Report No. 225

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SoilC - Feasibility of Grassland Soil Carbon Survey

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Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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EPA RESEARCH PROGRAMME 2014–2020

SoilC – Feasibility of Grassland Soil Carbon Survey

(2011-CCRP-DS-1.4)

EPA Research Report

Prepared for the Environmental Protection Agency

by

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ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The programme is financed by the Irish Government. It is administered on behalf of the Department of Communications, Climate Action and Environment by the EPA, which has the statutory function of co-ordinating and promoting environmental research. The specific project was – The Feasibility of Grassland Soil Carbon (Grant No. 2011-CCRP-DS-1.4).

We would like to thank Mr Philip O'Brien and Dr Frank McGovern of the EPA for their continuous support throughout the project. We are very appreciative of the help of Dr Chaosheng Zhang of the National University of Ireland Galway. Thanks also to all the willing and helpful landowners for granting us access to their lands. We acknowledge our HYDROMET colleagues in the SoilC project and the contributions of James Eaton and Nicola McGoff.

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EPA RESEARCH PROGRAMME 2014–2020
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-737-2 September 2017

Price: Free Online version

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Executive Summary

Land management practices that enable sequestration of atmospheric carbon into soils are considered to be one of the tools in the effort to reduce atmospheric carbon. Some soils are thought to have the potential to sequester carbon, but the processes and the amount of carbon that soils can additionally sequester is poorly understood. There is increasing evidence in the literature that soils in several countries (e.g. China, France, Germany, New Zealand) are currently not carbon saturated and therefore have significant potential to increase their soil organic carbon (SOC) concentrations. This study aims to examine Irish soils, and particularly grassland soils, to determine if there is potential for them to sequester carbon above and beyond their current (in situ) levels of SOC concentrations.

The present study uses data from an existing soil carbon (C) database in Ireland and applies the boundary line analysis (BLA) method to estimate the maximal amount of organic C that can potentially be stored in whole soils (also known as the saturation level). This study quantifies the C deficit (i.e. the amount of C that can additionally be sequestered) in Irish soils, and examines the influence of land use and soil depth on SOC concentration and on soil C deficit. Of the 36 sites, 29 had a carbon deficit > 0. This suggests that Irish soils have a significant C deficit, with a large potential for additional C to be stored. The greatest potential for sequestration is in cropland soils (current mean C saturation of 38%), followed by grasslands (mean C saturation of 48%), while forest soils have the least potential for C sequestration (mean C saturation of 56%). Furthermore, we found that there is greater potential for C sequestration at deeper soil depths (mean C saturation of 48% and 30% at 10–25 cm and 25–50 cm depths, respectively) than at a shallower soil depth (the 0–10 cm section has a mean C saturation of 60%). Therefore, the design and implementation of appropriate land management practices may be able to increase SOC sequestration, and this increase could be included in national greenhouse gas inventories. However, a larger soil database of Irish soils is now required to quantify more accurately the potential of C sequestration in Irish soils.

If it can be proven on a wider scale across Ireland that Irish grasslands sequester (fix) significant amounts of atmospheric C in their soils, then this may be used to offset agricultural C emissions. However, this will only be acknowledged in Intergovernmental Panel on Climate Change greenhouse gas accounting methods when Ireland can produce evidence-based measurement, reporting and verification of C sequestration.

1 Introduction

1.1 Aims and Objectives

The main aim of this work is to assess if Irish soils, and in particular grassland soils, have potential for carbon (C) sequestration. This concept has arisen because of a number of recent international publications that suggest that agricultural soils may not be C saturated. Our objectives were therefore:

1. to sample a number of representative Irish agricultural soils for soil organic carbon (SOC);
2. to use proven methods to estimate the level of C saturation of these samples; and
3. to compare the in situ SOC levels and the C saturation values, to quantify the C deficit.

1.2 Literature Review

Worldwide, soils contain about 1500 Pg of organic C in the upper 100 cm soil layer (Batjes, 1996), which is twice the estimated amount of C in the Earth's atmosphere (720 Pg), and close to three times the amount of organic C in terrestrial plants (560 Pg) (Baes *et al.*, 1977; Lal, 2004). However, soils are thought to have lost between 90 and 156 Pg C between 1850 and 2000 due to human intervention, land use change, disturbance and erosion (e.g. land conversion to cropland/arable land or deforestation) (Lal, 1999; Houghton, 2003). The management of soils to conserve and increase existing saturation by sequestering atmospheric C is now an urgent and major challenge in the context of climate change mitigation (Fornara *et al*., 2011; McBratney *et al*., 2014). The possibility of using soils as C sinks is already acknowledged in international negotiations regarding climate change. Within the United Nations Framework Convention on Climate Change (UNFCCC), Articles 3.3 and 3.4 of the Kyoto Protocol stipulate that soils can be counted as atmospheric C sinks in national greenhouse gas inventories, in an effort to meet the targets for the reduction of greenhouse gas emissions (IPCC, 2007).

It is critical to understand the main stabilisation mechanisms of organic C in soils so that we can focus on innovative soil management practices to optimise C sequestration in soils. These mechanisms include: selective preservation due to recalcitrance of soil organic matter (SOM) (biochemically protected); spatial inaccessibility of SOM due to hydrophobicity or occlusion into soil aggregates (physically protected); and interaction with mineral surfaces (chemically protected) (Sollins *et al*., 1996; Six *et al*., 2002; Lützow *et al*., 2006; Dungait *et al*., 2012; Wiesmeier *et al*., 2014). The last is often considered the most important stabilisation mechanism of organic C in a wide range of soils (Arrouays *et al*., 2006; Wiesmeier *et al*., 2014). Several parameters influence the SOC stabilisation potential of soil mineral surfaces, such as land use or climate (indirectly), and clay type (Six *et al*., 2002; Stockmann *et al.*, 2013). With the same proportion of silt and clay particles, 2:1 clay mineral (which consist of one tetrahedral silica sheet and one octahedral alumina sheet) dominated soils have a greater potential for C stabilisation than 1:1 clay mineral (which consist of one octahedral alumina sheet between two tetrahedral silica sheets) dominated soils (Six *et al*., 2002; Feng *et al*., 2013). Soils have limited potential to stabilise SOM against microbial mineralisation, and several studies have reported that there is an upper limit to SOC storage, which represents the soil C saturation level (Six *et al*., 2002; Stewart *et al.*, 2007, 2008). It is now widely considered that soil C does not increase linearly (i.e. without limit), but increases asymptotically to a maximum or saturation value. Even if C continues to be added to soil (e.g. by manure or crop residue), the saturation model states that there can be no further increase in soil C beyond the asymptotic saturation value. This theoretical maximum SOC (saturation value) is considered to be the maximum potentially achievable (Six *et al*., 2002; Stewart *et al.*, 2007, 2008). Baldock and Skjemstad (2000) proposed that each mineral matrix has a unique capacity to stabilise organic C depending on the presence of mineral surfaces capable of adsorbing organic matter, as well as on the chemical nature of the mineral fraction, the presence of cations and the architecture of the soil matrix. Six *et al.* (2002) noted that the whole soil C saturation is not only a function of SOC stabilisation potential of mineral surfaces, but also occurs because of the cumulative behaviour of the three main stabilisation mechanisms of organic C into soils (biochemical, physical and chemical protection).

