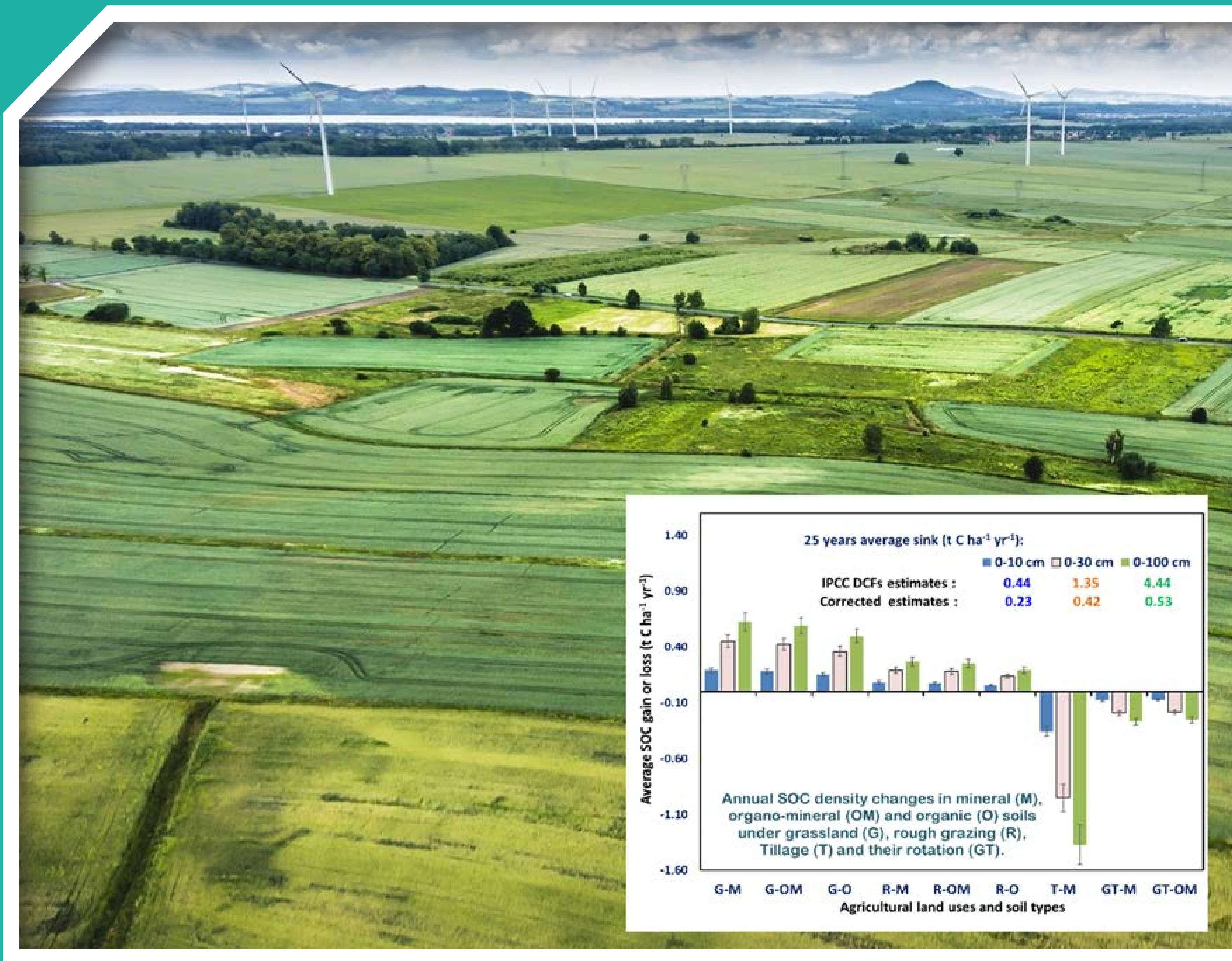
Report No.325

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Sourcing and Assessing Agricultural Activity Data for Modelling and National Estimates of Greenhouse Gases and Air Pollutants

Author: Mohammad Ibrahim Khalil



www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing

We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement

- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management

- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment

- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions

- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development

- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment

- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection

- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education

- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change

- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Sourcing and Assessing Agricultural Activity Data for Modelling and National Estimates of Greenhouse Gases and Air Pollutants

(2015-CCRP-FS.21)

EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Dublin

Author:

Mohammad Ibrahim Khalil

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of Communications, Climate Action and Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The author would like to thank Bruce Osborne (University College Dublin) for hosting this fellowship and providing academic/research support; and the EPA, namely Phillip O'Brien and Marc Kierans (now the Department of Communications, Climate Action and Environment), for extending technical supports and collaboration.

The author would also like to thank John Muldowney (Department of Agriculture, Food and the Marine), Gerry Brady (Central Statistics Office) and Gary Lanigan (Teagasc) for providing inputs and suggestions; and Professor Jeremy Simpson (Head of School) for extending administrative and relevant support for the fellowship.

DISCLAIMER

This report is based on research carried out/data from 2015 to 2017. More recent data may have become available since the research was completed.

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.

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

ISBN: 978-1-84095-914-7 July 2020

Price: Free Online version

Project Partners

Mohammad I. Khalil
University College Dublin Research Fellow
UCD School of Biology & Environmental Science and UCD Earth Institute
University College Dublin
Belfield
Dublin
Ireland
Email: ibrahim.khalil@ucd.ie; mi.khalil.dr@gmail.com

Bruce A. Osborne
Academic Supervisor/Host
UCD School of Biology & Environmental Science and UCD Earth Institute
University College Dublin
Belfield
Dublin
Ireland
Email: bruce.osborne@ucd.ie

Contents

List of Figures

List of Tables

List of Boxes

Executive Summary

The principal greenhouse gases (GHGs), nitrous oxide, methane and carbon dioxide, together with air pollutants emitted from agriculture and other sources, have major climate change and ecosystem-related impacts. The Paris Agreement emphasises the need for enhanced mitigation measures, reduced GHG assessment uncertainties, better quantified sinks and the tailored use of different offsetting mechanisms to keep the global temperature rise below 2°C. The Intergovernmental Panel on Climate Change (IPCC) has estimated that the contribution of agricultural activity and land use, land use change and forestry (LULUCF) to global anthropogenic GHG emissions is 14% and 18%, respectively. In Ireland, the contribution of agricultural activity to GHG emissions is 32.2%, which is more than double the IPCC value, and the commitment to a reduction of 30% in non-Emissions Trading System emissions by 2030, in accordance with the Paris Agreement, while implementing the goals and objectives of Food Wise 2025, will be challenging. The additional challenges are to improve the accuracy of the emissions assessments, particularly from major source categories such as enteric fermentation, manure management and agricultural soils, and to identify mitigation approaches.

Ireland has been using the IPCC Tier 1 default methodology for reporting purposes because of both limited agricultural activity data (AAD) and the limited availability of relevant/appropriate emission factors (EFs). Higher tier reporting is, however, needed to facilitate the improvement of National Inventory Report (NIR) estimates of emissions and removals within the agriculture, forestry and other land use categories. This requires the collection, compilation and assessment of readily available activity data and the identification of information/knowledge gaps. However, the availability of AAD for NIR improvement purposes is constrained by intellectual property rights and the lack of data-sharing agreements across public agencies/organisations.

Sourcing, collecting and collating AAD and a review of existing databases formed the backbone of this project to develop methodologies for improved national inventory reporting. This includes estimation of GHGs and air pollutants from manure management and soil organic carbon (SOC) stock changes in agricultural soils. Initially, the National Farm Survey (NFS) data collected by Teagasc and data from a Survey of Agricultural Production Methods (SAPM) collected by the Central Statistics Office (CSO) were reviewed. The NFS data consisted of key AAD associated with manure management, which represented 57% of commercial holdings, comprising 81% of the land area, 95% of agricultural outputs and 93% of livestock in Ireland; these AAD were verified in a three-layer system. Although the NFS data can be used for national inventory reporting improvement purposes, the data, collected at random, were limited to 975 holdings in 2012, of which only 2% were verifiable. Furthermore, this information was not representative of the total population and farm holdings having a standard economic output of less than €8000. In addition, it was not based on an equal number of holdings per county and therefore was not representative of all livestock categories, land uses or management practices. Finally, the NFS data had limited scope for statistical analyses because of inadequate, variable and disaggregated data (quantity/proportion) for housing, manure storage and feed types, as well as a lack of information on manure-spreading methods and storage methods.

The SAPM data, generated by the CSO, represented 65% of the key national farm holdings and contained significantly more information on manure management and land use classes than the NFS survey. These data may be used for improvement of national inventory reporting, but they are constrained by major uncertainties associated with the data collection process, inadequate disaggregation of data, particularly for manure storage and spreading methods, and incompatibility and dissimilarity issues. There is also a lack of information on the amount of feed, fertiliser and lime used, and limited scope for incorporating any additional activity data.

Detailed activity data generated by Bord Bia and the Department of Agriculture, Food and the Marine (DAFM) were unavailable for review. Three Nitrate Derogation files supplied as hard copy by the

DAFM were studied. The AAD collected annually by the DAFM were found to be useful for national inventory reporting improvement purposes but it would be labour intensive to make use of the data in their current form. Significant difficulties were also encountered in obtaining AAD from public agencies, mainly because of copyright/institutional legal procedures. Therefore, it is suggested that EPA permanent staff/inventory team members should be given full jurisdiction to collect such data, thereby avoiding any further delays in the assessment and utilisation of this information for national inventory reporting improvement purposes.

For the estimation of emissions of GHGs and air pollutants from manure management, the CSO database was used. However, this was also limited by disaggregation of AAD required for the categorisation of a number of farms based on the range/type of application methods used. Information on the quantification/proportion of livestock slurry and solid manure applied to major land use types and the timing of application was also inadequate. Following consultation with a DAFM expert, further shortcomings of the CSO's precise estimations were identified, and additional information to supplement the analysis and quantification of data was obtained. Missing information (e.g. number of individual livestock categories/subcategories) was computed and methodologies for calculating the proportion of slurry and manure applied to major land use types and how this was applied across farm categories were developed.

Among livestock categories, the proportion (%) of slurry to solid manure produced during the housing period was higher for pigs (99:1) than for cattle (61:39). A major proportion of the slurry was applied to grassland (97% based on number of farms vs 73% based on livestock population); the amounts applied in spring and summer were similar (40–42% vs 36–40%) and significantly higher than the amounts applied in autumn (18–24%). Most solid manure, derived mainly from loose-bedded houses, was applied to grassland (90% vs 77%), with more applied during spring (31–61%) than during autumn (26–49%) or summer (13–21%). Farmers mostly used a splash plate for applying slurry (90%) and side discharge to spread solid manure (60%). The 2010 estimated national total amounts of slurry produced from cattle and pigs were 30.9 Mm^3 and 32.1 Mm^3 based on number of farms and livestock population, respectively; the equivalent figures for solid manure from sheep, poultry, goats and horses were 319.8 Mm^3 and 320.3 Mm^3, respectively The results imply significant limitations in the CSO data, including in the number of available places during the housing period (e.g. cattle vs poultry) and the methods of slurry and solid manure application. Expert advice and the collection of information from other verifiable sources will be required to enable the information to be beneficial for users.

The SOC pool has the potential to act as a major source or sink of GHGs. To improve Tier 2 reporting, data generated previously for Ireland through overlaying land use and soil maps using ArcGIS were reprocessed to improve depth distribution models and pedotransfer functions ($R^2 = 0.53–1.00$), for determination of SOC concentrations and bulk densities. Then, soil (National Soils Database and indicative soil type) and land use (Land Parcel Identification System, 2000–2014) maps were overlaid to categorise the key land uses on mineral, organo-mineral and organic soils, and to identify historical land use changes. The SOC density was higher in organic than in organo-mineral and mineral soils and, for different land uses, SOC density was higher for rough grazing, followed by grassland, rotation/ley and tillage. The corresponding SOC densities in the 0- to 30-cm soil layer for the different land uses, measured in 2006, were 242, 207, 162 and 80 $t\,C\,ha^{-1}$, respectively; the estimated SOC reference values for 1990 are 238, 198, 166 and 99 $t\,C\,ha^{-1}$, respectively.

