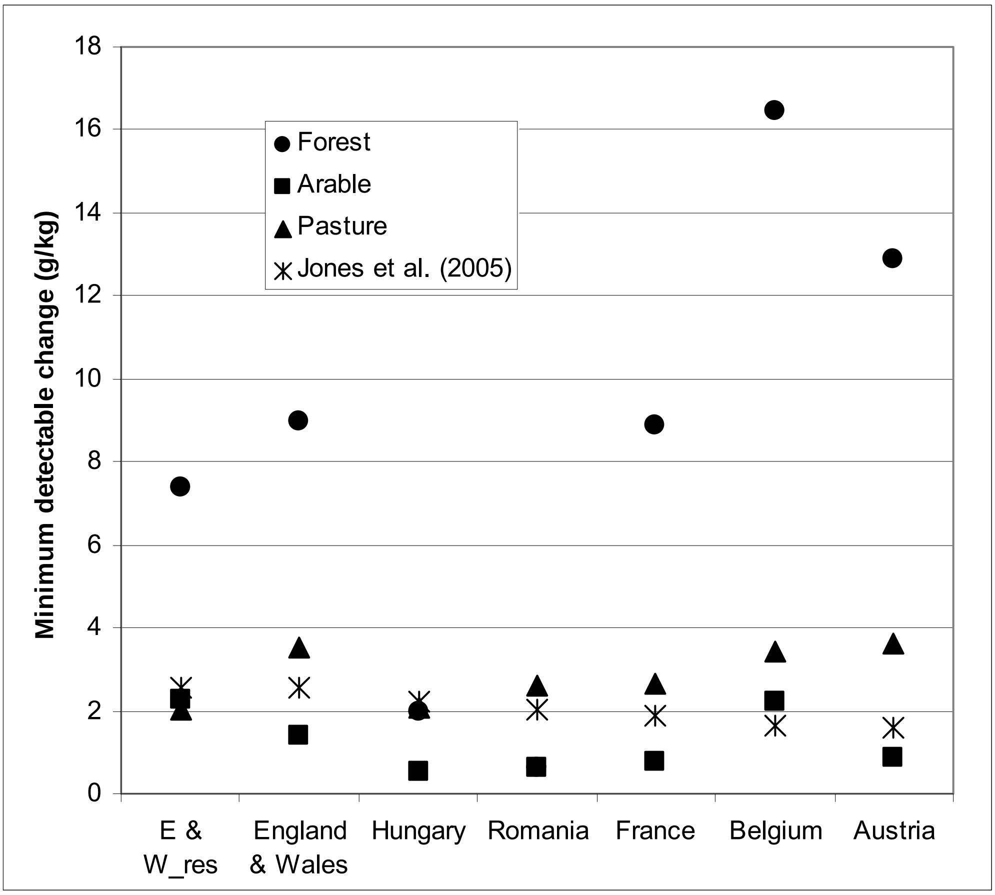
Figure 2: Median coefficients of variation in SOC concentration according to site area; The analytical value corresponds to the coefficient of variation obtained by multiple analyses of the same sample.

Figure 3: Calculated standard deviation of SOC concentration, using the topsoil SOC map of Jones et al. {, 2005 #117} for the countries represented in the ENVASSO project.

Figure 4: Location of the identified monitoring sites where SOC concentration is measured (33,334 sites)

Figure 5: Minimum detectable change for SOC concentration using α equal to 5 %, according the national variances of values of topsoil SOC concentration predicted across Europe using the topsoil SOC map of Jones et al. {, 2005 #117} and, depending on the number of sites taken into account.

Figure 6: Number of years needed to detect a change in SOC concentration at a mean rate of 0.6% yr^{-1} (relative to the existing SOC concentration). Grey: all monitoring sites; black: sites where SOC concentration has been measured to date.