SOC research is increasing worldwide. This is motivated by the potential that the soil has to become a manageable sink for atmospheric carbon dioxide and thus to mitigate climate change, as well as the known benefits of increased SOC for the functioning of soils (McBratney *et al*., 2014). Soil C saturation is a concept suggesting a limit to SOC accumulation (Stewart *et al*., 2008). For each soil, the difference between the SOC saturation level and its actual SOC concentration is defined as the SOC deficit, or that amount of C that has the potential to be added to the soil. Various methodologies have been used to estimate the SOC saturation level (Hassink, 1997; Qin *et al*., 2013; Beare *et al*., 2014).

Several studies (Hassink, 1997; Angers *et al*., 2011; Feng, 2012; Wiesmeier *et al*., 2014) have used empirical equations to estimate the maximum amount of SOC that can be bound to fine soil mineral particles (e.g. silt and clay fractions), but often neglect to examine the SOC saturation level in whole soils, as suggested by Six *et al*. (2002). Hassink (1997), using least squares regression, found that the mass proportion of fine soil particles in the whole soil could be used to predict soil C saturation capacity. His model was:

$$SOC = 0.37x + 4.07 \qquad \text{(Equation 1.1)}$$

where *SOC* is the SOC content of fine soil particles ($mg\,C\,g^{-1}$) and *x* is the proportion of fine soil in the whole soil ($g\,100\,g^{-1}$ soil). Six *et al*. (2002) used a similar technique resulting in two different models: one for soils dominated by 1:1 and the second for soils dominated by 2:1 minerals. Feng (2012) and Feng *et al*. (2013), using boundary line analysis (BLA) methodology of the upper 10% of the fine fraction, suggested that the least squares method of both Hassink (1997) and Six *et al*. (2002) underestimated, by a factor of approximately two, the upper limit of SOC saturation of the fine fraction. In an analysis of the C saturation deficit in French agricultural topsoils, Angers *et al.* (2011) estimated the organic C concentration bound to fine mineral particles to be 85 ± 2.5% of the SOC found in whole soil. In an analysis of the C sequestration potential of soils in south-east Germany, Wiesmeier *et al.* (2014) reported that the proportion of SOC bound to fine soil particles [silt and clay particles (< 20 µm)] relative to the SOC in whole soil was in a rather narrow range in cropland, with a median value of 77%. Grassland and forest soils generally showed lower proportions of SOC bound to fine soil particles (with a median of 60% and 38%, respectively), and higher variability (values ranged from 49% to 68% for grassland soils, 26% to 46% for forest soils) (Wiesmeier *et al*., 2014). This study suggests that substantial additional amounts of carbon could be stored under the three different land use regimes in German soils. Beare *et al.* (2014), in a study of soils in New Zealand, found that nearly all soils examined had a saturation deficit > 0. They found that the median saturation deficit was $12\,mg\,C\,g^{-1}$ (1.2% SOC) at 0–15 cm depth, and $15\,mg\,C\,g^{-1}$ at 15–30 cm depth. This was in soils with total SOC median values of $44.4\,mg\,C\,g^{-1}$ at 0–15 cm depth and $20.5\,mg\,C\,g^{-1}$ at 15–30 cm depth. Stated another way, the New Zealand study means that (for the 0–15 cm depth) an additional $12\,mg\,C\,g^{-1}$ could be added to the existing $44.4\,mg\,C\,g^{-1}$ to give a total of $56.4\,mg\,C\,g^{-1}$ (or an increase of 27%). For the 15–30 cm depth the potential C increase is 73%. This study suggests that there is significantly more C saturation deficit at the deeper levels. Qin *et al*. (2013), in a study on SOC sequestration potential in cropland in China, found that upland and paddy croplands had a SOC potential of $17.2\,t\,C\,ha^{-1}$ and $26.1\,t\,C\,ha^{-1}$ respectively. Based on whole soil SOC of $34.7\,t\,C\,ha^{-1}$ and $45.4\,t\,C\,ha^{-1}$ for upland and paddy cropland, respectively, this Chinese study suggests SOC saturation of 67% and 63%, respectively. Stewart *at al.* (2007) concluded that the saturation of soil C does occur and therefore that the greatest efficiency in soil C sequestration will be in soils further from C saturation.

In an earlier study of C in Irish soils (Kiely *et al*., 2010), it was found that grassland soils (of different textures) had a C density ~ $49\,t\,C\,ha^{-1}$ (for a depth of 0–10 cm), with ~ $102\,t\,C\,ha^{-1}$ (for a depth of 0–30 cm) and ~ $145\,t\,C\,ha^{-1}$ (for a depth 0–50 cm). For example, if we assume such soils are 75% saturated with C, this suggests a potential C deficit of ~ $48\,t\,C\,ha^{-1}$ for a depth 0–50 cm, a not insignificant potential. A caveat here of course is that significant extra research is required to fully quantify the potential.

In this study, we examined a SOC database of Irish soils from various land uses (grassland, cropland and forestry) and at different soil depths. We used the dataset to develop least square equations to estimate the SOC saturation magnitude in relation to the mass proportion of soil mineral particles (silt and clay < 50 μm). The technique we used is the BLA method (Webb, 1972; Feng, 2012), which assumes that the top 10% of soils in the dataset were SOC saturated. The remaining 90% were then considered to be below saturation and therefore to have potential to sequester additional C. The latter can also be regarded as the C deficit in soils. With different land uses and different soil depths in the SOC soil dataset, we were able to examine the range of SOC saturation for different land uses and different soil depths. Identifying and classifying soil types in Ireland, from the dataset presented here, that have the potential to sequester C is the first step to examining land use and management practices that enable enhanced C uptake and storage in soils.

1.3 Layout of Report

The GrassC project aimed to quantify the C saturation level in Irish grassland soils. The materials and methods employed in this study are introduced in Chapter 2. The sampling design and sampling scheme are explained, in addition to specific methods for physical and chemical analyses of soil samples. The main analytical method of BLA is explained and described in Chapter 2. Chapter 3 presents the results of the level of in situ soil C (SOC concentration) relative to the estimated SOC saturation and thus the extent of C deficit in the soils sampled. Chapter 4 discusses the C deficit values with regard to different soil types, different land uses and different soil depths. Chapter 5 includes a summary and overall recommendations.

2 Materials and Methods

2.1 Soils Database

This work focused on the analysis of the SoilC database (Kiely *et al.*, 2010; Xu *et al.*, 2011), for which soil samples were collected at 62 locations across Ireland to a depth of 50 cm (Figure 2.1). These 62 sites represent a subset of the 1310 sites of the Irish National Soil Database (NSD) (Fay *et al.*, 2007) and were chosen as three random replicates of the 15 associations of soil types and land uses, in which the NSD sites were classified, plus 17 extra sites among the most common soil associations. The resulting 62 sites are representative of Ireland's major land uses and soil types, and include five land covers (grassland, cropland, forest, peatland and rough grazing) and nine soil types (brown earth, brown podzolic, gley, grey brown podzolic, lithosol, peat, peaty gley, peaty podzol and podzol) (Kiely *et al.*, 2010). Soil samples were collected using an half-inch Dutch auger (Eijkelkamp, the Netherlands) for a continuous profile from the surface down to 50-cm depth, divided into the following sections: 0–10 cm, 10–25 cm, 25–50 cm. At each sampling site, a 20 × 20 m quadrat was laid out, with the sampling position in the centre. The quadrat was then divided into four equal 10 × 10 m grids, and one sample was collected at each corner of the four 10 × 10 m grids, resulting in nine samples from each sampling site. These nine samples were then bulked to one composite sample for the determination of SOC concentration for the whole soil, which was carried out using a dry combustion analyser (CN-2000 Leco, St Joseph, MI, USA). The particle-size analysis (silt and clay particles < 50 μm) was done using the pipette method [see Kiely *et al.* (2010) for further details on the method]. As this study focuses on mineral soils, peat soils and soils with a C content > 12% were excluded from the database, following the definition given by Hammond (1981). Thirty-six of our sites were suitable for this study.

