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Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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SoilC – Measuring and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils

STRIVE

Environmental Protection Agency Programme

2007-2013

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

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EPA STRIVE Programme 2007–2013

SoilC – Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils

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STRIVE Report

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Prepared for the Environmental Protection Agency

by

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DISCLAIMER

The EPA STRIVE Programme addresses the need for research in Ireland to inform policy makers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The goal was to measure and model the soil carbon stocks and stock changes in a representative number of Irish soils. An intensive field and laboratory campaign was carried out over the period 2006–2007 on 71 sites throughout Ireland. Most of these were a subset of the National Soil Database (NSD) sites. Each site was sampled at several increments over a depth of 50 cm for soil carbon concentration, bulk density, texture and soil elemental properties. In addition, water samples were collected at 55 stream sites close to the soil sampling sites on seven occasions from October 2006 to October 2007, and analysed for dissolved organic carbon (DOC). Regression equations were generated to explain the relationship between soil organic carbon (SOC) concentrations and loss on ignition (LOI) data. The modelling of SOC was not successfully completed due to time and resource constraints. Some key findings are as follows:

- The SOC concentrations of peat soils were on average 37%, while the mineral soils all had < 5% SOC. Arable sites has the lowest SOC concentrations, ranging from 1.4 to 2.5%, and grassland SOC ranged from 3.2 to 6.3%. Rough grazing SOC ranged from 11 to 25%, while forest SOC ranged from 9.5 to 21% and peats SOC ranged from 33 to 42%.
- Bulk density was found to vary significantly with soil type: with peats ranging from 0.17–0.25 g cm^{-3}, organo-mineral soils ranging from 0.2–1.3 g cm^{-3} and mineral soils ranging from 0.8–1.3 g cm^{-3}.
- For texture, the majority of soils were found to fit into the loam, sandy loam and clay loam (mid) sections of the USDA (United States Department of Agriculture) soil textural triangle. No pure clay or pure silt soils were encountered.
- The national SOC stock to a 50 cm depth, calculated from carbon densities and the known spatial extents of the various land uses and soil types, were very similar at 1061.5 Tg and 1063.6 Tg, respectively.
- Carbon fractionation (e.g. active, slow and passive components) was carried out for soils from eight grassland sites in the south of Ireland. The fractions varied with site and with depth (see Table 7.5 of the End of Project Report). These results show that in most cases the passive pool (carbon in sand and stable aggregates and non-recalcitrant carbon in silt and clay) is the largest fraction at about 50%, with the active pool (microbial and particulate organic matter) and slow pool (recalcitrant carbon in silt and clay) each at about 25%.
- In a 50 m × 50 m grassland plot in Dripsey (County Cork) we sampled 50 points at three depths (0–10 cm, 10–20 cm and 20–30 cm) and found that the SOC values ranged from 2.7 to 13.1% with a mean of 6.6%) at the 0–10 cm depths. Using statistical analysis similar to Conen et al. (2003), the estimated time interval to provide significant SOC changes was determined (α = 0.05, statistical power = 0.90). The hypothesis that SOC loss is at least as large as predicted (2.053 g/100 g soil) could be detected at this site after 63 years. Theoretically, it could be halved to 31 years if the sample size were increased from 50 to 200. If 10% of the SOC carbon were reduced over the next 50 years, the sample size needed to detect this change should be at least 27.
- The stream water DOC concentrations were found to range from 0.9 to 25.9 mg L^{-1}, with monthly means (of all 55 sites) ranging from 4.55 mg L^{-1} in April to 8.33 mg L^{-1} in December. The estimated stream water DOC exports ranged from 1,121 to 15,622 kg m^2 yr^{-1}, with the higher values from the peatland catchments and the lower values from the arable catchments.

The findings of this research have a role to play in informing policy makers and stakeholders to improve sustainable management of Irish lands in respect to carbon management.

1. Introduction

1.1 Aims and Objectives

The objective of this research was to estimate soil carbon stocks in representative Irish soils. The specific objectives were as follows:

1. To carry out a literature review of past and current research in relation to soil organic carbon (SOC).
2. To measure SOC concentrations and bulk density to a depth of 50 cm at more than 50 sites from a subset of the 1,310 National Soil Database (NSD) sites plus 10 peatland sites, and to use this data to estimate soil carbon stocks in Ireland.
3. To analyse the soils for SOC, based on loss on ignition (LOI), and compare the results with the standard SOC method.
4. To measure at eight grassland sites the carbon fractionation of SOC which includes the active (microbial), slow (particulate organic) and passive pools.
5. To carry out an intensive soil sampling campaign at the University College Cork (UCC) HYDROMET Dripsey research catchment to test the delectability of soil carbon stock changes.
6. To analyse for dissolved organic carbon (DOC) at 55 stream sites close to the soil sampling sites.
7. To prepare an End of Project Report.

It was also an objective to model soil carbon but this was not successfully completed.

1.2 Literature Review

1.2.1 Current Knowledge of Soil Organic Carbon

Soil organic carbon is of global importance as it is the largest carbon stock in most terrestrial ecosystems (Eswaran et al., 2000; Jobbagy and Jackson, 2000). Soil organic carbon is of local importance as it is an essential component (~ 58%) of soil organic matter (SOM). It is composed of living biomass, detritus (recognisable dead biomass) and humus (non-living amorphous floral and faunal residues). These SOM 'pools' are the result of factors of soil formation, including climate, topography, parent material, biota, time and human activity (Jenny, 1941). The amount of SOM is determined by the balance between the input of surface litter into the soil profile and losses due to microbial decomposition, erosion and leaching. In mineral soils, high levels of SOM may indicate a fertile soil and the SOM typically decreases with soil depth. Soil organic matter acts a reservoir for nutrients by binding nitrogen, phosphorus, sulphur and other nutrients, and by forming aggregates that are necessary for soil structural stability. Nutrients are then made available to plants through mineralisation.

The current global stock of SOC is estimated to be 1500–1550 Pg (Batjes, 1996; Lal 2004; Post et al., 2001; Schlesinger, 1995), which is double the estimated amount in the earth's atmosphere (720 Pg), and more than triple the stock of organic carbon in terrestrial flora (560 Pg; Baes et al., 1977; Bolin, 1970; Lal, 2004). Peatlands have a disproportionately large amount of soil organic carbon, accounting for a quarter to a third (357–455 Pg) of the global SOC stock (Batjes, 1996; Eswaran et al., 1993; Gorham, 1991; Post et al., 1982), while occupying only about 3% of global land cover. Even though SOC stocks are heavily influenced at the local scale by land use and management practices, regional and global trends do exist. The most obvious trend is the relationship of SOC to climate. Globally the average SOC stock (to 1 m depth) ranges from 50–150 Mg ha^{-1}, but can be as low as 30 Mg ha^{-1} in arid climates and as high as 800 Mg ha^{-1} in cold climates (Lal, 2004). Soil organic carbon is considered to increase as temperatures decrease and as precipitation increases. Soil organic carbon stocks double or triple for each 10 °C decrease in mean annual temperature (Brady and Weil, 1996). Low rates of precipitation limit plant growth and therefore organic matter inputs to the soil. High rates of precipitation often create waterlogged soils, leading to slow decomposition rates, and hence the build-up of SOM. Stocks of carbon in undisturbed terrestrial ecosystems shift from the vegetation pool to the soil pool as one moves away from the equator. Temperate forest ecosystems have an estimated 63% of their carbon in the soil pool and the remaining 37% in the vegetation pool (Janzen, 2004). In contrast, tropical forest ecosystems contain about 50% of their carbon in soils and 50% in vegetation (Metz et al., 2001; Janzen, 2004).

Studies investigating soil organic carbon in Ireland are few, focusing mostly on grasslands (Brogan, 1966; McGrath, 1973, 1980; McGrath and McCormack, 1999). McGrath (1980) found that the mean carbon content at the 0–10 cm depth of permanent pasture was 5.3% and for tilled soils was 3.4%, indicating that SOC changes with land use. Zhang and McGrath (2004) found that over a 32-year period, grassland SOC concentrations decreased in the interior of Ireland, while increasing along the eastern coast. McGrath and Zhang (2003) found grassland concentrations of SOC followed the west–east precipitation gradient, with highest concentrations of SOC on the west coast, lower values in the interior lowlands and lowest values on the drier south-east coast. High SOC concentrations were also reported for mountainous areas receiving high levels of precipitation (> 1500 mm yr^{-1}). Tomlinson (2005), using a combination of sources, estimated the SOC stock in the Republic of Ireland to be 2048 Tg in 1990, and 2021 Tg in 2000. One of Tomlinson's (2005) most salient findings is that mineral soils account for 47% of Ireland's SOC stock, while peatlands cover about 17% of the land and they account for the remaining 53%. The NSD's (Fay et al., 2007) was the first detailed examination of Irish soils for SOC. The sampling was spread throughout the country at approximately a grid spacing of 5 km × 5 km, and soil samples were taken for a depth of 10 cm. Amongst their findings were that there was evidence of land use, anthropogenic and climate effects on SOC concentrations.

The Great Soil Groups are acid brown earth, brown podzols, gley, grey brown podzols, lithosol, peat, peaty gley, peaty podzol, podzol and shallow brown earth, and are described in detail in Gardiner and Radford (1980). The differences in carbon content and bulk density of mineral soils are reflected in their carbon density (Mg ha^{-1}). Differences in the bulk density and carbon content of organic soils (peat) are mostly negligible and the carbon stock of peat soils is primarily a function of the depth of the peat profile. Although soil type is an important gauge of SOC, other factors such as land cover, slope and precipitation also affect SOC.

1.2.2 Land Cover in Ireland

With the purpose of estimating a national soil carbon stock for this project, Ireland was divided into five main land-use classes: arable land, grassland, forest, peatland and rough grazing land. Arable land, or cropland, defined as areas under permanent crop production and tillage, represents between 5–8% of the land area in Ireland (Tomlinson, 2005; McGettigan et al., 2006; Eaton et al., 2008). Arable land soils are likely to have the lowest SOC concentration of any land-use class for two reasons: the repeated disturbance and break down of soil aggregates during tilling, and the reduced inputs of organic material due to harvesting of crops. Currently, Ireland is the least forested country in the European Union, with estimates of forest cover in the range of 8.3–9.4% (McGettigan et al., 2006; Tomlinson, 2005; Forest Service, 2000). Afforested lands most often contain introduced coniferous tree species, primarily Sitka spruce (*Picea sitchensis* (Bong.) Carr.) due to climate suitability, rapid growth and good timber quality. Coniferous forests currently represent about 80% of Irish forests (Renou and Farrell, 2005). 44% of state forest lands occur on peaty soils (Coillte Teoranta, 1999). Over half of the land area of Ireland is covered by grassland (54.3%), mainly in the form of pasture. Land uses such as silage and hay making also represent a percentage of the grassland class.

The peatlands of Ireland (include raised bogs, blanket bogs and fen peats) are estimated to hold 53% of the total SOC in the Republic of Ireland on 13.8–17.2% (Gardner and Radford's 1980; Hammond, 1981; Tomlinson, 2005; McGettigan et al., 2006 (wetland + peatland class); Connolly et al., 2007). The paucity of knowledge about the bulk density of the various peat types and the spatial variability of peat depth make Tomlinson's 2000 estimate of Ireland's SOC stock in peatlands, 1071 Tg, difficult to verify. Nevertheless, peat will likely represent the majority of soil carbon in Ireland because its carbon concentration (44% by McGrath and McCormack (1999) or upwards of 50% by Hammond (1981)) is many times greater than that found in mineral soils (0.5–6%). Soil organic carbon stocks in peats have the potential for the greatest change because they have the highest carbon concentrations.

