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Organic carbon stocks in agricultural soils in Ireland using combined empirical and GIS approaches

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ABSTRACT

Substitution of the Intergovernmental Panel on Climate Change (IPCC) default methodology by country-specific activity data is recommended for improved estimation of baseline soil organic carbon (SOC) stocks and their changes. In the Republic of Ireland (ROI), previous studies focused either predominantly on grassland or on all land cover types but were depth-limited. To improve the accuracy, Tier 2 approaches are proposed by the IPCC. This requires an analysis of high spatial resolution databases (such as the Irish NSDB – National Soil Database) and maps, collated for major land cover, soil types and land use areas in Ireland. In this study, data were overlaid using ArcGIS to derive information for disaggregated soil types and agricultural land use areas. Empirical models were developed using separate measurement data to estimate the NSDB-derived SOC concentrations for deeper layers, using a depth distribution function and the bulk density (ρ_d) using pedotransfer functions. The soil type specific models ($R^2=0.87$–0.99) had an improved estimate of SOC densities when mineral and organic soils (peat) were treated separately. The estimated SOC densities for grasslands on mineral plus organo-mineral soils at the 0–10, 0–30, 0–50 and 0–100 cm depths were 52.2, 127.1, 170.9 and 213.8 t C ha^{-1}, respectively. For arable lands, the corresponding SOC densities were 29.9, 81.3, 117.6 and 167.5 t C ha^{-1}. Nationally, for all soil types, the corresponding stocks (the products of SOC density and land cover area) were estimated to be 246.9, 608.1, 829.5 and 1079.3 Tg for grassland, and 13.5, 36.7, 50.2 and 67.0 Tg for arable lands in the three soil layers. The total national SOC stocks were estimated to be 888 at 0–30 cm and 1832 Tg at 0–100 cm reference depths. For the complete soil profile, including peats >100 cm depth, the national estimate was 2824 Tg. The combined empirical models and Geographical Information System technique provide robust estimates of SOC stocks for disaggregated land covers and soil types, enabling Ireland to consider moving from Tier 1 to Tier 2 accounting methodology. This improved national inventory of the ROI is important for estimates of the C stock related to the Land Use, Land Use Change and Forestry (LULUCF) categories.

1. Introduction

Recent international negotiations, though yet to be finalized, have concluded that significant reductions in anthropogenic greenhouse gas (GHG) emissions are required to keep global temperature below 2 °C relative to pre-industrial times (COP 16, 2010; The Cancun Agreements). It is recognized within the United Nations Framework Convention on Climate Change (UNFCCC) that significant efforts are required to place global agriculture and food production on an environmentally sustainable, climate resilient low carbon pathway. Globally, agricultural activity is estimated to be responsible for approximately 14% of anthropogenic GHG emissions (Intergovernmental Panel on Climate Change, IPCC, 2007). However, in the Republic of Ireland (ROI) the current estimate is 30% (McGettigan et al., 2010). Despite a recent decrease in Irish national GHG emissions (due to the economic downturn, EPA, 2010), agricultural emissions remain a significant component of Ireland's emissions profile. Improved agricultural management practices have the potential to reduce GHG emissions from agricultural sectors (Smith et al., 2008). The SOC pool, one of the most important reservoirs of the global-C cycle, may have the potential to act as major source or sink of GHGs due to its large extent and active interaction with the atmosphere (Gal et al., 2007; Lal, 2004).

The Tier 1 approach, based on readily available activity data and default emission values as per IPCC guidelines, is used to establish trends in carbon stocks (IPCC, 1996, 2006). Whereas Tier 2 emphasises

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the development of country and regional specific emission factors for key activities, and Tier 3 requires additional resources to develop more sophisticated methodologies including modelling approaches, leading to provide improved estimates of GHG budgets. The higher tiers reflect more robust emission accounting, which are required to identify more specific mitigation options across land use management (LUM) and land use change (LUC). Due to the lack of detailed, spatially explicit activity data, about 56% of the Annex-I countries use IPCC Tier 1 methods and about 25% use Tier 2 methods within their inventory procedure (Lokupitiya and Paustian, 2006). In progressing to a Tier 2 approach, robust country-specific research and activity data are essential to reflect the diversity of practices which influence soil carbon within a country, and to further refine their analysis to include regional variation. This is also relevant to LULUCF sector, and that quantification of baseline SOC stocks across soil depth associated with the variety of land uses and practices is required to assess the change in SOC with LUC. This is highly relevant for sustainable management of the soil and thereby identification of the source and sink categories for offsetting GHG emissions. However, the application of improved technologies to increase soil carbon sequestration, though limited by saturation and resiliency, could counteract the benefit of carbon sequestration by enhancing the emissions of potent GHGs such as N_2O and CH_4 (Mosier et al., 1998; Six et al., 2004) and these need to be taken into account for mitigation/offsetting.

