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Soil Organic Carbon and Land Use Mapping (SOLUM)

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Rialtas na hÉireann
Government of Ireland

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EPA RESEARCH PROGRAMME 2021–2030

Soil Organic Carbon and Land Use Mapping (SOLUM)

(2016-CCRP-MS.40)

EPA Research Report

A copy of the end-of-project Technical Report is available on request from the EPA

Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers 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

Currently, land use, land use change and forestry (LULUCF) reporting for national inventory purposes largely relies on tier 1 reporting methodologies because of the lack of availability of soil property and other activity data at an adequate spatial resolution. In order to better inform coherent climate mitigation strategies and to enhance knowledge in this area, the Soil Organic Carbon and Land Use Mapping (SOLUM) project developed a spatially integrated soils and land use dataset for Ireland that could inform more robust tier 2 and 3 estimates of soil organic carbon (SOC) stock changes.

The spatially integrated Land Use and Soil Inventory for Ireland (LUSII) was developed using existing datasets, including the Land Use and Coverage Area Frame Survey (LUCAS) and the Soil Information System (SIS) for Ireland. LUCAS data were reclassified, and a rule-based approach was developed that ascribed soil attributes to grassland land use classes that are relevant for the LULUCF sector of national greenhouse gas emission and removals inventories. Soil data were then aligned with the land use points, whereby soil data from SIS were reclassified into soil groups in accordance with World Reference Base (WRB) taxonomic classes. A rule-based classification approach using soil texture as a key variable was also incorporated. The ability of this approach to potentially detect changes in land use and associated soil carbon over time was demonstrated using the repeated LUCAS survey data, county-specific soil data and orthophotography information.

Tier 2 SOC factors for different soils, land uses and management types were developed using a newly collated soils database and a novel approach of classifying soils into clusters based on soil textural properties. Building on the existing National Soil Database and through the interrogation of SIS data, a systematic and robust approach to stratifying soils into categories, from which SOC factors could be derived, was developed using principal component analysis (PCA) to identify which important physical, chemical or geographical features may be used to categorise soil series into groups (clusters). The development of tier 2 factors incorporated a rule-based approach to derive soil clusters and land use classification within a geospatial framework. While it is not possible to directly compare reference SOC values for tier 1 and 2 approaches because of the soil classification systems used, the comparison of land use and management factors on SOC reference values highlighted some contrasting trends between these approaches. However, these differences are very small and within the bounds of statistical uncertainty. The overall uncertainty of the tier 2 models developed is 47%, which is nearly half of the uncertainty estimate cited for tier 1 methods, and adopting tier 2 methods could improve the LULUCF inventory. However, the introduction of new tier 2 models for reporting SOC stock changes could have a large impact on overall emission/removal trends.

Finally, the Estimation of Carbon in Organic Soils – Sequestration and Emissions (ECOSSE) biogeochemical model was used to simulate SOC in Irish agricultural systems to gain a better process-based understanding of the main factors influencing soil carbon stock changes at the point/site scale and at the country scale under mineral soils with different land use/management practices. When sourcing the main model inputs, particularly data for the soil characteristics, the lack of data on repeated measurements of SOC over time for Irish sites became apparent. In response, SOC data from the National Soil Database, Teagasc/SIS and LUCAS databases were used, with data carefully matched to identify 83 grassland sites that could be modelled. These grasslands were then grouped into management categories, defined by stocking rates, to assess the impacts of management intensity on SOC. The model outputs indicated an overestimation of SOC, highlighted the sensitivity of the model to the initial SOC inputs and demonstrated the need for replicated measurements of SOC over time to improve model evaluation and eventual parameterisation.

This report provides an overview of the activities and outputs of the SOLUM project. A further detailed report including all methodological approaches and analyses can be found in Saunders *et al*. (2021).

1 Introduction

1.1 Background

The impact of land use, land use change and forestry (LULUCF) on soil organic carbon (SOC) stocks and greenhouse gas (GHG) emissions is important in terms of national GHG inventory reporting as part of a strategy to offset GHG emissions. Globally, the loss of SOC due to LULUCF activities has been estimated to be ~156 Pg of carbon to the atmosphere between 1850 and 2000, comprising 18% of global emissions (Houghton, 2003). This is mainly due to the conversion of forested areas to agriculture and the conversion of grassland to cropland. Land use change can, however, also enhance the carbon sink strength of particular systems, as a result of increases in above- and below-ground biomass. Conversions from arable ecosystems to grassland, as well as afforestation, can lead to significant carbon sinks (Guo and Gifford, 2002). In addition to gross changes in land use, recent research has shown strong underlying patterns of agricultural land use change in Ireland (Zimmermann *et al.*, 2016), with constant shifts between cropland and grassland. While these short-term changes may significantly influence SOC stocks and GHG emissions and removals, there is a lack of information on the impact of these short-term transitions. Conversely, grassland and arable management may offer significant potential to increase SOC stocks through optimal nutrient and tillage management and reductions in fallow periods (Ceschia *et al.*, 2010). Soil disturbance has been shown to trigger SOC loss because of the disruption of soil aggregates that protect SOC and increased aeration, which enhances mineralisation rates (Roberts and Chan, 1990). The carbon emissions and potential sequestration linked to LULUCF are acknowledged in the United Nations Framework Convention on Climate Change (UNFCCC) and need to be reported in national GHG inventories (Höhne *et al.*, 2007; Schlamadinger *et al.*, 2007).

Currently, LULUCF reporting for national inventory purposes relies largely on tier 1 reporting methodologies, which use default emission factors and require the most basic and least disaggregated activity data (Duffy *et al.*, 2021), with the main limiting factors being the lack of availability of soil property and other activity data at an adequate spatial resolution. The recent development of new high-resolution data products, together with recent advances in Earth observation data will provide a new foundation for the development of tier 2 and/or tier 3 LULUCF GHG reporting methodologies in Ireland.

1.2 National Greenhouse Gas Emission Inventory Estimates

An initial step in preparing national GHG inventory estimates is to assemble the required activity data, such as land use and associated management, and match them with appropriate carbon stock, carbon/GHG emissions and removal factors and other relevant data (IPCC, 2006). The development of tier 2 approaches for reporting SOC stock changes requires high-resolution information on land use activity, soil type and robust SOC models or reference SOC estimates for different land use strata (SOC_{ref}; IPCC, 2006). Many previous attempts to develop national methods for reporting SOC stock changes have concentrated exclusively on either the activity data, such as the land use characterisation as assessed in the ILMO project, which was funded by the Environmental Protection Agency (EPA) (Cawkwell *et al.*, 2017), or the modelling of SOC (Khalil, 2020). Clearly, these two aspects (activity data and SOC models) are not mutually exclusive, and the development of a national system requires careful consideration of the approaches used to collect activity data and carbon stock change estimates (Paustian, 1997). The reporting requirements set out in Decision 2/CMP.8 permit the choice of two methods for the representation of land areas for national reporting (IPCC, 2014). Method I uses a spatial reference approach that delineates the geographical boundaries that contain multiple land uses, for example the stratified random sample grid adopted by the Irish National Forest Inventory (Forest Service Ireland, 2007) and the Eurostat Land Use and Coverage Area Frame Survey (LUCAS) (Gallego and Delince, 2010). Method II is based on spatially explicit and complete geographical coverage of all land uses subject to Articles 3.3 and 3.4 of the Kyoto Protocol on the reporting and accounting of LULUCF activities (UNFCCC, 1997). Previous attempts at matching coarse-scale land cover data from the Coordination of Information on the Environment (CORINE) data series with coarse-scale soil mapping (General Soil Map) provided a general estimate of land use and soil interactions (O'Brien, 2007). However, it was acknowledged that these data sources failed to capture the spatial complexity of land use and soils in Ireland (Black *et al*., 2009). Other remote sensing approaches that have been assessed, such as radar or multispectral analysis, are subject to significant uncertainties due to misclassification issues (Raab *et al*., 2015; Ali *et al*., 2016). Moreover, few studies have considered the statistical uncertainty of method II approaches (Magnussen *et al*., 2005). In contrast, the statistical method for estimating uncertainty associated with random sampling of permanent sample plots (method I) is well established (Magnussen *et al*., 2005).

1.3 Soil Organic Carbon Models

An understanding of SOC stocks and changes at the national and regional scales is necessary to further our understanding of the global carbon cycle, to assess the responses of terrestrial ecosystems to climate change and to aid policymakers in making land use/management decisions. The estimation of mineral SOC stock changes using Intergovernmental Panel on Climate Change (IPCC) tier 2 approaches requires derivation of country-specific reference SOC (SOC_{ref}) stocks for particular soil types and land use categories (IPCC, 2006). Process-based modelling approaches allow an estimate of SOC change to be made in a manner that accounts for the underlying processes driving such change to be made, and a range of process-based models have been applied to Irish SOC data to date (Abdalla *et al*., 2013, 2014; Black *et al*., 2014; Khalil, 2014; Necpalova *et al*., 2014). The Estimation of Carbon in Organic Soils – Sequestration and Emissions (ECOSSE) (Smith *et al*., 2010a,b) and DayCent (Parton *et al*., 1998) models appear to be better suited for agricultural soils (Khalil, 2014), while models such as CenW (Kirschbaum, 1999) and YASSO (Liski *et al*., 2005) are more robust for forest soils because they characterise the vegetation and soil interactions (Black *et al*., 2014). Dealing with dynamic SOC stock changes requires a modelling approach linked to spatially resolved data. Such approaches have the added advantage of being able to identify specific geographical areas of SOC stock change (Falloon and Smith, 2002; Black *et al*., 2014). The use of any system for estimating SOC stock changes at the regional scale is, however, constrained by data availability and a sufficient understanding of the ecosystem to which it is applied (Paustian *et al*., 1997).

1.4 Aims and Objectives

A robust understanding of SOC stocks and the potential for change, particularly within the LULUCF sector, is important in order to better inform mitigation strategies for GHG emissions and enhance removals. To enhance our knowledge in this area, the primary objective of the Soil Organic Carbon and Land Use Mapping (SOLUM) project was to develop a spatially integrated soil and land use dataset for Ireland that will provide:

- more robust estimates of reference SOC stocks;
- an enhanced methodology for reporting SOC stock changes;
- a better process-based understanding of the influence of land use, management and climate on SOC stocks, carbon stock changes and GHG dynamics;
- the capability to inform tier 2 reporting activities and land-based mitigation methodologies;
- robust uncertainty analysis in the national GHG inventory for SOC stock changes and GHG emissions and removals associated with LULUCF.