Based on the SOC reference values, this indicates that the grassland and rough grazing land uses act as sinks, whereas the tillage and grassland/tillage rotation land uses act as sources. An overestimation of SOC density for organo-mineral soils using the IPCC default SOC density change factors (DCFs) was observed and empirical approaches were taken to minimise the overestimations. The corrected annual carbon sequestration rates for the four agricultural land uses combined, over 25 years, were 0.23, 0.42 and 0.53 $t\,C\,ha^{-1}\,year^{-1}$ for the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers, respectively. The corresponding national agricultural SOC stocks for 2006 were 316, 838 and 1679 Tg, respectively. The long-term projections resulted in carbon sinks of 1.24, 3.09 and 5.48 $Tg\,C\,year^{-1}$, respectively, demonstrating a potential to offset 24%, 59% and 106% of the total GHGs emitted from Irish agriculture. These results imply that using higher spatial resolution databases and geographic information system and modelling approaches could provide robust estimates of SOC densities/stocks and their changes over time (Tier 2). However, the IPCC default values for proportional gains or losses used to estimate any changes in density resulted in highly variable values in soils having contrasting SOC contents. This highlights the importance of replacing the apportioning approach, even for the “4 per 1000” initiative, by a “mass by area (depth-specific)” approach for more precise estimations. This includes sub-categorisation of mineral and organic soils, calculation of country-specific DCFs for individual land uses/management practices, and the estimation of weighting factors for backwards and forwards projections.

1 General Introduction

Nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) are the principal greenhouse gases (GHGs) and these, together with air pollutants emitted from agriculture and other sources, have major climate change and ecosystem-related impacts. According to the Intergovernmental Panel on Climate Change (IPCC, 1997, 2007), agricultural activity and land use, land use change and forestry (LULUCF) are responsible for approximately 14% and 18%, respectively, of global anthropogenic GHG emissions. In Ireland, the contribution of agricultural activity to GHG emissions is 32.2% and remains a key component of the total GHG emissions, despite a recent decrease in national emissions (Duffy *et al*., 2016). Agricultural GHGs are produced mainly through biological processes, with sources that are both biogenic and anthropogenic, and the degree of variation in emissions (spatial and temporal) depends on agricultural management systems and differences in, for example, animal and feedstock types, manure management, soil type, land use and environmental factors (Chadwick *et al*., 2000). Under the terms of the European Union (EU) Climate and Energy Package and its associated Effort-Sharing Decision, Ireland has been set a 30% reduction target by 2030 relative to 2005 levels for non-Emissions Trading System (ETS) emissions (EPA, 2014). This target is particularly challenging for Irish agriculture as increased production is envisaged following the implementation of Food Wise 2025 (DAFM, 2017). This reduction is among the highest of all of the developed countries and places an increased emphasis on accurate assessments of emissions and the quantification of mitigation approaches.

The major source categories of GHG emissions (and air pollutants) from Irish agriculture are enteric fermentation, manure management and agricultural soils. These source categories make a significant contribution to the two important non-CO_2 GHG emissions (i.e. CH_4 and N_2O). The livestock sectors account for over 80% of the agricultural output value and emissions of CH_4, which has a 25 times higher global warming potential than CO_2, primarily as a result of livestock enteric fermentation, with over 14 million ruminants (dairy and non-dairy) playing a dominant role. For N_2O, a potent GHG gas, with a 298 times higher global warming potential than CO_2, emissions occur mainly via two biological pathways, nitrification and denitrification, which are influenced by chemical/organic fertiliser application, manure management, and animal and atmospheric deposition. N_2O emissions are highly uncertain, both temporarily and spatially, particularly in grazed grassland, mainly because of localised nitrogen loading from urine patches (Oenema *et al*., 1997), which may account for 60–80% of the annual N_2O budget (Smith *et al*., 1998). In Ireland, N_2O emission factors (EFs) from grazed grassland vary considerably, ranging from less than 1% to over 5% (e.g. Abdalla *et al*., 2009; Osborne *et al*., 2010; Li *et al*., 2011; Harty *et al*., 2016), and measurements for arable lands are mostly limited to spring barley (e.g. Abdalla *et al*., 2010).

The Irish government has underpinned the national effort in combating climate change to help meet international obligations and targets to reduce GHGs, and introducing the necessary mechanisms to achieve the goals (DCCAE, 2017). The Environmental Protection Agency (EPA) has been designated as the single national entity with overall responsibility for producing National Inventory Reports (NIRs) of GHGs and GHG projections, including data collection for estimating anthropogenic GHG emissions by sources and removals by sinks, as well as implementing the national quality assurance/quality control system and its uncertainty estimates (Duffy *et al*., 2016). The Tier 1 approach has several limitations and can result in large uncertainties in national inventory reporting, making it difficult to address planning and policy issues to mitigate GHGs. Despite this, Ireland has been using the IPCC default accounting methodologies, primarily because of both limited activity data and the limited availability of relevant/appropriate EFs, except for livestock systems, for which Tier 2 reporting is being used. Overall, higher tiers are needed to achieve high precision and to provide a flexible and structured method of assessing how different scenarios and measures affect both GHG emissions and soil carbon dynamics. However, higher tiers require high-resolution climatic, soil and other activity data, as well as disaggregated emissions and carbon stock data, in order to (1) reduce inventory uncertainty and (2) introduce more flexibility into the inventories to allow for the reporting of mitigation measures.

The application of available models for use in Irish agro-ecosystems is associated with large uncertainties in predicting background N_2O emissions (e.g. Abdalla *et al*., 2010; Khalil *et al*., 2013a), leading to errors in EF calculations, while also providing limited information on the sensitivity of EFs to management and climatic conditions. Modelling (regional/national) has many uncertainties and significant knowledge gaps still exist and need to be addressed. The major challenge is how to scale up the relatively more robust field-scale models, with large variations in data requirements, to catchment, regional and national scales (Chen *et al*., 2008) with limited activity data. This includes the sourcing and collation of activity data from diverse sources to meet the data requirements of specific process-based models for the prediction of GHG emissions. The Department of Agriculture, Food and the Marine (DAFM) has funded the Agricultural Greenhouse Gas Research Initiative for Ireland (AGRI-I), led by Teagasc, and initiated a number of linked projects with Teagasc, University College Dublin (UCD), Trinity College Dublin (TCD) and other institutes. These seek to identify mitigation options and facilitate the improvement of inventory estimates of emissions and removals within the agriculture sector, including the effects of agriculture, forestry and other land use (AFOLU) and land use changes. However, the availability of activity data for the improvement of NIRs at Tier 2 and 3 levels is constrained by intellectual property rights and a lack of data-sharing policies across organisations. In addition to AGRI-I and other initiatives, either completed or ongoing, it is imperative to gather, compile and assess readily available activity data and identify knowledge gaps in order to improve the estimation of GHG emissions and provide the information required for the adoption of mitigation options on a sectoral basis.

As per regional and international agreements, the EPA has been submitting NIRs to the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Long-Range Transboundary Air Pollution (CLRTAP)/United Nations Economic Commission for Europe (UNECE) following the revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories and Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) and the good practice guidelines (GPGs). As per the decision taken at the 19th session of the Conference of the Parties (COP 19), the EPA is to implement the IPCC 2006 guidelines for NIRs under the UNFCCC and CLRTAP, starting in 2015, and this requires the development of methodologies and computational protocols (IPCC, 2006, 2007, 2014; UN, 2015a,b). These guidelines emphasise the research required to develop appropriate methodologies/procedures and to identify activity data gaps through the compilation and use of emerging models that are suitable for Irish conditions. This includes improved methodologies for upscaling of GHG emissions from site to national scales, which most countries are striving to develop. However, these are associated with difficulties in accessing activity data, and the adoption of policies to make data available to stakeholders and researchers/modellers is required. These would allow for precise estimation of GHGs and their EFs, and thereby improvement of NIRs using higher tiers, and, where feasible, identification of mitigation options for implementation.

Because of major limitations (e.g. labour, cost and time) in collecting data from individual farms/farm units, several options are being used to obtain the required data, including the use of censuses and surveys/questionnaires, on a yearly basis and/or over specific time intervals. Surveys and questionnaires are normally used to gather information for statistical purposes. They are relatively inexpensive, easy and quick to administer, cover different topics and locations using different media and are used to obtain opinions from a large number of individuals. However, there are challenges in obtaining accurate and valid data. Often they consist of closed-ended questions, meaning that responses are limited, resulting in invalid answers and a limited number of replies. Data on farm outputs, costs and income are collected at random in order to be representative of the national population of farms. What is required is a baseline data set of farm management practices and facilities for implementation of the National Action Programme under the Nitrates Directive (91/676/EEC) and to facilitate the preparation of accurate GHG and air pollutant inventories.

The soil organic carbon (SOC) pool, one of the most important reservoirs of the global carbon cycle, has the potential to act as a main source or sink of GHGs because of its large extent and active interaction with the atmosphere (Lal, 2004; Gal *et al*., 2007). Agricultural land has an important role in the global carbon cycle, and the management practices used can determine the carbon source or sink categories. Annual soil respiration rates correspond to short-term net exchange and do not give an indication of long-term soil carbon sequestration (Johnson *et al*., 2007). However, detailed information on the environmental benefits of terrestrial carbon pools is sparse and disparate in European studies (Holland, 2004). To achieve the targets set out under the Kyoto/post-Kyoto Protocols, the overall GHG balance under variable inputs, soils and environmental conditions should be accounted for, including the elucidation of factors regulating the processes forming and releasing GHGs (Baggs *et al*., 2003; Six *et al*., 2004; Helgason *et al*., 2005; Venterea *et al*., 2005) and an assessment of management-related trade-offs (e.g. Khalil and Inubushi, 2007).

To transition to a higher tier approach to reporting GHG and pollutant inventories, robust country-specific information is required to reflect the diversity of management practices, soils and environmental conditions. Further refinements to include regional variations will also be important. The quantification of baseline SOC stocks with soil depth associated with the variety of land uses and practices is essential in order to adequately assess changes in SOC over time with land use change. This is highly pertinent for sustainable management of the soil and the identification of the magnitude of sources and sinks for offsetting GHG emissions. To achieve these goals, this fellowship developed methodologies that reflect the soil and environmental conditions correctly and provide more accurate estimates of carbon and nitrogen emissions for inventory reporting. This project was also aimed at developing the necessary tools and data systems to capture the impact of mitigation actions within agricultural production systems. The main objectives (modified) of this project were to:

- source, collate and assess current agricultural activity data (AAD) and develop proxies and methodologies to estimate carbon and nitrogen emissions for national inventory reporting;
- identify potential data gaps, and liaise with data providers to fill the data gaps, for developing Tiers 2 and 3 methodology for agricultural GHG and air pollutant reporting;
- analyse national emissions of GHGs and air pollutants, particularly from manure management, as well as SOC densities/stocks in agricultural soils;
- review emerging models based on research activities in Ireland and compile the input parameters and validation data needed to run the models.

The main targets of this work were to:

- contribute to and extend the use of AAD, GHG emissions data and EFs in collaboration with the AGRI-I and EPA inventory teams;
- identify data gaps and, where possible, fill these gaps in order to validate emerging models and for national inventory reporting in collaboration with researchers and stakeholders;
- provide recommendations on the next steps for developing institutional arrangements within the national emission inventory and emission projection systems, leading to Tier 2 and Tier 3 developments;
- contribute to and improve national inventory data projection reports and related activities.

2 Sourcing and Assessing Activity Data on Agricultural Management Practices in Ireland

2.1 Introduction

The major source categories of GHG emissions from Irish agriculture are enteric fermentation, manure management and agricultural soils (IPCC, 2014; Duffy *et al.*, 2016). These source categories make nationally significant contributions to the two important non-CO_2 GHG emissions (i.e. CH_4 and N_2O). In Ireland, N_2O EFs for grazed grassland vary considerably, ranging from less than 1% to over 5% (e.g. Abdalla *et al.*, 2009; Osborne *et al.*, 2010; Li *et al.*, 2011), and measurements for arable lands are mostly limited to spring barley (e.g. Abdalla *et al.*, 2010). Overall, emissions of N_2O from the agriculture sector account for over 95% of the uncertainty in the 2016 inventory (Duffy *et al.*, 2016). Because of the lack of measured EFs or AAD to develop appropriate methodologies, Ireland has been using the IPCC Tier 1 accounting methodology, with the exception of the livestock sector, for which Tier 2 reporting is being used. Through the DAFM-funded AGRI-I, led by Teagasc, a number of linked projects have the objective of improving inventory estimates of emissions and removals and their changes within the AFOLU sectors.

It is recognised that the links between agriculture, the environment and climate are very complex and dynamic and, as yet, are not fully understood. To model these complex interactions requires large numbers of AAD, with minimum errors, derived from either sampling or measurement and analysis, or both. These data could be used to provide precise estimates of national GHG emissions and SOC densities/stocks and their changes in AFOLU sectors. For detailed site and regional EF assessments, it is unlikely that such data could be obtained through field measurements only, so the development of alternative approaches using both measured and survey data (empirical), such as those from government censuses or official registers, may be more realistic. This census or survey approach unifies criteria within geographical areas and between international organisations/members, such as information on households, populations, farms, businesses and the economy. The collection of such data is, however, difficult, and data collection methods often do not have the rigour to represent diverse social contexts properly.