2.2 Statistical Methods

In order to study the influence of land use and soil depth on SOC concentrations, statistical analyses were conducted using the R software package (version 3.0.1). Non-parametric Wilcoxon paired-sample tests were performed to compare differences in SOC concentrations at different depths (0–10 cm versus 10–25 cm, and 10–25 cm versus 25–50 cm), as well as differences between mass proportions of fine soil mineral particles, since the data were dependent and did not satisfy the assumption of normality. Non-parametric Kruskal–Wallis tests were used to compare differences in SOC concentrations for different land uses (grassland, cropland, forest) in each layer of the soil profile, as well as differences between mass proportions of fine soil mineral particles, since the data were independent but did not satisfy the assumption of normality. The Kruskal–Wallis test was followed by a multiple comparison test, following Siegel and Castellan (1988) when the data were significantly different.

2.3 Calculation of the C Saturation Level and C Deficit using Boundary Line Analysis

Since the SOC concentration of the specific mineral fractions of silt or clay (i.e. fine soil) was not available, despite knowing the fractions of clay, silt and sand (< 2 mm), the C saturation level was calculated based on the SOC concentrations in the whole soils [also described by Six *et al.* (2002) as the saturation level of the soil] of the Irish dataset. The saturation equation for Irish soils was determined using the BLA method. This technique, first introduced by Webb (1972), is used to estimate the upper or lower limit of a response to independent variables (Feng *et al.*, 2013). Firstly, data were separated in five equal bins according to the mass proportion of fine particles (silt + clay particles < 50 μm) in the whole soil (g fraction 100 g^{-1} soil). The five equal bins of soils contained an equal range of mass proportion of fine mineral particles from 0 to 100 g fraction g^{-1} soil. Then, the soils with the upper 10% of SOC concentrations were identified for each bin. For these soils, we assumed that the SOC concentrations had reached their saturation level. Finally, the upper 10% of SOC concentrations and the corresponding fine particle mass proportions were used in a linear regression analysis. The equation obtained from the linear regression represents the

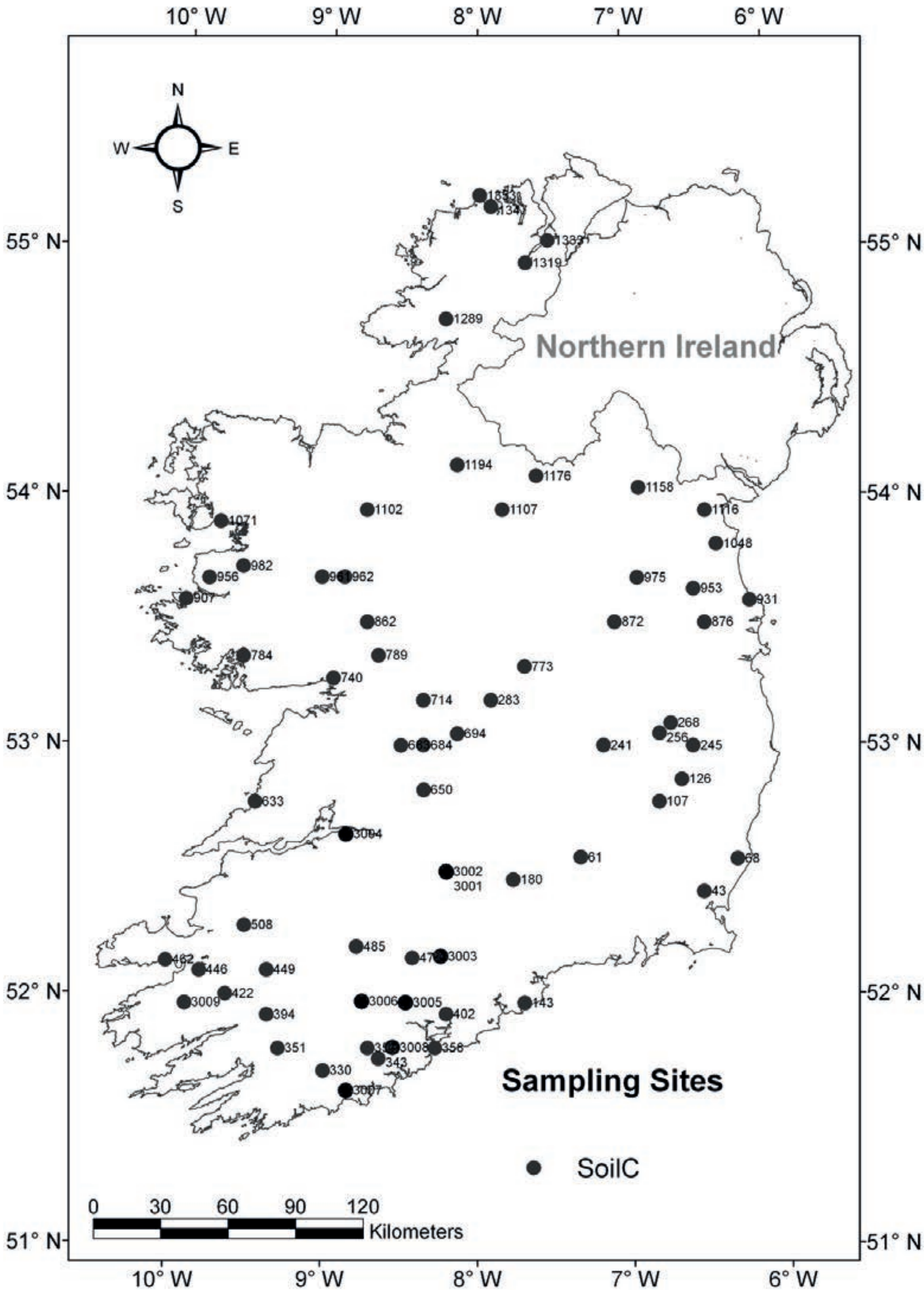

Figure 2.1. Map of Ireland with the locations of the sampling sites (Kiely *et al.*, 2010).

saturation line for our sample of Irish whole soils. The upper 10% of SOC concentrations was chosen arbitrarily; however, we tested the BLA method with different upper percentages (5%, 15%, 20%) of SOC concentrations and no significant difference between the regression equations was found when the other thresholds were chosen (not shown).

The C saturation deficit ($C_{deficit}$, g C kg^{-1}) corresponds with the difference between the theoretical SOC saturation value in whole soil (C_{sat}, g C kg^{-1}) and the measured SOC concentration (g C kg^{-1}). It is estimated as follows:

$$C_{deficit} = C_{sat} - SOC \qquad \text{(Equation 2.1)}$$

The above C saturation equation was compared with saturation equations found in the literature (Feng, 2012).

3 Results

3.1 SOC Concentrations and Mass Proportions of Fine Soil Mineral Particles

The SOC concentrations of the mineral soils of the SoilC Irish database ranged from 6.45 to 95.45 g C kg^{-1} (Figure 3.1), with an average value of 30.38 g C kg^{-1} (Table 3.1). This corresponds with a SOC concentration of 0.65–9.55%. We found that the SOC concentrations decreased with depth in all three ecosystems (grassland, forest and cropland; Figure 3.2). The average SOC value for the 0–10 cm upper soil layer was 42.47 g C kg^{-1}, and it declined to 29.84 g C kg^{-1} for the 10–25 cm section and to 18.84 g C kg^{-1} for the 25–50 cm layer. The SOC concentrations in the three sections of the soil depth profile were significantly different ($p < 0.05$).