2 Land Use and Soil Inventory for Ireland

2.1 Introduction

The primary objective of this work package was to develop a spatially integrated soil and land use database for Ireland that can provide robust estimates of reference SOC stocks and potentially inform tier 2 reporting of activities and land-based mitigation methodologies. The intent was to exploit existing datasets – LUCAS and the Soil Information System (SIS) for Ireland – and overcome the two limitations of these data for site-specific attribution, as (1) LUCAS does not record information on grassland type and use, and (2) SIS is a map of soil associations, not of individual soil types, designed to be used only at 1:250,000 scale and not at point locations. As well as a number of older national land cover datasets for Ireland, there are datasets that were produced by the EU and Copernicus (Bossard *et al*., 2000), e.g. CORINE, and ad hoc land cover maps, covering counties and provinces of Ireland (Cawkwell *et al*., 2017, 2018), but there is no national land use dataset for Ireland that meets the spatial resolution and nomenclature requirements for the scope of this project. For agriculture, the Department of Agriculture, Food and the Marine (DAFM) maintains the Land Parcel Identification System (LPIS), which processes the Basic Payment Scheme (BPS). This database includes agricultural land use information mapped at the field parcel scale and is updated annually. It was not within the scope of this project to map land use or agriculture intensification; instead, it created a point-based database of typical land uses and their occurrence on specific soil types by producing the Land Use and Soil Inventory for Ireland (LUSII).

Soil data for Ireland are presented in the General Soil Map and the SIS, as soil association data; the range of soils series common in a soil landscape unit is described, but not the specific soil type at a particular point. Greater spatial detail is available from other data sources in Ireland, such as from the published county soil bulletins (Gardner and Radford, 1980) and the Teagasc/EPA soils and subsoils map (Fealy *et al*., 2009), along with field records (e.g. pits and augers). However, these cannot be directly attributed at a point scale without additional interpretation. This issue of scale and point attribution of soil properties to points from maps and vice versa is a well-articulated problem in the literature (McBratney *et al*., 2003). Geospatial methods are available that use topographical and land use data to ascribe a soil type to a point from a range of soils within a soil association (Kerry *et al*., 2012; Nauman and Thompson, 2014). However, this approach depends on the existence of a database linking soil type to land use. Previous attempts (O'Brien, 2007) at matching coarse-scale land cover data (CORINE) with coarse-scale soil mapping (General Soil Map) provided a general estimate of land use and soil interactions, but it was acknowledged that these data sources failed to capture the spatial complexity of land use and soils in Ireland (Black *et al*., 2009).

2.1.1 *Grassland classifications in Ireland*

Land cover and land use databases tend to ignore the large variation in grassland management between farms and across regions. For example, soil carbon stocks and emissions from an intensive dairy farm and an extensive beef system would be very different, but the land use of both is likely to be classed as "grassland" in most international systems, and this is one of the key drawbacks of the spatially detailed LPIS database. Managed grasslands could be divided along an axis of intensification from intensive (improved) through to semi-improved grasslands and to extensive/natural according to their management. These management actions change the emission profiles of a given type of grassland and thus the soil carbon stocks.

The main characteristics of an ideally improved agricultural grassland include monoculture swards and intensive cutting and grazing. In many countries, and as in the European regulations (e.g. Commission Regulation 796/2004), an area is considered to be "permanent grassland" if the land is covered with grass for at least 5 years or more. Per definition, there are no trees or scrub in improved grasslands.

In between the intensively used grasslands or in specific regions, there can be plots of less intensive or extensive grassland. These types of grasslands (e.g. hay meadows) could be considered to be semi-improved grasslands. The Eurostat Farm

Structure Survey (FSS) identifies three different types of permanent grassland: (1) pasture and meadow, (2) permanent pasture on good- or medium-quality soils and (3) rough grazing. In Ireland, classification tends to further refine on an axis of intensification/habitat (Fossitt, 2000; Sheridan *et al*., 2011). The classification used by LUSII is outlined in Box 2.1.

2.1.2 Principal data: Land Use and Coverage Area Frame Survey

LUCAS is coordinated by the statistical office of the European Union – Eurostat – and is carried out every 3 years (2009, 2012, 2015 and 2018). A stratified random point sample (see Figure 2.1) is created for Europe, and teams physically visit each point where possible and make detailed observations of land cover and land use (see Figure 2.2), while recording photographs of each point and of the horizon from the point in the four cardinal directions (see Figure 2.3).

In 2009, soil samples were also collected using a multistage stratified random sampling approach (McKenzie *et al*., 2008) based on land use and terrain information, systematically selecting 10% of the general LUCAS land cover/use points. In the 2009 survey, 233 topsoil samples (top 20 cm) were collected in Ireland (174 from grasslands), and the soil properties measured included the presence of coarse fragments (%), clay content (%), silt content (%), sand content (%), organic carbon content (g/kg) and

Box 2.1. Classification for LUSII

1 Permanent

- 1.1 Improved – managed
  - 1.1.1 **Intensive:** grassland with a single-species sward; typically grazed on an intensive 21- to 28-day rotation
  - 1.1.2 **Improved:** fertilised monocultural grasslands, for which the LPIS history is checked for the preceding 5 years and which carry fewer livestock units than the intensive grassland class
  - 1.1.3 **Semi-improved:** pasture and meadow, excluding rough grazing; permanent pasture on good- or medium-quality soils (can normally be used for intensive grazing); signs of management and the presence of rushes, other species, etc.
- 1.2 Unimproved – not managed/indirect management
  - 1.2.1 **Semi-natural:** rough grazing, enclosed
  - 1.2.2 **Extensive:** rough mountain and hill grazing

2 Temporary – cropland to grassland transitions

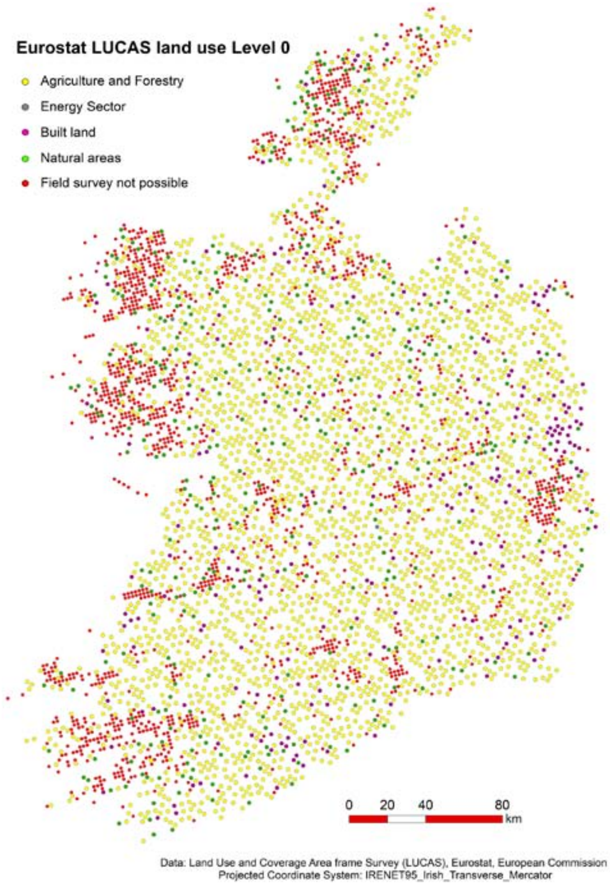


Figure 2.1. Complete LUCAS point database for Ireland in 2015. Colour coded to level 0 land use class [as listed on https://ec.europa.eu/eurostat/documents/205002/6786255/LUCAS2015_C3-Classification_20160729.pdf (accessed 25 April 2022); also available on SAFER].

Land cover			
A00	ARTIFICIAL LAND	A10	Built-up areas
		A20	Artificial non built-up areas
B00	CROPLAND	B10	Cereals
		B20	Root crops
		B30	Non-permanent industrial crops
		B40	Dry pulses, vegetables and flowers
		B50	Fodder crops (mainly leguminous)
		B70	Permanent crops: fruit trees
		B80	Other permanent crops
C00	WOODLAND	C10	Broad-leaved woodland
		C20	Coniferous woodland
		C30	Mixed woodland
D00	SHRUBLAND	D10	Shrubland with sparse tree cover
		D20	Shrubland without tree cover
E00	GRASSLAND	E10	Grassland with sparse tree/shrub cover
		E20	Grassland without tree/shrub cover
		E30	Spontaneously re-vegetated surfaces
F00	BARE LAND AND LICHENS/MOSS	F10	Rocks and stones
		F20	Sand
		F30	Lichens and moss
		F40	Other bare soil
G00	WATER AREAS	G10	Inland water bodies
		G20	Inland running water
		G30	Coastal water bodies
		G50	Glaciers, permanent snow
H00	WETLANDS	H10	Inland wetlands
		H20	Coastal wetlands

Figure 2.2. Land cover categories from the LUCAS database. Source: Eurostat (2022).

other nutrient measures. This survey was repeated in 2018; however, as of July 2020 the results remained unpublished. Note that bulk density was not measured in 2009 but is included in the suite of observations for 2018.

2.1.3 *Principal data: Soil Information System of Ireland*

The Irish SIS is the national digital resource for soils in Ireland. It includes soil profile, soil chemistry and soil property data. Each of the 89 soil series in Ireland are described completely in standard pedological format, and the series are grouped as associations and are mapped at the 1:250,000 scale. Soil association maps are typically a small-scale product and each association is a collection of soil series occurring together in an area (a common soil landscape unit). Therefore, with a soil association map it is not possible to definitively say what the soil properties are at a location with a mapped association, beyond the range of properties of the soil series represented by that association. Each association is named for the dominant soil series, but each has multiple series and occurs in multiple places. Each series belongs to a subgroup and, in turn, to the 11 great soil groups. The challenge in LUSII, therefore, is to ascribe particular soil attributes to observations of land use within the associations at a LUCAS point.

