The role of soil organic matter content in soil conservation and carbon sequestration studies: case studies from Lithuania and the UK

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Abstract

Soil organic matter (SOM) data are presented from two long-term European experimental research sites: (i) SOM data from a soil conservation site in the U.K. and (ii) SOM data from a carbon sequestration benchmarking site in Lithuania. Detailed SOM information, which also incorporates soil organic carbon (SOC), is vitally important because it plays a fundamental role in both soil conservation and carbon sequestration studies. Land management of pedogenic carbon is a recognized means of improving soil fertility, reducing soil erosion rates, enhancing soil structural stability and promoting carbon sequestration. Therefore, its benefits extend from local to global scales. For instance, the first case study illustrates the environmental benefits of changes in SOM content before (as bare soil) and after (converted to grassland) the adoption of the soil conservation technique of set-aside. The second case study introduces various analytical approaches used to calculate SOM, and demonstrates the potential difficulty of international carbon benchmarking, as part of the global policy to ameliorate climate change.

Keywords: soil erosion, runoff plots, agriculture, grasslands, global warming, climate change, carbon benchmarking, IPCC, Kyoto Protocol.
1 Introduction

Soil organic matter (SOM) content influences many soil properties, including water retention, extractable bases, capacity to supply macro- and micro-nutrients, soil aggregate stability and soil aeration. SOM is increasingly recognized as an indicator of soil quality, that is, a component of biosphere sustainability and stability [1]. Soil organic fraction accounts for 50-90% of the cation exchange capacity (CEC) of mineral surface soils, which allows macronutrient cations (K, Ca, Mg) to be held in forms available to plants. Through CEC, organic matter also provides much of the soil pH buffering capacity [2]. Nitrogen, phosphorus, sulphur, and micronutrients are stored as constituents of SOM, which are slowly released by mineralization, thus aiding plant growth. Humic acids are constituents of SOM and these accelerate soil mineral decomposition, releasing macro- and micro-nutrients as exchangeable cations.

Soil organic carbon (SOC), the major component of SOM, consists of micro-organisms cells, plant and animal residues at various stages of decomposition, stable ‘humus’ synthesized from residues and nearly inert and highly carbonized compounds, such as charcoal, graphite and coal. Carbon is a major food source for soil fauna. Increasing SOM, especially SOC, changes the biological properties of soils. Therefore, increased SOC generally increases soil fauna and thus improves biodiversity. SOM plays a central role in increasing soil porosity, thus increasing infiltration rates. In turn, this increases the water holding capacity of soil and makes tillage operations easier. The resultant increased water availability for plants decreases both runoff and the pollution of watercourses with agrochemicals.

Impacts of SOM enrichment on soil carbon dynamics are well documented [3, 4]. Conversion of natural vegetation to agricultural land-uses can decrease SOM and, conversely, conversion of cultivated land back to natural vegetation can replenish SOM [5, 6] and return lost soil carbon via increased soil carbon storage [2]. Therefore, increased grass production will increase SOC and SOM and, thus, help ameliorate global-warming by sequestering carbon from atmospheric CO₂ into the soil store [7].

A particular concern in many European areas is the general decline in SOM. According to the European Soil Bureau, based on the limited data available, nearly 75% of the total area analysed in the Mediterranean region of Southern Europe has a low (≤3.4%) or very low (≤1.7%) SOM content. Typically, agronomists consider soils with <1.7% organic matter to be in a pre-desertification stage. The problem is widespread. For instance, SOM values for England and Wales show the percentage of soils with <3.6% organic matter rose from 35% to 42% in the period 1980-1995, which is chiefly due to changing management practices. For the same period, in the Beauce region, south of Paris, SOM decreased by half, which is attributed to the same reasons [8]. Because SOM decline is a crosscutting issue that also affects associated soil parameters, such as fertility, erosion and conservation, plus carbon sequestration estimates, it is extremely difficult to approximate its true environmental and financial cost.
With these concerns and issues in mind, this work presents SOM data from two European long-term experimental research sites: (i) SOM data from a soil conservation site in the U.K. and (ii) SOM data from a carbon sequestration benchmarking site in Lithuania.