Averaged over the depth 0–50 cm, the forest sites had the highest SOC concentrations, with an average value of 44.33 g C kg^{-1}, followed by the grassland sites with an average value of 32.82 g C kg^{-1}, while the cropland sites had the lowest SOC concentrations, with an average value of 20.72 g C kg^{-1}. A significant difference was found between the SOC concentrations of the forest sites compared with the other land uses in the top layer of the soil profile only ($p < 0.05$). In the deeper layers (10–25 cm and 25–50 cm) there was no significant difference between the SOC concentrations of the different land uses ($p > 0.05$).

The mass proportions of fine particles ranged from 2.78 to 87.88 g fraction 100 g^{-1} soil, with an average value of 52.60 g fraction 100 g^{-1} soil. The three sections of the soil profile (0–10 cm, 10–25 cm and 25–50 cm)

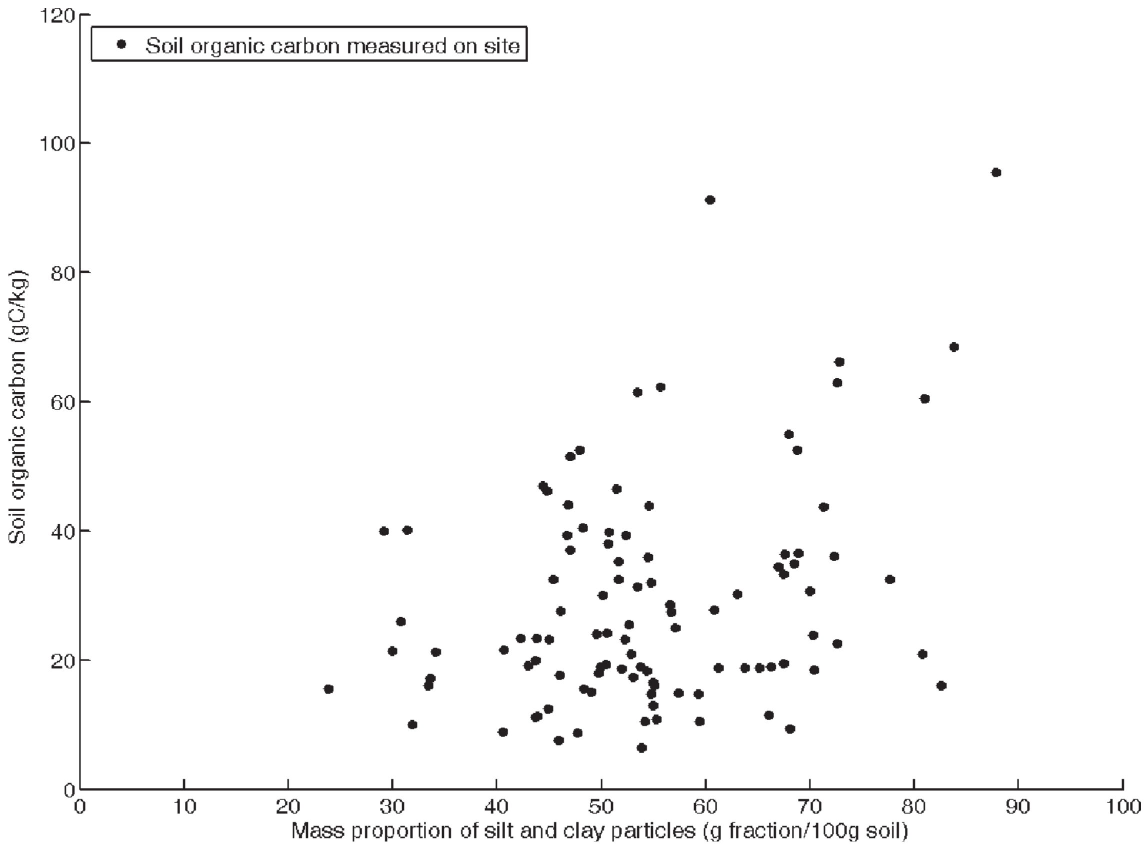

Figure 3.1. Distribution of the SOC concentrations of all the sites of the study depending on their mass proportion of silt and clay particles.

Table 3.1. SOC in g C kg^{-1} and mass proportion of silt + clay particles as a percentage of the total mineral particles in g fraction 100 g^{-1} soil, for different land uses and different depths in Irish soils. Note that SOC in percentage = 0.1 × the SOC in g C kg^{-1}

		SOC (g C kg^{-1})			Mass proportion of silt and clay particles as a percentage of the total mineral particles (g fraction 100g^{-1} soil)		
Land use	Depth (cm)	Mean (SD)	Maximal value	Minimal value	Mean (SD)	Maximal value	Minimal value
Grassland	0–10	48.24 (12.37)	74.00	32.50	51.59 (18.86)	77.83	5.93
	10–25	31.85 (10.77)	58.00	16.00	49.83 (18.47)	82.66	3.83
	25–50	18.34 (12.41)	64.00	6.45	51.52 (15.81)	80.81	2.78
Arable land	0–10	24.95 (8.21)	39.35	14.75	50.96 (10.27)	67.52	30.79
	10–25	23.30 (6.24)	32.50	14.85	50.63 (11.39)	70.01	29.96
	25–50	13.90 (3.87)	19.00	8.90	50.86 (13.50)	70.41	23.86
Forest	0–10	62.48 (28.99)	95.45	36.10	67.31 (15.09)	87.88	47.03
	10–25	37.93 (19.89)	68.50	21.50	60.93 (18.35)	63.80	40.71
	25–50	32.58 (21.83)	60.50	12.50	60.82 (15.02)	80.96	44.95

SD, standard deviation.

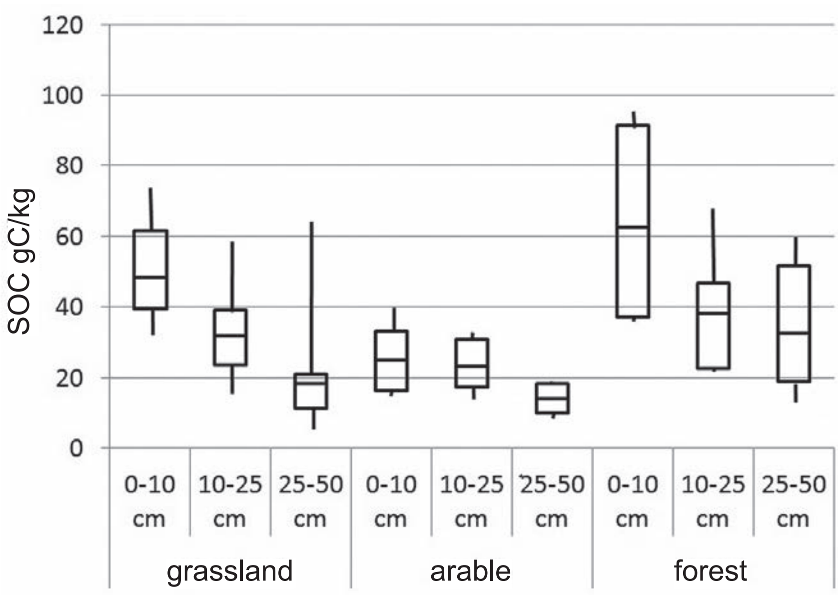

Figure 3.2. Mean SOC in g C kg^{-1} for each land use at different depths ± standard deviation. Land uses include: grassland (n = 19), cropland land (n = 12) and forest (n = 5).

had close average values of mass proportions of mineral particles (53.56 g fraction 100 g^{-1} soil, 51.54 g fraction 100 g^{-1} soil and 52.59 g fraction 100 g^{-1} soil, respectively), with the top layer (0–10 cm) significantly different from the middle layer ($p < 0.05$). At the top layer, the grassland and the cropland sites had close average values of mass proportions of fine particles (50.98 g fraction 100 g^{-1} soil and 50.82 g fraction 100 g^{-1} soil, respectively), while the forest sites had a higher average value (63.02 g fraction 100 g^{-1} soil). However, there was no significant difference between the mass proportions of fine particles for the different land uses ($p > 0.05$).