2.1.4 *Ancillary data*

For classification and data processing within the LUSII rule base, a number of ancillary datasets were used. They were also used to aid the interpretation of LUCAS photography and included the Ordnance Survey Ireland (OSi) Prime 2 model;[1] a digital elevation model (DEM), 30 m spatial resolution; orthophotography (1995, 2000, 2005, 2015);[2] Earth observation data, Landsat-8 (2015) and Sentinel 2a/b

1 Orthophotography and Prime 2 provided by OSi in accordance with the National Mapping Agreement.

2 Orthophotography and Prime 2 provided by OSi in accordance with the National Mapping Agreement.

Figure 2.3. Examples of point imagery from the LUCAS 2015 database. Source: https://ec.europa.eu/eurostat/web/lucas/data/primary-data/2015 (accessed 8 July 2022).

(2017 and subsequent years);[3] Teagasc soils and subsoils maps (Fealy *et al*., 2009); semi-improved grassland surveys (by the National Parks & Wildlife Service, NPWS) (Martin *et al*., 2007), LPIS (Zimmermann *et al*., 2016) and the Forest Inventory and Planning System (FIPS) (Forest Service Ireland, 2007).

2.2 Methodology and Results

The workflow for attributing improved land use data to LUCAS points and intersecting with soils information from SIS is shown in Figure 2.4. The work was conducted in three stages: (1) improving the classification of LUCAS grassland points; (2) processing the SIS association map and simplifying the soil attributes; and (3) ascribing soil attributes to land use.

2.2.1 Reclassifying LUCAS

The LUCAS points had to be refined, removing non-mineral soil points (peats, water, sealed surface), including cultivated peats, and further processed using rules based on ancillary data (land use history in LPIS, for example). The points were examined against the Prime 2 dataset to identify transitional/boundary points.

The clean point database was then examined on a point-by-point basis using the LUCAS photographic archive to confirm and enhance the land use classification against the schema outlined above. All LUCAS 2015 grassland points (~2200 points) were analysed in a geographical information system (GIS) framework, and the classification was interpreted, with reference to the original field photographs, LPIS, FIPS, Prime 2, satellite data (Landsat-8, Sentinel 2 and SPOT) and drainage network data, into relevant grassland land use classes. The rule base lists all

3 Landsat-8 data courtesy of the US Geological Survey. Sentinel data courtesy of the Copernicus Open Access Hub.

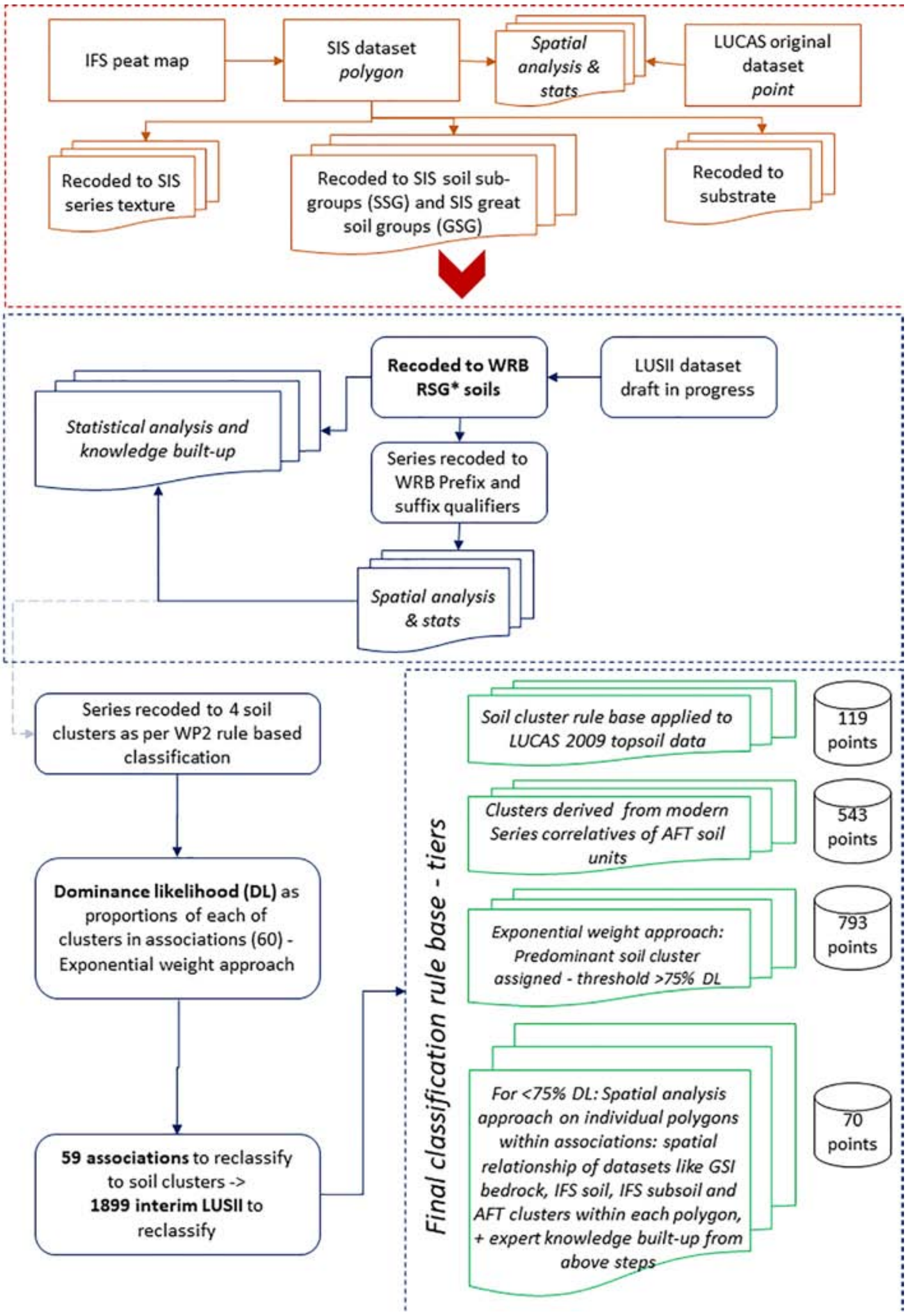


Figure 2.4. Workflow for the construction of LUSII. AFT, An Foras Talúntais; GSI, Geological Survey Ireland; IFS, Irish Forest Soils; RSG, reference soil group; WP2, second work package; WRB, World Reference Base.

cleaning and attribution rules used in processing LUCAS and SIS for LUSII; the complete rule base is available in SAFER.

2.2.2 Re-classifying SIS

Soil data ascribed to each land use point were derived from a reclassification of the SIS data to soil groups in accordance with the IPCC guidelines on soil classification (Hiraishi *et al*., 2014), which also deal with the heterogeneity of Irish soils. As it is not possible to downscale the SIS soil association map to particular soil properties at a particular point, it is necessary to simplify the associations. In the SIS, some of the associations can be ascribed to a single IPCC soil type; more complex associations can be disaggregated with ancillary data.

To address the issue of reducing complexity, the base soil properties information for each series was assessed for statistical separation and a clustering approach was taken (the soil clustering method was developed in work package 2 using the soil properties in the recorded soil series data). This identified four discernible clusters of soils within Irish soil series, loosely labelled as:

- loamy – class 1;
- clay – class 2;
- silty – class 3;
- sandy – class 4.

Each soil series was assigned to a cluster, as was each association. The class description for each association was determined with a weighted sum based on ranked occurrence of reclassified series. As well as reclassifying SIS, the 189 LUCAS soil samples were classified in the same way using these cluster values and assigned a land cover/land use in the same way.

The cleaned LUSII land use points were then intersected with reclassified soil data and attributed the following appropriate soil value depending on the point provenance:

- tier 1: LUCAS 2009 topsoil data;
- tier 2: An Foras Talúntais (AFT) soil survey map;
- tier 3: a more than 75% threshold applied to series-derived soil clusters, with maximum percentage soil cluster assigned with >75% certainty;
- tier 4: spatial approach on individual polygons within associations.

2.2.3 LUSII database

The LUSII database contains points with a land use description and soil cluster value. The database is stored as the Economic and Social Research Institute (ESRI) geodatabase and is available through SAFER. The results are shown in Figures 2.5 and 2.6.

2.2.4 Accuracy assessment

The accuracy of land use attribution was tested against an independently acquired set of expert observations of a subset of 198 points in LUSII (with overlap between points ascribed to experts). The accuracy was good (see Table 2.1), with the largest error between intensive and improved grassland; however, this has no impact on the soil carbon modelling, as these two classes are combined.

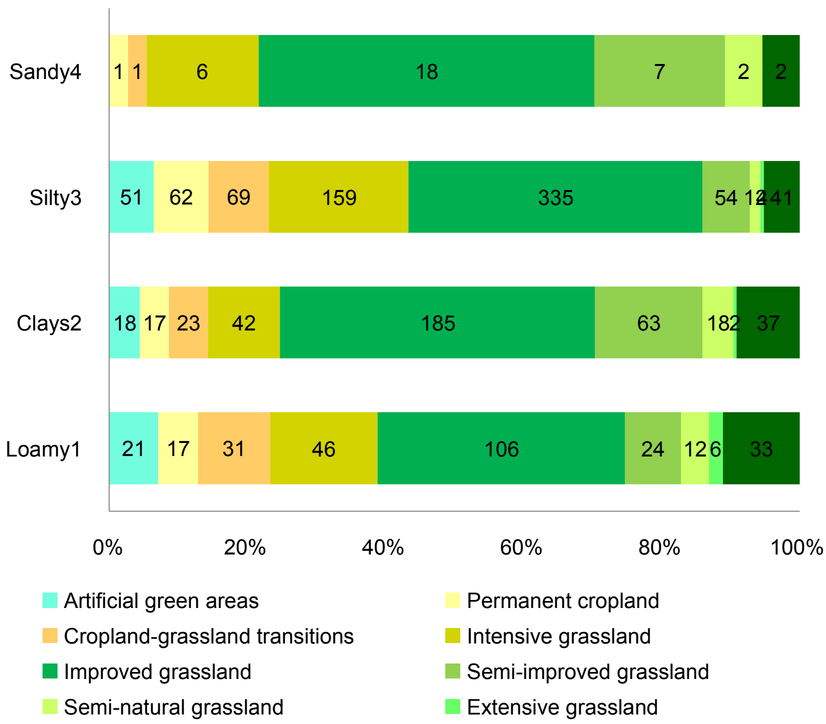
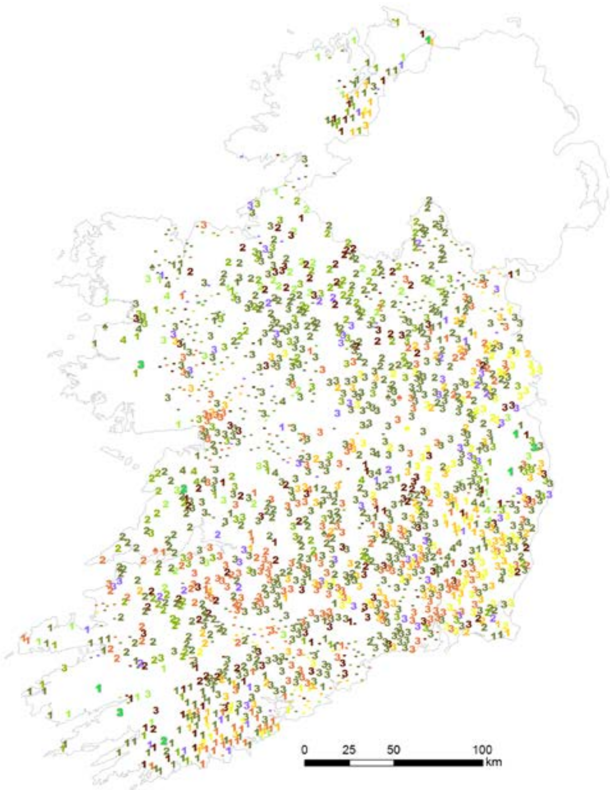