An agricultural census gathers information on all individual agricultural holdings (1) by direct enumeration, (2) using complete/administrative reporting systems, constrained by resources mainly, or (3) by sampling, requiring basically the same type of resources although the size of the operation can be much smaller. However, data quality can be poor because of an inability to apply appropriate statistical analyses and errors in reporting. However, a census of agriculture can be invaluable in providing a statistically sound source of agricultural information (FAO, 2015). At the EU level, an example is the triennial Farm Structure Survey (FSS), which provides reliable data on the structure of agricultural holdings (EC, 2016). Examples at the national level are the Census of Agriculture (CoA), carried out in 2010 (CSO, 2012), the National Farm Surveys (NFSs) conducted by Teagasc, although with limited samples selected at random (Hennessy *et al.*, 2011, 2012), and the AAD collected by the DAFM through various schemes (DAFM, 2014, 2017).

Overall, higher tiers of reporting are required to have higher levels of precision, particularly Tier 2 methodology, to provide reliable and verifiable estimates of GHG emissions and changes in SOC densities/stocks. This requires sourcing and collation of AAD from diverse sources to meet the data requirements of the different models. However, the availability of AAD for the improvement of national inventory reporting at the Tier 2 level is constrained by limited census/survey data, coupled with intellectual property rights issues and a lack of data-sharing policies. In addition to the findings of AGRI-I and other relevant projects, either completed or ongoing, it is imperative to gather, compile and assess readily available activity data collected through research/surveys and elucidate the data gaps. These could enable improved estimates of GHGs, air pollutants and SOC densities/stocks to be provided, and the identification and adoption of mitigation options on a sectoral basis at national/regional levels.

2.2 Materials and Methods

This task dealt mainly with data generators across research (e.g. Teagasc) and academic (e.g. UCD, TCD and University College Cork – UCC) organisations and public bodies (EPA, DAFM, Central Statistics Office – CSO, Met Éireann, Economic and Social Research Institute – ESRI, and Office of Public Works – OPW) for the collection and compilation of AAD. The steps taken are described in the following sections.

2.2.1 *Step 1: collection of activity data*

Following the workshop agreements, sectoral and whole-farm AAD (replicated and spatially explicit where possible; Figure 2.1), relating to crop, pasture and animal management systems, were sourced through meetings and personal contacts or through telephone/email correspondence with researchers dealing with agricultural GHG emissions and SOC stock changes measured either *in situ* and/or using eddy covariance techniques. Stakeholders were also contacted regarding AAD and its availability/usability in this project. The IPCC 2006 guidelines, process-based models and national inventory reporting spreadsheet supplied by the EPA were reviewed and the AAD requirements for this project were identified. Follow-up meetings/correspondence, a workshop and steering committee meetings involving the researchers, data generators/providers and modellers also took place during the 2-year project period, where data provision and availability were discussed.

2.2.2 *Step 2: development of database formats*

In consultation with the EPA and UCD data management experts, a database format was initially built to accommodate the AAD required for inventory purposes and for modellers. The aim was to link this to a new GHG data repository and analysis facility being developed with Higher Education Authority (HEA) funds as part of the new UCD Earth Institute, but this remained incomplete because of modifications to the research initiated by the EPA. However, proxies for common context indicators that are relevant to AGRI-I and national inventory reporting activities were developed based on expert judgement. These are mostly relevant for later activities, described in detail in Chapters 3 and 4.

2.2.3 *Step 3: collation and assessment of activity data*

While attempts are still ongoing to collect AAD to satisfy project objectives, activity data collected by

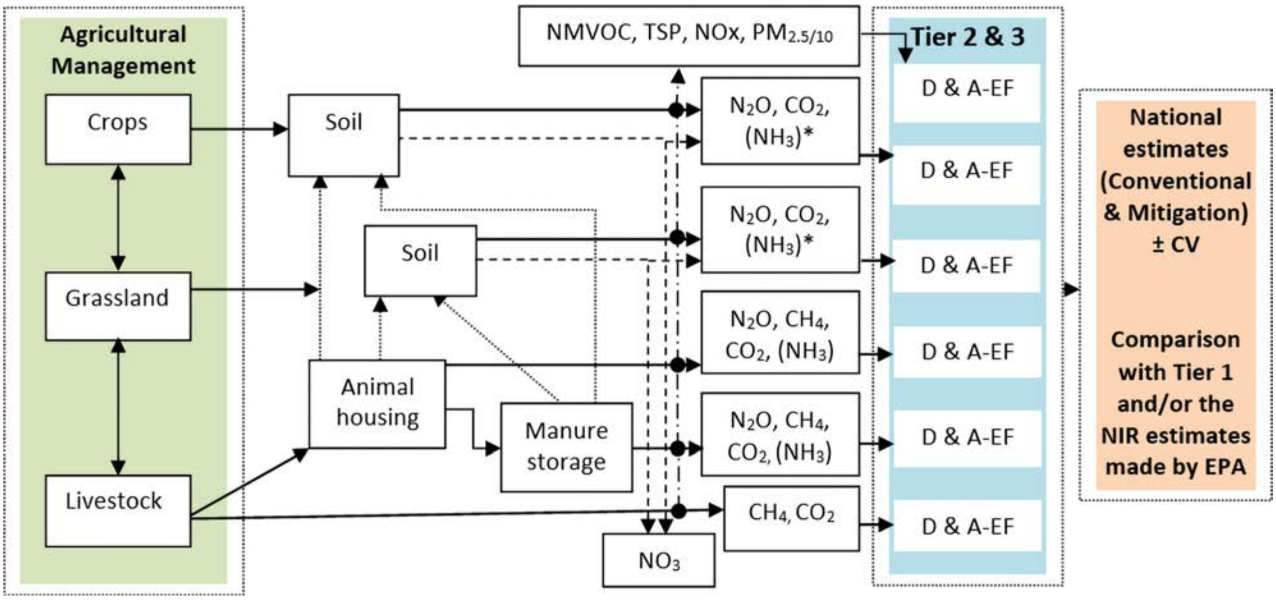


Figure 2.1. Steps involved in the collection and assessment of AAD, including quantification of disaggregated (D) and aggregated (A) emissions of GHGs and air pollutants, and EFs, with uncertainty estimates generated for inputs and outputs. CV, coefficient of variation; NH_3, ammonia; NMVOC, non-methane volatile organic compound; NO_3, nitrate; $PM_{2.5/10}$, particulate matter ≤2.5 µm/≤10 µm; TSP, total suspended particles.

Teagasc through the NFS (Hennessy *et al*., 2011, 2012), the CoA 2010 (CSO, 2012) and Nitrates Derogation files (three files; Michael O'Donoghue and John Muldowney, DAFM, 2015, personal communication) were reviewed to match the AAD data requirements. Because of the unavailability of data files, a brief overview of activity data generating/collecting through livestock schemes by Bord Bia is also provided.

2.2.4 National Farm Survey by Teagasc

The NFS has been conducted by Teagasc on an annual basis since 1972. The survey is operated as part of the Farm Accountancy Data Network of the EU and fulfils Ireland's statutory obligation to provide data on farm outputs, costs and income to the European Commission. A random, nationally representative sample of farms is selected annually in conjunction with the CSO. Each farm is assigned a weighting factor so that the results of the survey are representative of the national population of farms.

2.2.5 Census of Agriculture by the CSO

The purpose of the 2010 CoA was to compile statistics on the structure of all agricultural holdings. These data were vital to meet national and EU requirements for regular statistics on agricultural activity. A census questionnaire was sent to all agricultural producers for completion. This Survey of Agricultural Production Methods (SAPM) was carried out on a sample of 40,000 farm holdings in September 2010 as part of the EU FSS. The survey covered farm practices relating to crop rotation and soil conservation, manure and slurry storage and usage, grazing levels and livestock housing.

2.2.6 Nitrates Derogation by the DAFM

The Nitrates Derogation for Ireland is pursuant to EU Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. The Nitrates Derogation is available to grassland farms on an individual basis. The derogation applies only to grazing livestock on the holding. Farmers who wish to avail of the derogation have to make an annual application and farm in accordance with a fertiliser plan and set conditions (DAFM, 2017). As part of the eligibility criteria, farmers must (1) have a farm holding with 80% or more grass; (2) have grazing livestock; (3) make an annual online application; (4) not import livestock manure; and (5) undertake in writing to fulfil the conditions set out in the derogation and adhere to the requirements of Statutory Instrument (S.I.) 134 of 2014 (Nitrates Derogation Regulations).

2.2.7 Origin Green/Carbon Navigator initiated by Bord Bia

Origin Green is the national sustainability programme initiated by Bord Bia for the Irish food and drink industry. This programme has been independently verified at every stage, enabling Ireland's farmers and food producers to set and achieve measurable sustainability targets, reduce their environmental impact and serve local communities more effectively (Bord Bia, 2016, 2017). Bord Bia, in collaboration with Teagasc through various livestock-related schemes, has focused on improved farm sustainability through the Origin Green programme reference to beef and dairy farm assessments, in particular. Both organisations have developed carbon models for these sectors through a number of pilot programmes and the audits are conducted on an 18-month cycle. The farm assessment procedures carried out by Bord Bia are provided in Figure 2.2.

2.3 Results

2.3.1 Sources of national databases and agricultural activity data requirements

Following several months of meetings and discussions with data generators, including stakeholders (EPA, DAFM, CSO, UCD, UCC, Teagasc and similar), the useful sources of AAD available in Ireland were identified; these are listed in Table 2.1.

A review of activity data reported by various sources and the EPA NIRs found some conflicting terminologies relating to the collection and reporting of data (e.g. zoning and cattle subcategories). The input parameters required by commonly used models that have been applied in Ireland for the simulation of GHGs and SOC densities/stocks were reviewed (Khalil *et al*., 2013a, 2016). This also included inconsistencies and incomplete data sets with regard to the estimation of GHG EFs and SOC densities/stocks and their

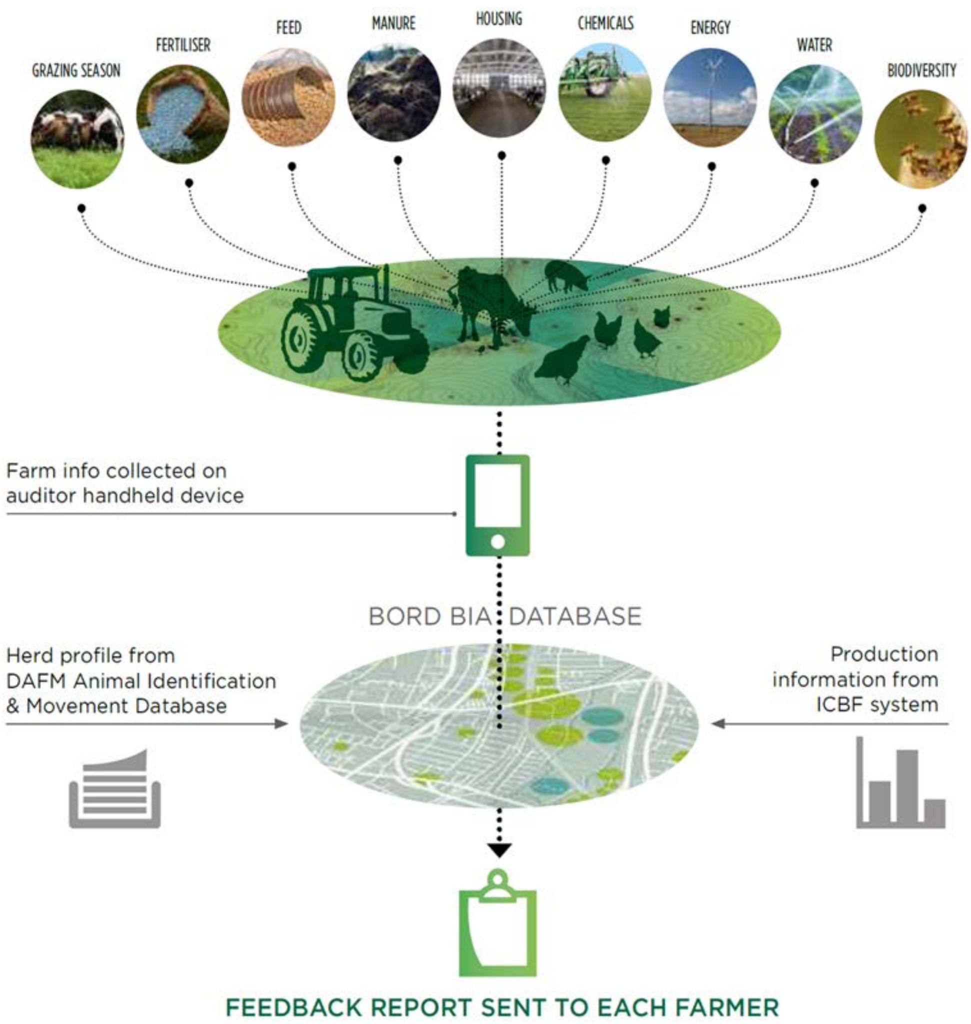


Figure 2.2. Farm assessment procedures carried out by Bord Bia. ICBF, Irish Cattle Breeding Federation. Source: Bord Bia (2016).