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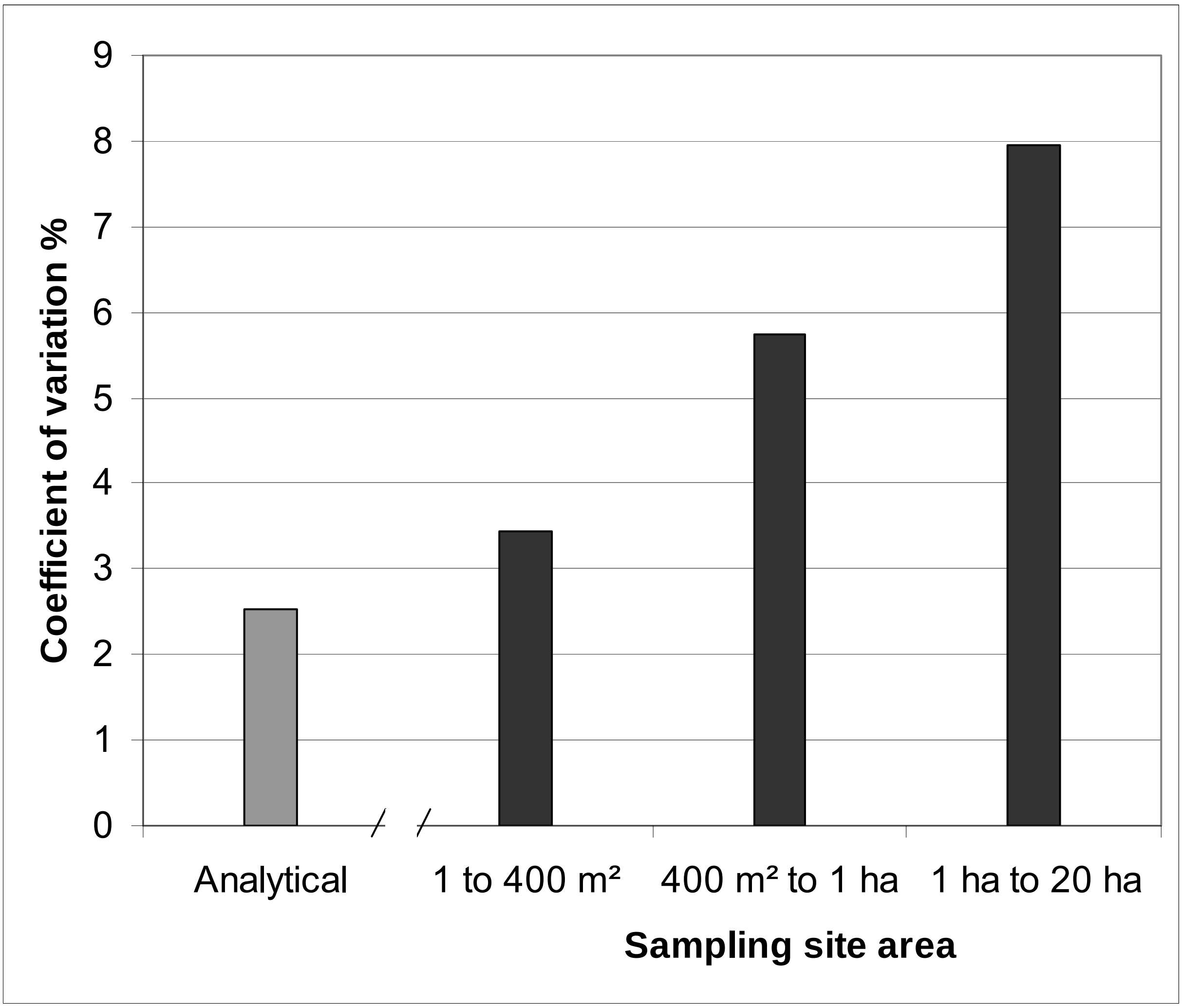