Figure 2.5. Percentage occurrence of LUSII land use classes within soil clusters (figures in black represent number of land use class observations within each soil cluster).



Soil cluster	Land cover
1 Loamy 2 Clayey 3 Silty 4 Sandy 5 Undefined	Cropland-grassland transitions Intensive grassland Improved grassland Semi-improved grassland Semi-natural grassland Extensive grassland Forestry Permanent cropland Artificial green areas

Figure 2.6. Final LUSII land cover and soil clusters point inventory. Because of the complexity of the data and to ease legibility, the colours represent different types of land use and numbers represent the soil clusters. The full-resolution map is available on SAFER.

Table 2.1. Accuracy assessment of land use attribution results (%)

Land use	Artificial green areas	Cropland-grassland transitions	Extensive grassland	Forestry	Improved grassland	Intensive grassland	Permanent cropland	Semi-improved grassland	Semi-natural grassland
Omission	0	0	0	8	17	51	0	0	0
Commission	0	5	0	8	40	3	0	53	25
Producer's accuracy	100	100	100	92	83	49	100	100	100
User's accuracy	100	91	100	92	59	97	100	47	75

Note: Observed agreement/overall accuracy is 0.77; agreement by chance is 0.22; kappa coefficient is 0.70.

To attempt to test the soil attribution, each of the LUCAS topsoil points with associated LUSII data was ascribed a cluster value based on its recorded data for silt content, clay content, etc., and compared with the predicted cluster using the standard LUSII method. The results are relatively poor, with an overall correspondence of 53% and with cluster 3 having a 66% correspondence between sampled values and

SIS-predicted values (see Table 2.2). However, this can be attributed to the fact that the LUCAS sample data are based on the 20 cm of topsoil while SIS data on soil properties are based on the entire profile.

2.2.5 Land use change

There have been four LUCAS surveys of Ireland (in 2009, 2012, 2015 and 2018), which recorded land use and land cover, but the location of survey points changes, so the degree of change was assessed. Each survey point from the four surveys was ascribed a Prime 2 GUID (globally unique identification code),[4] with each GUID representing a stable geographical object in the Prime 2 database; in the case of most of the LUCAS points the "object" is a field. If points from two surveys have the same GUID, then the samples/observations are taken from the same field. Figure 2.7 shows that within the four LUCAS surveys (of approximately 4800 points each), most observations are unique, i.e. a GUID occurs only once (10,059 GUIDS were identified in total). Only 196 points were sampled in the same place over the four surveys. Therefore, the LUCAS database is not appropriate for monitoring change at locations for modelling purposes (it is designed to monitor change at the national statistical scale).

Table 2.2. Accuracy assessment by comparing soil clusters derived from LUCAS 2009 point sample soil data and the same point data attributed through reclassified SIS

	LUCAS topsoil-derived soil cluster (truth)				
SIS-derived soil cluster (predicted)	**1**	**2**	**3**	**4**	**Grand total**
1	13		17	2	32
2	6	10	12		28
3	23	14	61	2	100
4				1	1
Grand total	42	24	90	5	161
Omission (%)	69	58	32	80	
Commission (%)	59	64	39	0	
Producer's accuracy (%)	31	42	68	20	
User's accuracy (%)	41	36	61	100	

Note: Observed agreement/overall accuracy is 0.53; agreement by chance is 0.43; kappa coefficient is 0.18. Matching observations are on the diagonal. This is an excerpt; the original file is available on SAFER.

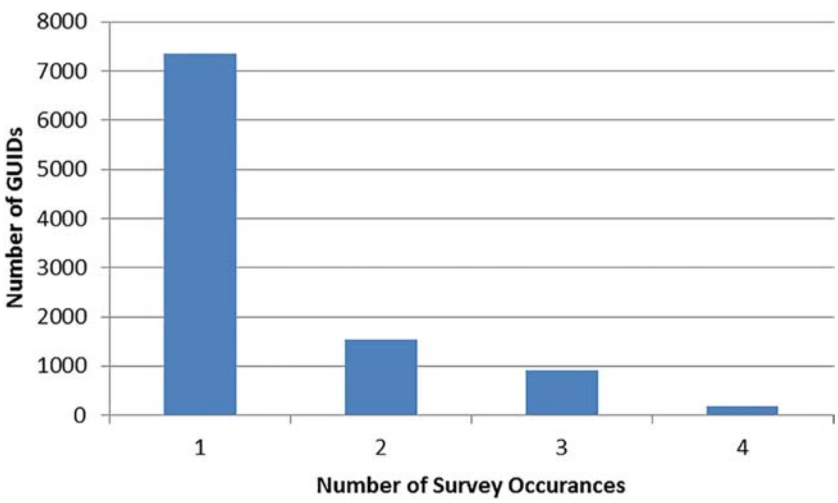


Figure 2.7. Number of times a Prime 2 GUID occurs in the four LUCAS surveys (2009–2018).

4 See https://osi.ie/wp-content/uploads/2018/04/PRIME2-Client-Documentation-Concepts-V-02.4.pdf (accessed 1 June 2022).

Table 2.3. National land use change matrix between 1995 and 2015

1995 Land cover	2015 Land cover						
	BL	C	CG	F	IG	U	Total
BL	111						111
C	1	85	12		23		121
CG			84				84
F				84	3		87
IG	20	12	26	20	1020	13	1111
U	1			2	6	37	46
Total	133	97	122	106	1052	50	

Note: Grey shading indicates that the landcover was unchanged. This is an excerpt; the original data are available on SAFER. BL, built land; C, cropland; CG, cropland to grassland transition; F, forestry; IG, improved grassland; U, unimproved grassland.

For the national LUSII, change assessment points were visually inspected against the 1995 and 2005 orthophotography and ascribed a land use for GHG modelling, improved grassland, unimproved grassland, cropland or forest. Table 2.3 shows that in this period land use appeared stable (grey boxes are unchanged) with 94% or points unchanged. There is an increase in forestry and a decrease in cropland. See Chapter 3 for calculation of soil emissions impacts.

2.3 Discussion and Conclusions

This work has shown that simplified information about soils can be extracted from the SIS database for ascribing soil properties to a point, but the accuracy could be improved. Using level 1 land use data on improved grassland, unimproved grassland, forestry, cropland and built land (settlements), with five soil types, clusters 1, 2, 3 and 4, and organic soils, gives only 20 permutations to be sampled (built land is assumed to be sealed), and this should be the basis for a national fixed soil observatory. The simple soil properties needed for assigning the soil to a cluster can be collected. In future, land use data, at the field scale, should be ascertained using the new OSi National Land Cover and Habitats Map and the EPA land use mapping developed for reporting under the LULUCF Regulation [Regulation (EU) 841/2018].

3 Development of Tier 2 Soil Organic Carbon Stock Change Factors for LULUCF Reporting

3.1 Introduction

Changes in SOC stocks are dependent on land use management, soil type or structure and geochemical processes influenced by climatic and topographical factors (Houghton and Skole, 1990; Don *et al*., 2011). However, estimation of SOC stocks and stock changes following disturbance due to land use transition is subject to considerable uncertainty. The IPCC provides guidance on how carbon stock changes should be estimated for reporting to the UNFCCC and the Kyoto Protocol. Estimating the change in SOC content in mineral soils requires the determination of reference soil carbon stocks associated with all land use types (IPCC, 2006). A major limitation of the IPCC approach is that soils are unlikely to reach a steady state, assuming the default 20-year period, before transitioning from one land use to another (Agostini *et al*., 2015). Process-based model (tier 3) approaches offer a more robust representation of soil carbon dynamics following land use change (Parton *et al*., 1994; Liski *et al*., 2005; Smith *et al*., 2010a), but these require extensive calibration and are difficult to implement at the national scale. Therefore, most national inventory reports to the UNFCCC still use tier 1 or 2 approaches. Numerous previous research assessments have attempted to derive robust tier 2 SOC reference (SOC_{ref}) and land use change factors values using generalised soil classification systems, but with limited success (Scott *et al*., 2002; Eaton *et al*., 2008; Wellock *et al*., 2011; Xu *et al*., 2011; Black *et al*., 2014). In all of these studies, the grouping of soils into principal or general groups was done without any statistical validation to justify such categorisations. Furthermore, these classifications do not consider how soil-forming processes or soil textural or chemical properties may influence SOC dynamics. An alternative approach, to be used at the national level, could be the characterisation of SOC dynamics due to land use change based on specific soil series. The national Irish soils series is defined based on underlying parent material and soil textural properties (Creamer *et al*., 2014). Data limitation is another reason why previous attempts to develop tier 2 SOC factors were not successful. Black *et al*. (2014) collated a national database representing 227 sample sites located primarily on forest and grassland soils. This project was aimed at improving this database by including the recently obtained SOC data from the SIS project (Creamer *et al*., 2014) and the 2015 LUCAS soil data (Orgiazzi *et al*., 2018).