1.2.3 Measurement and Monitoring of Soil Carbon

The total organic carbon stock of a soil is generally reported as a mass per unit area (e.g. kg m^{-2} or Mg ha^{-1}) to a predetermined sampling depth. Bulk density gives the mass of the soil per unit volume (kg m^{-3}). The majority of SOC occurs at shallow depths (0–30 cm) in mineral soils and these depths are most likely to be affected by land use (e.g. tillage and drainage). The SOC stock is estimated by multiplying the bulk density by the percentage of organic C for a predetermined sampling depth (Equation 1.1). Summing the stocks of all depths allows up-scaling the stock calculated to the areal extent represented by the sampling design (Equation 1.2).

$$C_d = BD_d \times \%OC_d \times d_d \qquad \text{Equation 1.1}$$

$$C_{total} = \sum_{d=1}^{D} C_d \qquad \text{Equation 1.2}$$

C_d = soil organic carbon stock (kg m^{-2}) for depth interval *d* (m)

BD_d = bulk density (kg m^{-3}) of soil for depth interval *d* (m)

$\%OC_d$ = percentage of organic carbon content (kg C m^{-2}/ kg m^{-2} soil) for depth interval *d* (m)

d_d = depth of depth interval *d* (m)

D = deepest soil interval sampled (m)

C_{total} = total organic carbon stock (kg m^{-2}) = sum for all depth intervals from 1 to *D*

1.2.4 Monitoring Soil Organic Carbon Change

The stock method measures carbon stocks in the same area periodically (herein known as the ΔT method), and divides the difference in stocks by the amount of elapsed time (typically years) between the sampling intervals. This method is useful in terms of quantifying changes in soil carbon stocks over a period of years, Conen et al. (2004).

1.2.5 Dissolved Organic Carbon

Dissolved organic carbon is defined as the carbon contained in solution of less than 0.45 µm in size. It is found in rivers, lakes, ground water, oceans and soil water. Concentrations of DOC in natural waters can range from less than 1 mg L^{-1} to greater than 50 mg L^{-1} (Thurman, 1985). Riverine DOC is considered a unidirectional flux; it represents a loss of carbon from ecosystems. It is generally one to two orders of magnitude less than the land–atmosphere carbon fluxes (120 Pg C yr^{-1}; Hope et al., 1997).

2. Methods

Objectives

The objectives of this chapter were to describe briefly: the locations and methods of soil sampling; the laboratory methods; and the analytical tools used in this report.

2.1 Site Selection and Classification

Soil samples were collected at 71 locations throughout Ireland to a depth of 50 cm (Figure 2.1). Sixty-two of these sites were from the NSD's 1310 nationwide sites (Fay et al., 2007). A further nine sites were sampled, including eight grassland soils and one undisturbed blanket peatland in south-west Ireland. These additional grassland sites were selected to measure a range of key soil properties at 10 grassland sites'. The 71 sites represent five land-cover types (arable, grassland, peatland, rough grazing and forest) and nine soil types (brown earth, *n* = 9; brown podzolic, *n* = 10; gley, *n* = 10; grey brown podzolic, *n* = 16; lithosol, *n* = 2; peat, *n* = 15; peaty gley, *n* = 2; peaty podzol, *n* = 5; podzol, *n* = 1). With two unsuitable sites, the resulting 69 sites sampled are representative of the major land uses and soil types throughout Ireland.

Dissolved organic carbon was measured in 55 stream locations nationwide. These streams were chosen as the lowest-order streams, with easy road access, in closest proximity to the soil sampling sites (Figure 2.1).

2.2 Field Methods

The sites were located in the field using the GPS coordinates given by the NSD. The data point was centrally located within the soil sampling plot. At each site a 20 m × 20 m quadrat was laid out on a north–south central axis. Photographs, elevation, land cover, land-use history, vegetation and soil profiles were recorded at each site. At each site, bulk density and soil samples were collected. At each sampling point, visible (and distinguishable) surface litter was removed prior to sampling, but no attempt was made at removing the O horizon. This was an a priori decision for ease of sampling across dissimilar soil types and land uses. Sampling was carried out between May 2006 and February 2007.

Soil samples for bulk density (BD) were taken using the core method at five points: the corners and centre of the square plot. A fixed volume bulk density sampling ring was used, 5 cm deep and 8 cm diameter (Van Walt). At each bulk density sampling point, core samples were taken at six depths: 0–5 cm, 5–10 cm, 15–20 cm, 20–25 cm, 40–45 cm and 45–50 cm. Soil samples for elemental analyses were collected at nine points on the quadrat, using a half-inch Dutch auger. Soils were collected for a continuous profile from the surface to 50 cm deep, broken into the following sections: 0–10 cm, 10–25 cm and 25–50 cm deep.

For the in situ small-scale soil study at Dripsey (Section 8), a 50 m × 50 m plot was laid out, divided into 25 No. 10 m × 10 m subplots, and two samples were collected randomly from each subplot. The samples were collected using a half-inch Dutch auger for a continuous profile from the surface to 30 cm deep, broken in the following sections: 0–10 cm, 10–20 cm and 20–30 cm deep. These soil samples were only collected to 30 cm due to the shallow nature of the soils in this location.

Water samples for DOC measurement (Section 5) were collected on seven occasions at all 55 sites. On each occasion water samples were collected nationwide within a 48 hour period. Water samples were collected using 500 ml plastic-bottle grab samples. The samples were stored on ice and returned to the laboratory for analyses within 48 hours.

2.3 Laboratory Methods

All the soil samples were returned to the laboratory, dried at 50 °C, physically crushed, and sieved through a 2 mm aperture sieve. The soils collected for organic carbon analyses were bulked for drying and sieving, resulting in one composite sample per depth per site (three per site: 0–10 cm, 10–25 cm and 25–50 cm).

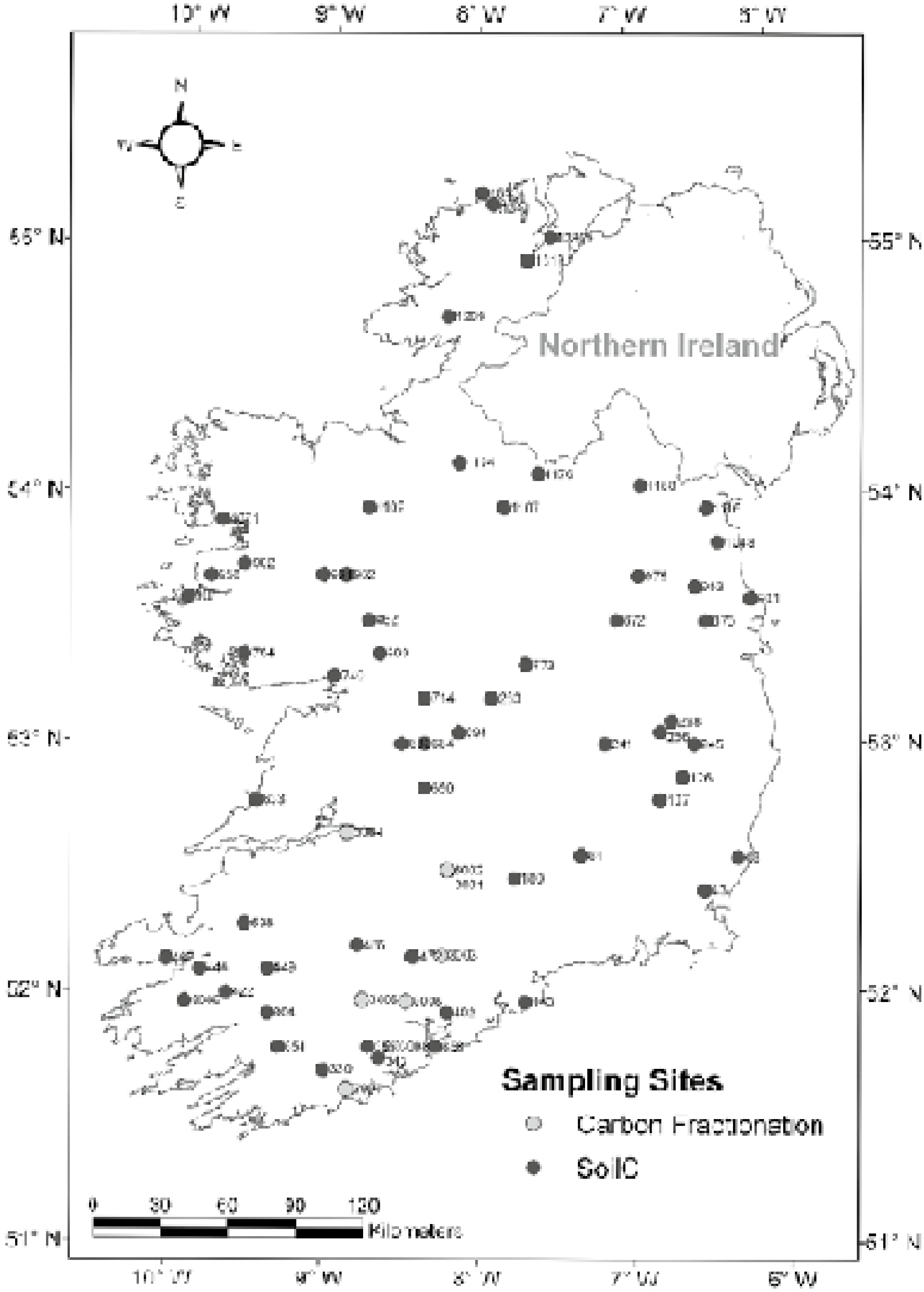

Figure 2.1. Location of SoilC sampling sites. The soil sampling sites chosen from the NSD are in black (SoilC). The eight grassland sampling sites (carbon fractionation) are in grey.

Soil organic carbon was analysed using dry combustion methods on a CN elemental analyser (Elementar). All the soils were treated with HCl to assess carbonate content of the soil prior to carbon analysis. If the soils were reactive to HCl they were considered carbonate soils. Only 40 soils were reactive out of the 207 tested. These soils were treated with HCl prior to analysis of SOC by dry combustion to remove the abundance of inorganic carbon. Organic matter content was also estimated on all the soils by LOI. The dried and sieved soils were subsampled and dried for one hour at 150 °C. These dried samples were then weighed to within 0.0001 g. The samples were then ashed at 360 °C for two hours in a computerised 'force air' (Blue M) ashing oven and reweighed (Gavlak et al., 1994). Particle-size analyses (PSAs) were carried out using the pipette method.

Water samples for DOC measurements were returned to the laboratory and filtered through ashed (450 °C for two hours) GF/C filter paper (pore size 0.45 µm) prior to analysis with a Shimadzu total organic carbon analyser (TOC-V CPH). The data from the water samples generated DOC concentrations in mg L^{-1}.

3. Soil Organic Carbon and Physical Properties

Objectives

The objectives of this chapter were to determine the bulk density and SOC concentration for soils sampled from different soil types and land uses throughout Ireland.

3.1 Background

This section presents the results of our nationwide assessment of the SOC content, bulk density and texture of Irish soils to a 50 cm depth. Soils with higher clay content preserve SOC, while soils with a higher sand content are associated with lower SOC levels (Nichols, 1984; Needleman et al., 1999). Soil organic carbon is intimately linked to soil organic matter. The bulk density of a soil is substantially less when soils contain high amounts of organic matter (e.g. peat soils). Bulk density is a fundamental soil property measuring how densely a soil is packed. Bulk density plays a vital role in plant productivity affecting rooting depth, water retention, soil permeability (hydraulic conductivity), nutrient use efficiency and aeration. It also impacts on the natural environment by affecting run-off, nutrient transport, erosion and the soil-water regime (Lal and Kimble, 2000). It is considered an important soil quality indicator (from the perspective of food, fibre and water quality) due to its relationship with soil organic matter, nutrients and the physical properties of water retention, texture and porosity. Particle size analysis (or texture analysis) measures the percentage of various sized soil particles (i.e. sand, silt and clay) of a soil sample. It gives a fundamental soil property strongly influencing other soil properties such as water retention, bulk density and nutrient retention or leaching.