Table 2.1. Sources of relevant national databases identified

Database	Activity data covered	Sources
Land Parcel Identification System (LPIS)	Land uses	DAFM
Co-ordination of Information on the Environment (CORINE)	Land cover	EPA and EU
National Soils Database (NSDB)	Soil properties (e.g. SOC concentration)	EPA and Teagasc
Irish Soil Information System (ISIS)	Soil properties (e.g. texture, pH and SOC concentration)	Teagasc and EPA
Indicative soil types (ISTs)	Soil properties (e.g. mineral, acidity and drainage classes)	EPA and Teagasc
CoA	Land use and management	CSO and EPA
Agriculture statistics	Land use and management	CSO
Animal identification and movement (AIM)	Livestock statistics	DAFM
Carbon Navigator	Beef and dairy management data	Bord Bia and Teagasc
Meteorology	Weather for synoptic stations	Met Éireann

changes in agricultural soils. These estimates are also constrained by limited input parameters for simulations using existing process-based models. Table 2.2 provides a summary of the activity data required to improve national inventory reporting and the input parameters required to run process-based models.

Table 2.2. Categories and subcategories of activity data across agricultural sectors required for Tiers 1–3 reporting and modelling approaches

Activity data categories	Subcategories
Zone/region	Administrative and agro-ecological zones/regions
Farm particulars	Number of herds per farm, total farm size (own + rented), area farmed
Land use	Total grassland (pasture, hay and silage), total pasture, permanent pasture, rough grazing, temporary grassland, arable/tillage (cereals and horticulture, i.e. annual and perennial plants), farm forestry, fallow + set-aside, home garden, woodland (old), energy crops, area not in agriculture, other areas
Livestock and poultry held	Cattle: cows (dairy and suckler), others (beef), cattle (male + female: 0–1, 1–2 and > 2 years), bulls
	Sheep: ewes (< 2 and > 2 years), other sheep (< 1 and > 1 year), rams
	Pigs: boars, female breeding pigs, < 20 and > 20 kg body weight
	Poultry: layers, breeding birds, table birds and other poultry including fowl (turkeys, geese and ducks)
	Goats: as for sheep
	Horses: thoroughbred brood mares, other thoroughbred mares, other brood mares, other horses and ponies
	Deer: breeding females/males (< 1 and > 1 year) and other
	Other: ponies, mules, jennets and asses
Total grazing days (boarding in and out)	Commonage, grassland and others (dairy, cattle, sheep, horses): number of animals and days
Period indoors	Average full turnout and housing (date/days)
Housing type	Bedded, cubicles and slatted across subcategories
Manure management	Slurry tank (underground: roofed slatted/cubicles; overground: covered and uncovered) and lagoons (lined and unlined)
Total manure and slurry	Exported and imported
Manure spreading, including crop residues	Amount, percentage total spread, spreading method and timing: January–April, May–July, August–September and October–December
Feeds	Across livestock categories and subcategories: silage/forage and concentrates or high and low protein
Tillage practices	Types (deep, minimum/reduce, no and conservation) and timing
Chemical fertilisers and lime used	Names/types, amount, land use and area, allocation/application timing; amount, types and timing of lime application
Physical production	Economic and biomass yield; meat and milk (export, import and fed)
Mitigation measures	Inhibitors, diets, storage, treatment, etc.
Basic soil properties	Soil types, particle size distribution, bulk density, pH, cation exchange capacity, SOC, etc., across soil layers/profile
Meteorological data	Minimum and maximum temperature, precipitation, sunshine hours, potential evapotranspiration, albedo, etc.

2.3.2 *Review of National Farm Survey and Census of Agriculture databases*

National Farm Survey information collected by Teagasc

In 2012, a representative sample of 975 farms participated in the NFS out of a total national population of 79,292 farms. Farms were assigned to six farm systems on the basis of farm gross output, as calculated on a standard output basis. Standard output measures were applied to each animal and crop output on a farm. Only farms with a standard output of €8000 or more, the equivalent of six dairy cows, 6 hectares of wheat or 14 suckler cows, were included in the sample. Farms were then classified into one of the six farm systems on the basis of their main outputs. Farms falling into the pig and poultry systems were not included in the survey because of an inability to obtain a representative sample of these systems. Further details on the data collected and analysed have been reported by Hennessy *et al*. (2012).

In the 2012 NFS, farms with less than €8000 of standard output were no longer included in the sample. Until 2012, the threshold for inclusion of farms in the survey had been €4000 of standard output. The excluded farms represented 18% of the total farm population but they contributed only about 5% of the sector’s gross output. Therefore, a straightforward comparison between the 2012 results and the results from preceding years could easily lead to an incorrect interpretation of the intervening changes. Accordingly, the results presented in this publication included revised figures for previous years, which facilitated a direct comparison between 2012 and previous years. Nevertheless, the population of farms represented in the 2012 NFS sample, 79,103 farm holdings, corresponding to 93% of the sector's output, was smaller than the populations represented in previous years.

The extent of the usefulness of the NFS data is illustrated in Box 2.1.

Box 2.1. Advantages, disadvantages and barriers to use of the NFS data collected by Teagasc for the inventory of GHGs and air pollutants associated with manure management

Advantages

The NFS is conducted on an annual basis using 13 dedicated data recorders.

Most key activity data associated with manure management are available.

NFS data represent 57% of commercial holdings (out of 139,000 holdings), 81% of the land area, 95% of agricultural outputs and 93% of livestock.

NFS data are verified using a three-layer system, i.e. on farm, internally and at the EU level.

NFS data are kept in a readily available form for use.

Disadvantages

NFS data for 2012 are limited to 975 holdings that are selected at random and only 2% of the collected data are verified.

NFS data do not represent the number of holdings equally on a county basis or account for all of the livestock population (there is a lack of information for pigs, poultry and some minors at farm scales) or land use change and management, including the differences from one year to another.

NFS data do not represent farm holdings having a standard output of less than €8000, i.e. data are not available for small farm holdings.

NFS data might have limited scope for statistical analyses, i.e. analyses of uncertainty/probability density functions associated with activity data.

NFS data consist of limited disaggregated data for housing, manure storage and feed types, as well as manure-spreading methods where agitation is included.

Housing type, storage type and spreading methods vary from farm to farm and year to year and therefore the quantities/proportions change over the years.

The NFS team does not have access to the data and some terms used differ from those used by other agencies collecting data of a similar nature.

Barriers

Other than data by zone, bulk or county, data are not available/deliverable.

There is limited manpower to cover further holdings in order to provide better representation.

Because of other obligations, the immediate availability of personnel for obtaining activity data and to gather information is limited.

Census of Agriculture by the CSO

This report presents the results of the CoA conducted by the CSO in 2010. This work was undertaken within the framework of the statistical programme of the EU and, in particular, Regulation (EC) No. 1166/20081. A similar census was conducted in all EU Member States during 2009/2010 in order to collect comparable statistics across the region.

The results of this survey (the CoA 2010 followed by the SAPM) are being used in the development of EU and national policies on agriculture and the environment. As this was the first time that the SAPM had been carried out, there are no previous data available for comparison. Of the 40,000 holdings sampled, 25,885 responses were received, giving a response rate of 65%. The sample was stratified based on the size of the holding and whether or not a farm was involved in specialist pig or poultry production. The outputs available are mainly grossed to the population of farm holdings sampled in the CoA 2010.

The extent of the usefulness of the CoA 2010 data is illustrated in Box 2.2. For the CoA 2010, the register of agricultural holdings used to contact farmers was constructed by amalgamating the CSO intercensal Agriculture Register and DAFM's 2009 Corporate Client System. CoA questionnaires were sent to 153,906 farmers in the week preceding the reference date of 1 June 2010 and up to five reminders were issued in order to maximise the overall response rate. In an effort to reduce the response burden on farmers, all questions relating to cattle, cereals and potatoes were eliminated from the 2010 CoA questionnaire, as sufficient data were found to be available from existing DAFM data sources. Data on cereals and potatoes were obtained from DAFM's Single Payment Scheme (Council Regulation No. 1782/2003), whereas data on cattle were obtained from DAFM's animal identification and movement (AIM) system (Council Regulation No. 1760/2000). The CoA 2010 was therefore the first census to use a combination of administrative records and paper questionnaires to collect the required data in order to reduce the overall burden on respondents.

2.3.3 Activity data in Nitrates Derogation files

The DAFM administers the Nitrates Derogation system, which allows farmers to exceed the limit of 170 kg of livestock manure nitrogen per hectare set down in the Nitrates Regulations, up to a maximum of 250 kg per hectare, subject to adherence to stricter rules. This includes farm mapping, indicating the location of individual fields and corresponding soil samples with a farmyard sketch, farming in accordance with a fertiliser plan and maintaining fertiliser accounts. Nitrates Derogation applicants cannot import livestock manure onto their holding. The introduction of the Land Parcel Identification System (LPIS) and the online submission of applications for various agri-environmental schemes (e.g. Basic Payment Scheme; Green, Low-Carbon, Agri-Environment Scheme) have the advantage of providing information on agricultural management and practices. After several meetings/discussions with DAFM personnel, three files (hard copies) on the Nitrates Derogations were supplied to examine the availability of AAD required for the development of national inventory reporting, with an emphasis on manure management. The AAD available from the files are provided in Table 2.3.

About 135,000 farmers are registered under the scheme (cross-compliance) and ~1% of farms are inspected at random on a yearly basis, as well as on a region-by-region basis. The AAD include a Nutrient Management Plan and Soil Analytical Reports (although these are limited as no information is provided on SOC content) that are submitted every 4 or 5 years to the DAFM. Despite some missing information, the yearly activity data at the farm/parcel level collected by the DAFM would be highly useful, although the manpower requirements to compile the large volume of data, which exist mainly as hard copy, would be a major constraint. However, the major limitation is making the data available for research and reporting purposes, as these data are legally protected.

2.3.4 Activity data from Bord Bia

Attempts were made to compile and evaluate the AAD collected by Bord Bia, through various schemes, for use in inventory reporting, particularly for manure management-induced emissions of GHGs and air pollutants. Based on information gathered through meetings and seminars, the activity data for livestock populations and manure management collected by Bord Bia could satisfy some requirements for inventory reporting but were unavailable for this study. It was

Box 2.2. Advantages, disadvantages and barriers to use of the SAPM data collected by the CSO for the inventory of GHGs and air pollutants, with the emphasis mainly on manure management

Advantages

The SAPM has generated a large amount of data, representing 65% of the national farm holdings for key categories, and the coverage is significantly higher than that of the NFS carried out by Teagasc.

The SAPM covered most key activity data related to manure management and land use classes.

SAPM data on a county basis are available for inventory improvement purposes.

Disadvantages

SAPM data were collected by sending questionnaires by post to all farm holdings, leading to a major uncertainty associated with the data collection process, unless the data can be verified by a statistically valid and acceptable number of holdings. Any verification processes used are still unknown.

SAPM data cannot be compared with previous records because of incompatibility issues and limited activity data of a similar nature collected previously.

SAPM data have limitations in terms of the quantification of information on respective/corresponding activities, as most data were collected/recorded using a range scale and any statistical estimations/weighted averages might lead to significant uncertainties.

SAPM data consist of the number of housing with livestock places and limited disaggregated data on manure storage and spreading methods.

Information on the amount of feed, fertiliser and lime used, as well as the feeding/application methods used and timing, is not available.

There may be limited scope to incorporate any additional activity data required by agencies unless a similar survey is carried out.

Some terms used differ from those used by other agencies collecting data of a similar nature.

Barriers

Access to bulk/raw data for all farm holdings is not possible unless permission is given by the CSO authority and this can be time-consuming to obtain.

It is important to identify a main contact point within the CSO to obtain further information regarding data collection procedures and approaches, advice/suggestions and assistance in finding ways to access available activity data in a timely manner.

Because of other obligations, the immediate availability of personnel for obtaining activity data is limited.

also understood that a major issue could be obtaining information on activity data for pigs and poultry, which are not being collected by Bord Bia, as well as activity data from the Sustainable Dairy Assurance Scheme (SDAS)/Carbon Navigator, which were also not available for research purposes. The 2016 updates on the above, across sectors, are provided in Table 2.4.