In this study, we attempted to develop tier 2 SOC factors for different soils (SOC_{ref}), land uses (F_{lu}) and management types (F_{MG}); we also developed a newly collated soils database and introduced a novel approach of classifying soils into clusters based on soil textural properties. The current National Inventory Report (NIR, 2020) has identified new activity data from the LPIS, which can be used to better characterise transitions between croplands, improved grasslands and unimproved grasslands. It is evident from analyses presented in the NIR (2019) that SOC_{ref} values for some cropland and improved grasslands may never reach a steady-state condition, because conversions from one land use to another can occur frequently (e.g. 3–10 times within a 20-year cycle). This introduced additional complications in deriving factors for transitioning land uses because the introduction of more factors increases the need for larger datasets (see the data limitations section). We propose dealing with transitioning grassland/croplands (Tr_CL) as a management regime under croplands, rather than as distinct grassland subcategories. The $SOC_{ref,}$ F_{lu} and F_{MG} for different soils and land uses were modelled using a three-factor simple general linear model.

3.2 Methodology

For a detailed description of the methodology used, please refer to the full technical report (Saunders *et al*., 2021).

In summary, soils were classified into categories using the SIS dataset, which was interrogated using principal component analysis (PCA) to identify which important physical, chemical or geographical features may be used to categorise soil series into groups.

The final assignment of soil series into categories was done using *k*-means cluster analysis (Kaufman and Rousseeuw, 1990).

The predicted SOC_i values for each soil group and land use were derived using a generalised linear model (GLM) with soil cluster, land use and management regime as dependent factors.

$$SOC_{0-T(i,j,h)} = GLM = \exp[a + CL_i + Flu_j + FMG_h] \quad (3.1)$$

where *a* is the intercept of the linear model, using factors CL (soil clusters = four soil clusters), F_{lu} [land uses, $j = 3$ classes, crop (CrL), forest (FL) and grasslands (GL)] and F_{MG} (management regime factors; grassland only, $h = 3$ regimes, II = improved, I = unimproved and III = transitioning grasslands) parameters from the statistical model. Soil data for settlement were excluded from the analysis on account of the small sample size ($n = 3$).

Once national models were developed, the LUSII database was used as the basis for determining mineral SOC stock changes using soil cluster and land use attributes for 1995, 2005 and 2015. The LUSII database is derived from LUCAS, which is a land cover sample grid at 2 km, representing 400 ha per point. The soil sample grid is a random sample of 10% of the LUCAS grid, representing 4000 ha per sample. Soil clusters were derived from the SIS series soil texture data for each sample point. The land cover for 1995, 2005 and 2015 was determined for each point using methods outlined in Chapter 2. Tier 2 SOC_{0-T} values were developed, as described in equation 3.1, and used to estimate soil stock changes. The geospatial and advanced model could not be used because there was no information on soil carbon inputs in the LUSII database.

3.3 Results and Discussion

3.3.1 *Defining soil clusters*

Classification of soil series clusters

The selection of final factors to use in the *k*-means cluster analysis was based on two criteria: (1) the availability of data (i.e. the soil data that are commonly available) and (2) a measure of the goodness of fit of the *k*-means classification. This is based on an assessment on the decomposition of deviance expressed as the total sum of squares (TSS), between sum of squares (BSS) and within sum of squares (WSS) clusters. The ideal cluster would have properties of internal cohesion and external separation, i.e. the BSS to TSS ratio should be 1. Table 3.1 shows the goodness of classification when factors were excluded from the cluster analysis. The BSS to TSS percentage increased from 31% to 99% when all factors identified in PCA were included, compared with when only soil texture was included (i.e. percentage of sand, silt and clay). A similar optimisation was carried out to test whether the number of clusters influenced the goodness of fit to confirm the gap and elbow statistics. This confirmed that four clusters are the optimal size for this classification (data not shown).

The dimensional scatterplot from the final *k*-means cluster analysis shows a reasonable level of cohesion within clusters and separation between clusters (Figure 3.1).

3.3.2 *The tier 2 model*

The model fit and all coefficients for the GLM (equation 3.1, Table 3.2) were significant ($p < 0.05$). The model residual standard error was 0.4326 based on 563 degrees of freedom. There was no significant model bias (–8 t C ha^{-1}) in the prediction of SOC_{0-T}.

3.3.3 *National SOC stock changes*

Soil carbon stock changes at the national level

Upscaling the two models to the national scale using the LUSII database showed that land use change and management resulted in a net removal of –228.7 kt CO_2 from mineral soils in 2005, but there was

Table 3.1. The effect of including identified factors on the goodness of classification (BSS to TSS percentage) using *k*-means for four cluster groups

Factors included	BSS to TSS (%)
Texture, SOC, cation exchange capacity, topex	31.2
Texture, SOC, topex	53.2
Texture, SOC	75.4
Texture	99.7

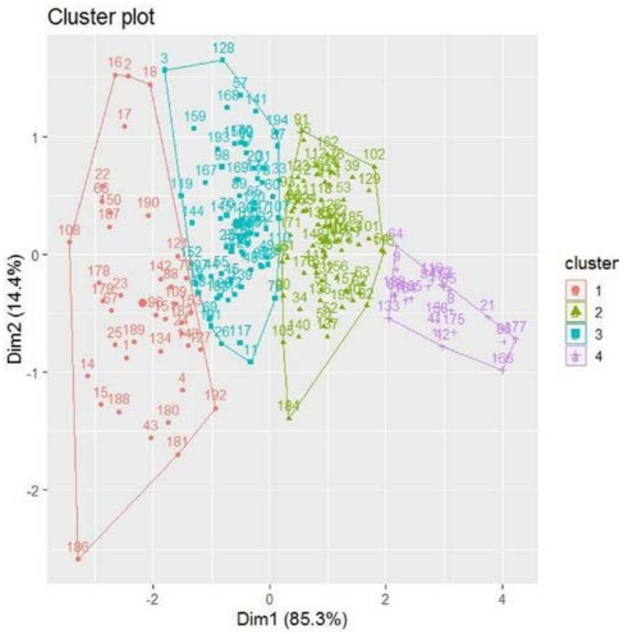


Figure 3.1. A cluster plot showing the clear separation of soil clusters (1–4) based on soil textural properties. The numbered points in the scatterplot represent the soil pit row number in the data.

a shift to a net emission of 181.4 kt CO_2 from mineral soils by 2015 (Table 3.3).

For the 1995–2005 time series, mineral soil emissions from land converted to croplands (permanent cropland and cropland grassland transitions) was 562 kt CO_2 per annum. This increased to 891 kt CO_2 per annum for the 2005–2015 time series as a result of increased transitions from improved grassland, in particular transitioning from grassland to cropland.

The observed increase in removals from mineral soils in lands converted to forest land is associated with the increase in forest area between 2005 and 2015 (Table 3.3). The forest inventory currently adopts a tier 3 model, namely the carbon budget model (CBM), for reporting emissions and removals from mineral soils from afforested and managed forest land, so it is unlikely that the new tier 2 approach will be adopted in the LULUCF inventory. Currently reported mineral soil removals from "grasslands remaining grasslands" for 2005 and 2015 are –1246 and –1563 kt CO_2 (NIR, 2019), compared with tier 2 estimates of –24 and –74 kt CO_2 for the same periods (Table 3.3). The SOC emission/removal trends in grasslands remaining grasslands are driven by conversions between improved and unimproved grasslands (NIR, 2019; Table 3.3).

3.4 Conclusions

3.4.1 The new soil classification system for carbon reporting

A combination of PCA (to identify factors) and cluster analysis (using identified factors from PCA) provides

Table 3.2. The statistics of fitted coefficients used for the GLM

Class	Stratum	Coefficient	Standard error	*t*-value	*Pr* (>|*t*|)
Intercept		4.22634	0.08043	52.55	$<2\times10^{-16}$***
Soil cluster	1	0			
	2	0.29236	0.04969	5.884	6.89×10^{-9}***
	3	0.08811	0.04453	1.979	0.048341*
	4	–0.23284	0.07448	–3.126	0.001861**
F_{lu}	CrL	0			
	FL	0.36125	0.08436	4.282	2.18×10^{-5}***
	GL	0.2673	0.07987	3.343	0.000883***
F_{MG}	I	0			
	II	–0.10519	0.04408	–2.386	0.017347*
	III	–0.36278	0.10077	–3.6	0.000346***

Note: See equation 3.1. In this table soil clusters are as defined in Table 3.6 in the full end of project technical report (Saunders *et al*., 2021). The soil clusters are defined based on soil textural properties as (1) loamy, (2) high clay (>29%), (3) silty and (4) sandy (>71%). Land use categories (F_{lu}) are cropland (CrL), forest land (FL) and grassland (GL). The management regimes are unimproved grasslands (I), improved grassland (II) and cropland that frequently transitions to grassland (i.e. cropland with grassland fallow (III)). *F*-value = 14.36, $p<2.2\times10^{-16}$*, adjusted $r^2=0.1409$, Akaike information criterion = 673.57.**

***$p<0.05$; **$p<0.01$; ***$p<0.001$.**

Table 3.3. Net emission/removals from mineral soil associated with land use transition over the periods 1995–2005 and 2005–2015

Land use transition	Mineral soil carbon emissions/removals (t CO_2 per year) 1995–2005	2005–2015
Cropland to grassland transitions converted from	227,849	891,538
Cropland to grassland transitions		
Permanent cropland	31,288	45,658
Forestry	0	0
Improved grassland	196,560	810,581
Unimproved grassland	0	35,299
Permanent cropland converted from	323,446	204,572
Cropland to grassland transitions	–11,115	204,572
Permanent cropland		
Forestry	0	0
Improved grassland	334,561	0
Unimproved grassland	0	0
Forestry converted from	–221,285	–464,766
Cropland to grassland transitions	0	0
Permanent cropland	0	0
Forestry		
Improved grassland	–195,439	–410,222
Unimproved grassland	–25,845	–54,544
Improved grassland converted from	–545,982	–313,025
Cropland to grassland transitions	–364,825	0
Permanent cropland	–242,462	–472,860
Forestry	17,450	88,583
Improved grassland		
Unimproved grassland	43,855	71,253
Unimproved grassland converted from	–72,707	–136,890
Cropland to grassland transitions	–13,509	0
Permanent cropland	0	0
Forestry	8679	8679
Improved grassland	–67,877	–145,570
Unimproved grassland		
Grand total	–288,679	181,428

Note: Grey shading indicates transitions that do not occur but rows are kept in the table for consistency. Negative values indicate a net removal of CO_2.

a systematic approach to classifying soils into groups for the purpose of defining SOC_{ref} values using an approach that is in line with tier 2 IPCC methodologies. It also provides the modelling framework as a means of identifying factors that may influence SOC dynamics.