2 Strategies for soil conservation

The extent and severity of erosion on European soils has markedly increased over the last fifty years, particularly on arable land. Unfortunately, soil conservation in Europe has not generally received sufficient attention, until recently [9]. Set-aside is a scheme designed to provide farmers with a subsidy to leave land uncultivated and, in doing so, act as a possible soil conservation measure [6, 10]. In the prevailing economic climate, it is feasible that steep to moderate slopes with erodible soils, and other vulnerable parts of fields (i.e. depressions, minor dry valleys and land adjacent to water courses), be put into non-rotational set-aside [11, 12]. This could decrease erosion rates and potentially increase soil organic matter content, with concomitant decreases in soil erodibility.

In the U.K., agri-environment schemes aim to secure environmental benefits above those of Good Farming Practice and cross-compliance. Introduced in 1987, to implement EU Council Regulation 797/85, they were designed to prevent loss of habitat and landscape features associated with intensification at sites targeted by the Environmentally Sensitive Areas (ESA) Scheme. Subsequently, in 1991, the Countryside Steward Scheme (CSS) was established to provide incentives to landowners, farmers and other land managers to take specific measures to conserve, enhance and/or re-create important landscape types. In 1994, the Habitat Scheme (HS) was initiated to create, protect and enhance wildlife habitats by removing land from agricultural production and promoting environmentally sound land-management practices. Shortly after this, in 1995, the Moorland Scheme (MS) was launched with the objective of protecting and improving the upland moorland environment. In 1998, the Arable Stewardship Pilot Scheme (ASPS) was created to assess alternative arable management options for conserving and enhancing farmland biodiversity [13]. More recently, in December 2003, the UK government initiated a new agri-environment initiative, known as the Environmental Stewardship Scheme (ESS), which encourages farmers to deliver simple, yet effective, environmental management of their land (http://www.defra.gov.uk/erdp/reviews/agrienv/default.htm).

3 Strategies for sequestering carbon to the soil store

Global CO₂ concentrations are increasing and it is useful to examine these changes in terms of carbon ‘sources’, ‘sinks’ and ‘pools’. The current gross increase in atmospheric CO₂ is 6.5 Gt of carbon per year (1 Gegaton or Gt is 10⁹ t). This comes mainly from the ‘sources’ of burning of fossil fuels with a further 1.6 Gt from deforestation. The CO₂ ‘sink’ in terrestrial ecosystems...
(vegetation and soils) is believed to be ~2.0 Gt C per year, while the oceanic sink absorbs about a further 2.7 Gt C per year. Therefore, the net increase in atmospheric CO$_2$ is ~3.4 Gt C per year. It is estimated total amounts of carbon in the soil ‘pool’ is ~1550 Gt organic C and 1700 Gt inorganic C. The latter is mainly in the form of calcium carbonate (CaCO$_3$). Both of these are much greater than the pools in either the atmosphere (750 Gt C) or in all living organisms (550 Gt C). Therefore, if carbon can be taken from the atmosphere, a small increase in the soil organic pool (0.1-0.2% per year) could counteract the current increase in CO$_2$ content of the atmosphere (~1.5 parts per million by volume per year) [14].

Considerable organic carbon can be sequestered into soils, as carbon is an integral part of soil organic matter (SOM). Soil organic carbon (SOC) constitutes about 55-60%, typically about 58%, of SOM. The potential to sequester atmospheric carbon within the soil store is a growing paradigm in soil science. The consensus is that carbon sequestration is not a panacea to global warming. However, sequestration would form a valuable contribution and allow some extra time while solutions to the problems are sought.

4 Soil carbon modelling

Carbon cycle models provide a valuable tool for understanding and predicting the turnover of soil organic carbon and, in doing so, assist national and international carbon sequestration estimates. To improve soil carbon modelling performance and reliability, and to demonstrate the rate and success of set-aside, it is paramount that all governments and agencies obtain national and regional SOM data to act as a benchmark for future studies. Thus, they should direct their policy to monitor the status of their national soils and to achieve proper soil use and conservation [9]. Models require the input of characteristic soil and climate data, such as soil texture, SOM, rainfall, temperature and evapotranspiration [15]. Therefore, transferable soil data, beyond those of institutional and national boundaries, has international importance for soil carbon model inclusion and quantification of the global carbon budget. Unfortunately, to date, differences between international protocols employed to determine SOM content produce different estimates and interpretations.

Universal or harmonized quantification of SOM concentrations is essential. Data comparability could be achieved by harmonization of analytical protocols. At present, due to methodological differences between regional and national laboratories, problems of SOM data comparison and acceptance exist, particularly where results are presented for international publication or inclusion in soil carbon models. Consequently, there is a need to develop transfer functions between analytical protocols used to determine SOM content.