Based on the sustainability report for 2016, activity data for beef (Sustainable Beef and Lamb Assurance Scheme) have been gathered from over 49,000 farms; this also included information from the national Irish Cattle Breeding Federation (ICBF) and DAFM AIM databases (Bord Bia, 2016). Over 117,000 audits have been conducted since 2011. Through the SDAS, Bord Bia has also collected information on almost 17,000

Table 2.3. Agricultural activity data collected through the Nitrates Derogation application by the DAFM

Activity data categories	Subcategories
Farm type	Total farm size, land use (key), area of land use categories, nitrogen index and its corresponding area
Livestock categories	Number across age groups and housed for slurry, stocking rate
Manure storage types	Slurry and solid manure storage types, amount of solid manure and slurry produced, capacity of solid storage
Application of manure	Amount of slurry and solid applied (no methods of application)
Feed type	Feed types (mostly mixed)
Inorganic fertiliser	Type and amount of inorganic nitrogen fertiliser applied
Liming	Area and amount of lime applied

Table 2.4. Roll-out of farm assessments by sector

Sector	2016 update
Beef	Commenced 2011. Over 117,000 farm assessments have been conducted to date. Carbon footprint model updated in 2016 to account for alterations in footprinting methodology
Dairy	Commenced January 2014. Over 20,000 farm assessments have been conducted to date
Grain	Pilot programmes commenced in 2014. Assessment tool developed based on carbon footprinting and other criteria as identified by the Sustainable Agriculture Initiative's Farm Sustainability Assessment methodology
Horticulture	Industry pilot carried out in 2015. A dedicated online resource for the Revised Sustainable Horticulture Quality Assurance Scheme is now available: https://hort.bordbia.ie/ (accessed 14 May 2020)
Lamb	Sustainable Beef and Lamb Assurance Scheme rolled out
Pig	Methodology being developed in conjunction with the Carbon Trust to quantify carbon and other sustainability criteria
Poultry/eggs	Revised scheme launched and methodology developed in conjunction with the Carbon Trust to quantify carbon and other sustainability criteria

Source: Bord Bia (2017).

of Ireland's dairy farms. It has completed over 20,000 carbon audits, with 13,000 farms becoming certified members, with the farms accounting for over 70% of Ireland's dairy farms. A summary of further relevant information is shown in Table 2.6.

2.4 Discussion

Among the project objectives, the AAD available from different data-generating organisations were successfully identified. Some relevant AAD are generated elsewhere that are somewhat useful to assess and estimate agricultural GHG emissions and air pollutants for the development of national inventory reporting methodologies. This includes the compilation of input parameters required for running process-based models and the development of proxies for other model input requirements. The main constraint for the wider use of the information was the limited availability of the data to academic/research institutes. Accordingly, AAD collected by the CSO, Teagasc, the DAFM and Bord Bia (relevant documents were not available), through surveys and agricultural schemes, followed by CoA 2010 data supplied by the CSO in 2013 to the EPA, were compiled and analysed (see Chapter 3).

The NFS data collected annually by Teagasc were not freely accessible, based on initial meetings and discussions with the relevant researchers. The NFS data were linked mainly to the assessment of economic benefits, through an annual farm survey but with a particular concern for environmental implications and the impact on GHG emissions. Basing reported estimates on a survey results in large uncertainties in the activity projections and therefore estimates of GHG emissions and their projections. Therefore, the use of NFS data to prepare NIRs and for UNFCCC reporting and the adoption of policy options to mitigate GHGs and air pollutants may not be possible. The collection of activity data and the development of confidence intervals are prerequisites for making use of the NFS data for reporting purposes and this should be taken into account by stakeholders and researchers.

The CoA/SAPM was conducted by the CSO only in 2010 and previous data are not available for comparison. The data were made available for this project through the EPA. Some progress that has been made in the estimation of manure production from livestock systems and the amount and timing of applications to various land uses is detailed in Chapter 3. These AAD are useful for the estimation of manure production types, storage and field application through further development of the calculation procedures/methodologies. Importantly, the survey was conducted without considering the involvement of farms as specialist pig or poultry producers, and overall gross results were reported. The questionnaire data were supplemented with administrative information and information from agricultural schemes from the DAFM, to reduce the overall burden on respondents.

The DAFM has been sourcing farm activity data and environmental information through various schemes, including the measures taken and activities carried out under the Common Agricultural Policy, such as cross-compliance, direct payments and Nitrates Derogation. The data are collected to improve biodiversity/landscapes, improve soil and water management, reduce GHG/ammonia emissions and foster carbon sequestration/conservation initiatives. In the case of the Nitrates Derogation, the information (three files) was supplied as hard copy, leading to significant difficulties in compilation of the data and determining if the ADD collection process through the scheme is consistent. However, there have been recent advancements in the online submission of applications for Nitrates Derogation, including soil test results and fertiliser management plans, although there are still some limitations, including in the uploading of PDF files. Considering other important sources of data collection, there is an apparent lack of co-ordination of environmental information across all divisions of the DAFM. A dedicated team is warranted to co-ordinate activities across disciplines for database compilation and to promote DAFM activities online at the land parcel level. These activity data could be highly useful for research and inventory purposes.

The Origin Green programme of Bord Bia is a world-leading sustainability programme. Developed under Origin Green, the SDAS is the first national dairy scheme to set out requirements for best practice on Irish dairy farms in animal health and welfare, land management, biosecurity, safe farming practices and the production of safe milk. The SDAS calculates the GHG emissions of each participating dairy herd using the Carbon Navigator tool, leading to measures that improve carbon efficiency on Irish dairy farms. The scheme is a rigorous, independently verified and internationally accredited programme. The activity data generated by Bord Bia (and also including the data collected by the DAFM and ICBF) will have huge implications for improving national inventory reporting and for other research-relevant activities. The major issue was obtaining activity data for pigs and poultry, which are not collected by Bord Bia. The activity data on livestock populations and manure management from Bord Bia, including data from the SDAS/Carbon Navigator, could satisfy some of the requirements, but these data were unavailable for this study. A clear understanding of the animal statistics, data collection mechanisms and calculation procedures used by Bord Bia, and how this information can be matched with activity data generated by the DAFM and Teagasc, will be important.

Given the overall importance of disaggregated activity data to satisfy the project objectives, including improvements in national inventory reporting, there is a need to explore the availability of statistically valid data on a zonal basis to make these data more representative. The research work on AAD generated by various organisations revealed that disaggregated activity data are required for both modelling and further national inventory reporting development. This includes the identification of mitigation options.

2.5 Conclusions

Based on the information gathered and the documents reviewed, useful AAD, subject to further development of methodologies and proxies to fill data gaps, are available to improve national inventory reporting for GHGs and air pollutants, particularly those associated with manure management. Legally binding procedures (e.g. Data Protection Act 2018) at the institutional level and copyright of research data are the main limiting factors in obtaining AAD from various organisations. Direct institutional/organisational involvement is critically important and it is recommended that the EPA facilitates an arrangement in which such information can be used by researchers and other end-users. Further conclusions are as follows:

- There should be a general consensus on the need for activity data, with the possibility of this being made open access using a shared platform, as well as an examination of the best ways of collecting and archiving this information. All available information should be considered, not just the statistically valid data.
- Data related to agricultural activities are important for several end-users, but continuity of funding to maintain any system that is developed is a significant issue that is clearly of national interest. This includes the identification of mitigation opportunities, which requires long-term studies.
- There is a lack of collaboration/co-ordination in the sharing of activity data between agencies. Currently available activity data (Carbon Navigator/SDAS data from Bord Bia, AIM and other relevant data from the DAFM, NFS data from Teagasc; CSO data) are fragmented and not easily accessible.
- Attempts should be made to remove barriers to data accessibility through anonymous contributions and a common agreement from providers that any information would be for research purposes only.
- A decision at the highest level may be required to remove any barriers to wider access to activity data. This will be essential to meet international and EU obligations and meet national objectives to reduce environmental pollution and mitigate the effects of climate change.

3 Accounting of Solid and Liquid Manure Storage and their Management Using Census of Agriculture 2010 Data

3.1 Introduction

Livestock production- and management-induced emissions of GHGs and air pollutants have major atmospheric and ecosystem-related impacts. Identification of category/subcategory hotspots associated with these emissions and the estimation of EFs, including the use of the IPCC defaults (Tier 1), are key objectives in the preparation of reasonable and transparent NIRs (Tier 2; IPCC, 2014). These also provide a basis for the assessment of technological/management approaches to emissions reductions. For this, data on manure (solid and liquid) production across livestock categories, housing types and periods, storage types and manure type-based application methodologies are required.

In Ireland, the EPA has been preparing NIRs for GHGs and air pollutants derived from manure management systems (Duffy *et al*., 2016). To do this, the inventory team has been using AAD collected through the Farm Facilities Survey. These include detailed data on manure management practices collected in 2003 (Hyde *et al*., 2008). The Farm Facilities Survey considered a representative sample of farms covering the four designated Nitrates Directive regions (DAFM, 2014). In addition to the results of the Farm Facilities Survey, individual subcategories were used to apportion manure management systems within a model. Where necessary, expert opinion, particularly for the partitioning of the year into pasture and housing periods, was considered. For national inventory reporting, the EPA inventory team also used annual census data published by the CSO. However, the 2003 Farm Facilities Survey data are old and do not represent ongoing management practices. They are also insufficient for quantifying the proportions of manure applied, and the timing of application, to major land use types and in different seasons. In addition, the data do not represent current subcategories/disaggregated manure management systems; such data are needed to provide precise estimates of emissions of GHGs and air pollutants.

The EPA therefore sought an improvement in national inventory reporting accounting methodologies, with an emphasis on manure management, by supplementing the number and types of recent AAD available. Useful AAD are available but these are limited in terms of disaggregation and are often available only from a single source. Administrative data (DAFM, Bord Bia, CSO, Teagasc and others) are thought to be more useful but are potentially time-consuming to collate and analyse, depending on the data loads expected. Manure management is a complex system, with various inter-related factors involved in the production and release of GHGs and air pollutants. Therefore, attempts were made to establish relationships between data across sectors (crops, grassland and livestock) and to identify mitigation options for GHGs and air pollutants, to enable cost-effective abatement measures to be recommended. Because of the lack of availability of AAD from other sources, data from the 2010 CoA, collected by the CSO, were used. The main objectives of this task were to:

- develop methodologies to calculate the proportions and amounts of livestock slurry and solid manure produced and the period of storage across livestock categories;
- estimate the proportions and amounts of livestock slurry and manure applied to major land use types and in different seasons;
- assess the proportions and amounts of livestock slurry and manure applied using various methods of application.

3.2 Materials and Methods

The CoA was a special survey carried out by the CSO in 2010. Because of the lack of availability of AAD from Bord Bia and Teagasc, the EPA inventory team collected these data from the CSO in 2013 and provided this information for use in this project. A preliminary review was carried out in order to improve the methodologies used in the calculation of emissions of GHGs and air pollutants from manure management systems and to identify any additional shortcomings for their precise estimations. Then, the collected data were collated and assessed using standard mathematical/statistical procedures to enable the efficient delivery of data to the EPA inventory team for updating the NIRs and to modellers for simulation of GHGs and air pollutants from manure management systems.

During the special survey, the CSO collected disaggregated AAD, including on manure management, leading to categorisation of a number of farms based on the applications used (1–24%, 25–49%, 50–74% and 75–100% of farms). This made quantification of the proportions of livestock slurry and manure applied to major land use types, and the timing of application, difficult. Based on the compiled data sheets, information on the total number of farms under different farm categories/types across application ranges was available. However, the total number of individual livestock categories, thought to be useful in estimating the proportions of slurry and manure application under different farm categories/types, was missing.

Therefore, the steps in Figure 3.1 were taken to distribute livestock categories to the total number of farms for various farm types. Then, the sum of the amount of manure produced by the total number of farms was converted to the amount of manure for each livestock category under major land use types and seasons across application ranges. This represented 15,543 (60%) holdings out of 25,885 farms surveyed, with responses of "none" and "blank" information excluded. This included calculation of the amount of slurry (liquid) and solid manure production (farmyard manure, FYM) across livestock categories, housing types and periods, storage types and application methodologies (see Figure 3.1). Each step in Figure 3.1 follows a calculation procedure including the number of livestock in each category and subcategory and the proportions and amounts of slurry and FYM.