The tier 2 model presented provided SOC factors that can be directly applied to the LULUCF GHG inventory land use categories. However, the inventory would need to incorporate the rule-based model to derive soil clusters using the NIR-specified land use classification and a spatial framework.

The LUSII land use tracking results are in broad agreement with land use change trends reported in the Irish GHG inventory. However, the sampling error associated with low sampling intensity (1 sample = 4000 ha) introduced a higher level of uncertainty than other sample grids (e.g. NFI). Use of the proposed new EPA geospatial framework using a raster grid (Smith, 2019) may be more appropriate for tracking land use change and reporting SOC stock changes, as long as the soils cluster rule-based model can be implemented at the national scale. The upscaling exercise suggests that the introduction of new tier 2 models for reporting SOC stock changes could have a large impact on overall emission/removal trends for the LULUCF sector. For croplands, the current inventory system estimated a net removal of –57 kt CO_2, compared with a net emission of 1096 kt CO_2 in 2015. However, 891 kt CO_2 of these emissions come from permanent transitions from grassland to cropland using the LUSII system; this is in contrast to no reported transitions to cropland in the Irish LULUCF inventory. For grasslands, the current inventory reports large removals of –1562 kt CO_2, compared with a much lower removal of –74 kt CO_2 if the new tier 2 approach is adopted. The overall emissions from the LULUCF for 2015 could increase by 2643 kt CO_2, which is an increase of 55% for the year 2015. However, if there are no transitions from grassland to cropland, as suggested in Duffy *et al*. (2019), the increase would be only 1752 kt CO_2 per year, an increase of 36%. It should, however, be stressed that the real implication of using the newly developed model first needs to be tested by defining the soil clusters in the proposed national inventory spatial land use framework and then assessing the GHG trends because the LUSII land use change trends are different from those presented in the current inventory (NIR, 2019).

4 Soil Organic Carbon Process-based Modelling Using the ECOSSE Biogeochemical Model

4.1 Introduction and Background

The main objective of this work was to apply the ECOSSE model (Smith *et al*., 2010a) to predict SOC and gain a better process-based understanding of the main factors influencing SOC storage and carbon stock changes at the point/site scale and at the country scale, primarily focusing on Irish agricultural land with mineral soil and under different land use/management practices. The specific tasks included in this work were obtaining model inputs using currently available sources/databases on Irish soil and land use data; process-based modelling and evaluation of model performance to predict SOC; uncertainty and sensitivity analysis (SA); and, finally, planning for the upscaling of model predictions.

4.2 Materials and Methods

4.2.1 ECOSSE model inputs, grassland categorisation and site selection

This study uses the ECOSSE v.6.2b model in "site-specific" mode (with daily time step inputs and outputs used). A detailed description of ECOSSE is provided in Smith *et al*. (2010a). The main model input data were (among others) climate and atmospheric data, soil inputs (i.e. starting SOC, a number of soil, physical, chemical and water parameters), crop inputs (i.e. type, yield) and information on management practices (i.e. fertilisation, manure inputs and timing). The main data sources for these model inputs were Met Éireann Re-analysis (MÉRA)[5] (Gleeson *et al*., 2017; Met Éireann, 2018; Whelan *et al*., 2018), the European Monitoring and Evaluation Programme (EMEP) (EMEP, 2018, 2019), Teagasc/SIS (Teagasc, 2018), LUCAS (Tóth *et al*., 2013; JRC and ESDAC, 2018), the Irish National Soil Database (NSDB) (EPA, 2007; Fay and Zhang, 2020) and the LPIS (Zimmermann *et al*., 2016). Some soil inputs could be directly derived from processed data and some had to be computed using pedotransfer functions (i.e. Wolff, 1864; Van Bemmelen, 1890; Falloon *et al*., 1998). Because of the lack of available SOC data with repeated measurements over time during this study, the initial or starting SOC input values[6] (SOC_{start}) required during the model initialisation were obtained from NSDB datasets. Yield was estimated from stocking rates (SRs) derived from Green *et al*. (2016) using information from O'Donovan and Egan (2017).

Grassland categories (Table 4.1) were assigned to each site based on the land use and management information derived from LPIS data and the SRs derived from Green *et al*. (2016) using a conversion factor of 85 kg N per livestock unit (Smiddy and Hyde, 2017). Only grassland sites were selected because of the low numbers of matching sites for other land use types. Information on fertiliser inputs was adapted from literature sources (information is provided in Table 4.2 and notes to the table). ECOSSE v.6.2b has no grazing input option, and therefore the manure model inputs were used as "grazing alternative". The cattle excrement inputs were included through conversion of the SRs (Green *et al*., 2016) into manure inputs using a factor of 85 kg N per livestock unit (Smiddy and Hyde, 2017) and parameters for manure provided in ECOSSE[7] (Smith *et al*., 2010b). Manure model inputs were split into five equal inputs evenly distributed across the year. Further correction of manure inputs over the winter months was applied in the model by using one-half of the application value for a single application per season out of a maximum of five.

The potentially suitable sites were first selected from the LUCAS and Teagasc/SIS databases[8] (Tóth *et al*., 2013; JRC and ESDAC, 2018; Teagasc, 2018).

5 MÉRA data processing was performed by Dr Reamonn Fealy (Teagasc).

6 Modelling was done for the top 10 cm.

7 Parameters used were 25% dry matter content in fresh cattle organic manure and 2.4% nitrogen content in cattle manure dry matter (Smith *et al*., 2010b).

8 Sites that lacked information on sampling date/year were excluded.

Table 4.1. Grassland management categories depending on stocking rates

Grassland management category[a]	Abbreviation	SR (kg org. N ha^{-1} y^{-1})
Minimal[b]	MI	≥70
Reduced–low[b,c]	RL	71–110
Low[b]	L	111–150
Medium–low[b]	ML	151–170
Medium[b]	M	171–190
Medium–high[b,d,e]	MH	191–210
High[b,d,e]	H	211–250

[a]The categorisation of selected sites into grassland categories was done by combining information on land use and SR values. This was done separately for each selected site for which land use information was obtained from the LPIS for each year of simulation and each site, and the SR values were obtained from the model by Green *et al.* (2016) for each site.

[b]Adapted from Coulter *et al.* (2005), Lalor *et al.* (2010), Humphreys (2012), Lalor and Walsh (2017), Teagasc (2017) and Dillon *et al.* (2018).

[c]"Reduced-L40" with a 40 kg N ha^{-1} total fertilisation limit (adapted from Walsh, 2017) was initially introduced, but was later merged with "reduced-low" to reduce the number of categories.

[d]The category "high" has lower nitrogen fertilisation rates than the "medium–high" category, which reflects the fertilisation advice for higher and medium SRs provided by Teagasc; see examples in Lalor and Humphreys (2012) and Teagasc (2017).

[e]A limit of 170 kg N ha^{-1} per year applies in Ireland, which means that the amount of livestock manure applied per year, added to what the livestock deposit directly, must be <170 kg N ha^{-1} (Good Agricultural Practice for Protection of Waters; Statutory Instrument No. 605 of 2017; Nitrates Biodiversity & Engineering Division; DAFM, 2017). This can have implications for the permissible SR; however, it is known that a large number of farmers in Ireland have applied for derogations (Finnerty, 2017). Therefore, a higher limit was considered, and this was taken into account when establishing the categories "medium–high" and "high".

Note: See Table 4.2 for the fertilisation inputs.

Table 4.2. Amount and timing of fertiliser application[a] (per day of the year) based on "advice" and "practice" (in brackets),[b] with the annual fertilisation rates split into five applications

Category	Day 75	Day 117	Day 147	Day 189	Day 246	Total[c] (kg N ha^{-1} y^{-1})
Minimal[d,e]	0	0	0	0	0	0
Reduced–low[d,e,f]	20 (20) *0*	20 (20) *0*	0 (0) *0*	30 (28) *2*	0 (0) *0*	70 (68)
Low[d,e]	23 (23) *0*	32 (21) *11*	20 (20) *0*	33 (23) *10*	33 (23) *10*	141 (110)
Medium–low[d,e]	33 (23) *10*	50 (32) *18*	33 (22) *11*	56 (43) *13*	29 (22) *7*	201 (142)
Medium[d,e]	64 (33) *31*	52 (40) *12*	36 (33) *3*	60 (56) *4*	25 (22) *3*	237 (185)
Medium–high[d,e,g,h]	73 (64) *9*	53 (50) *3*	48 (46) *2*	72 (63) *9*	34 (32) *2*	280[h,i] (255)
High[d,e,g,h]	70 (62) *8*	50 (50) *0*	39 (46) *7*	66 (53) *13*	25 (32) *7*	250 (243)

[a]The maximum number of application inputs per season in ECOSSE is 5.

[b]The "advice" and "practice" fertilisation rates were adapted using information obtained from the literature (see table note c). Test-simulations showed that the ECOSSE model is not sensitive to introduced differences between "advice" and "practice", and finally the simulations on selected sites were performed using fertilisation rates based on "advice".

[c]Nitrogen fertiliser amounts applied in simulations were based on the extracted SR values for sites and were cross-checked against the maximum permissible nitrogen rates (Teagasc, 2017) depending on the site location (counties).

[d]See Table 4.1, note "b".

[e]The categorisation of selected sites into grassland categories was done by combining information on land use and SR values. This was done separately for each selected site where land use information was obtained from the LPIS for each year of simulation and each site, and the SR values were obtained from the model by Green *et al.* (2016) for each site.

[f]See Table 4.1, note "c".

[g]See Table 4.1, note "d".

[h]See Table 4.1, note "e".

[i]Depending on the maximum permissible fertilisation rate for selected counties (Teagasc, 2017).

Note: Differences are in italic.

MI, minimal; RL, reduced–low; L, low; ML, medium–high; M, medium; MH, medium–high; H, high.