5 Case studies: soil conservation and carbon sequestration

This work presents results of two case studies (i) SOM data from a long-term soil conservation site in the U.K. and (ii) SOM data from a carbon sequestration benchmarking site in Lithuania.
5.1 Soil conservation: the Hilton Experimental Site, UK

Soil conservation investigations, employing the set-aside approach, are being conducted at the Hilton Experimental Site, Shropshire, U.K. (52.0°033’5.7”N, 2.0°19’18.3”W) (Figure 1). The site covers 0.52 ha with an upper elevation of 67.46 m and slopes to the south and west. The region experiences a temperate climate with a mean annual precipitation at Hilton of 648.3 mm.

An array of ten 25 m² (10 x 2.5 m) plots was constructed (1981-82) on the slope beneath the Hilton meteorological station, varying from moderately sloping (7°, 12%) to moderately steeply sloping (15°, 27%). After several years in a bare condition, the array of plots was put into set-aside, being sown with a temporary ley grass mixture on 22/04/1991 [6]. Seeds consisted of a mixture of perennial ryegrass (Lolium perenne) (varieties: Liprior, Condesa, Meltra, Antrim and Sabel), Timothy (Phleum pratense) and Huia White clover (Trifolium repens), spread at a standard application rate of 13 kg ha⁻¹ (~80 g per 25 m²), as advised by the U.K. Ministry of Agriculture, Fisheries and Food (MAFF), now known as the Department of the Environment, Food and Rural Affairs (DEFRA). Subsequent set-aside management followed U.K. Ministry of Agriculture regulations [16]. These included two grass cuts between July and September and
the grass cuttings retained on the plots. Fifty topsoil (0-5 cm deep) samples (~60-80 g dry weight each) were removed using a hand-trowel (~10 cm width) from the experimental plots in December 1985, 1988, 1990 and April 1991, 1993, 1995, 1999 and 2001 (n = 400). Five samples were removed from each plot from interrill positions at 2, 4, 6, 8 and 10 m on the south side of plots on each sampling occasion. Soil organic matter contents of the fine-earth fraction (<2 mm) were determined by loss-on-ignition at 375°C for 16 hours [17].

On the 10 bare soil plots, during a monitoring period of more than 5 years (1985-1991), soil organic matter significantly decreased (Table 1). For this period, average total erosion was 47.2 t ha⁻¹ y⁻¹. During the ley establishment period (20/05/1991-19/12/1991) erosion rates were moderate, with a mean plot erosion rate equivalent to 0.82 t ha⁻¹. However, vegetation monitoring suggested that once cover was ~30%, runoff and erosion rates notably reduced. Conversion of the 10 plots to set-aside reversed the trend of declining soil organic matter contents, which then significantly increased, especially in the first four years. Mean SOM content increased from 2.04% by weight (1991) to 3.11% (2001), compared with nearby permanent grassland values of ~4.5%. Erosion rates on the set-aside plots with a developed ley cover were very low, the mean rate over 69 plot years was 0.52 kg y⁻¹ (S.D. 0.36). This is equivalent to a mean rate of 0.21 t ha⁻¹ y⁻¹ (S.D. 0.14).

Table 1: Long-term SOM data (% by weight) for field plots at the Hilton Site.

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<td>1.66</td>
<td>1.39</td>
<td>1.49</td>
<td>2.10</td>
<td>2.66</td>
<td>2.39</td>
<td>2.71</td>
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<tr>
<td>A2</td>
<td>2.40</td>
<td>2.06</td>
<td>1.74</td>
<td>1.89</td>
<td>2.05</td>
<td>2.91</td>
<td>2.78</td>
<td>2.59</td>
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<td>A3</td>
<td>2.99</td>
<td>2.62</td>
<td>2.50</td>
<td>2.41</td>
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<td>3.22</td>
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<td>2.56</td>
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<td>3.34</td>
<td>4.00</td>
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<tr>
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<td>1.67</td>
<td>1.52</td>
<td>1.78</td>
<td>1.95</td>
<td>2.94</td>
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<td>B2</td>
<td>1.89</td>
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<td>1.75</td>
<td>2.38</td>
<td>2.88</td>
<td>2.71</td>
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<tr>
<td>B3</td>
<td>2.45</td>
<td>2.10</td>
<td>2.23</td>
<td>1.94</td>
<td>2.61</td>
<td>3.08</td>
<td>3.42</td>
<td>3.47</td>
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<tr>
<td>B4</td>
<td>2.46</td>
<td>2.31</td>
<td>2.38</td>
<td>2.18</td>
<td>3.26</td>
<td>2.68</td>
<td>3.31</td>
<td>3.03</td>
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<tr>
<td>B5</td>
<td>3.05</td>
<td>2.90</td>
<td>2.76</td>
<td>2.55</td>
<td>2.78</td>
<td>3.44</td>
<td>3.39</td>
<td>3.62</td>
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<tr>
<td>Mean</td>
<td>2.54</td>
<td>2.24</td>
<td>2.13</td>
<td>2.04</td>
<td>2.50</td>
<td>2.82</td>
<td>3.16</td>
<td>3.11</td>
<td>400</td>
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<tr>
<td>S.D.</td>
<td>0.51</td>
<td>0.52</td>
<td>0.54</td>
<td>0.44</td>
<td>0.57</td>
<td>0.60</td>
<td>0.64</td>
<td>0.68</td>
<td></td>
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</tbody>
</table>