3.2 Saturation Model for Irish Soils

The BLA is a linear regression technique that was used considering only the upper 10% of SOC concentration for each land use type of the sites, classified by mass proportion of fine soil mineral particles. This method resulted in the following equation to quantify the level of organic C saturation in Irish soils (Figure 3.3):

$$C_{sat} = 0.90 \times (silt + clay) + 10.59 \qquad \text{(Equation 3.1)}$$

where C_{sat} represents the organic C saturation level (g C kg^{-1}) and *silt + clay* represents the mass proportion of fine particles (g fraction 100 g^{-1} soil).

3.3 Influence of Land Use on the C Deficit

For each study site, the organic C concentration was compared with the estimated saturation level in order to determine if there is potential for C sequestration in Irish soils. From the 36 sites used in this study, 29 sites had SOC concentrations below the estimated C saturation level in the upper 50-cm soil depth. The saturated sites comprised five grasslands and two forests. The 29 under-saturated sites had a wide range of C deficit magnitudes (difference between the estimated SOC saturation value and the measured whole SOC concentration). Croplands represented the highest C deficit, which ranged from 12.21 to 62.25 g C kg^{-1}, with an average value of 35.45 g C kg^{-1}. Compared with the potential C saturation of whole soils, cropland soils had a mean C saturation of 38%. The C deficit for grassland sites ranged from 1.12 to 68.74 g C kg^{-1}, with an average value of 26.98 g C kg^{-1} (thus a mean C saturation of 48%). Forest sites presented the lowest C deficit, which ranged from 1.13 to 53.27 g C kg^{-1}, with an average value of 22.79 g C kg^{-1} (thus a mean C saturation of 56%) (Figure 3.4).

3.4 Influence of Soil Depth on the C Deficit

The C deficit was higher in the deeper sections of the soil profile. In the 0–10 cm layer of the soil profile, the C deficit ranged from 1.12 to 47.72 g C kg^{-1}, with an average value of 19.57 g C kg^{-1}. Compared with the potential C saturation of whole soils, the top layer of the profile had a mean C saturation of 60%. In the 10–25 cm section, the C deficit ranged from 3.54 to 68.74 g C kg^{-1}, with an average value of 28.67 g C kg^{-1}

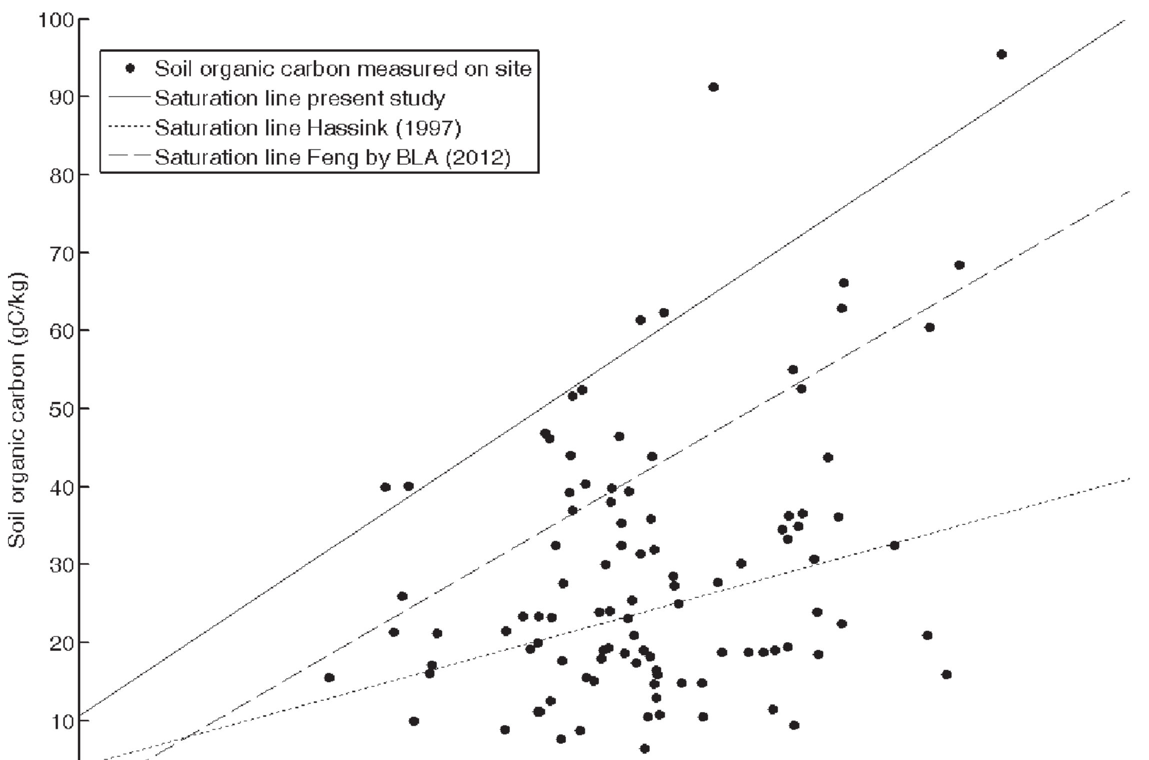

Figure 3.3. Relationship between SOC concentration and mass proportion of soil mineral particles in Irish soils and comparison of different SOC saturation models.