3.3 Results

The total number of livestock for each category, the housing periods and total manure production based on the number of places and livestock population obtained from the 2010 CoA are presented in

Livestock (CSO database, referring to CoA, SAPM): Livestock category – places/population – slurry (S) and FYM production (proportions derived from the Nitrates Directive)

↓

Housing periods: For each livestock category (Days, Weeks, Months)

Housing types: Number of places ⟶ Number of livestock under (1) cubicle (solid and slatted), (2) loose (solid and slatted), (3) other indoor and (4) out-wintering pads

↓

Calculation of individual and thereby weighted proportions: S and FYM

↓

Manure storage type: (1) S/Liquid, (2) Solid manure/FYM and (3) Lagoon

↓

Calculation of manure production (m^3): Livestock category – number of livestock – total S and FYM: number of livestock × (proportion S or FYM/100) × weighted production/week × weeks housed

↓

Amount of manure (m^3) applied across agricultural land uses (LU) and Seasons (Sn): Proportion from SAPM (number of farms vs. number livestock, proportion applied)

Major land uses: grassland, maize, tillage and other
Seasons: spring, summer and autumn

Total LU/Sn = (Total S or FYM produced × proportion for corresponding LU/Sn)/100

↓

Amount of manure (S and FYM; m^3) applied across methods of application: Proportion derived from areas under various application methods × total S/FYM production (number of places/population)

Figure 3.1. Steps taken for the estimation of slurry and solid manure (FYM) production.

Table 3.1. Livestock number, housing period and total manure production during the housing period across livestock categories

Livestock type	Number on farm[a]	Manure production ratio (weighted av., $m^3\,week^{-1}$)		Housing and grazing period (weeks)	Manure production during housing (%)		Total manure production (Mm^3) (no. places/livestock)[b]	
		Slurry	Solid		Slurry	Solid	Slurry	Solid
Cattle	6,606,585	0.23	0.19	14.86	60.64	39.36	13.527/13.123	7.046/7.227
Sheep	2,865,510		0.027	9.86		100.00		1.949
Pigs	1,516,291	0.22	0.24	52.14	99.37	0.63	17.188/17.170	0.118/0.138
Poultry	10,924,807		0.54[c]	52.14		100.00		0.310
Goats	10,520		0.026	12.00		100.00		0.003
Horses[d]	113,527		0.83	25.71		100.00		2.409

[a]Source: CSO (2012).

[b]Single values are based on number of places.

[c]Per 1000.

[d]Includes mules, jennets and asses.

Table 3.1. Among the livestock categories, only cattle and pigs were found to produce slurry and the weighted average slurry production for cattle and pigs was very similar, at 0.23 and 0.22 $m^3\,week^{-1}$, respectively. However, the ratio of slurry production to solid manure production for cattle was higher than that for pigs. Other than pigs, of which negligible numbers are kept outside, and poultry, which remain inside for the whole year, the estimated housing period was highest for horses, at 26 weeks, followed by cattle (15 weeks), goats (12 weeks) and sheep (10 weeks). Among livestock categories, the proportion (%) of slurry to solid manure produced during the housing period was higher for pigs (99:1) than for cattle (61:39). Slurry production from other livestock was not considered, leading to the production of 100% solid manure, mostly from loose-bedded houses.

Total (national) manure production was estimated using both the number of places and the population for key livestock categories such as cattle and pigs (see Table 3.1). There was no significant difference between the values estimated using number of places and population. The total amount of slurry produced from cattle was 13.5 Mm^3 based on number of places and 13.1 Mm^3 based on livestock population, whereas that produced from pigs was 17.2 Mm^3 based on both number of places and livestock population; the corresponding solid manure values for cattle were 7.0 Mm^3 and 7.2 Mm^3 based on number of places and livestock population, respectively, whereas those for pigs were 0.12 Mm^3 and 0.14 Mm^3, respectively.

The amount of solid manure estimated for horses (2.4 Mm^3) was lower than that for cattle but higher than that for sheep (1.95 Mm^3) and poultry (0.31 Mm^3); the amount of solid manure derived from goats was very small.

Table 3.2 shows the estimated proportions (%) of livestock slurry and manure applied to various land uses and in different seasons in 2010. Based on the estimated amount of manure applied to various land uses, there were large differences between the proportions calculated using the number of farms/spaces and the proportions calculated using the livestock population when the AAD relevant to these were available only for cattle and pigs. The results show that, for cattle and others, a major proportion of the slurry was applied to grassland (97% based on number of farms vs 73% based on livestock population), and the amounts applied in spring and summer were similar (40–42% in spring vs 36–40% in summer) and significantly higher than the amounts applied in autumn (18–24%). Similarly, most solid manure was applied to grassland (90% vs 77%), with more applied during autumn (49% vs 26%). The spring application of solid manure was larger (31% vs 61%) than the summer application (21% vs 13%).

Because of the lack of data, the proportions for cattle were used to estimate the amount of manure applied onto various land uses and in different seasons for other livestock categories, excluding pigs. Unlike in Table 3.2, there was no significant difference between the two values estimated using number of places and

Table 3.2. Estimated proportions (%) of livestock slurry and manure applied onto various land use types and in different seasons

	Slurry		Solid manure	
	Cattle and others	Pigs	Cattle and others	Pigs
Land use/season	No. farms/livestock	No. farms/pigs	No. farms/livestock	No. farms/pigs
Land uses				
Grassland	96.9/73.4	–/67.5	90.4/76.8	–/65.2
Maize	0.9/11.6	–/12.4	1.7/15.9	–/8.7
Tillage	1.9/12.9	–/19.2	7.9/15.9	–/26.1
Other	0.3/2.2	–/–	–/–	–/–
Seasons				
Spring	42.2/39.3	–/42.1	30.5/61.3	–/66.2
Summer	39.6/36.3	–/34.6	20.9/12.8	–/12.1
Autumn	18.2/24.4	–/23.3	48.6/26.0	–/21.6

Table 3.3. Estimated amount (Mm^3) of livestock slurry and manure applied onto various land use types and in different seasons

	Cattle	Sheep	Pigs	Poultry	Goats	Horses
Land use/season	No. places/ cattle	No. places/ sheep	No. places/ pigs	No. places/ poultry	No. places/ goats	No. places/ horses
Slurry						
Land uses						
Grassland	13.24/12.71		16.65/18.10			
Maize	0.13/0.12		0.16/0.17			
Tillage	0.26/0.25		0.33/0.36			
Other	0.04/0.04		0.05/0.05			
Seasons						
Spring	5.76/5.53		7.25/7.88			
Summer	5.41/5.20		6.81/7.40			
Autumn	2.49/2.39		3.13/3.40			
Solid manure						
Land uses						
Grassland	6.12/6.53	0.688	0.107/0.125	0.280	0.0030	2.177
Maize	0.12/0.12	0.013	0.002/0.002	0.005	0.0001	0.041
Tillage	0.54/0.57	0.060	0.009/0.011	0.025	0.0003	0.191
Seasons						
Spring	2.07/2.30	0.232	0.036/0.042	0.095	0.0010	0.736
Summer	1.41/5.20	0.159	0.025/0.029	0.065	0.0007	0.503
Autumn	3.29/3.39	0.370	0.057/0.067	0.151	0.0016	1.171

population (Table 3.3). As calculated using number of places, the major amount of slurry derived from cattle (13.2 Mm^3) and pigs (16.7 Mm^3) was applied to grassland. The remainder (0.04–0.26 Mm^3 for cattle and 0.05–0.33 Mm^3 for pigs) was applied to tillage, maize and other land uses. The highest amount of solid manure was estimated for cattle and horses and the major amount of this was applied to grassland (6.1 vs 2.2 Mm^3). Including the smaller amount of manure derived from other livestock categories, sheep produced the highest amount, followed by poultry and goats, with more manure applied to tillage than maize.

Among the seasons, spring application of slurry derived from cattle (5.8 Mm^3) and pigs (7.3 Mm^3), based on number of places, was slightly higher than the amount applied in summer (5.4 and 6.8 Mm^3, respectively), which was significantly greater than the amount applied in autumn (2.5 and 3.1 Mm^3, respectively). However, solid manure derived from all livestock categories was applied more during autumn (0.002–3.3 Mm^3) than during spring (0.001–2.1 Mm^3) or summer (0.001–1.4 Mm^3).

Average estimates of the proportions of slurry and solid manure applied across livestock categories showed uncertainty for grassland (up to 8% of variance); however, this was smaller than that for maize and tillage (5–28%) and the "other" category (53%), although this represented only 2% of the total coverage. In the case of seasonal applications, the variance ranged from 3% to 13%. However, further evaluation of the possible use of these estimated values for GHG and air pollutant inventories is required. Among the application methods, farmers mostly used a splash plate for slurry (90%) and side discharge for solid manure (60%) (Figure 3.2). The total amount of slurry applied using a splash plate was 27.7 Mm^3, which was remarkably higher than the amount applied using other methods (0.5–1.3 Mm^3). In case of solid manure, the estimated amount applied through side dressing (rotary) (6.8 Mm^3) was considerably higher than that applied using other methods (0.2–3.4 Mm^3).

3.4 Discussion

All livestock categories were distributed to calculate the total numbers of farms under various farm types and therefore convert the sum of manure production for all farms to the sum of manure production for each livestock category under major land use types and seasons across application ranges. Irrespective of livestock category, the CSO received information from the survey that was mainly representative of cattle, and the proportional distributions of cattle slurry and solid manure across land uses and seasons (except for pigs) were used. The estimated proportions of slurry applied to various land uses, in particular, were well matched with data from the Teagasc NFS 2009–2010 report, whereas the estimated proportions for solid manure varied to some extent (Hennessy *et al*., 2011). However, there were large differences between the proportions estimated using the number of farms and the proportions estimated using livestock populations. Therefore, further refinement using expert advice and data/information to minimise these errors, emphasising other key livestock categories, is required.

There were no large differences in the amount of manure production between the calculations based on the number of places and the calculations based on livestock populations. However, the livestock population during the housing period (commonly winter for key categories) is preferred for calculating the amount of manure produced, except for poultry,

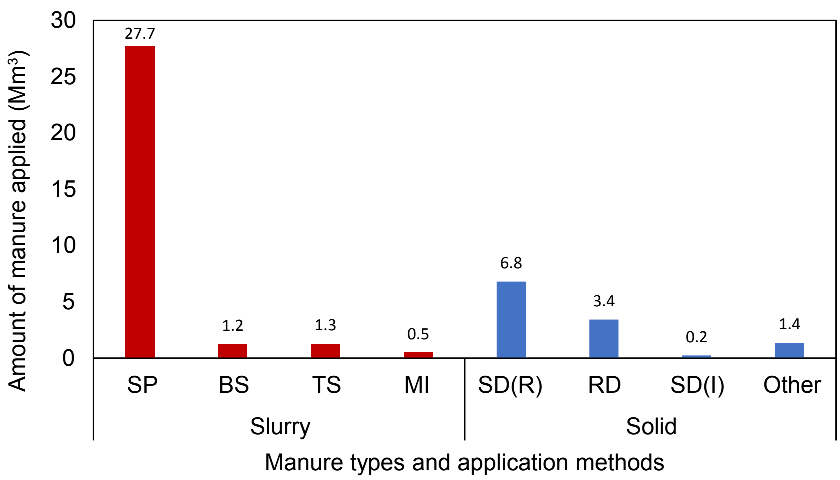


Figure 3.2. Amounts of slurry and solid manure applied using various methods across agricultural land uses. BS, bandspreading; MI, injection; RD, rear dressing; SD(I), side dressing (impeller); SD(R), side dressing (rotary); SP, splash plate; TS, trailing shoe.

for which the population estimates vary widely, with huge counting errors. Based on the above proportional distribution, the amounts of slurry and solid manure applied to various land uses and for the different seasonal categories adopted by the CSO were representative. Major proportions of slurry were applied onto grassland and the amounts of slurry applied in spring and summer were similar. In contrast, Hyde *et al*. (2008) and Hennessy *et al*. (2011) estimated that the major proportion of slurry was applied during summer, followed by spring, with almost double the amount applied during each compared with the autumn.

Similarly, the major receiver of solid manure was grassland, with the other two land uses receiving only a small amount of manure. However, it was observed that farmers applied solid manure more during autumn than during spring and summer, with spring application being larger than summer application. These findings are in line with information obtained by other researchers in Ireland (e.g. Hyde *et al*., 2008; Hennessy *et al*., 2011). For seasonal application, however, estimates based on the number of places differed from estimates based on the number of livestock, particularly for the cattle category, and this issue should be revisited by collecting data/information from other agencies.