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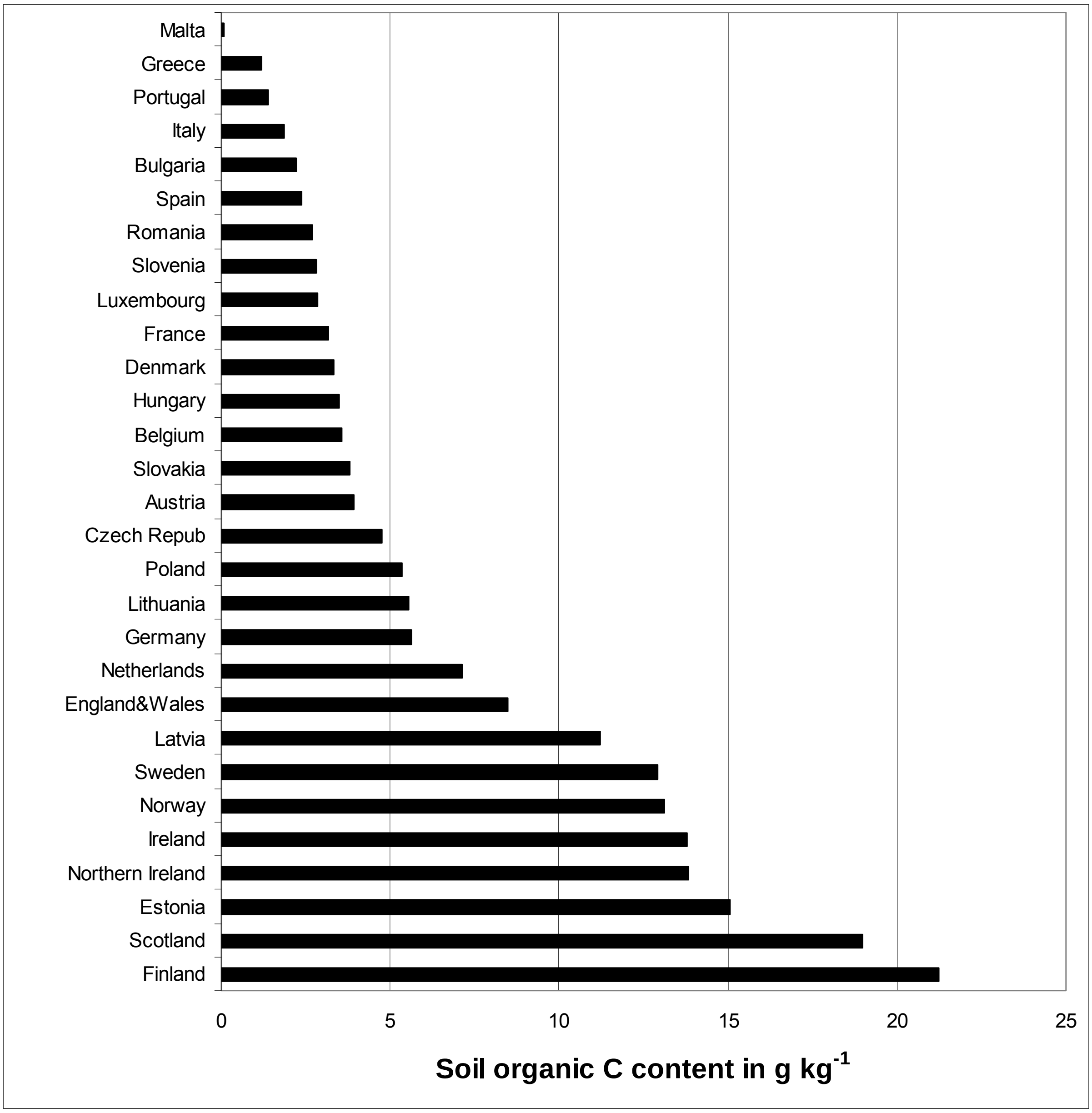