With reference to the Kyoto Protocol, and accounting rules set out within the Marrakech Accords (UNFCCC, 1998, 2002), it is relevant that revisions to inventory methodology are compatible with the net-net accounting rules. This includes the comparison of emissions and removals during the first commitment period (2008–2012), and the second commitment period (2013 to either 2017 or 2020 to be decided) of the Kyoto Protocol from cropland, grazing land management, and revegetation with the base year (UNFCCC, 2011). Recently, in a number of countries, pedotransfer functions and regression modelling, taking into account soil, land use, drainage, climate, etc. have been used to obtain a more complete and detailed spatial distribution of SOC stocks (e.g. Jones et al., 2004; Meersmans et al., 2008, 2009; Scott et al., 2002; Sleutel et al., 2003; Soussana et al., 2004). However, enormous uncertainty prevails with national SOC stock estimates, and often a description of the vertical distribution of SOC with depth and its spatial variation is lacking. The SOC distribution with depth has been examined either by grouping the measurements into fixed depth increments or by fitting continuous functions to the data (e.g. Omonode and Vyn, 2006). Exponential functions have been widely used (e.g. Hilinski, 2001; Meersmans et al., 2009; Sleutel et al., 2003; Soussana et al., 2004) while logarithmic, power or polynomial functions have also been employed (e.g. Arrouays and Pélissier, 1994; Bernoux et al., 1998; Jobbagy and Jackson, 2000). In line with commitments under the UNFCCC, the Republic of Ireland publishes annual estimates of changes in SOC stock (McGettigan et al., 2010). Due to limited country-specific data (except forestry), the ROI uses the IPCC Good Practice Guidance Tier 1 methodology (IPCC, 1996, 2006) but is committed to achieve Tier 2 or better methodology. In the ROI, previous studies predominantly focused on grassland (Brogan, 1966; McGrath, 1973, 1980; McGrath and McCormack, 1999) and afterwards successful interpolations for SOC values to map the SOC distribution at a finer resolution using coupled geostatistics and GIS techniques was limited to the near surface soil (McGrath and Zhang, 2003; Zhang and McGrath, 2004). Estimates of SOC stocks in the ROI up to now were derived mainly from: national data including Co-ordination of Information on the Environment (CORINE) land cover map; the General Soil Map (GSM); and UK datasets (e.g. SOC concentrations and bulk densities for specific soil types) with limited spatial resolution (Eaton et al., 2008; Tomlinson, 2005). In temperate regions, the differential estimates of SOC density for arable lands have been reported to be 24–43% lower than for grassland (e.g. Lettens et al., 2004; Liebens and Van Molle, 2003; Meersmans et al., 2009, 2011). In the ROI, the previously estimated SOC density difference for 0–30 cm falls within the ranges (13–25%) (Eaton et al., 2008; Xu and Kiely, 2009).

To reconcile the above discrepancies and the lack of information on SOC stocks for disaggregated agricultural land covers and soil types, a more detailed spatial assessment of baseline SOC stocks is required. Data on measured SOC concentrations and bulk densities are required which would reflect the SOC stocks (Gifford and Roderick, 2003; Lee et al., 2009) and combined with modelling and GIS techniques is a suitable technique to estimate soil C stocks of disaggregated agricultural land covers (Cruickshank et al., 2000; Eaton et al., 2008; Tomlinson, 2005; Xu and Kiely, 2009; Xu et al., 2011; Zhang et al., 2011). Recent works (Lewis, 2012; Lewis et al., 2012) show that in a pristine blanket peatland that both the SOC and bulk density remain essentially constant from the 10 cm depth to the bottom of the soil profile (in some cases > 5 m). The objectives of this study were: (i) to collate spatially explicit pedon data and land areas for disaggregated agricultural land covers available in the ROI; (ii) to develop empirical models from measured data to estimate SOC concentrations and bulk densities up to 100 cm depth; (iii) to estimate SOC density (i.e. the product of SOC concentration and bulk density) for selected grid-points of the NSDB using the models (from (ii) above), relating to the Great Soil Groups and Indicative Soil Types; and (iv) to calculate the national SOC stocks, disaggregated into grassland and arable lands using the highest resolution spatial data available.

2. Methodology

2.1. Data acquisition

Data were collated for land cover, land use, soil type and soil organic carbon (SOC) concentration and related properties to estimate the SOC densities (the product of SOC concentration and soil mass per unit area) and thereby stocks (the product of SOC density and land cover area) for disaggregated agricultural land cover classes in the ROI. The approach was to develop empirical models using pedon data available in the ROI and use these to estimate the SOC densities at increments of 10 cm down to 100 cm soil depth. For this, currently available relevant higher spatial resolution maps and databases were acquired. The steps followed a conceptual framework are shown in Fig. 1.

Measured SOC concentration data to a depth of 10 cm were acquired from the National Soil Database (NSDB) of the ROI (Fay et al., 2007). The NSDB is a soil geochemistry database for a total of 1310 fixed sampling sites on the national grid-arrays (10 km × 10 km segment). Land cover at the sampling sites comprised of grassland, arable, forestry, and peat land types. In a later study, measurements of SOC concentration and bulk density (ρ_d) data to a depth of 50 cm were made at 69 selected sites of the NSDB (Kiely et al., 2009). For validation of models, independent but limited datasets on SOC concentrations and bulk density measured recently across soil depths (> 100 cm) in projects of Teagasc (Irish Agriculture and Food Development Authority) were also collated and interpolated to match with soil depths (Diamond and Sills, 2011; Richards et al., 2009). These include soils of county Waterford and of three profiles per location for arable lands (Oak Park only) and grassland (Johnstown Castle and Oak Park). Three data-points under grassland were also taken from the datasets used for model development and the overall number of GSGs under a land cover ranged from 1 to 12 (total 40 data-points).

To integrate the measurement data (Kiely et al., 2009), the CORINE map (a computer-aided visual interpretation of satellite imagery) was initially used to identify land cover classes based on the year 2000 (CLC, 2000; CORINE is managed in Ireland by the Environmental Protection Agency, EPA, Ireland; and the analysis is