3.2 Results and Discussion

3.2.1 Bulk Density

Bulk density is an important physical property of soils that is often estimated using pedotransfer functions instead of direct measured due to the labour-intensive measurement methods. As a broad overview, we found bulk density to range from 0.05 g cm^{-3} in peat soils/peatland to 1.63 g cm^{-3} in grey brown podzolics/arable lands, with the corresponding *mean* bulk density (of *n* samples) being 0.17 g cm^{-3} for peat soils and 1.31 g cm^{-3} for grey brown podzols (Figure 3.1 and Figure 3.2). Mean bulk density per soil type and land-use class is presented in this section. The (pure) mineral soils, acid brown earths (ABE) and shallow brown earths (SBE) were similar, with mean bulk density values ranging from 1.02 to 1.21 g cm^{-3} and from 1.01 to 1.22 g cm^{-3}, respectively (Figure 3.1a and b). Brown podzolics (BP) had the smallest range of mean bulk density values ranging from 0.94 to 1.07 g cm^{-3}, with the highest bulk density occurring at 20–25 cm deep and then decreasing to 1.04 g cm^{-3} at the 45–50 cm depth (Figure 3.1c). Gley and grey brown podzolic soils (GBP) had mean bulk densities ranging from 0.86 and 0.88 g cm^{-3} at the surface to 1.3 g cm^{-3} at depth (Figure 3.1h and d). Podzol soils (Pod) had mean bulk densities ranging from 0.53 to 1.23 g cm^{-3} with the lower values reflecting the high organic matter content of the surface layers (Figure 3.1e). Peat soils had the lowest bulk density, with mean values from 0.17 to 0.25 g cm^{-3} and an irregular depth profile of decreasing bulk density to 25 cm deep and then increasing bulk density to 40–50 cm (Figure 3.1g). This trend is due to the presence of mineral soils underlying some peat soils. The organo-mineral soil types, lithosols (Lith), had low bulk density values ranging from 0.24 to 0.57 g cm^{-3}. These are shallow soils so the bulk density values only span 0–20 cm depth (Figure 3.1j). Peaty gley soils (PG) covered the full range of bulk density values found in other soils, ranging from 0.21 to 1.26 g cm^{-3} (Figure 3.1i) and peaty podzols (PP) also had a broad bulk density range of 0.2 to 0.89 g cm^{-3} (Figure 3.1f). These bulk density values indicate the organic nature of the top layers of these soil types and the increase in mineral fractions at depth in these soils.

Bulk density varies with the structural conditions (Blake and Hartge, 1986) of a soil, which are affected by factors such as soil compaction and tillage. Land use can be an important factor influencing the bulk density of a soil as it influences the vegetation cover and the degree and frequency of soil disturbance. Arable lands had the highest mean bulk densities at 1.14 to 1.29 g cm^{-3}, followed by grasslands with bulk density values ranging from 0.87 to 1.18 g cm^{-3} (Figure 3.2a and 3.2b). Forests had mean bulk densities of 0.45 to 0.95 g cm^{-3} (Figure 3.2c). Of the nine forested sites sampled, four were broadleaf forests and five were coniferous. In general, forests in Ireland consist of small remnant patches of old broadleaf forests and large commercial patches of coniferous plantations. These coniferous plantations were often planted on marginal lands, with peat being the dominant soil type for 44% of state-owned forests (Coillte Teoranta, 1999). This difference in forest type, and possibly associated soil types, results in a large range of values, making any definitive statements about forest effects on bulk density difficult to make. Rough grazing lands had mean bulk density values of 0.26 to 0.94 g cm^{-3} (Figure 3.2e) and peatlands had the lowest bulk density values ranging from 0.14 to 0.32 g cm^{-3} (Figure 3.2d).

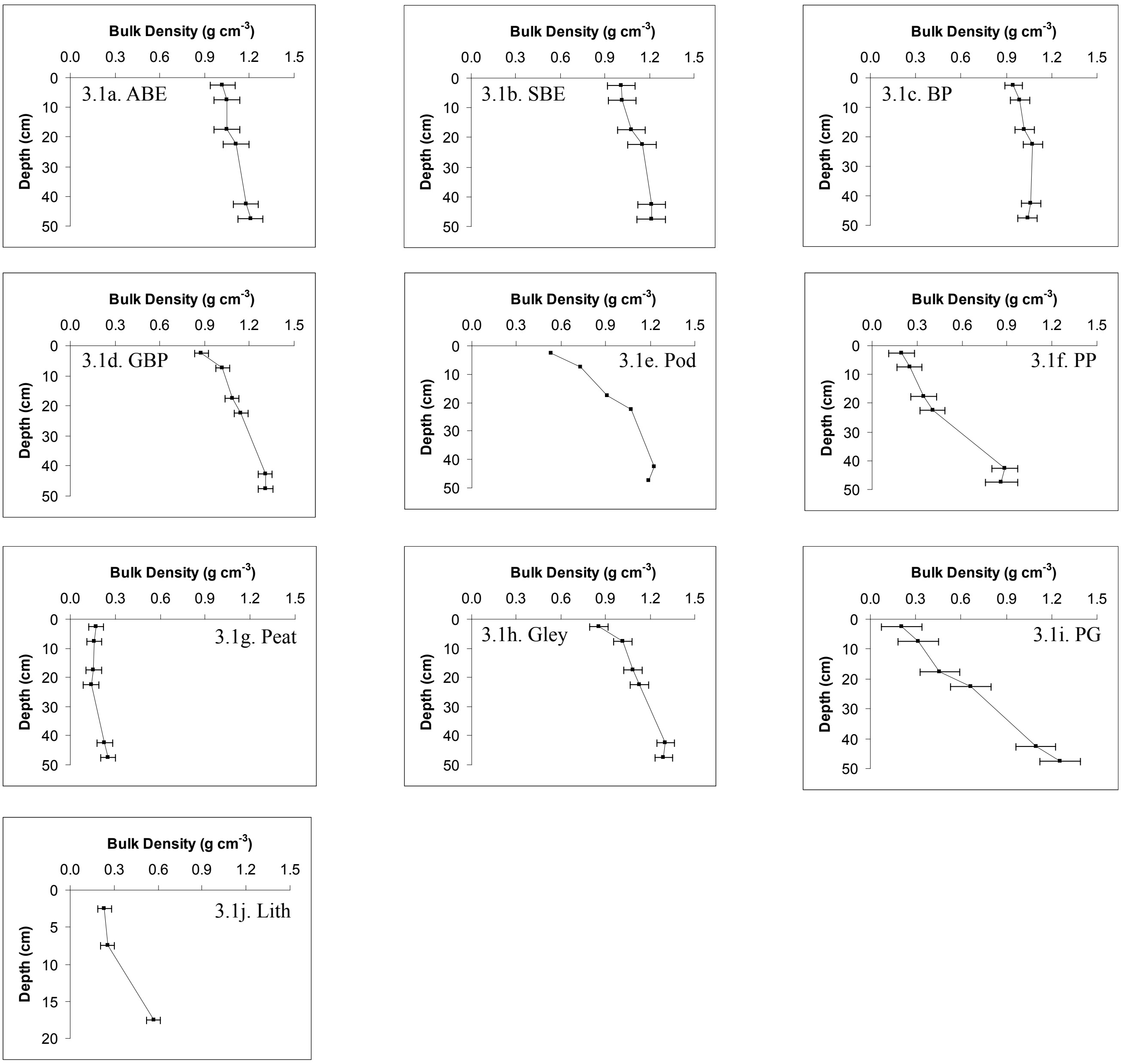

Figure 3.1. Mean bulk density of each soil type +/– 1 standard error. Soil type included: (a) Acid brown earth (ABE, *n* = 5), (b) Shallow brown earth (SBE, *n* = 4), (c) Brown podzolic (BP, *n* = 10), (d) Grey brown podzolic (GBP, *n* = 16), (e) Podzol (Pod, *n* = 1), (f) Peaty podzol (PP, *n* = 5), (g) Peat (Peat, *n* = 14), (h) Gley (Gley, *n* = 10), (i) Peaty gley (PG, *n* = 2), (j) Lithosol (Lith, *n* = 2). The line connecting the mean values on each graph is for illustration purposes only.

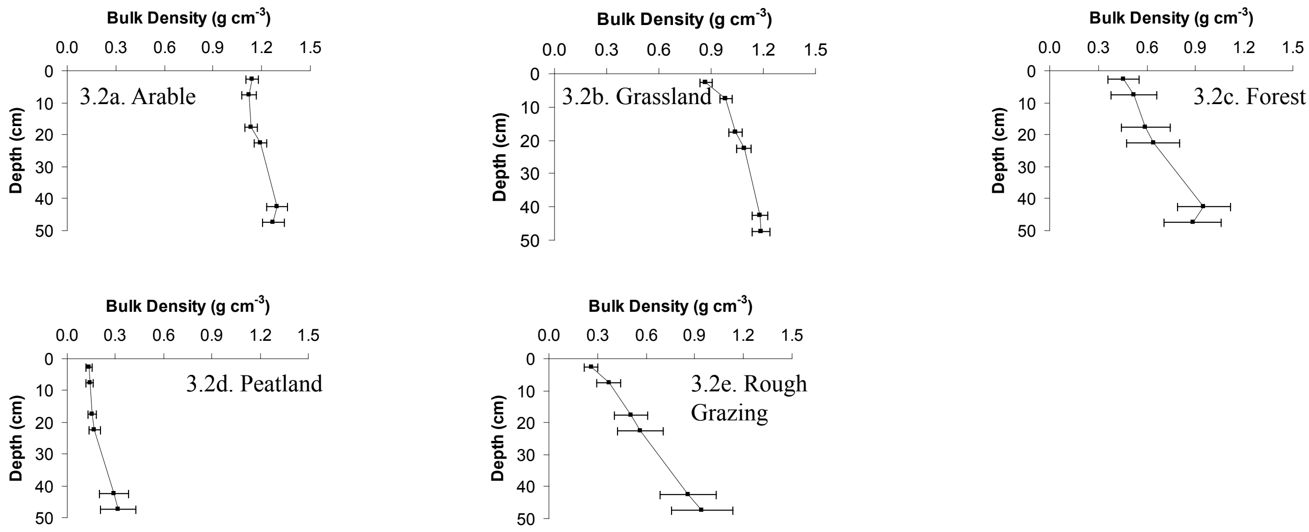

Figure 3.2a–e. Mean bulk density of each land-use class +/– 1 standard error. The line connecting the mean values on each graph is for illustration purposes only.