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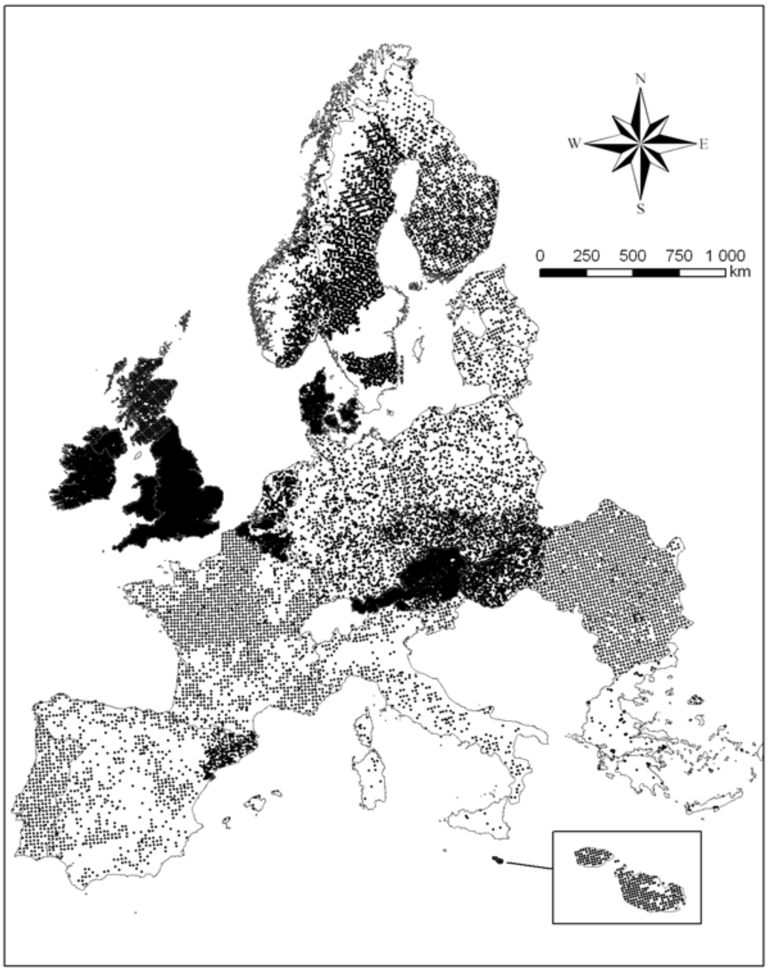

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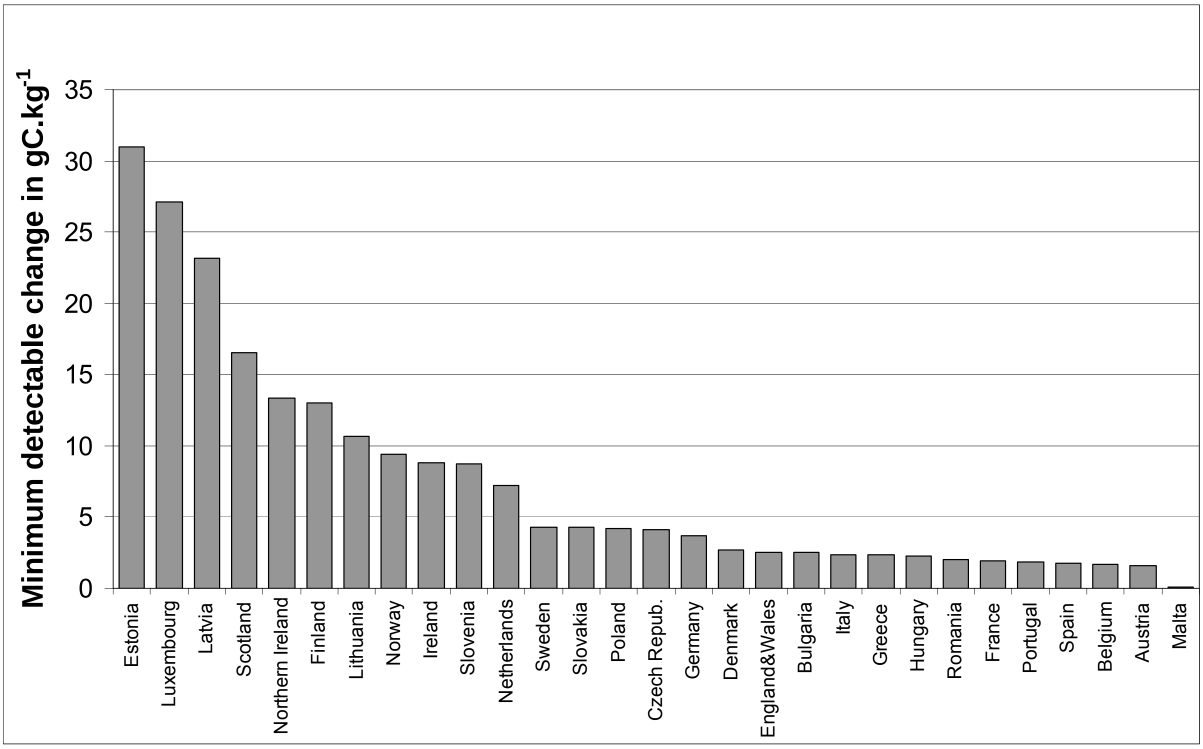