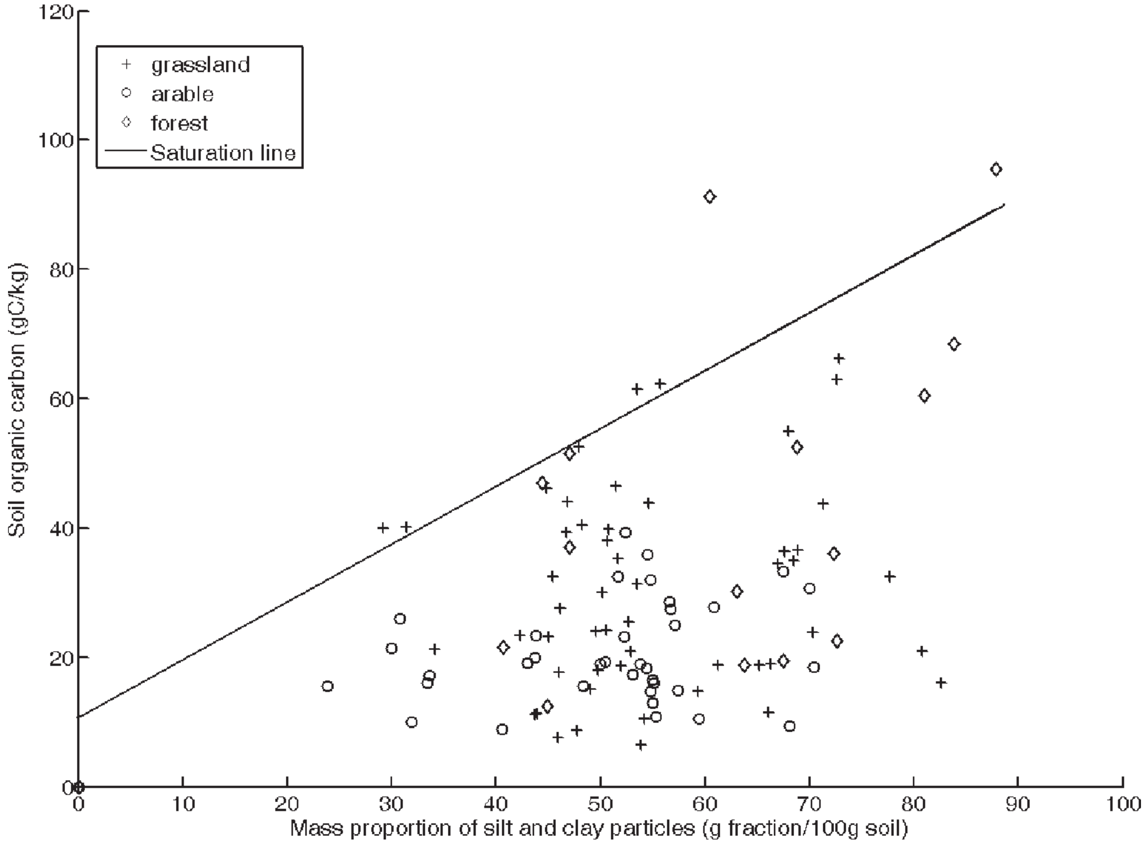

Figure 3.4. Relationship between SOC concentration and mass proportion of soil mineral particles in Irish soils for different land uses in respect of the carbon saturation line.

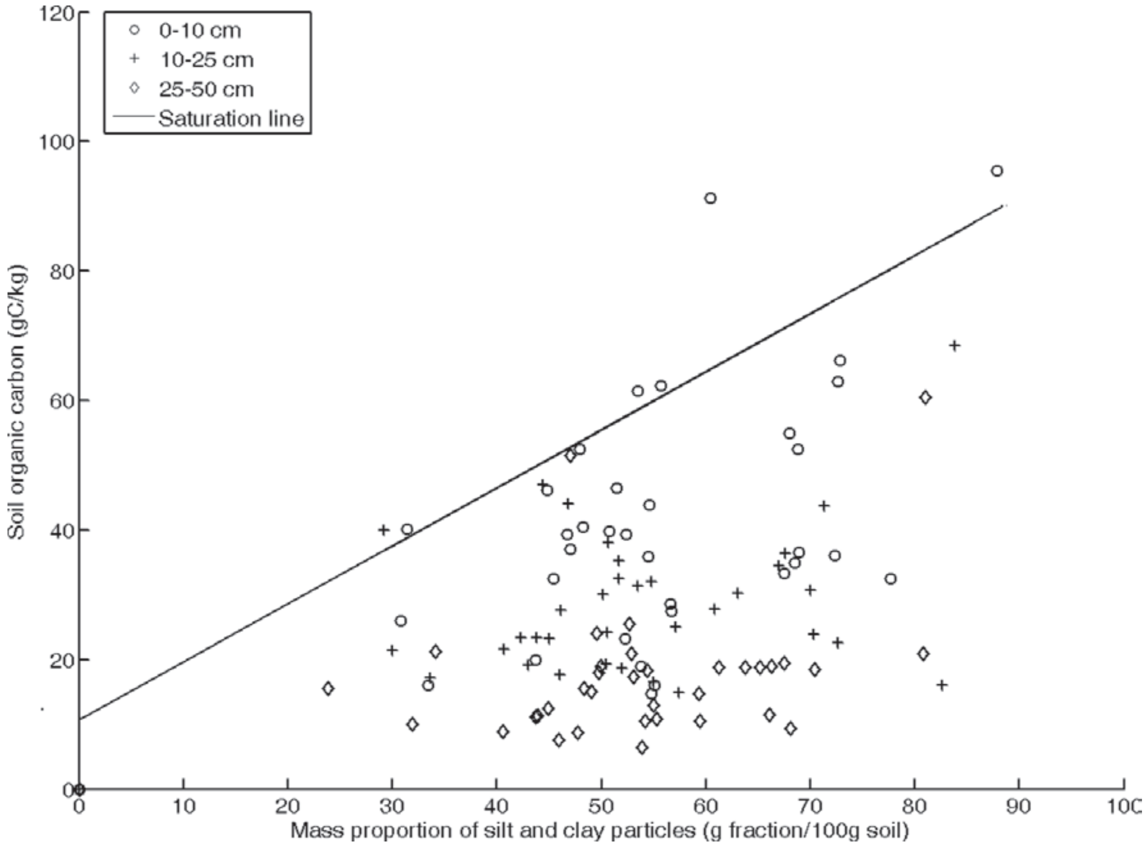

Figure 3.5. Relationship between SOC concentration and mass proportion of soil mineral particles in Irish soils for different soil depths in respect of the carbon saturation line.

(thus a mean C saturation of 48%). The 25–50 cm section had the biggest C deficit, which ranged from 1.13 to 62.25 g C kg^{-1}, with an average value of 40.34 g C kg^{-1} (thus a mean C saturation of 30%) (Figure 3.5). In the six sites that were C saturated (four grasslands and two forests), the saturation occurred in the top section of the profile (0–10 cm), except for one grassland site, where the saturation also occurred in the 10–25 cm section (Figure 3.5).

4 Discussion

4.1 Influence of Soil Depth and Land Use on SOC and C Deficit

The results of this study show that SOC concentrations decrease with soil depth. The three layers of the soil profile (0–10 cm, 10–25 cm and 25–50 cm) had similar average values of mass proportions of mineral particles (53.56 g fraction 100 g^{-1} soil, 51.54 g fraction 100 g^{-1} soil and 52.59 g fraction 100 g^{-1} soil, respectively), but the SOC concentrations decreased significantly with deeper depths, indicating that the potential for greatest C sequestration is not at the near surface (0 to 10 cm) but at deeper depths (10 to 50 cm). This may be explained by a lack of organic C inputs (e.g. litter) to deeper layers, or by a slower SOC decomposition rate at shallower depths. This result suggests the potential opportunity for a land management practice to add C to deeper depths.

The forest sites have higher SOC concentrations than grasslands and croplands in the top layer of the soil profile. This is not surprising as organic C inputs (e.g. tree foliage) are generally higher in forests than in other land uses at the near surface (Tate, 1995). Furthermore, in Ireland there has been a widespread practice for several decades of using peatlands or marginal lands (unsuitable as grassland or cropland) for new forest plantations, so that, prior to forestry planting, these areas already had SOC concentrations that were higher than grasslands or croplands (Renou, 2005).

The results of this study show that there is no significant difference of organic C concentrations for the different land uses at deeper depths, which is surprising. Most studies on SOC in the literature report that croplands have significantly lower SOC concentrations than grasslands or forests, mainly due to the practice of tillage, which disturbs soil aggregation, and cropland harvests, which provide minimal organic C inputs into soils (Davidson and Ackerman, 1993; Guo and Gifford, 2002).