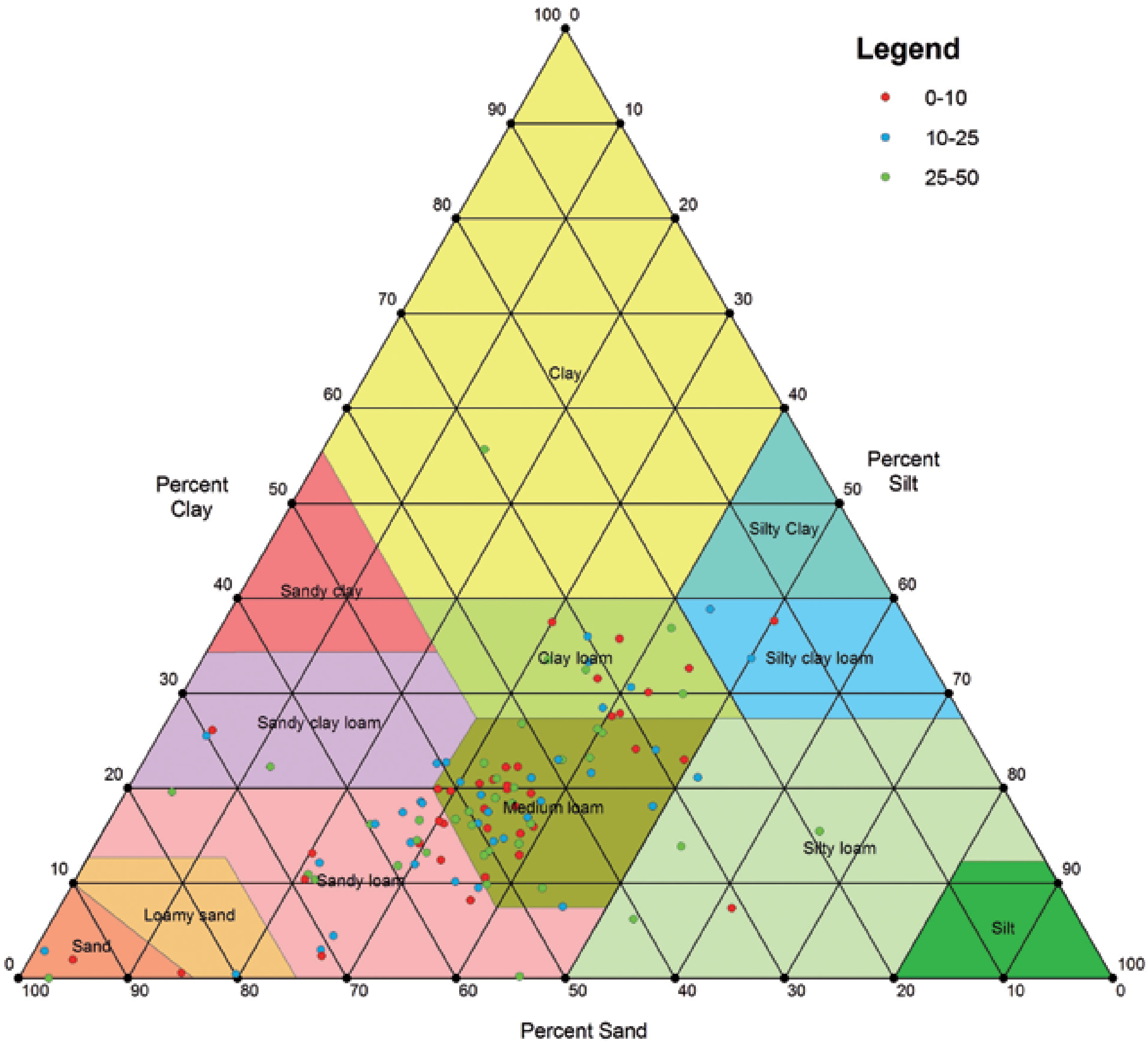

Figure 3.3. Particle size analyses results on a USDA texture triangle. The three different depths are illustrated in different colours.

3.2.2 Particle Size Analyses

Particle size analyses resulted in the percentage of sand, silt and clay for each site at three depths: 0–10 cm, 10–25 cm and 25–50 cm. Peatland sites and sites with organic rich soils (including peaty podzols, peaty gleys and lithosols (i.e. organo-mineral soils)) were not assessed for particle size. This resulted in only 43 of the 71 sites sampled being assessed by particle size analyses. These were 35 of the 59 NSD sites and eight of the Munster grassland sites. The results are presented in Figure 3.3 using the USDA texture triangle. Most soils were found to fall in the mid-regions of the USDA soil textural triangle – namely medium and sandy loams.

3.2.3 Soil Organic Carbon

The overall range of soil organic carbon content for all sites at 0–50 cm depth was 0.7–54.8% (Table 3.1 and Table 3.2). This wide range is due to the presence of peat soils which have high carbon content. The SOC range for the surface 0–10 cm layer is 1.5–52.5%, for the 10–25 cm depth is 1.3–54.8% and for the 25–50 cm depth is 0.7–52.6%. The mean SOC values show a decrease with depth, however the presence of peat soils keeps the range per depth very large. The NSD (Fay et al., 2007) reports SOC values in the top 10 cm to range from 1.4% to 55.8%, similar to our results.

Table 3.1. Soil organic carbon content for each soil type by depth. Values are per cent.

Soil Type	0–10 cm				10–25 cm				25–50 cm			
	Mean	Standard Error	Minimum	Maximum	Mean	Standard Error	Minimum	Maximum	Mean	Standard Error	Minimum	Maximum
Acid brown earth	3.65	0.73	2.00	6.23	2.70	0.33	1.92	3.81	1.57	0.23	0.89	2.12
Shallow brown earth	3.84	0.10	3.59	4.01	3.07	0.35	2.41	4.00	1.47	0.10	1.20	1.70
Brown podzolic	4.63	0.68	1.45	9.13	3.13	0.28	1.45	4.69	1.92	0.38	0.77	5.16
Grey brown podzolic	4.53	0.47	1.61	9.55	2.95	0.31	1.72	6.50	1.42	0.13	0.65	2.55
Gley	5.02	1.11	1.48	13.44	3.45	0.91	1.25	11.25	1.56	0.28	0.75	3.48
Podzol	11.08	–	11.08	11.08	4.86	–	4.86	4.86	3.82	–	3.82	3.82
Peaty podzol	27.62	7.07	13.46	50.17	20.21	8.71	8.49	54.80	7.29	2.60	2.95	17.43
Peaty gley	21.01	11.02	9.99	32.03	16.39	9.65	6.74	26.04	6.55	2.30	4.25	8.85
Lithosol	37.47	5.90	31.57	43.36	13.36	2.49	10.87	15.85	1.62	0.83	0.79	2.44
Peat	43.61	1.72	31.14	52.51	43.23	2.43	23.04	51.88	37.67	4.21	3.30	52.55
Total mean	16.25	3.20	10.74	23.15	11.33	2.83	6.28	18.37	6.49	1.23	1.94	10.01

Table 3.2. Soil organic carbon content for each land-use class by depth. Values are per cent.

Land Use	0–10 cm				10–25 cm				25–50 cm			
	Mean	Standard Error	Minimum	Maximum	Mean	Standard Error	Minimum	Maximum	Mean	Standard Error	Minimum	Maximum
Arable	2.51	0.25	1.45	3.94	2.29	0.18	1.45	3.2	1.38	0.11	0.89	1.9
Grassland	6.33	1.43	2.7	43.84	4.63	1.55	1.25	46.33	3.21	1.66	0.65	47.93
Forest	20.4	6.76	3.15	52.51	21.22	7.97	2.2	54.8	9.5	3.86	0.75	35.32
Rough grazing	24.93	4.13	5.96	43.36	17.35	4.36	3.19	38.25	10.72	5.11	0.79	47.03
Peatland	42.17	3.13	13.44	52.06	36.85	4.59	11.25	51.22	33.33	6.27	3.3	52.55
Total mean	19.27	3.14	5.34	39.14	16.47	3.73	3.87	38.76	11.63	3.4	1.28	36.95

4. Soil Carbon Stocks

Objectives

The objectives of this chapter were to determine the SOC density for different soil types and different land uses and then to use these results to determine the national SOC stock.

4.1 Carbon Density Calculations

The SOC density (Mg ha^{-1}) of a soil (C_d) was estimated by multiplying the fine soil density by the percentage of organic carbon for a predetermined sampling depth. The fine soil density (FD_d) was used rather than the bulk density (BD) as the latter estimate includes the in situ volume of coarse fragments (> 2mm) (Equation 4.1). The densities for each sampling depth were then summed to get an estimate of the carbon density (C_{total}) at each site (Equation 4.2; Table 4.1).

$$C_d = FD_d \times \%OC_d \times d_d \qquad \text{Equation 4.1}$$

$$C_{total} = \sum_{d=1}^{n} C_d \qquad \text{Equation 4.2}$$

C_d = soil organic carbon density (Mg ha^{-1}) for depth interval *d* (cm)

FD_d = fine soil density (g cm^{-3}) of soil for depth interval *d* (cm)

$\%OC_d$ = percentage of organic carbon content for depth interval *d* (cm)

d_d = depth of depth interval *d* (cm)

C_{total} = total organic carbon density (Mg ha^{-1}) = sum for all depth intervals from 1 to *D*

n = number of depth intervals

4.2 Results

The soil organic carbon densities at the 69 sites ranged from 23.9 to 498.3 Mg ha^{-1} for the 0–50 cm depth. The large range in the 0–50 cm soil organic carbon densities was roughly five times the range of carbon densities found in the 10 cm depth intervals, which varied from 5.6 to 147.8 Mg ha^{-1}. This large variation in carbon density reflects the diversity of Irish soils with their increasing bulk density with depth and their decreasing SOC with depth. To further understand the effect of depth on soil organic carbon, 10 cm depth intervals were compared within each land use and soil type. Soil carbon densities decreased significantly with depth for agricultural lands (grassland and arable) and for soils without a prominent O horizon (shallow brown earth, acid brown earth, brown podzolic, grey brown podzolic and gley). Carbon densities of arable lands and grasslands decreased from 24.9 and 46.6 Mg ha^{-1}, in the surface layer (0–10 cm), and to 15.2 and 18.8 Mg ha^{-1} in the 0–40 and 0–50 cm layers, respectively). Trends in carbon densities for the other three land-use classes (peatlands, forests and rough grazing) were less clear. This may be due to the combining of diverse land uses within each of these classes. For example, forests may contain broadleaved or coniferous forest; peatlands are either raised or blanket peatlands, and rough grazing is an intermediate class between grasslands and peatlands. Only the peatland class displayed a monotonic decrease in carbon density with depth. The slight increase in the carbon density from the 30–40 cm depth to the 40–50 cm depth for both the forest class (36.8 to 43.4 Mg ha^{-1}) and the rough grazing class (45.9 to 55.3 Mg ha^{-1}) is possibly due to the influence of mineral horizons at this depth and a corresponding increase in bulk density.

Soil organic carbon densities are variable throughout the depth profile of any given soil. Densities of carbon in soils without a prominent organic horizon (e.g. acid brown earths, brown podzolics, gleys, grey brown podzolics and shallow brown earths) decreased significantly with depth, ranging from 33.1 to 39.1 Mg ha^{-1} for the 0–10 cm depth interval, and from 13.3 to 18.1 Mg ha^{-1} for the 40–50 cm interval. Although highly variable, the carbon density in soils with a prominent surface organic layer (peats, peaty gleys, peaty podzols and podzols) did not vary significantly between depth intervals (Figure 4.2). The variability in SOC density in peaty gleys, peaty podzols and podzols is often due to the depth of the surface organic layer. Due to the shallowness of lithosols, depth was not a significant factor.