Among the slurry application methods, farmer mostly used the splash plate method, which is in line with information obtained from the Farm Facilities Survey 2003 (Hyde *et al*., 2008), in which the trailing-shoe method was completely absent, and the Teagasc NFS 2009–2010 (Hennessy *et al*., 2011). However, among the CoA 2010 data there should be a higher number of trailing-shoe users and the injection approach is in reality not used under Irish conditions, as reported by Teagasc. Therefore, further refinement using expert advice is required before trailing shoe can be made acceptable to users. Farmers in Ireland mostly use side and rear discharge methods for the application of solid manure, which, again, is in line with the findings of the Farm Facilities Survey and the Teagasc NFS 2009–2010. Information from other sources was difficult to find to support the use of disaggregated methods of solid manure application in Ireland.

The livestock numbers used in calculations were the average annual numbers and the estimation of manure production might therefore be overestimated, as the numbers of livestock during winter are expected to be lower than the numbers in other seasons. Accordingly, seasonal AIM data are required to best estimate the amount of manure produced during the housing period. An expert from the DAFM emphasised that the storage period for pigs and poultry, in general, should be 26 weeks (with 100% housed) and the housing period for sheep and goats should be 6 weeks. In addition, the slurry to solid manure production ratio, and consequently the total production of solid and liquid manure, should also be revisited (e.g. the pig slurry to solid manure production ratio from Denmark can be used). This relates to the amount of straw used in houses for bedding purposes and the resultant changes in the production ratio.

Importantly, the use of straw-bedded solid-floor housing has been growing in Ireland, leading to an increase in the production of solid manure, and this should be taken into account. For most livestock categories, the conversion of number of places to total livestock numbers, linked to variations in population from one year to another, is preferred. This is required to obtain precise estimates of total manure production over different years, except for poultry, particularly under deep litter (layers occupy a major share within poultry) conditions. Information on the amount of manure applied using various methods was absent in the data collected through various schemes by the DAFM and thus we had to rely on survey records and expert opinion for this information.

According to a DAFM expert, the following proportions of slurry and solid manure are produced under each housing type: loose: 100% solid for straw-bedded; slatted: mostly slurry (70–80%); and out-wintering pads: 55% solid. The amount of cattle slurry applied during spring should always be higher than the amount applied during summer and autumn. In addition, IPPC legislation on pig and poultry manure storage facilities and periods of storage, as well as legislation on the methods and timing of spreading introduced by the Irish EPA and/or the EU, should also be reflected in both methodologies and accounting/quantification.
In addition to the above, the information generated during the reporting period can be used to estimate emissions of GHGs and air pollutants from manure management by using analytical data (insourcing and outsourcing), such as data on nitrogen, organic carbon and volatile solids contained by various manure types, and/or IPCC default values. It was not possible to

complete this within the project period because of time constraints, as the EPA assigned us another task.

3.5 Conclusions

The methodologies developed using the CoA 2010 AAD to estimate manure production (the proportions and amounts across livestock categories, land uses and seasons) from livestock manure management are useful. However, further improvements are suggested, with particular concerns around data gaps for precise estimation of manure production during housing/storage and application of the methodology to various land uses, to provide precise estimations of the amounts of GHGs and air pollutants produced. In this study, the livestock numbers used were average annual numbers so the estimates of manure production might be overestimates, as the livestock numbers during winter are lower than those during the other seasons. Improvements in the methodologies developed will require the use of seasonal AIM data. The storage period for pigs and poultry and the housing period for sheep and goats, and the slurry to solid manure production ratios and therefore total production, should be revisited and linked to the amount of straw used in houses for bedding purposes. The conversion of number of places to total livestock numbers might be important, considering the variations in livestock populations from one year to another. The amounts of slurry applied using different methods could have a significant impact on the estimation of emissions of GHGs and air pollutants compared with the solid manure application methods used. The results imply that the information generated can be used to estimate emissions of GHGs and air pollutants from manure management. The parameters required to calculate emissions of GHGs and air pollutants, such as data on nitrogen, organic carbon and volatile solids contained in various manure types, can be IPCC default values and/or measured values (insourcing and outsourcing).

4 Historical Changes in Soil Organic Carbon Stocks in Irish Agricultural Soils Estimated by Integrating Modelling and Geographic Information System Approaches

4.1 Introduction

Recent international negotiations underscore the importance of significantly reducing anthropogenic GHG emissions to keep the global temperature rise below 2°C relative to pre-industrial times. The Paris Agreement emphasises the need for enhanced mitigation measures, reduced GHG assessment uncertainties, better quantified sinks and the tailored use of different offsetting mechanisms (UN, 2015b). However, technological and economical limitations, and large uncertainties in achieving these goals, exist. In addition to improved agricultural management practices, the SOC pool has the potential to act as a major source or sink of GHGs because of its large size and active interaction with the atmosphere. Because of the lack of detailed, spatially explicit activity data, Annex I countries use the IPCC GPGs Tier 1 methodology, which includes proportional (%) default EFs for GHGs and SOC stock (here density) change factors (DCFs), for inventory reporting (IPCC, 2014). For quantification of the baseline SOC density/stock, robust country-specific activity data (Tier 2 approach) are essential to account for the diversity of practices that influence soil carbon within a country or region, and to identify potential land uses and soil types for achieving the 4 per mille SOC initiative (Minasny *et al.*, 2017).

Ireland mostly uses the IPCC GPGs Tier 1 methodology and EFs to estimate GHG emissions, and, to a limited extent, DCFs for SOC changes, for national inventory reporting, because of inadequate country-specific data (Duffy *et al.*, 2016). However, Ireland is committed to achieving improved estimates of GHGs and SOC density/stock changes by developing higher tiers. This will be supported by the AGRI-I project, funded by the DAFM, which is aimed at (1) developing robust EFs, particularly for N_2O; (2) investigating carbon stocks and fluxes for grassland and arable systems; (3) assessing the impact of soil type, management and regional climatic conditions; and (4) validation of existing models and the provision of a database for spatial analysis, leading to national estimates for grassland and arable systems. Additional projects funded by the EPA and the DAFM are linked to these activities, for example "Scaling soil process modelling to national level" (TCD/UCD), "Survey of GHG emission and sink potential of peatlands" (UCC) and others (e.g. by the Teagasc Dairy and Economic Groups). From these activities, Tier 2 methodology development for some land uses might be possible, but the estimation of national GHG emissions and projected SOC stocks and their changes will depend on the use of appropriate models and their predictability closer to real figures, and upscaling from land parcel to national levels.

Pedotransfer functions (PTFs) and regression modelling have been used to obtain a more complete and detailed spatial distribution of SOC content, with or without geographic information system (GIS) techniques (e.g. Soussana *et al.*, 2004; Meersmans *et al.*, 2009; Khalil *et al.*, 2013b). To reconcile existing discrepancies and the lack of information on SOC densities/stocks for disaggregated agricultural land covers and soil types, a more detailed spatial assessment of baseline SOC densities/stocks covering disaggregated agricultural land uses, soil types and management scenarios at the land parcel level, leading to the option of upscaling to national/regional levels, is required. This would contribute to national assessment methodologies and provide an improved understanding of the consequences of historical changes in SOC densities/stocks and could help to identify potential GHG mitigation and offsetting approaches. This would also build capacity in the understanding and application of model interfaces.

The end target is to provide a tool for the quantitative assessment of the consequences of different scenarios for carbon densities/stocks and GHG emissions. Importantly, the ability of the tools to predict coupled emissions of GHGs and changes in SOC densities/stocks in agricultural soils in Ireland is highly important (Khalil *et al*., 2013a). The Irish agricultural system is dominated by grassland, which has significant offsetting potential to improve the overall GHG balance through the management and inclusion of carbon sequestration. However, information on carbon densities/stocks and sequestration is limited in terms of the quantification of grassland and arable carbon sinks and management strategies that enhance carbon sinks. This requires model refinement, as well as sensitivity and uncertainty analyses of the AAD and DCFs/EFs.

Estimates of SOC densities/stocks in Ireland are currently derived mainly from national data, including Co-ordination of Information on the Environment (CORINE) land cover maps, the General Soil Map (GSM) and UK data sets (e.g. SOC concentrations and bulk densities for specific soil types), but with limited spatial resolution (Tomlinson, 2005; Eaton *et al*., 2008). Following previous research funded by the EPA, SOC densities/stocks across major land cover categories and general soil groups (GSGs) were estimated through the development of empirical models and PTFs (Khalil *et al*., 2013b). However, information on the impacts of land use and land use change (LULUC) on SOC density/stock changes over a longer period was lacking. This information is, however, highly relevant to the research needed for the development of LULUCF inventories. This is in line with the Paris Agreement and UNFCCC reporting obligations. This task was aimed at:

- refinement of depth distribution models (DDMs) to calculate SOC concentrations beyond a depth of 100 cm and PTFs to estimate bulk density;
- identification of key agricultural land use classes, and land use management practices and their changes at parcel level, through overlaying and analysing national databases;
- attainment of data on SOC concentrations (and thereby densities/stocks) for particular land use classes and their rotations on specific soil types;
- synthesis/collation of the fractional contribution of key soil variables, inputs and management practices to SOC densities/stocks across agricultural land uses and soil types;
- development of methodologies and models to estimate baseline data for SOC densities/stocks and their historical changes across agricultural land use categories and soil types.

4.2 Materials and Methods

Information on soils and weather and data from the LPIS, the National Soil Database (NSDB), indicative soil types (ISTs) and CORINE, etc., were sourced and collected by the EPA from the DAFM, the CSO, Met Éireann and Teagasc and supplied to this project at a limited scale. Because of depth inconsistencies in the Irish Soil Information System (ISIS) soil databases and other limitations, ISTs were considered for the categorisation of soil types (calcareous and non-calcareous; well and poorly drained; mineral, organo-mineral and organic soils) corresponding to agricultural land use categories and other key variables. The NSDB, ISIS and IST databases were reviewed to identify relevant soil variables, inputs and management interventions required to estimate SOC densities/stocks and their changes in agricultural soils.

A framework on how to compile and use these models for the estimation of SOC densities/stocks and their changes over time was made, leading to the development of a reporting tool. However, further expert views were taken into account following the presentation of the results to academics/researchers and stakeholders. These were needed to supplement the AAD required for generating national estimates of GHG emissions and SOC density/stock changes using the GIS technique. These generated further data on land use types, soil types and SOC concentrations across soil types (ISTs) under land cover/use. Information on agricultural land use areas was not available and corresponding statistical data collected and compiled by the CSO were used.

Based on UNFCCC reporting requirements, methodologies and models for estimating SOC density/stock changes in agricultural land use and land use change (ALULUC) categories were developed. In a previous study, DDMs and PTFs were developed to estimate SOC concentrations and bulk density across major land covers and GSGs (Khalil *et al*., 2013b). Because of a lack of relevant measurement data, bulk density was mainly used to obtain soil mass by volume, as this was considered to be the best approach for estimating SOC density/stock changes based on the previous work. The model-derived data were processed to refine the DDMs and PTFs covering various soil types, as per the ISTs (EPA, 2006), representing major soil characteristics (e.g. acidity, mineral/organic, and drainage classes) that impact on biogeochemical functions in soils regulating SOC gains or losses, and the corresponding key agricultural land uses and whether this included a rotation of more than one land use. For this, the IST database was overlaid on the NSDB from 2006, containing SOC data from a depth of 10 cm (further details are available in Khalil *et al*., 2013b), and on the LPIS (consisting of historical changes in land use at the parcel level from 2000 to 2014) from 2006.

Following the overlaying of the NSDB, the IST and the LPIS maps using the GIS identified 490 of the 1310 sampling/grid points included in the NSDB. These were synthesised and compiled for assessment of SOC concentrations and densities (SOC concentration × soil mass, with the soil mass calculated using bulk density values for the respective depths because of a lack of soil mass weight by volume measurements) up to a depth of 100 cm using the refined DDMs and PTFs described previously. We considered 2006 as the base year for the analysis as soils were sampled around this year for the determination of SOC concentrations as part of the NSDB.

We have redefined SOC stocks, which were computed by multiplying the SOC densities by the total agricultural farmed/land use unit areas reported by the CSO (www.cso.ie), taking into account the proportion of land uses on three soil categories derived from 490 sampling points, to differentiate the amount of SOC between a unit and key land use categories at national levels. Synthesis/collation of the fractional contribution (proportional) of key soil variables, inputs and management, as well as estimation of SOC densities/stocks and their historical changes in agricultural soils, were carried out. Figure 4.1 outlines the steps taken.