Considering that the NSDB database (EPA, 2007; Fay and Zhang, 2020) predates the other two databases, the SOC_{start} was assigned by potentially matching NSDB sites to selected LUCAS and SIS sites in ArcGIS. SOC_{start} from NSDB was theoretically assigned to the year 2002.[9] Of all finally selected LUCAS and SIS sites, 91% were within at least 10 km of the matching NSDB site. Sites were selected on the basis of each of the two matching sites (NSDB matched LUCAS or NSDB matched SIS) having the same land use/management at the start of simulation. Information on soil associations from Teagasc/SIS (Teagasc, 2018) was used for additional screening.[10] Finally, 94 grassland sites[11] were selected in total (without excluding potential outliers), which formed two final datasets containing 42 LUCAS sites and 52 Teagasc/SIS sites. Each selected site included the information on SOC_{start} (assigned to 2002) and the second observed/measured SOC "end" value required for model evaluation, i.e. LUCAS sites: 8 years of simulation run from 2002 "start" (including 2002) to 2009 "end"; SIS sites: 10, 11 or 12 years of simulation run from 2002 "start" (including 2002) to either 2011, 2012 or 2013 "end" (depending on when the "end" SOC was measured).

4.2.2 Assessing model performance

Results were examined by plotting measured and simulated SOC values, as well as regression analysis and a number of model prediction indices (outlined in Figure 4.2b). Because of the lack of information on local variability of observed SOC for individual Irish sites, the model diagnostics could be performed only across all sites. This was done on the combined LUCAS and SIS dataset of selected sites (i.e. 83 sites out of a total of 94, after excluding a total of 11 potential outliers).

The sensitivity of the model to changes in inputs (within introduced estimated input boundaries) was assessed using a Monte Carlo analysis. In this study, the Latin hypercube (LHC) sampling (which forms part of the so-called Monte Carlo propagation of uncertainty procedure; Helton and Davis, 2002) was chosen for generating inputs within input boundaries.[12] Because of the large number of inputs (and therefore very long scripts) the simulation runs were done on a reduced number of repetitions (in hundredths) to cut the time taken to run long scripts. Python scripts used for SA were adapted from Wang and Duan (2015). On account of the high dimensionality (25 input parameters[13]) and potential correlations of some of these parameters, it was assumed that the so-called δ (delta) indicator from delta moment–independent measure (DMIM) SA, which is explained in Plischke *et al*. (2013), would be a more suitable method for SA because it allows for potential correlations. In order to examine potential correlations, the Pearson correlation coefficient was used for checking the findings in conjunction with the earlier SA. Upon the successful completion of point-based modelling (at the site scale), the plan was to upscale the SOC prediction models to the national scale using the national inventory data outlined in Chapter 2.

4.3 Results and Discussion

Results from the process-based modelling of SOC for selected LUCAS and SIS Irish grassland sites were examined by plotting observed versus simulated SOC values and are presented in Figure 4.1a. The model prediction indices (i.e. r^2 of 0.072, root mean square error of 36.85%, and a model efficiency value of –0.36; Figure 4.1b) indicate that there is poor correlation between modelled and measured values and that the model efficiency is low. An average difference between ECOSSE-modelled SOC and observed SOC values was calculated for different grassland management categories (Figure 4.1c); results indicate an overall overestimation of predicted SOC (i.e. positive

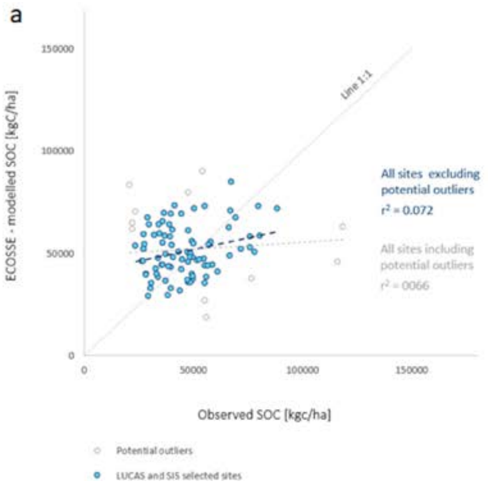
9 This represents the year from which the model simulation is run forward.

10 Only the matches where both sites were located on the same soil association type or on the soil associations that contained at least one same soil series type were selected. Sites located on organic soils/peat and alluvium (river, marine) and sites with > 10% SOC were also excluded.

11 Sites with arable and mixed (arable + grassland) land use were excluded on account of low numbers of matching sites required for both modelling and model evaluation.

12 This work still needs to undergo further checking and potential improvements, i.e. Python scripts used in this analysis are very long because of the large number of input parameters (25) and they need checking for potential errors.

13 Input parameter refers to input.



b

ß0 [a]	ß1 [a]	ResidSterr[a]	r^{2} [b]	p-value [c]	RMSE [d] [%RMSE]	ME [e]
29779.72	3.225e-01	14277.40	0.072	0.014	17048.07 [36.84]	-0.36

[a] Y = ß0 + ß1·X, where Y= simulated SOC [kgC/ha], expressed as yearly average, X=measured SOC [kgC/ha], ResidSterr = Residual standard error, degrees of freedom df=81; [b] r^2 = coefficient of determination; [c] p-value (F-statistics); [d] RMSE = Root Mean Square Error; %RMSE = RMSE · [100/Observed Mean]; [e] ME = Model Efficiency.

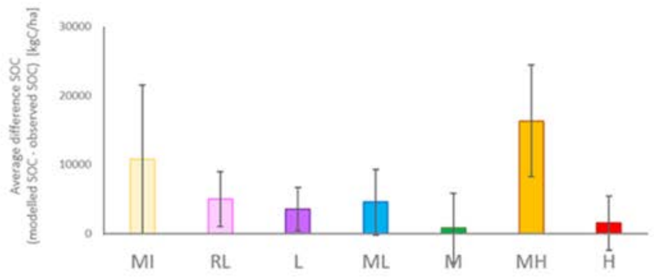


Figure 4.1. Results from process-based modelling of SOC for selected LUCAS and SIS Irish grassland sites. (a) Observed SOC vs ECOSSE-modelled SOC for LUCAS and SIS sites. (b) Regression analysis comparing simulated and measured SOC data, and accompanying model prediction indices. (c) Average difference between ECOSSE-modelled SOC and observed SOC for different grassland management categories. Note: (a) total number of selected sites 93; total number of selected sites after exclusion 11; potential outliers 84. (b) Results derived from ECOSSE simulation runs across all selected Irish grassland sites; total of 84 LUCAS- and SIS-selected sites after excluding 11 potential outliers. r^2 from Zimmermann *et al*. (2018), RMSE from Smith and Smith (2007) and Smith *et al*. (1997), and ME from Abdalla *et al*. (2014). (c) Total number of sites is 84 after excluding 11 potential outliers; error bars represent standard error; grassland categories (MI, RL, L, ML, M, MH and H) are defined in Table 4.1.

values on average) for all grassland management categories; however, it should be noted that some of the categories had a very small number of sites (e.g. the minimal, MI, category had only three sites in total), which could have influenced the results. It is difficult to evaluate whether these modelling results reflect the true performance of the ECOSSE model to predict SOC for selected Irish grassland sites or whether they are influenced by potential mismatching of the SOC_{start} input values (obtained from a different NSDB database), caused by the lack of available data on repeated measurements of SOC at the time of this study. Because of the potential presence of short-range soil variability in Ireland (Doyle and Collins, 1982; Fealy *et al*., 2009), there is a risk that sites could be mismatched during the selection process, despite the fact that information on soil associations was accounted for during the selection process in this study. The influence of potential outliers on the results can be seen in Figure 4.1a, where an improvement in the regression line can be observed after excluding 11 potential outliers. There is also a possibility that there are other sites in the current data that still need to be excluded, but these may be difficult to detect without additional repeated measurements of SOC over time. A strong relationship was observed between initial SOC inputs (SOC_{start}) and the ECOSSE predicted SOC ($r^2 = 0.99$), which indicates good performance of the model spin-up.

Overall, the results demonstrate that, for modelling purposes, SOC data from databases are no substitute for repeated long-term field measurements of SOC; this is especially apparent if site SOC values differ among and between databases. Therefore, it is recommended that the models presented here could be re-evaluated and potentially improved using additional SOC data. This should be partially possible for the LUCAS sites, as additional LUCAS soil point data became available in late 2020 (ESDAC, 2020), but this was unfortunately outside the SOLUM project timeframe. Because of the lack of suitable Irish data from controlled experiments, a French[14] grazed and

14 UE-Ferlus, INRAE, Lusignan, France (further details can be found at http://www.soere-acbb.com/; accessed 26 April 2022).

fertilised grassland treatment plot[15] was used for ECOSSE modelling of SOC to gain further modelling insights. One such insight was that the modelled trends in SOC over time can be different from the observed ones, which is not surprising considering that the literature shows mixed results (McSherry and Ritchie, 2013) on the effect of grazing on SOC. Here, the SOC trend is represented by the slope of the curve, with a positive slope indicating that the system is gaining SOC and a negative slope indicating that it is losing SOC over time.

An attempt was made to perform SA at the site scale on a selected single Irish site and across all of the years of the simulation run. The SA results for the DMIM overall effect on the model to predict SOC were assessed based on the δ means. The results indicated that the model is very sensitive to the SOC_{start}, which was also supported by the Pearson correlation coefficient results. Upscaling the ECOSSE SOC prediction models to the national scale was planned following the successful completion of point-based (at the site scale) modelling. Considering that the findings on ECOSSE modelling of SOC at the point/site scale for Irish sites indicated the need for better SOC_{start} input data (repeated measurements of SOC are required over time), the upscaling of these models in the future is recommended. Some preliminary plans for potential upscaling are outlined in Premrov *et al.* (2020a,b).