The total depth to which SOC densities are calculated can cause large variances in overall density calculations. Significant differences were found in the SOC densities due to both land use (Figure 4.1) and soil type (Figure 4.2) for each depth investigated. Differences in the carbon densities between land-use classes and soil types become more pronounced as the total depth to which the estimated carbon density increases (e.g. 0–10 cm and 0–50 cm). For the 0–50 cm depth, arable lands (97.3 Mg ha^{-1}) contain less carbon than all other land-use classes. Grasslands (141.8 Mg ha^{-1}) contain significantly less carbon than peatlands and rough grazing lands (224.2 Mg ha^{-1} and 226.6 Mg ha^{-1}, respectively. The SOC density of forested lands (207.3 Mg ha^{-1}) was significantly higher than arable lands. Although differences in soil carbon densities between land-use classes reflect management and the intensity of land use; land use in general largely depends on soil type. In general, soils without a prominent organic horizon contained significantly less soil carbon than soils with a prominent surface organic layer, as indicated in Figure 4.2. These soils (acid brown earths, brown podzolics, gleys, grey brown podzolics and shallow brown earths) to a depth of 50 cm had carbon densities ranging from 101.8 to 123.1 Mg ha^{-1}. Soils with a prominent surface organic layer (peaty podzol, peaty gley, podzol, lithosols and peat) had a much larger range of carbon densities, from 113.6 to 301.4 Mg ha^{-1}. Lithosols and podzols are the exceptions to this trend. Lithosols extending only to a depth of 20 cm accumulate the same amount of carbon in 20 cm (113.6 Mg ha^{-1}) as other mineral soils with a limited O horizon do in 50 cm. The lack of a difference between podzols and other mineral soils is likely due to a lack of replication in the podzol class (n = 1). Because differences in carbon densities largely depend on the presence of an organic horizon, soil type is the better indicator of soil organic carbon than land use.

4.3 Scaling Up: National Estimates of Soil Organic Carbon

Regional or national SOC stocks are estimated by multiplying a carbon density of a particular land use by the area of that land-use class, or by multiplying a carbon density of a soil type by the land area of the soil type. The strength of this study is that the carbon densities for each land use and soil type class were calculated from Irish data specifically gathered for the purpose of calculating carbon stocks. These carbon density data

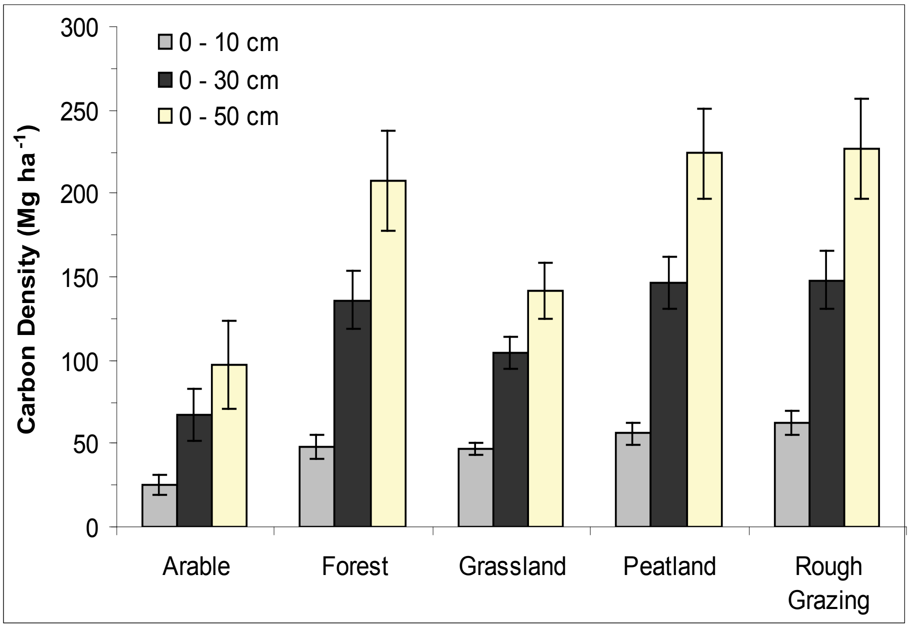

Figure 4.1. SOC density (Mg ha^{-1}) for each land use at three depth intervals: 0–10, 0–30 and 0–50 cm depth.

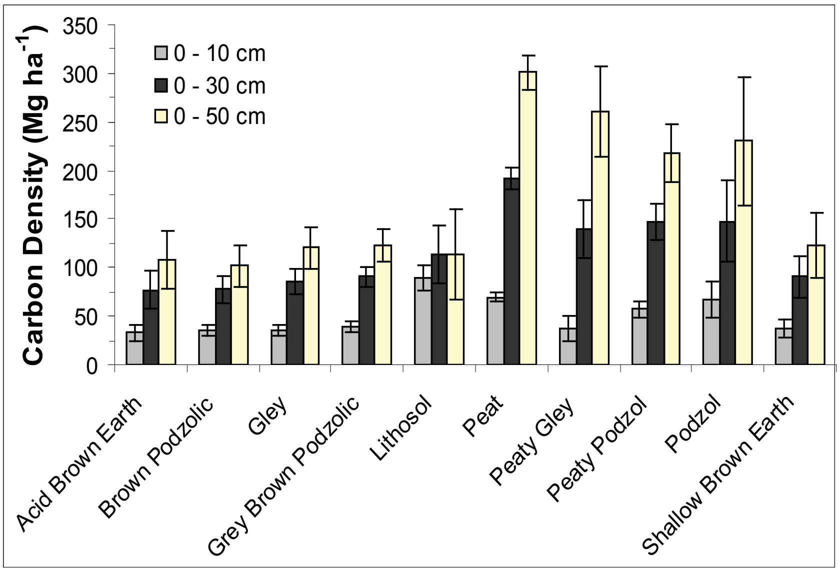

Figure 4.2. SOC density (Mg ha^{-1}) per soil type at three depth intervals: 0–10, 0–30 and 0–50 cm depth.

were combined with a land-use map from Corine 2000 (the European Commission's Coordinate Information on the Environment) and older soil maps (Gardiner and Radford, 1980). It is difficult to estimate the accuracy of calculating a national soil organic carbon stock using this method without knowing the errors which surround each source of spatial data. Improvements to the Corine 2000 map will result in a newer version of this map (expected in 2009) being generated, rather than an understanding of the errors in the original map. Even though soil type is a better predictor of soil carbon densities than land use, understanding changes due to land use cannot be neglected. Given the unknown uncertainties within the very coarse scale of the Gardiner and Radford (1980) *General Soil Map*, the better resolution of the Corine 2000 land-use map offers a potentially more reliable route to national estimates of soil carbon stocks.

Using land-use data, the soil organic carbon stock for the Republic of Ireland to a 50 cm depth was calculated as 1061.5 Tg ,and using soil-type data the stock was calculated to be 1063.6 Tg. Although these estimates are both based on carbon densities calculated from the 69 sites in this study, these estimates are surprisingly similar, given that estimates of the spatial area of the land-use and soil type classes come from different sources. Using the standard error associated with the carbon densities for each land use and soil type class, the lower and upper bounds on our estimate of the national soil organic carbon stock were calculated. The lower and upper bounds on our estimate of soil organic carbon based on land-use data (1061.5 Tg) are 919.4 Tg and 1203.6 Tg, respectively. The upper and lower bounds of our estimate based on soil-type data (1063.6 Tg) are 908.4 Tg and 1218.7 Tg, respectively. Both of these error ranges are less than 15% of the estimated SOC stock value.

Compared to other published values (Table 4.1) of the national soil carbon stock, our values to 50 cm depth (1061.5 Tg and 1063.6 Tg) are large. Eaton et al. (2008) estimated the national soil carbon stock to be 1469 Tg to 1 m depth (mineral and peat soils) and 2437 Tg for 1 m depth mineral soils and a full depth of peat soils. Tomlinson (2005) estimated a national soil carbon stock of 2021 Tg for the entire soil profile. If using an analogous approach to Eaton et al. (2008) (1 m mineral soil depth and entire peat depth), our estimate for the actual carbon stock for the entire soil profile would be the largest estimate to date (> 2437 Tg). This would suggest that past studies using carbon density data from similar soil type or land use in the UK have underestimated the actual soil carbon stock in Ireland.

4.4 Summary

The complexity of calculating SOC stocks for Irish soils arises not just from the range of soils found, but also from their spatial heterogeneity. This work covered a range of land uses and soil types which reflect the

Table 4.1. Estimates of the national soil organic carbon stock (Tg).

Spatial Data	Depth[a]	Area of Ireland[ab] (ha)	Estimated SOC Stock (Tg)	Source	Stock Adjusted[c] for Area (Tg)
Soil type	30 cm	6,841,891	742	This study	742
Soil type	50 cm	6,841,891	1064	This study	1064
Soil type	Complete soil profile	6,916,400	2021	Tomlinson, 2005	1999
Land use	30 cm	6,841,891	744	This study	744
Land use	50 cm	6,841,891	1062	This study	1062
Land use	100 cm	6,943,877	1469	Eaton et al., 2008	1447
Land use	100 cm for mineral soils and the complete soil profile for peatland	6,943,877	2437	Eaton et al., 2008	2401

[a] The estimated soil organic carbon stock depends on the depth to which it is calculated and the area of Ireland.

[b] The area of Ireland differs, depending on how the land area of Ireland has been calculated. This area used in this study reflects the current land area of Ireland according to Ordinance Survey Ireland (2008).

[c] The estimated soil organic carbon stock of other studies have been recalculated to eliminate differences due to differences in area. These adjusted stocks assume the land area of Ireland is 6,841,891 ha, as used in this study.

physical and chemical properties of Irish soils. The findings of this study illustrate that soil type is a better predictor of SOC density than land use, primarily with respect to soils without a rich organic layer. Land use is a broad categorisation that masks the effect of soil type, in part because soil type determines land use to a large degree. The national estimate of SOC stocks based on land use may yet be more accurate than those based on soil type, as estimates of the spatial extent of the various land uses are, at present, more accurate than estimates of the spatial extent of the various soil types.

The national SOC stocks to 50 cm depth, calculated from carbon densities and the known spatial extents of the various land uses and soil types, were very similar at 1061.5 Tg and 1063.6 Tg, respectively. These estimates suggest that past research may have underestimated national stocks.

It is intended that a study using a combination of data from the 69 sites of this project with the NSD data will yield a more accurate estimate of Irish carbon stocks.

5. Dissolved Organic Carbon

Objective

The objective of this chapter was to determine the range of DOC in streams throughout Ireland, near the sites used for the SoilC sampling.

5.1 Classification and Calculation Methods

5.1.1 Sampling Dates

Grab water samples at 55 stream sites close to the SoilC sampling locations were collected seven times over a twelve-month period. The sampling times are reported in hydrological days of year 2006–2007. The sampling dates are given in Table 5.1. Day 1 of the hydrological year for Ireland is 1 October 2006. Sampling began in 9 November 2006 (day 40) and ended in 4 October 2007 (day 369).

5.1.2 Watershed Delineation

Using ArcGIS v.9.2 (ESRI, 2006) and ArcHydro v.1.2 (ESRI, 2007), catchment attributes such as catchment area, precipitation, land use and soil class were generated for each of the 55 water-sample locations. ArcHydro was used to delineate catchment areas for each sample point. These catchments ranged in area from 2.2 to 7151 ha (Table 5.1). These catchments were then verified using Ordnance Survey Ireland Discovery Series Maps (1995, scale 1:50000).

5.1.3 Calculating DOC Exports

Over the period of the experiment, the cumulative precipitation (averaged over the 13 Met Éireann synoptic stations) was plotted against the hydrological day (Figure 5.1). The sampling year was then split into seven hydrological periods corresponding to the seven DOC sampling times. The boundaries of the hydrologic periods were (arbitrarily) chosen so as to make the precipitation pattern in the hydrologic period similar to the precipitation surrounding the DOC sampling date. The DOC export was estimated at each site for each of the seven time periods as the product of stream flow and DOC concentration.