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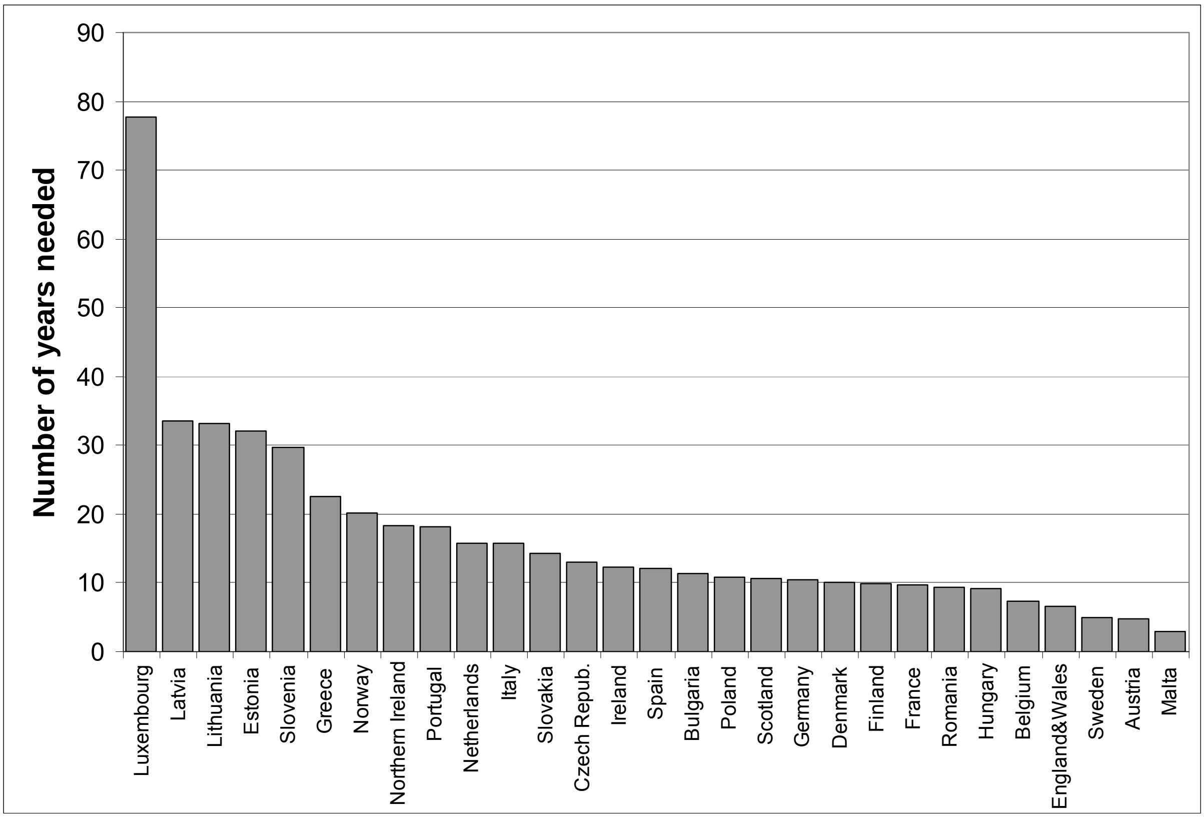

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