4.4 Conclusions

The study used the ECOSSE process-based biogeochemical model to simulate SOC for Irish agricultural land,[16] with main model inputs for soil and land use obtained from datasets that were available at the time of this study. SOC data for Irish grasslands on mineral soils were used from the three available soil databases (NSDB, Teagasc/SIS and LUCAS). The findings from this study demonstrate that repeated field measurements of SOC may not be easily substituted by obtaining SOC data required for modelling from different databases, especially if site SOC values differ among these databases. Results from ECOSSE process-based modelling of SOC for selected LUCAS and SIS grassland sites (with different grassland categories, see Table 4.1) indicate that there is a poor correlation between modelled and measured values and that the model efficiency is low, which could be a consequence of using unsuitable SOC_{start} data (obtained from NSDB) for the selected LUCAS and SIS sites. On account of the potential presence of short-range soil variability in Ireland, there is a likely risk of mismatching the sites from the three databases (NSDB, LUCAS and SIS), which could lead to the SOC_{start} input values obtained from NSDB database not being suitable for some of the selected sites from LUCAS or SIS databases. A positive difference was observed between modelled and observed SOC values on average, which indicates an overall overestimation of predicted SOC. The model SA indicated a strong dependence between SOC inputs (SOC_{start}) and SOC model outputs. Based on these findings, it is recommended that the models used in this study be improved and re-evaluated. This should be possible for the LUCAS sites, as additional LUCAS soil point data became available in late 2020 (ESDAC, 2020), but this was unfortunately outside the SOLUM project timeframe.

15 Only a single treatment plot was used from the larger experiment (paddock of a long-term grassland experiment). The treatment plot included data on repeated measurements of SOC over time. Thanks go to Dr Marie-Laure Decau, Dr Katja Klumpp and scientists from the National Research Institute for Agriculture, Food, and Environment (INRAE), France, for communication and the provision of field data from the French national observatory SOERE ACBB (Système d'Observation et d'Expérimentation sur le long terme pour la Recherche en Environnement Agro-écosystèmes Cycles Biogéochimiques et Biodiversité), which is part of the ANAEE-F French national infrastructures.

16 The modelling was done for Irish grassland sites; the sites with arable and mixed land use were excluded from this work because the number was not sufficient.

5 Concluding Remarks

Changes in land cover and land use are important processes that directly influence the amount of carbon held within terrestrial ecosystems, and it is crucial to better understand how these carbon stocks change over time, particularly in relation to the LULUCF sector. There is a growing body of evidence that has evaluated how estimates of carbon stocks and associated stock changes can be monitored through ground-based measurements, modelling activities and Earth observation techniques, and the SOLUM project has furthered our understanding of how these techniques can be used to monitor SOC stocks in Ireland.

Large geospatial datasets, such as LUCAS, provide an excellent source of land use information, which has been used as part of this project in combination with visual inspections of photography that allow the validation of land use information and the potential detection of land use change events at both national and regional scales. The LUCAS resource can be further used through the associated spatial database of soil cover across the EU, which contains key soil attributes such as organic carbon and particle size distribution. This is a useful development that helps to capture patterns of land use and how these change, and link these changes to changes in SOC stocks. Furthermore, the SOLUM project has also demonstrated that fundamental information on soil properties can be extracted from national data repositories such as SIS but that our ability to align land use with soil characteristics data could be improved. By using level 1 data on key land use classes, such as improved grassland, unimproved grassland, forest land, cropland and built land – associated with five soil types, particle cluster scenarios 1, 2, 3 and 4, developed as part of this project, and organic soils – this would give only 20 permutations that need to be sampled (built land is assumed to be sealed), and this should be the basis for a national fixed soil observatory. The collection of simple soil properties needed to assign soil to a particular cluster can be done cheaply and need be undertaken only once; for example, a campaign to sample 200 sites could be achieved in a single season by a two-person team. This approach would improve our ability to align land use with soil characteristics and provide a further mechanism to monitor SOC changes associated with land use over time. To further enhance this approach, additional land use and management data would be beneficial. Land use data at the field scale could be obtained using the new OSi National Land Cover and Habitats Map and the EU Area Monitoring System, while the proposed DAFM Basic Income Support for Sustainability database is likely to contain more information on intensification, such as stocking density, and this information would also be of benefit to refining the LUSII, developed as part of this project.

To enhance the information that underlies the national emission inventory report, tier 2 emission factors can be developed where appropriate data are available. In the SOLUM project the development of tier 2 emission factors to report SOC stock changes associated with the LULUCF sector highlighted contrasting trends between tier 1 and tier 2 estimates, with the calculated tier 2 SOC stocks being higher for unimproved grasslands than for improved systems. These estimates also differed from the IPCC methodology for cropland to grassland transitions. To further develop this work and investigate the impact of introducing the new tier 2 model in the LULUCF inventory, the soil cluster approach developed in this project could be implemented within the EPA spatial framework (Smith, 2019) using the rule-based model developed within LUSII. Further refinement of the current inventory to derive activity data on carbon inputs to SOC would be beneficial so that geospatial tier 2 and 3 models could be used. Our results also suggest that management or site-specific carbon inputs can be used to significantly improve model prediction. Finally, additional research to better characterise SOC dynamics in transitioning cropland to grassland and croplands under different types of management is required to help validate the outputs of the tier 2 approach. Further useful information will potentially become available for these purposes through other initiatives such as the Geological Survey Ireland (GSI) Tellus soil measurement campaign and research projects such as Terrain-AI.

In this project the ECOSSE biogeochemical model was also used to simulate SOC in Irish agricultural systems, with a view to gaining a better process-based understanding of the main factors influencing SOC storage and soil carbon stock changes at the point/site scale and also the country scale under mineral soils with different land use/management practices. The model outputs indicated an overestimation of SOC, highlighted the sensitivity of the model to the initial SOC inputs and demonstrated the need for replicated measurements of SOC over time, which will allow for a robust evaluation of the model. The work undertaken here could be further enhanced using additional time-dependent LUCAS SOC soil point data (which have become available but were outside the timeframe of this project; ESDAC, 2020), as this dataset will have repeated measurements of SOC. This will allow an opportunity to enhance the use of the ECOSSE model by improving the SOC model evaluation and eventual parameterisation for Irish LUCAS sites, as well as enabling the diagnostic evaluation of existing models and presenting an opportunity for more robust spatial upscaling. The literature shows mixed results on the effect of grazing and associated management intensity on SOC, and the modelling work presented here forms a strong basis for future studies that could investigate the effect of different grassland management practices in Ireland (i.e. "grazing intensities") should either historical or new data become available. The lack of openly available data from both national and international perspectives was a key limitation of this work and is a factor that needs to be addressed in order to develop this approach further. Finally, there is significant potential to further improve and upgrade the process-based modelling of grazed grasslands using the ECOSSE model by potentially introducing new types of grazed grassland vegetation parameters into the model that will account for grazing-induced vegetation changes and associated impacts on SOC. Such approaches also have significant potential for further spatial and temporal upscaling of SOC dynamics and will allow the modelling work to be aligned with both the new LUSII dataset and the application of the soil cluster analysis developed in this project.

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Abbreviations

BSS	Between sum of squares
CORINE	Coordination of Information on the Environment
DAFM	Department of Agriculture, Food and the Marine
ECOSSE	Estimation of Carbon in Organic Soils – Sequestration and Emissions (model)
EPA	Environmental Protection Agency
FIPS	Forest Inventory and Planning System
GHG	Greenhouse gas
GLM	Generalised linear model
GUID	Globally unique identification code
IPCC	Intergovernmental Panel for Climate Change
LPIS	Land Parcel Identification System
LUCAS	Land Use and Coverage Area Frame Survey
LULUCF	Land use, land use change and forestry
LUSII	Land Use and Soil Inventory for Ireland
NIR	National Inventory Report
NSDB	National Soil Database
OSi	Ordnance Survey Ireland
PCA	Principal component analysis
SA	Sensitivity analysis
SIS	Soil Information System
SOC	Soil organic carbon
SOLUM	Soil Organic Carbon and Land Use Mapping (project)
SR	Stocking rate
TSS	Total sum of squares
UNFCCC	United Nations Framework Convention on Climate Change

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- 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 um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht 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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Soil Organic Carbon and Land Use Mapping (SOLUM)

Authors: Matthew Saunders, Gabriela Mihaela Afrasinei, Jesko Zimmerman, Alina Premrov, Kevin Black and Stuart Green

Identifying Pressures

Soils contain more than twice the amount of carbon held in the atmosphere, but globally approximately 1600 million tonnes of carbon are lost from the soil each year as a result of cultivation and changes in land use and land management. Understanding the impacts of land use, land use change and forestry (LULUCF) on soil organic carbon (SOC) stocks and greenhouse gas (GHG) emissions is therefore important for national GHG inventory reporting and for mitigating climate change by reducing and offsetting GHG emissions. In Ireland around 65% of land area is devoted to agriculture, with 84% of that used for grass-based production systems. However, land parcels regularly shift between cropland and grassland systems, which may influence their carbon and GHG dynamics. The aim of this work was to develop a spatially integrated soils and land use dataset for Ireland that could provide:

- robust estimates of reference SOC stocks and potential changes;
- an understanding of the influence of land use, land management and climate on SOC stocks and GHG dynamics;
- the capability to inform tier-based reporting activities and land-based climate change mitigation methodologies.

Informing Policy

Under the EU Effort Sharing Regulation, Ireland has a target to reduce GHG emissions 30% by 2030 relative to 2005 emissions. However, Ireland has a greater ambition to reduce its emissions by 51% compared with 2018 levels. Ireland's agricultural sector is one of the largest emitting sectors, at 37% of Ireland's total emissions in 2020. Therefore, it is a key area where reductions are needed and where significant opportunities for land-based climate change mitigation options exist. The reporting mechanisms currently used to compile emissions from agricultural land use, and the models used to predict future change, can be improved by increasing the availability of soil property and agricultural activity data at higher resolutions in space and time. This will provide a platform from which reference SOC stocks can be derived. It will also improve our understanding of the drivers of SOC changes and allow us to develop and implement suitable carbon-neutral land management options.

Developing Solutions

Changes in land cover and land use are important processes that directly influence the amount of carbon held in terrestrial ecosystems. It is crucial that we better understand how these carbon stocks change over time, particularly in relation to the LULUCF sector. This research highlights how large geospatial datasets can provide an excellent source of land use information and can detect land use change events at both national and regional scales. These datasets can also be used with associated spatial databases of soil cover across the EU, which contain soil attributes such as organic carbon and particle size distribution, and can be used to link land management with changes in SOC stocks. This work also highlighted contrasting trends between tier 1 and 2 estimates of SOC stock changes associated with the LULUCF sector. The findings could be further developed by implementing the rule-based land use and soil inventory with the soil cluster approach in current national land use mapping activities.

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