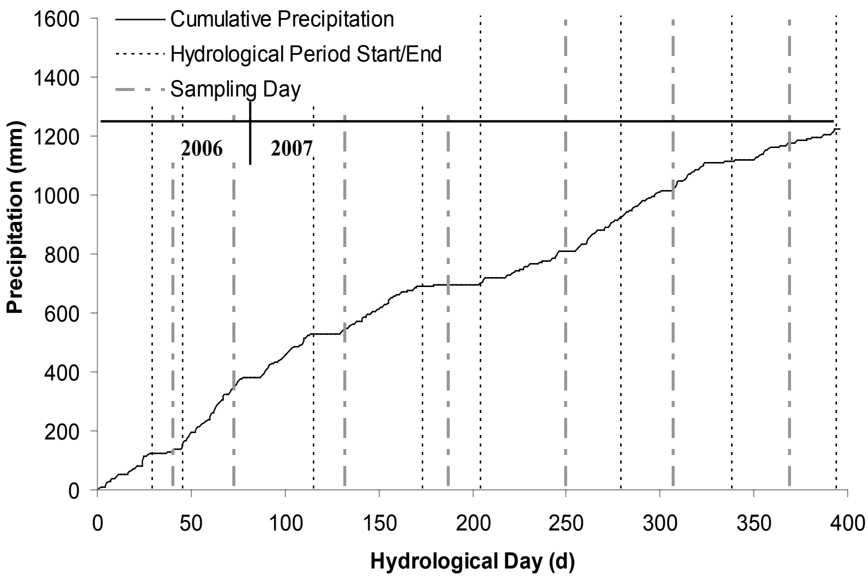

Figure 5.1. Cumulative precipitation, sampling days and hydrologic periods (1 October 2006 is hydrological day 1). Cumulative precipitation from the daily average for all synoptic stations.

Table 5.1. DOC concentrations (mg L^{-1}) per sampling day, averaged over the 55 DOC sampling sites.

Sampling Day	Hydrological Day	Mean	Standard Error	Minimum	Maximum	Range
9 November 2006	40	7.32	0.67	1.2	23.3	22.1
12 December 2006	73	8.33	0.69	1.9	25.9	24.0
9 February 2007	132	5.22	0.41	1.0	12.4	11.4
5 April 2007	187	4.55	0.47	0.9	18.4	17.5
7 June 2007	250	7.13	0.64	1.3	19.4	18.1
3 August 2007	307	6.90	0.59	1.2	15.6	14.4
4 October 2007	369	8.27	0.75	1.5	23.2	21.7

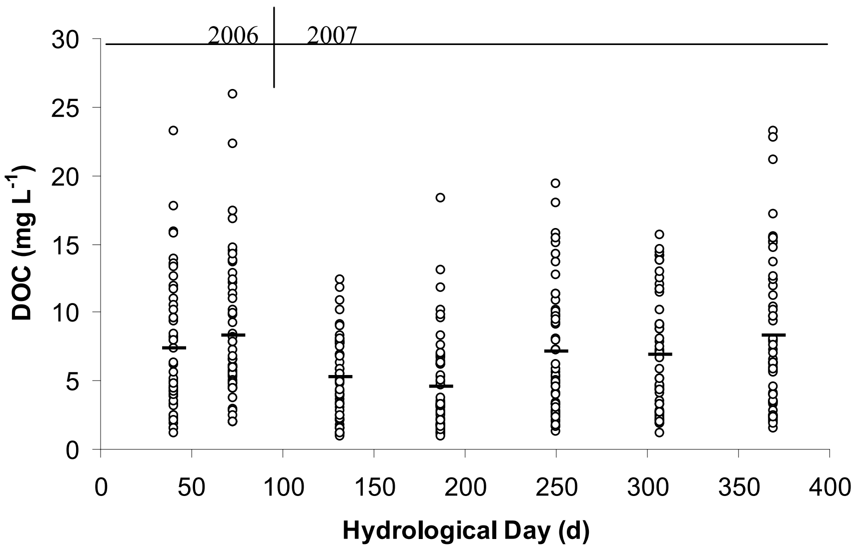

Figure 5.2. DOC concentrations (mg L^{-1}) per sampling day. Each circle represents a DOC concentration at one of the 55 sites. The black bar represents the mean DOC concentration per sampling day.

5.2 Results

5.2.1 DOC Concentrations

Table 5.1 and Figure 5.2 illustrate the range of DOC concentrations found. Water samples from February (mean 5.2 mg L^{-1}, day 132) and April (mean 4.6 mg L^{-1}, day 187) have significantly lower DOC concentrations than December (8.33 mg L^{-1}, day 73) and October (8.27 mg L^{-1}, day 369). April is also significantly lower than June (7.13 mg L^{-1}, day 250) and August (6.9 mg L^{-1}, day 307). The DOC concentration in November (7.32 mg L^{-1}, day 40) was not significantly different to any other time.

Figure 5.3 shows the temporal trends of DOC concentration for several land uses, indicating that forest and peatland have the highest concentrations. Note that most Irish forests are planted on peat soils, verifying the similarity of DOC concentrations between peatland and forest land uses.

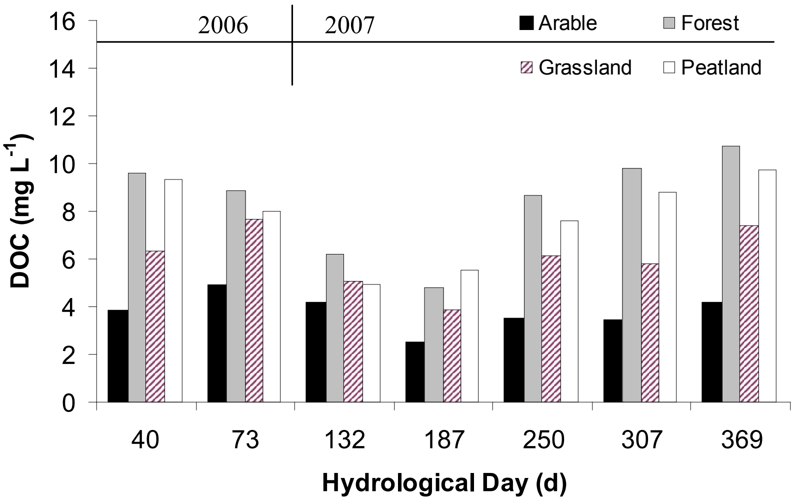

Figure 5.3. Temporal trend of DOC concentration (mg L^{-1}) for several land uses.

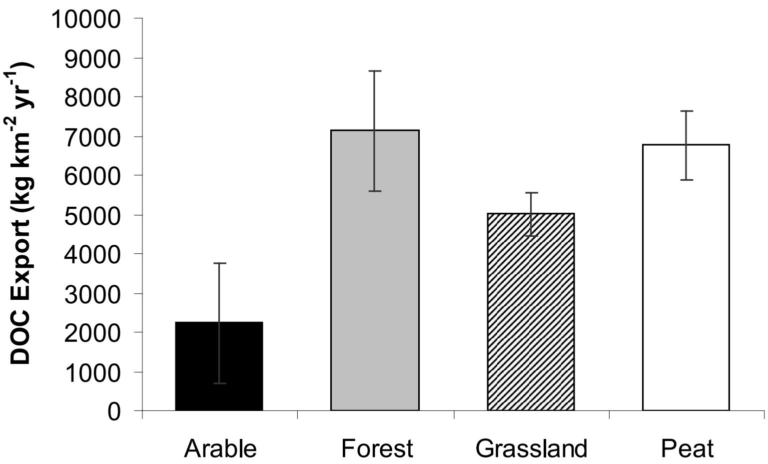

Figure 5.4. Comparison of annual DOC exports (kg km^{-2} yr^{-1}) for several land uses.

5.2.2 Annual DOC Exports

Annual DOC exports (kg km^{-2} yr^{-1}) were calculated for each site using DOC concentrations and discharge estimates. Annual DOC exports per site ranged from 1,121 to 15,622 kg km^{-2} yr^{-1}. In Figure 5.4 we show the DOC exports at each of the stream sites. The higher exports tend to be towards the west of the country (from catchments with organic/peat soils) while the lower exports tend to be at the east (from catchments with mineral soils of arable land use). In Figure 5.4 we show the DOC exports from the four main land uses.

5.3 Conclusions and Recommendations

Dissolved organic carbon concentrations and exports have a seasonal variation which can in large part be explained by the seasonal variation in temperature and discharge. Measuring either concentration or export will generate a similar story in regards to the mechanisms controlling DOC, but quantification of exports is necessary to ascertain carbon losses from catchments. It is not possible to identify with certainty the driving mechanisms of the variation of DOC concentrations and exports based on one year of observation. As precipitation in Ireland tends to have appreciable inter-annual variation (and temperature to a lesser extent), multi-annual studies are required not only to identify the driving processes of variation but also for model development.

6. Loss on Ignition

Objective

The objective of this chapter was to establish a relationship between SOC determined by the simple LOI method and SOC determined by the more conventional method.

6.1 Background

Using some of the data generated as part of the SoilC sampling, equations were developed for predicting the SOC of soils based on the weight LOI for eight soil types in Ireland. We had LOI and carbon data for 213 soil samples from all 71 sites for three depths. Loss on ignition is an economical and reliable laboratory procedure. Low to moderate combustion temperatures (360 °C) and relatively short combustion time (two hours) were used to limit weight loss of materials not associated with organic matter. The method we used in LOI is described in the End of Project Report. Loss on ignition (LOI) was calculated as follows.

$$\text{LOI (\%)} = \frac{\text{(oven-dry soil weight} - \text{ashed soil weight)}}{\text{oven-dry soil weight}} \times 100$$

Equation 6.1

6.2 Statistics

The effects of soil type and depth on the relationship between LOI and organic carbon content (OC) were investigated. Linear regressions were performed using the method of least squares in order to develop predictive equations for SOC from LOI data. The linear regression was of the following form.

$$\text{OC (\%)} = \alpha + \beta\,\text{LOI(\%)} + \varepsilon \,, \qquad \text{Equation 6.2}$$

where α is the intercept, β the slope and ε any unexplained variation. Analyses of covariance (ANCOVA) were completed to test for significant differences between the slopes of the regressions, grouping the data by soil type, depth and soil type × depth (Zar, 1999, Section 18.4).

6.3 Results

Least squares linear regressions estimating SOC from LOI were highly significant for all soil types ($p < 0.001$, Figure 6.1). All least squares linear regressions had a high coefficient of determination $r^2 = 0.92$ to 0.99).

6.4 Discussion

The depth at which soil samples were taken did not affect the slopes of the regression equations in this data set. Zerva and Mencuccini (2005) found a significant effect of depth when separated by soil horizon. As soil texture often varies with soil horizon, one might have expected to find the same in this study. The lack of a depth effect in this data set may be due to differences in sampling strategies. This study sampled across numerous soil types and land uses using predetermined depths (0–10 cm, 10–25 cm and 25–50 cm) and did not sample by soil horizon. Analyses of the regression coefficients, both slope and intercept, indicated five significantly different soil groups out of the initial eight soil types. Four of these five soil groups were significantly different from one another. Lithosols were the only soils not significantly different to any other soil type. In Ireland, lithosols are characterised as thin, highly organic soils overlying shattered bedrock, dissimilar to any other soil type in Ireland. The lack of significant differences for lithosols is likely due to the limited number of samples. Differences in slope between brown podzols/grey brown podzols and gleys may be attributed to differences in soil texture. The primary textural difference between these two groups is clay content. Gley soils often have high clay content throughout their soil profile, whereas grey brown podzolic accumulates clay in the B horizon. Brown podzolics have no discernable trend in relation to clay content. The higher intercepts of peat and peaty podzol soils versus mineral soils are likely due to the differences in SOM composition. The similarities in slopes and intercepts of brown earths and peaty gleys may be due to the limited number of peaty gleys sampled and the variation of brown