Pooled t (1985 v 1991) 5.24, P <0.001, d.f. = 98; (1991 v 2001) -9.23, P <0.001, d.f. = 98

Erosion rates were unresponsive to slope angle, suggesting leys are highly effective, even on steep slopes. Therefore, plot results confirm the logical suggestion that conversion of steep slopes with erodible soils to grass would greatly benefit soil conservation. Furthermore, there is considerable potential for set-aside to be targeted on steep and erodible land [5, 18].
5.2 Soil carbon sequestration: the Kaltinenai Experimental Sites, Lithuania

As a result of geopolitical changes, land use has changed markedly in the Baltic States (Estonia, Latvia and Lithuania). The collapse of the Soviet Union, in 1991, meant the guaranteed market for arable crops produced by the Baltic States was unavailable. This promoted land use change from arable production to grassland. For instance, in Lithuania, land use changed from predominantly arable (59.4%) in 1991 to grass (71.4%) in 2001. Although these changes were originally perceived as negative, in hindsight, there are potential environmental benefits. For instance, the Baltic States are increasingly viewed as a carbon sink. This has global implications because, as already mentioned, atmospheric carbon is increasingly stored in the soil system and thus helps ameliorate global warming. Furthermore, carbon sequestration assists the Baltic States adhere to international agreements, such as the Kyoto Protocol and the Agenda 21 for the Baltic region (the international agreement to improve environmental conditions in and around the Baltic Sea). In the longer term, it is possible that, states responsible for sequestering carbon will receive ‘carbon credits’; that is, payments received from the international community to sequester carbon. Therefore, the Baltic experience provides a useful case study for environmental managers and policy makers. Specifically, negative circumstances (i.e. initial agricultural collapse) can be turned into positive developments.

Figure 2: Plan of the field plots at the Kaltinenai Experimental Sites, Lithuania.
On-going post-Soviet agricultural transformation of Lithuania, from predominantly arable to grass production, provides a timely and unique opportunity to study carbon sequestration at a period of rapid agricultural change. For reasons mentioned earlier, it is imperative to possess background information on the current status of soil organic matter content. In doing so, this ‘snapshot’ provides a fixed-point against which it is possible to evaluate future long-term changes. Globally, numerous field-sites are ‘benchmarked’, collectively providing the basis for evaluations of changed soil properties.

In 2002, as part of a joint Anglo-Lithuanian investigation into soil carbon sequestration, samples were removed from 46 experimental soil plots at the Kaltinenai Experimental Sites, in the Zemaiciai Uplands of west-central Lithuania (55°34', 22°29') (Figure 2). These are permanent plots, 16 of which have been operational since 1982 and 30 since 1993 [19]. Soil samples were removed, which included both topsoil (0-20 cm depth) and subsoil (20-40 cm depth), thus providing an archive of 92 soil samples. SOM content for both the topsoil and subsoil horizons was determined by five separate techniques: (i) the traditional Western Europe approach of the loss-on-ignition method [17], (ii) the East European Tyurin titrimetric method [20], (iii) the Tyurin photometric method [21, 22]; (iv) the USDA Walkley-Black method [23] and (v) the Vario-EL III dry combustion approach.

Table 2 shows summary SOM benchmark data. There are noticeable differences between the results of each technique. Therefore, this highlights that when reporting analytical results, care must be taken to specify the precise analytical technique used and stresses the difficulties in comparing international data sets.