The intercept of our empirical equation line (Equation 3.1) defining C saturation is higher than in other studies (see Figure 3.3) (Hassink, 1997; Feng, 2012). This higher intercept could be explained by the higher SOC in Irish soils compared with similar soils, in terms of silt and clay content, in other countries. There is some evidence that Irish soils may have a uniquely high SOC (higher than many other international areas), which may be due to the widespread land use of grassland (> 60% of the total landscape of Ireland) and year-round rainfall, as suggested by Kiely *et al*. (2013). Also the slope of our C saturation equation is steeper compared with values in the literature, although it is close to that of Feng (2012).

Our results show that there is a large C deficit in the Irish soils studied. The C deficit in croplands and grasslands suggests that these sites have considerable potential to become C sinks. This finding could be used for mitigation policies if the appropriate management practices for increasing SOC were developed. Tillage is the most important practice that can have a negative effect on SOC content (Davidson and Ackerman, 1993). The minimisation of tillage practices would prevent the destruction of aggregates, and thus help preserve the current SOC protected by the aggregates. An increase of the organic C inputs into soils, the implementation of new plant varieties, the management of nutrient inputs, better crop rotations and, most importantly, the conservation of permanent vegetation cover on the ground would help increase the SOC (Follett, 2001; Ogle *et al.*, 2005). The selection of deep-rooted species would increase organic C inputs in the deeper sections of the soil profile, in croplands as well as in grasslands, contributing to an increase in SOC (Jobbágy and Jackson, 2000). Better control of the intensity and frequency of animal (e.g. cattle) grazing would also contribute to the preservation of current SOC in grasslands (Conant *et al.*, 2001). Together, these practices would contribute to the preservation of current SOC and to an increase of the SOC concentration (Ogle *et al.*, 2005).

4.2 Discussion of the Methodology

This study used SOC concentrations in whole soil, which includes organic C associated with silt and clay particles (i.e. the fine fraction), as well as organic C occluded in soil aggregates and particulate organic matter. Angers *et al*. (2011) estimated the organic C bound to fine mineral particles to be 85 ± 2.5% of the SOC in whole soil in French agricultural topsoils. Wiesmeier *et al.* (2014) reported a lower proportion of SOC bound to silt and clay particles (< 20 μm) related to SOC in whole soil in south-east Germany (77% in croplands, 60% in grasslands and 38% in forests). There is currently a lack of knowledge concerning the proportion of SOC in whole soil that is bound to silt and clay particles for Irish soils. The use of SOC concentration in whole soil that we used follows the definition of C saturation level provided by Six *et al.* (2002). This causes some difficulties in comparing our results with other studies, even if SOC bound to fine mineral particles generally represents the most important part of SOC in whole soil. On the other hand, our analysis considers more than the top 10 cm of soil, including the soil profile down to 50-cm depth, and evaluates the use of the BLA moving forward from Hassink's equation (see Wiesmeier *et al.*, 2014).

The uncertainties associated with the BLA method consist in considering the upper 10% of organic C concentrations in whole soil as saturated, and in the use of these potentially saturated sites in a regression to estimate the saturation level. Consequently, this method leads to an underestimation of the saturation level of Irish soils, as some of the sites used in the regression, and assumed to be C saturated, might not be saturated. Nevertheless, this study defines a lower boundary to the C saturation threshold for Irish soils.

The BLA technique provides a unique equation of SOC saturation level for Irish soils. Our saturation line displayed a higher intercept than those found in the literature because we used the organic C concentration in whole soils when other studies used the organic C concentration in fine particles (Wiesmeier *et al.*, 2014). Thus, the organic C stored in soils but not bound to mineral particles (particulate organic C and organic C occluded in aggregates) influenced the equation and, in particular, the intercept. Nevertheless, we believe that the intercept value of 10.59 g C kg^{-1} (or 1.06%) represents the concentration of organic C not bound to silt and clay in Irish soils. This is realistic for Irish soils, as work by Zhang *et al.* (2011) and Xu *et al.* (2011) found that almost no Irish soils have a SOC value < 2%. The slope of our saturation line is steeper than those found in the literature, but still close to that of Feng (2012), with the same BLA method (Figure 3.3). Other studies used a least squares regression analysis to obtain their C saturation equation, a method that Feng *et al.* (2013) suggested underestimates the maximal amount of organic C that can be bound to fine particles.

The saturation level for Irish soils found in this study is a theoretical estimation. SOC sequestration is controlled by environmental conditions (elevation, land slope, geographical location, distance to the ocean, etc.), human-induced conditions (land use and land management, land use changes, use of agricultural machinery and equipment, etc.), as well as history of the site. Thus, some soils are unlikely to reach saturation in natural conditions.

In this study, we neglected the impact of the mineralogical properties of clays because the existing soil database lacks any information on the dominant type of clay in our sampling sites. However, it was noted in previous studies (Baldock and Skjemstad, 2000; Six *et al.*, 2002; Feng *et al.*, 2013) that the mineralogical properties of clay influence the maximal amount of organic C that can be bound to mineral particles. Soils dominated by 2:1 clay have a higher protective capacity, and are thus likely have a higher saturation level.

4.3 Towards a More Complete Study of C Deficit in Irish Soils

This study demonstrates that it is possible to estimate the C deficit in mineral soils. In order to estimate the C deficit at a national scale, a more complete database is required, with samples collected down to 100-cm depth, and the soil profile divided into at least four sections (0–10 cm, 10–25 cm, 25–50 cm, 50–100 cm). Samples should then be analysed for the following characteristics: (1) organic C concentration in whole soil; (2) organic C concentration separately in the clay particles and in silt particles; (3) mass proportion of fine mineral particles (< 20 μm); (4) determination of the dominant type of clay (e.g. 1:1 or 1:2). In order to assess the SOC stocks, samples should also be analysed for soil bulk density.

5 Conclusions

This study demonstrates the existence of a significant C deficit in the Irish mineral soils studied, and shows that it is possible to estimate this deficit at a national scale. This research therefore shows that there is an opportunity for Ireland to increase its SOC concentration by implementing appropriate land management techniques. This would assist Ireland with its compliance with the UNFCCC requirements to cut carbon emissions, and would improve soil quality and limit erosion at the same time. However, this study highlights the lack of data on the physico-chemical properties of Irish mineral soils, which suggests that it would be beneficial to establish a new sampling and analysis scheme at the national scale. The method used in this study could then be used to improve the estimate of the C saturation level in Irish soils, as our study has probably presented an underestimation of the potential amount of C sequestration in soils. If such a sampling strategy were repeated every 5 to 10 years, it would be possible to quantify the evolution of the C deficit over time, and to evaluate the impact of the implementation of management practices on the C deficit and C sequestration in soils.

6 Summary and Recommendations

6.1 Summary

As of 2014, Irish agriculture contributed an estimated 33% of national greenhouse gas emissions, compared with an EU average of 9%. With the implementation of the Department of Agriculture, Food and the Marine's Food Harvest 2020, the 2020 projection for Irish agricultural emissions is for an increase of 9% (EPA, 2014). The most recent EPA report (2017) states that "total emissions from agriculture are projected to increase by 5% over the period 2015–2020." These projected increases have resulted in calls within Ireland and Europe for Ireland to reduce its agricultural greenhouse gas emissions (RIA, 2016).