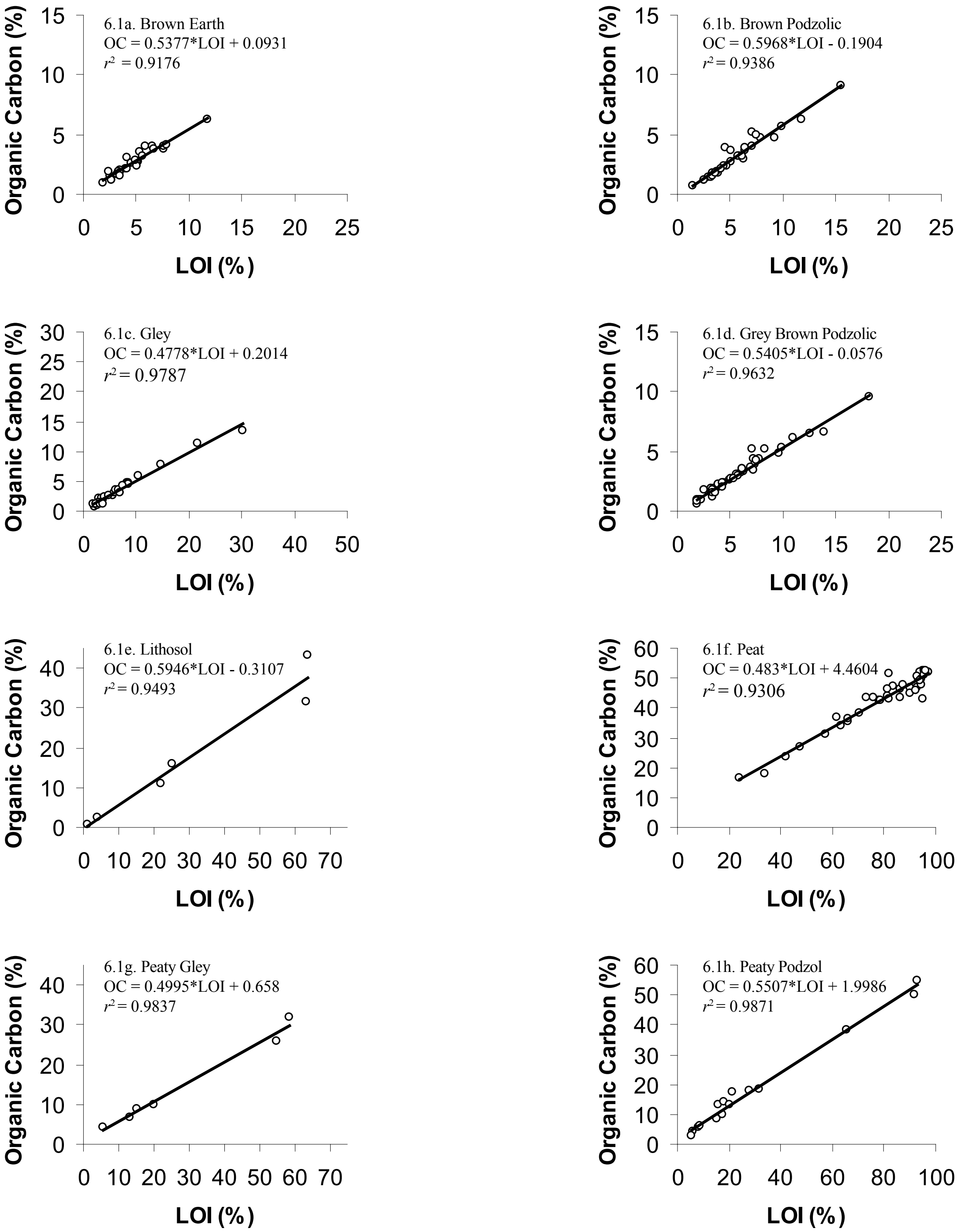

Figure 6.1(a)–(g). Least squares regression equations predicting organic carbon content for several soil types common in Ireland.

earth soils. Brown earths had the weakest coefficient of determination of all soil types (r^2 = 0.92).

6.5 Conclusions and Recommendations

Relationships predicting soil organic carbon from LOI data vary by soil type. The use of equations to predict organic carbon is warranted due to the high cost of dry combustion analyses compared to the relative ease of LOI techniques. In general, understanding the textural variations of the soil groups may also highlight significant variations due to clay content and organic matter composition. Least squares regressions capture 92–99% of the variance and will be useful predictors of organic carbon in Ireland. An interactive website has been developed to facilitate ease of use of these equations (http://soilcarbon.ucc.ie/loi/loi.php).

7. Grassland Farm-Scale Soil Study

Objective

The objective of this chapter was to determine the partitioning of SOC into the component parts of active, slow and passive pools, for the soils of eight grassland sites.

7.1 Background

The slow, active and passive pools are terms used in modelling SOC. From laboratory measurements we can determine separately the microbial and particulate organic matter (POM) fractions of SOC which is termed the active pool. Similarly we can determine the carbon in sand and stable aggregates and the non-recalcitrant carbon in silt and clay which is defined as the slow pool. We can also determine the passive pool of SOC which is the recalcitrant carbon in silt and clay. The eight grassland sites are in the south-west of Ireland (Figure 2.1 and Table 7.1) with known land-use history. The soil types are noted in Table 7.1.

7.2 Methods

At each of these eight grassland sites, a subset of the soils sampled were bulked and kept fresh for microbial analysis. In addition to the normal suite of variables (bulk density, carbon and particle size), these soils were analysed for exchangeable ions, total exchangeable cations (TEC), pH and percentage of organic carbon, and the carbon was fractionated into the slow, active, passive and microbial carbon pools.

7.3 Results and Discussion

7.3.1 Physical Parameters

Bulk density generally increased with depth, with the exception of sites 3005 and 3007. There was little change in bulk density in the profile of these two sites. The bulk densities ranged from 0.76 to 1.40 g cm^{-3}. This tight range was expected as all the sites are grasslands on mineral soils. The lower values occurred in the top soil layer (0–10 cm), possibly illustrating the effect of roots, organic matter content, livestock, and management practices such as ploughing and reseeding. In particular, sites 3001 and 3004 have low surface-layer bulk densities. All the eight grassland sites had similar textures, ranging between loam and sandy loam soils.

7.3.2 Chemical Parameters

From the chemical data results (reported in the End of Project Report), all the sites show a noticeable decline in the percentage of carbon (C) with depth, ranging from 7.83% in the surface to 1.16% at 50 cm deep. Nitrogen also decreases with depth. Nitrogen (N) decreases from 0.98% in the surface 10 cm to 0.15% at 50 cm deep. Soil pH ranged from 5.1 to 7.1. The pH values were constant or increased slightly with depth, except for site 3006. The C/N ratio is almost constant at approximately 8 for all sites except site 3006 for which it is approximately 11.

Table 7.1. Site attribute information for the eight grassland sites. Site numbers, names, latitude and longitude (Irish National Grid), elevation, soil type and carbon:nitrogen (C/N).

Site #	Site Name	Latitude	Longitude	Elevation (m)	Soil Type	C/N
3001	Solohead B wet	IR 86215	39415	98	Gley	8.00
3002	Solohead A dry	IR 86063	39614	102	Gley	7.86
3003	Kilworth	IR 83597	01850	51	Acid brown earth	8.15
3004	Pallas Kenry	IR 41445	56315	15	Grey brown podzolic	7.87
3005	Carraignava	IW 67979	81215	104	Brown podzolic	8.98
3006	Dripsey	IW 48413	81773	187	Gley	10.82
3007	Clonakilty	IW 41377	42064	69	Brown podzolic	8.25
3008	Ballinhassig	IW 62179	61176	79	Grey brown podzolic	8.02

7.3.3 Carbon Fractionation

Soil samples were analysed for the various fractions of carbon in accordance with Zimmerman et al. (2007). Each of the eight soil samples were collected at three depths (0–10 cm, 10–25 cm and 25–50 cm). These were dried and sieved. A subsample was analysed for total carbon (bulk soil carbon – SOC). Another subsample of the dry soil was selected for carbon fractionation, and each fraction was analysed for carbon content. The soils were physically fractionated by size and density. The first portion, the sand and stable aggregates (S&A) is a size fraction (> 63 µm, the slow pool). This sand and stable aggregates are then separated using a high-density liquid (sodium polytungstate) into two classes: particulate organic matter (POM) and sand and stable aggregates (S&A). The carbon content of POM is similar to that of plant material, as this material is composed of roots and organic pieces. The silt and clay (S&C) is another size fraction, < 63 µm. A subsample of the S&C is oxidised to remove all but the most recalcitrant of carbons. This is called the recalcitrant silt and clay carbon (RS&C) and is the passive pool. This portion of carbon is then subtracted from the original S&C, therefore making S&C represent all non-recalcitrant carbons in this size class. Dissolved organic carbon is < 0.45 µm in size and was measured in the water used to sieve the soil samples. The total fraction column (see Table 7.5 in the End of Project Report) represents the sum of all the carbon fractions. Microbial carbon was assessed on fresh soil samples. Due to procedural or storage errors the data generated was not usable. However we have estimated the microbial (active pool) amount from the difference between the total bulk soil samples and the total fractionated (see Table 7.5 in the End of Project Report).

The fractions varied with site and with depth (see Table 7.5 in the End of Project Report). These results show that in most cases the passive pool is the largest fraction at about 50%, with the active pool and slow pool each at about 25%.

The detailed fractions in Table 7.5 of the End of Project Report can be used for the modelling of carbon dynamics in grassland soils in Ireland. We propose to recruit a PhD student to use this data in a modelling exercise. Various models were reviewed, including RothC, Century, DnDc and Ecosse. RothC was chosen as the most applicable model for this aspect of the work. The main impediment to modelling using RothC was how it deals with highly organic soils and this aspect may be addressed using Ecosse when it becomes available.

7.4 Conclusions and Recommendations

This project used eight grassland sites in south-west Ireland with similar rainfall patterns for a carbon fractionation study. The results show that the relative components of active, slow and passive pools vary with soil depth and location. The passive pool is the largest component at approximately 50%, with the active and slow pools both at about 25% each. The data presented in Table 7.5 in the End of Project Report will be of benefit to other users of the data set and other modellers. The main use for the fractionation information is in modelling.

8. Grassland In-Situ Soil Study

Objectives

The objectives of this small-scale soil sampling study were to determine the number of samples and the time period needed to detect changes in SOC and to quantify what level of change could be detected (Conen et al., 2003).

8.1 Introduction

A 50 m × 50 m plot was laid out in a grass field of know land-use history in Dripsey (County Cork). The plot was divided into 25 No. 10 m × 10 m subplots. Samples were augured from two random points in each subplot to three depths (0–10 cm, 10–20 cm and 20–30 cm). The maximum sampling depth was 30 cm due to the shallowness of the soil at this site. GPS coordinates were recorded at the corners of the main plot to aid in a future re-sampling campaign. Using statistical analysis similar to Conen et al. (2003), the estimated time interval to provide significant SOC changes was determined (α = 0.05, statistical power = 0.90). The results of this work package will assist in the planning of future monitoring schemes at long-term experimental sites to determine the SOC changes and will help to define the practical limits to detecting such changes.

8.2 Results and Discussion

Although working only in a 50 m × 50 m plot, the variation in carbon content was considerable. Table 8.1 gives the mean per cent carbon (C) values for each layer sampled. Although the means ranged from 4.52% to 6.64%, the associated ranges were large. The carbon content of soil ranged from 1.52% to 13.13% for all depths sampled.

In Figure 8.1 we present one histogram for the 0–10 cm depth of the spread of carbon concentration. 86% of the 50 samples were within 4% of the SOC.