Table 2: Summary soil organic matter data (n = 92 soil samples).

<table>
<thead>
<tr>
<th>Analytical Technique</th>
<th>Mean</th>
<th>S.D.</th>
</tr>
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<tbody>
<tr>
<td>Walkley-Black</td>
<td>2.14</td>
<td>0.74</td>
</tr>
<tr>
<td>Tyurin photometrical</td>
<td>2.05</td>
<td>0.62</td>
</tr>
<tr>
<td>Tyurin titrimetrical</td>
<td>1.84</td>
<td>0.67</td>
</tr>
<tr>
<td>Loss-on-ignition</td>
<td>2.93</td>
<td>1.00</td>
</tr>
<tr>
<td>Dry combustion</td>
<td>1.94</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Despite the determination of organic matter content being a routine procedure carried out in soil analytical laboratories throughout the U.S. and other Western countries, there is no satisfactory universal method for determining SOM content. It can be determined indirectly by measuring SOC content and multiplying the result by the ratio of organic matter to organic carbon normally found in soil. Direct determination of organic matter usually involves destruction of the organic fraction by oxidation or ignition of the soil at high temperature. Soil weight loss is taken as a measure of organic content. However, the oxidation method has serious limitations, mostly because the oxidation process is incomplete, and the extent of oxidation can vary between soils.
This work highlights universal or harmonized quantification of SOM concentrations is essential and data comparability can be achieved by harmonization of analytical protocols. At present, due to methodological differences between regional and national laboratories, problems of SOM data comparison and acceptance exist, particularly where results are presented for international publication or inclusion in soil carbon models. One way of resolving this issue is for global use of the same technique. Until such times exist, alternatively, there is a need to develop transfer functions between SOM analytical protocols using ‘best fit’ or regression equations, which transform data sets from one format to another. However, the latter approach is not entirely accurate and data conversion errors exist.

6 Relevance and importance for sustainable planning

These case studies illustrate important planning and policy issues. Researchers are facing multiple environmental problems and are becoming increasingly involved and responsible for global environmental management. However, this requires a holistic approach. In the case of carbon sequestration we must consider soil and climate as dynamically-interacting, mutually-adjusting systems. Thus, we need to consider the effects of our environmental management, both in terms of effects on the ‘source’ or zone of export (i.e. removing carbon from the atmospheric system) and the ‘sink’ or zone of import (i.e. importing carbon into the soil system). Likewise, the study also stresses the importance of scale, as the issues are relevant at global, national and local scales.

In trying to comprehend global changes, we face many challenges. These include problems of data comparability, with different countries using slightly different procedures to assess the same soil properties. Therefore, it is important we must move towards harmonizing analytical procedures. Notable steps have already been taken in this direction, with the Kyoto Protocol recommending standardized approaches to the analysis of SOC. However, harmonization in turn poses challenges. How do we compare new international databases with old national databases? Therefore, an important approach is cross-calibration of national datasets, so that important historical data can be incorporated into long-term investigations. However, cross-calibration can produce some errors. In terms of international comparisons, we face problems not only of different analytical procedures, but also different definitions of the parameters. Nevertheless, rather than ignore the complexity of the problems, it is imperative we advance our knowledge and understanding to solve these problems and improve our management of our environment and its resources. As highlighted in the case study of the Baltic States, it was possible to change negative circumstances (i.e. initial post-Soviet agricultural collapse) into positive developments (increased carbon sequestration). Therefore, in the face of these and other major global challenges, we cannot afford to be too pessimistic, as it is possible to turn negative developments to our advantage.
7 Conclusions

SOM influences the biological, chemical and physical properties of soils and its benefits extend from local to global scales. Soil conservation and carbon sequestration are mutually important issues, coupled by the complexity of changes in SOM and the carbon cycle.

Set-aside has been shown to be a highly effective soil conservation measure, which can quickly and significantly increase soil organic content. That said, increased soil organic contents also contribute to soil carbon sequestration. Therefore, in accordance with long-term international strategies (e.g. the Kyoto Protocol, 1997), it is essential that land managers possess a thorough understanding of the long-term response and benefits of converting agricultural soils to grasslands and/or adopting grass ley set-aside for inclusion in future strategies and policy. Much more SOM benchmarking of international soils will make this an achievable goal and improve the harmonization of global SOM databases to enhance international estimates of soil carbon sequestration rates.

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