The latest land cover distribution statistics across Europe (Eurostat, 2012) estimate that Ireland has the largest proportion of land under grassland (67.1%) and the lowest proportion of land cover under woodland and shrubland (15.2%). This compares with an EU average grassland cover of 19.5%, and for woodland and shrubland of 45.2%. Sweden has the largest cover of woodland and shrubland, at 76.6%, and as woodland and forestry are known to sequester large amounts of C in their biomass and soils, Sweden benefits significantly in its estimates of atmospheric C removals using the established Intergovernmental Panel on Climate Change (IPCC) greenhouse gas accounting methodologies (IPCC, 2014).

Here, we suggest that grassland soils sequester C and that this should also be taken into account in greenhouse gas accounting methodologies. This report focuses on soil C and does not include other pathways, such as dissolved organic C (in streams) or methane from soil or animals. Ours is a two-point study. Firstly we review the international literature that verifies that temperate grasslands do sequester atmospheric C into the grassland biomass and soil. Secondly, we point to the international literature that shows that many soils under grasslands are currently under-saturated with C. Linking these two facts, we explain that grassland soils in Ireland are currently sequestering C in the roots and soils below the grassland soil surface.

Firstly, there is a wealth of international literature that has shown that temperate grasslands in Europe are currently sequestering C. This has been demonstrated using measurements of carbon dioxide uptake and release to the atmosphere. For example, the C budgets of nine grassland sites, using varying management practices and covering a major climate gradient across Europe, were measured by Soussana *et al.* (2007). They found that the C storage (net annual biome productivity below ground in soils and root systems) ranged from 0.25 to 1.75 $t\,C\,ha^{-1}$ per year. The sites with most C sequestered were on the western edge of Europe, with a temperate moist climate. By coupling C flux measurements with farm management data, Byrne *et al*. (2007) quantified the farm-scale C balance during 2004 for two dairy sites in south-west Ireland, and found that both were sequestering close to 2 $t\,C\,ha^{-1}$ in the year.

Secondly, there is now a growing body of international published research from China, Europe, New Zealand and the USA (Feng, 2012; Feng *et al*., 2013), showing that many grassland soils are not C saturated, and therefore have the potential to sequester additional C from the atmosphere if the land management regime favours this (Jones and Donnelly, 2004; Allard *et al*., 2007). The capacity of a soil to sequester organic C can in theory be estimated as the difference between the existing SOC and the SOC saturation value. This term is defined in the literature as either the SOC sequestration potential (SOCp) or SOC deficit. The C saturation concept assumes that each soil has a maximum SOC storage capacity that is primarily determined by the characteristics of the fine mineral fraction (Beare *et al*., 2014). Angers *et al*. (2011) found that a substantial proportion (< 70%) of French agricultural (grassland and cropland) topsoils are under-saturated with carbon to some extent. Weismeier *et al*. (2014), in a study of Bavarian soils, found that about 400 Mt CO_2 equivalents could be theoretically stored in the upper layer of cultivated soils – four times the annual emissions of greenhouse gases in Bavaria. Recent work has shown that the SOC concentrations of Irish mineral grassland soils range from 3.2 to 6.3% (Kiely *et al*., 2010; Xu *et al*., 2011). Furthermore, this group has found in a survey of Irish soils that 29 of the 36 sites examined are currently under-saturated. This suggests that Irish soils may have a significant C deficit, with potential for additional C to be stored. Furthermore, there is greater potential for C sequestration at deeper soil depths than in a shallower soil layer. However, some studies have found soil C losses (Bellamy *et al*., 2005).

A review by Conant (2010) examined the grassland management practices (Allard *et al*., 2007) that enable soil C sequestration, and demonstrated that many management techniques intended to increase livestock forage production also have the potential to augment soil C stocks, including fertilisation (Fornara *et al*., 2011, 2013), irrigation, intensive grazing, rapid incorporation of manure and the sowing of favourable forage grasses and legumes.

In an earlier study of C in Irish soils (Kiely *et al.*, 2010), it was found that grassland soils (of various textures) had a C density ~49 t C ha^{-1} for a depth of 0 to 10 cm, with ~102 t C ha^{-1} for a depth of 0 to 30 cm, and ~145 t C ha^{-1} for a depth 0 to 50 cm. For example, if we assume that such soils are 75% saturated with C, this suggests a potential carbon deficit of ~48 t C ha^{-1} for a depth 0 to 50 cm, a not insignificant potential. A caveat here of course is that a lot of extra research is required to fully quantify the potential.

6.2 Recommendations

While the research on grassland soil C indicates sequestration, some questions remain and therefore, measurement, reporting and verification (MRV) requires further research before Ireland can fully exploit its large land area under grassland for C sequestration. MRV requires a national effort of soil C monitoring across the country, for a period of years, to record the inter-annual changes to soil C and to verify the quantity of C sequestered for a wide range of Irish soil types and grassland land management practices (Emmett *et al*., 2010).

Irish grasslands sequester (fix) significant amounts of atmospheric C in their soils, which will only be acknowledged in IPCC greenhouse gas accounting methods when Ireland can produce evidence-based MRV of carbon sequestration.

The EU has now committed (EU summit, 23–24 October 2014) to examine methods for regulating land use, land use change and forestry, among other options, to increase C sequestration in grasslands and to incorporate this into national greenhouse gas budgets. To gain the benefits of this, the Irish funding agencies (e.g. the EPA, Department of Agriculture, Fisheries and the Marine, and Science Foundation Ireland) must urgently enable further independent scientific studies to strengthen the observations in this EPA report (RIA, 2016).

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Abbreviations

BLA	Boundary line analysis
C	Carbon
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
MRV	Measurement, reporting and validation
NSD	National Soils Database
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nations Framework Convention on Climate Change

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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SoilC - Feasibility of Grassland Soil Carbon Survey

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Authors: Gerard Kiely, Paul Leahy, Ciaran Lewis, Xianli Xu and Matteo Sottocornola

Identifying Pressures

As of 2014, Irish agriculture contributed an estimated 33% of national GHG emissions compared to an EU average of 9%. With the implementation of the Irish Department of Agriculture's Food Harvest 2020, the 2020 projection for Irish agricultural emissions is an increase of 9% (EPA, 2013). Land cover distribution statistics across Europe (EUROSTAT, 2012) estimate that Ireland has the largest proportion of land under grassland (67.1%) compared to an EU average grassland cover of 19.5%. Currently, there is no measurement, reporting and verification (MRV) strategy for carbon sequestration in Irish grassland soils. The lack of MRV and the high percentages of agriculture GHG emissions have resulted in calls within Ireland and Europe for Ireland to reduce its agricultural GHG emissions.

Informing Policy

This project has built upon the Irish soil carbon database, a previous EPA research output, by modelling the current saturation level of carbon in Irish soils. As a result, the amount of additional carbon that can be sequestered in Irish soils has been estimated. The main finding is that of 36 sites representative of the full spectrum of land use in Ireland, 29 had a positive carbon deficit, indicating further potential for carbon sequestration. Further analysis of the results suggests that future policy initiatives aiming at increasing soil carbon sequestration should target grassland soils in particular, as these have the greatest carbon deficit.

Developing Solutions

Globally it has been shown that current and new grassland land management practices enable the sequestration of carbon in soils. It has been demonstrated that many management techniques intended to increase livestock forage production also have the potential to augment soil carbon stocks, including fertilization, irrigation, intensive grazing, rapid incorporation of manure and the sowing of favourable forage grasses and legumes. However, the measurement, reporting and verification (MRV) of carbon sequestration through field and research methods in Ireland is limited. For Ireland to benefit from IPCC greenhouse gas accounting methods, a national research effort is urgently required so that Ireland can produce evidence-based Measurement, Reporting and Verification (MRV) of carbon sequestration in its grassland soils.

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