Using the formulas similar to Conen et al. (2003), we define the minimum detectable difference, δ, as the statistically significant difference between two estimates of mean SOC at the same site on two different occasions (μ_{t1} and μ_{t2}). As significance limits, we set the probability for falsely rejecting the null hypothesis at 5% ($\alpha = 0.05$). The probability for falsely accepting the null hypothesis at 10% ($\beta = 0.10$, i.e. statistical power = 0.9). Assuming simple random sampling, δ can then be estimated in a one-sample t-test from Equation 8.1.

$$\Delta = \sqrt{\frac{s^2}{n}}(t_{\alpha,\upsilon} + t_{\beta,\upsilon}) \qquad \text{Equation 8.1}$$

Given the change value of SOC, the number of sampling sites can be estimated from Equation 8.2.

$$n = \frac{(t_{\alpha,\upsilon} + t_{\beta,\upsilon})s^2}{\Delta^2}, \qquad \text{Equation 8.2}$$

where s^2 is an estimate of the population variance (σ^2), n is the sample size ($n_{t1} = n_{t2} = n$) ($\sqrt{s^2/n}$ is the estimated standard error of the mean), and $t_{\alpha,\upsilon}$ and $t_{\beta,\upsilon}$ are the critical t-values for the specified values of α and β with n – 1 degrees of freedom (ν). The estimate of δ assumes a normal distribution, that repeated sampling is performed by the same method (simple random sampling) and that the variance is equal on successive occasions.

Table 8.1. Per cent SOC per depth (cm) layer for in-situ small-scale soil study.

Depth	Mean	Standard Error	Variance	Minimum	Maximum	Range
0–10	6.64	0.24	2.97	2.75	13.13	10.38
10–20	5.04	0.30	4.41	1.76	12.02	10.26
20–30	4.52	0.27	3.57	1.52	10.41	8.89
0–30	5.40	0.23	2.65	3.26	10.95	7.68

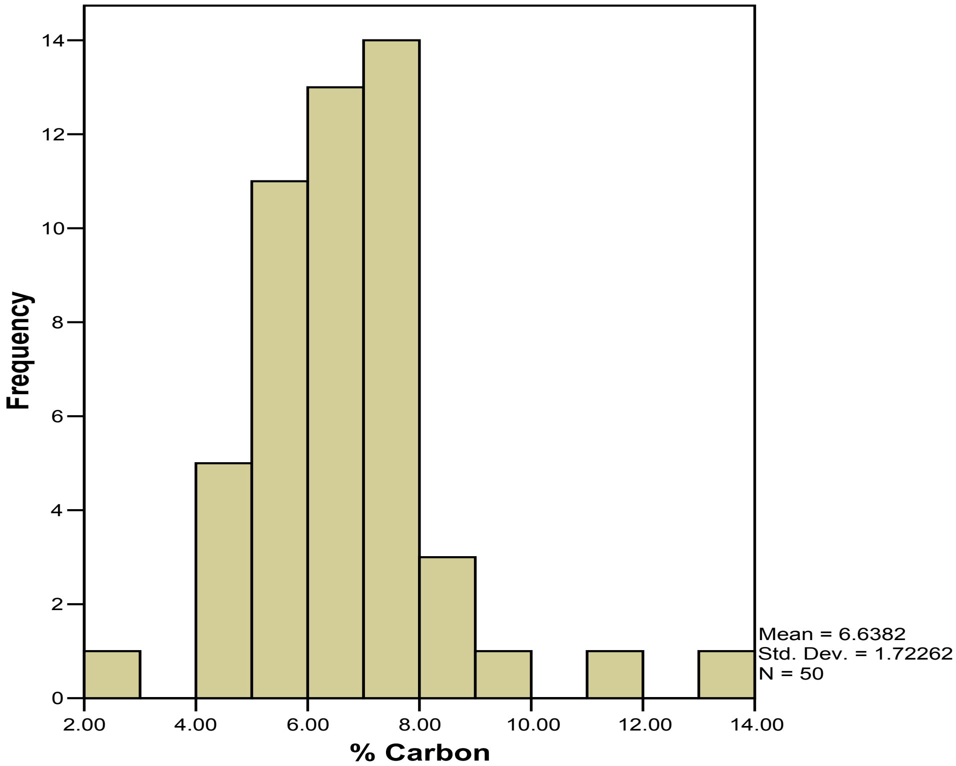

Figure 8.1. Frequency distribution of per cent carbon in 0–10 cm layer.

For the top 30 cm in this study (according to Figure 8.1), the minimum detectable change in SOC would be 2.053% (2.053 g/100 g soil). We set the same expected rate of change over the next 50 years as was used by Conen et al. (2003). This was close to a 10% reduction of the current SOC concentration, which means a reduction of 0.032% (0.032 g/100 g soil) per year. The hypothesis that the SOC loss is at least as large as predicted (2.053 g/100 g soil) could be detected at this site after 63 years. Theoretically, it could be halved to 31 years if the sample size were increased from 50 to 200. According to Equation 8.2, if 10% of the current SOC were reduced over the next 50 years, the sample size needed to detect this change should be at least 27.

8.3 Conclusions and Recommendations

Using statistical analysis similar to Conen et al. (2003), the estimated time interval to provide significant SOC changes was determined (α = 0.05, statistical power = 0.90). The hypothesis that SOC loss is at least as large as predicted (2.053 g/100 g soil) could be detected at this site after 63 years. Theoretically, it could be halved to 31 years if the sample size were increased from 50 to 200. If 10% of the SOC carbon were reduced over the next 50 years, the sample size needed to detect this change should be at least 27.

9. Conclusions and Recommendations

9.1 Soil Organic Carbon Concentrations, Bulk Density and Texture

To estimate the national soil carbon stocks of Ireland, the soil bulk density and soil carbon concentration must be known spatially and at different depths for different soil types. Bulk density results show clear trends with soil type and with land use. Peatlands, forests and rough grazing often occur on more organic soils, while grassland and arable lands occur on mineral soils. Although information on land use is easier to obtain, knowledge about the soil types is more important for carbon stocks, but not yet possible to obtain with the same degree of accuracy as for land use. However this is changing and it is likely than in Ireland within a few years a substantial database of the spatial variation of soil types will be publicly available and the results of this project can be revisited to improve our estimate of the SOC stocks.

Although bulk density varies significantly with soil type, it can be grouped into one of three classes:

Peat soils: 0.17–0.25 g cm^{-3};

Organo-mineral soils: 0.20–1.3 g cm^{-3};

Mineral soils: 0.80–1.3 g cm^{-3}.

This data set provides bulk density values which can be used to increase the accuracy of soil research requiring bulk density values.

Soil organic carbon concentration has a broad range in Irish soils:

Peat soils: SOC > 45%;

Organo-mineral soils: 45% > SOC > 5%;

Mineral soils: SOC < 5%.

Soil organic carbon values follow a similar pattern to bulk density values based on land-use classes and soil types. Although the patterns are the same, the trends are opposite. Soils and land uses with the highest bulk densities (i.e. mineral soils) have the lowest SOC values, and vice versa for organic soils. In this study, soils with an SOC value greater than 10% have a bulk density less than 0.2 g cm^{-3}, and soils with an SOC value less than 10% have bulk density values ranging from approximately 0.2 to 1.3 g cm^{-3}, while the lower SOCs of less than 4% have the highest bulk density values of 1.0 g cm^{-3}.

The combination of bulk density and SOC concentrations enables the estimation of carbon stocks. The texture of the soils examined in this project had a narrow range when plotted on the USDA textural triangle, with most falling in the textural classes of medium loam, sandy loam and clay loam, with almost no samples from clay, silt or sands. This is representative of Irish soils (Gardiner and Radford ,1980), where most Irish soils fall in the mid-zone of the USDA textural triangle.

9.2 Soil Organic Carbon Stocks

Soil sampling covered a range of land uses and soil types which reflect the physical and chemical properties of Irish soils. Soil type was found to be a better predictor of SOC density than land use, primarily due to the division between mineral and organic soils. Carbon concentrations appear to be the primary factor, with bulk density as the secondary factor, in explaining carbon stock variations. As found with the carbon concentration results, land use is a broad categorisation that masks the effect of soil type, in part because soil type determines land use to a large degree. Because mapping of land-use classes is vastly more accurate than mapping of soil types, national estimates of SOC stocks based on land use may yet be more accurate than those based on soil type. Improved mapping and knowledge of the spatial extent of the different soil types in Ireland could greatly improve the carbon stock estimates. The national SOC stock to a 50 cm depth, calculated from carbon densities and the known spatial extents of the various land uses and soil types, were very similar at 1061.5 Tg and 1063.6 Tg, respectively.

9.3 Dissolved Organic Carbon

Dissolved organic carbon concentrations in stream flow varied seasonally due to variation in stream discharge and the effects of temperature and biological processes. Peat soils export more DOC than either podzol or deep well-drained mineral soils. The stream water DOC concentrations were found to range from 0.9 to 25.9 mg L^{-1}, with monthly means (of all 55 sites) ranging from 4.55 mg L^{-1} in April to 8.33 mg L^{-1} in December. The stream water DOC exports ranged from 1,121 to 15,622 kg km^{-2} yr^{-1}, with the higher values from the peatland catchments and the lower values from the arable catchments.

9.4 Loss on Ignition Regression Equations

Equations predicting SOC from LOI data vary by soil type. These relationships account for 92–99% of the variance in the data and therefore are useful predictive tool for soil research in Ireland. The use of these equations is warranted due to the high cost of dry combustion analyses compared to the relative ease of LOI techniques. Different soil types have significantly different relationships between the percentage of LOI and the percentage of SOC. An interactive website calculator has been established to facilitate the conversion of LOI data into the percentage of SOC for various soil types (http://soilcarbon.ucc.ie/loi/loi.php).

9.5 Carbon Fractionation

In the grassland small-scale study the soil carbon samples were fractionated into active (microbial), slow (particulate organic matter) and passive (carbon in sand, silt and clay) components. The relative components of active, slow and passive pools vary with soil depth and location. The passive pool is the largest component at approximately 60%, with the active pool at approximately 25% and the slow pool the smallest component.

9.6 Measures of Detection of Change in Carbon Concentration

Using statistical analysis similar to Conen et al. (2003), the estimated time interval to provide significant SOC changes was determined (α = 0.05, statistical power = 0.90). The hypothesis that SOC loss is at least as large as predicted (2.053 g/100 g soil) could be detected at this site after 63 years. Theoretically, it could be halved to 31 years if the sample size were increased from 50 to 200. If 10% of the SOC were reduced over the next 50 years, the sample size needed to detect this change should be at least 27.

9.7 Recommendations

- The results of this study should be applied to the more widespread NSD 1310 sites to improve the estimate of carbon stock to 10 cm depth.
- A minor research project should be completed to repeat this study on a smaller soil set to include those soils of the NSD that lie in the textural classes not covered in this SoilC project (e.g. pure clays, sands and silts).
- As peatlands have a disproportionate stock of carbon relative to their extent of land cover in Ireland, peatlands are likely to release large amounts of carbon to the atmosphere, as CO_2 and CH_4, and to stream water, as DOC, should the climate become warmer and wetter as predicted.
- This study should be repeated on a multi-year cycle to assess the long-term impacts of changing climate and possible land-use and land-management changes.
- Regular monitoring by local authorities and the EPA on stream-water quality should be expanded to include analysis of DOC to assist future studies of total carbon balance from different ecosystems and also with regard to the negative impact of DOC on potable water quality.

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Acronyms and Annotations

ABE	acid brown earth
BD	bulk density
BP	brown podzol
DOC	dissolved organic carbon
FD	fine soil density
GBP	grey brown podzol
Lith	lithosol
LOI	loss on ignition
NSD	National Soil Database
OC	organic carbon
PG	peaty gley
Pod	podzol
POM	particulate organic matter
PP	peaty podzol
PSA	particle-size analysis
RS&C	recalcitrant silt and clay carbon
S&A	sand and stable aggregate
SBE	shallow brown earth
SOC	soil organic carbon
SOM	soil organic matter
UCC	University College Cork

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.
- Scardadh dramhuisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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