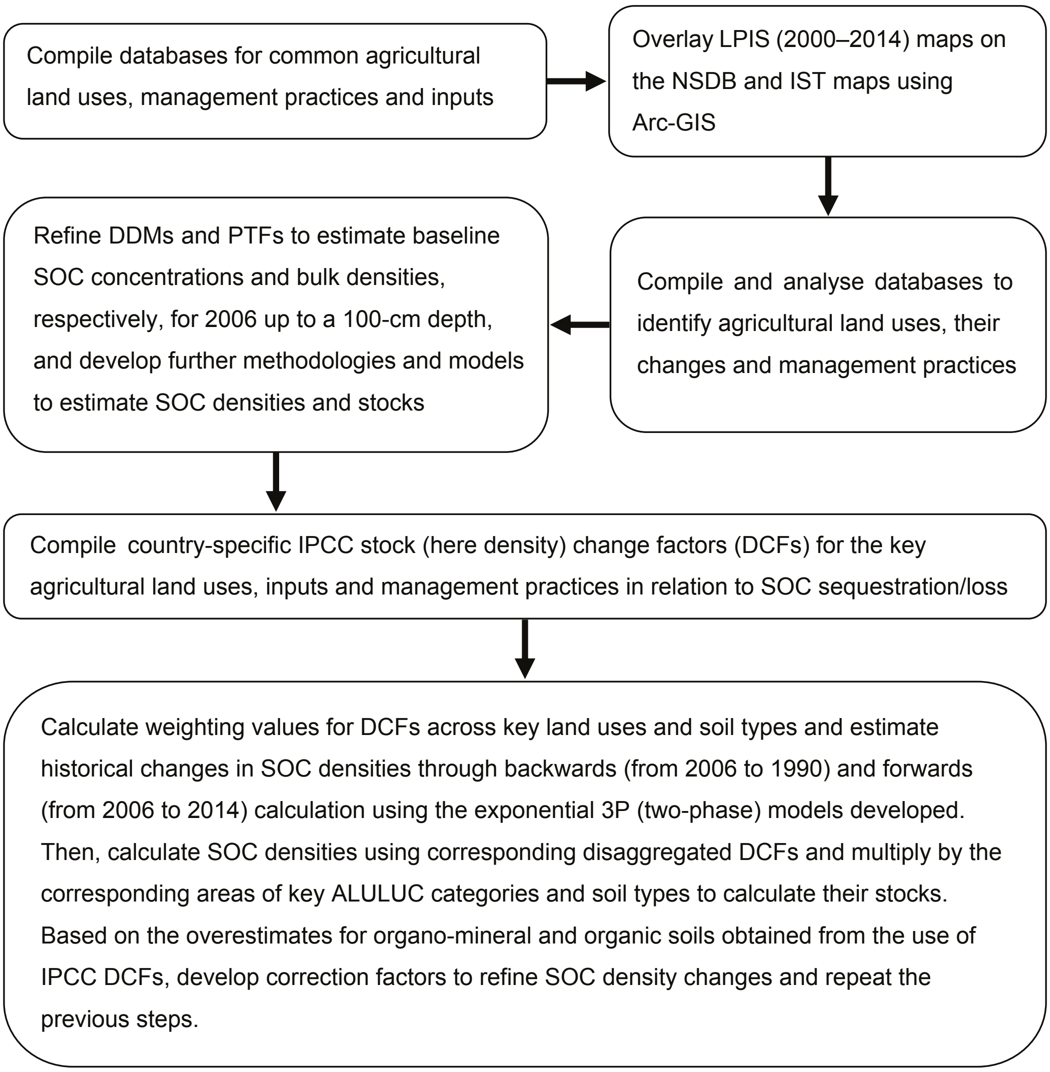


Figure 4.1. Flow path for estimation of historical SOC densities/stocks in agricultural soils.

4.2.1 Development of two-phase models

The IPCC has indicated that an equilibrium state of SOC stocks (here densities) is likely to be reached in 20 years, through either carbon gain or carbon loss. This may relate to the concept that, ultimately, at some point, saturation of soil carbon will occur, although there are conflicting results in the literature regarding the time it will take to reach this point (Wiesmeier *et al.*, 2016). For example, grassland soils that sequester a significant amount of carbon did not reach saturation after 43 years of intensive management (Fornara *et al.*, 2016). Based on the common trend of SOC dynamics referring particularly to the breakdown of the equilibrium state/occurrence of land use change, faster gains or losses are presumed to be taking place during initial periods (e.g. 5 years). Thereafter, the processes are slower because of the limited gains or losses that occur in a continuous cropping system/pattern. This led to the development of the key land use-specific conceptual two-phase (exponential 3P) models shown in Table 4.1.

4.2.2 Disaggregated agricultural areas and SOC density change factors

Based on the land use and soil databases used, the key agricultural land use categories selected to better represent Irish agricultural systems were tillage, temporary grassland, rough grazing and grassland. These land use categories and their subcategories are provided in Table 4.2. The IPCC proposes relative stock (here density) change factors (DCFs) for mineral (proportional) and organic (by mass) soils, whereas SOC concentrations in mineral soil under arable and grassland are highly variable under Irish conditions. To minimise errors associated with proportional averaging across mineral soils consisting of highly variable SOC contents, the soils were split into (1) mineral soils, containing < 10% SOC, and (2) organo-mineral soils, containing > 10% but < 20% SOC. This categorisation was also used to evaluate the impacts of apportioning on overall estimates of SOC density for soils with contrasting SOC concentrations and therefore densities.

The management categories and inputs for the different land uses were selected based on CSO data and expert opinion/advice. The relative DCFs were derived from country-specific (temperate, cool climate) IPCC defaults for key land uses, management practices and inputs matching the Irish categories and subcategories. Based on Irish expert opinion, highly degraded soils are generally absent in Irish agricultural systems and so the highly degraded soil category was omitted. A small degraded area (8%) was considered only for organic soils with a SOC content of > 20% under agricultural practices. The DCF by mass per area for organic soils proposed by the IPCC was converted to a proportional amount in order to match the estimation procedures applied to mineral soils. The degraded areas were considered to be sources of carbon and the other areas were considered to be sinks under a grassland system. The weighting factors for each land use were calculated using the default DCFs and the corresponding land use areas derived from the CSO database for the corresponding year. The degraded and non-degraded classifications were used only to develop models to take into account the loss of SOC from surface layers for reasons other than those associated with severe degradation/erosion. This approach was adopted to minimise the error in the estimations, as the presence of highly degraded soils is negligible under Irish conditions.

Table 4.1. Conceptual two-phase (exponential 3P) models for estimation of SOC density changes across major agricultural land uses

Agricultural land uses	Exponential 3P models[a]	SSE	MSE	RMSE	R^2
Grassland	$SOC_{mpz} \pm [\Delta SOC_{pz} \times 0.080036 \times \exp(-0.093944 \times Y_{eq}) + 0.0022839]$	7.74×10^{-5}	1.55×10^{-5}	0.003934	0.967
Rough grazing	$SOC_{mpz} \pm [\Delta SOC_{pz} \times 0.0809556 \times \exp(-0.106038 \times Y_{eq}) + 0.0022869]$	1.09×10^{-5}	2.18×10^{-6}	0.001475	0.994
Tillage	$SOC_{mpz} \pm [\Delta SOC_{pz} \times 0.1411633 \times \exp(-0.089195 * Y_{eq}) + 0.0105468]$	4.34×10^{-5}	8.67×10^{-6}	0.002945	0.994
Rotation	$SOC_{mpz} \pm [\Delta SOC_{pz} \times 0.0494766 \times \exp(-0.075598 \times Y_{eq}) + 0.0015639]$	1.53×10^{-5}	3.05×10^{-6}	0.001748	0.986

[a]ΔSOC_{pz} = SOC density change derived by multiplying its measured/estimated value with the weighted average of the corresponding DCF at a specific soil layer/depth; SOC_{mpz} = measured SOC density at a specific soil layer/depth; Y_{eq} = number of years since the first SOC density equilibrium is reached.

MSE, mean square error; R^2, coefficient of determination; RMSE, root mean square error; SSE, sum of squared error.

Table 4.2. Key agricultural land uses and their subcategories associated with management and inputs and the corresponding DCFs for SOC density changes

Main land uses	Management	Proportion of area	Inputs	Proportion of area	DCF
Tillage/arable (M and OM soils)	Full	0.80	Low	0.15	0.63
			Medium	0.20	0.69
			High, no manure	0.50	0.77
			High, manure	0.15	0.99
	Reduced	0.15	Low	0.15	0.69
			Medium	0.20	0.75
			High, no manure	0.50	0.83
			High, manure	0.15	1.07
	No/zero	0.05	Low	0.15	0.73
			Medium	0.20	0.79
			High, no manure	0.50	0.88
			High, manure	0.15	1.14
	Weighted average of DCF for tillage on M and OM soils				*0.78*
Temporary grassland (M and OM soils)	Full	0.95	Low	0.20	0.78
			Medium	0.35	0.85
			High, no manure	0.35	0.94
			High, manure	0.10	1.22
	Reduced	0.05	Low	0.20	0.84
			Medium	0.35	0.92
			High, no manure	0.35	1.02
			High, manure	0.10	1.32
	Weighted average of DCF for temporary grassland on M and OM soils				*0.91*
Grassland (M and OM soils)	Pasture	0.56	Low (non-degraded)	0.38	1.00
			Medium (improved)	0.40	1.14
			High (improved)	0.22	1.27
	Hay	0.06	Low (non-degraded)	0.38	1.00
			Medium (improved)	0.40	1.14
			High (improved)	0.22	1.27
	Silage	0.26	Low (non-degraded)	0.38	1.00
			Medium (improved)	0.40	1.14
			High (improved)	0.22	1.27
	Weighted average of DCF for grassland on M and OM soils				*1.12*
	Rough grazing	0.12	Low (non-degraded)	0.70	1.00
			Medium (improved)	0.30	1.14
	Weighted average of DCF for rough grazing on M and OM soils				*1.04*
Grassland (O soils)	Pasture	0.56	None (degraded)	0.08	0.95
			Low (non-degraded)	0.30	1.00
			Medium (improved)	0.40	1.14
			High (improved)	0.22	1.27
	Hay	0.06	None (degraded)	0.08	0.95
			Low (non-degraded)	0.30	1.00
			Medium (improved)	0.40	1.14
			High (improved)	0.22	1.27

Table 4.2. Continued

Main land uses	Management	Proportion of area	Inputs	Proportion of area	DCF
Grassland (O soils)	Silage	0.26	None (degraded)	0.08	0.95
			Low (non-degraded)	0.30	1.00
			Medium (improved)	0.40	1.14
			High (improved)	0.22	1.27
	Weighted average of DCF for grassland on O soils				*1.11*
	Rough grazing	0.12	None (degraded)	0.10	0.95
			Low (non-degraded)	0.65	1.10
			Medium (improved)	0.25	1.14
	Weighted average of DCF for rough grazing on O soils				*1.03*

M, mineral; OM, organo-mineral.

Measured data for DCFs for the corresponding land uses, management practices and inputs were unavailable for Ireland. Preliminary estimates showed that the IPCC DCF-derived rates of SOC density change differed between the mineral, organo-mineral and organic soils for key land uses (grassland, rough grazing and grassland–tillage) except for tillage, and between the soil layers, particularly between 0–30 cm and 0–100 cm (Khalil and Osborne, 2017). As the IPCC DCFs consider a soil depth up to 30 cm (plough depth layer), the following equation was developed to correct DCF-induced rates of SOC density change for deeper soil layers using corresponding values for SOC density in the 0- to 30-cm and 0- to 100-cm layers for key land uses and soil categories that were measured in 2006:

$$RC\rho_{0\text{–}100\,cm} = RC\rho_{0\text{–}30\,cm} + \{(RC\rho_{0\text{–}30\,cm} \times (SOC\rho_{0\text{–}30\,cm}/SOC\rho_{0\text{–}100\,cm})\} \quad (4.1)$$

where SOCρ is the SOC density and RCρ is the rate of SOC density change for a given soil depth.

Given the importance of factors that influence carbon gains or losses within a soil type rather than the inherent SOC concentrations, equations were also developed to minimise the excess sinks or sources derived from using land use-, management- and input-associated IPCC DCFs for organo-mineral and organic soils. To achieve reasonable correction factors (CFs), we assumed an equal contribution of land uses, management practices and inputs to SOC density changes in all soil categories. Accordingly, the corresponding ratios of SOC density for mineral soils to organo-mineral and organic soils in the 0- to 10-cm and 0- to 30-cm layers for key land uses and soil categories measured in 2006 were used. As the amount, rather than the percentage, of SOC loss increases with increasing SOC concentration (e.g. Khalil *et al*., 2007), we deducted an additional 5% from the organo-mineral and organic soils over the IPCC DCF-derived fraction of SOC density. Based on the above, the following equation, which is equally effective for both organo-mineral and organic soils regardless of land use, was developed:

$$CF_{0\text{–}10\text{ or }30\,cm} = (MC\rho_{0\text{–}10\text{ or }30\,cm}/OMC\rho_{0\text{–}10\text{ or }30\,cm}) - \{(MC\rho_{0\text{–}10\text{ or }30\,cm}/OMC\rho_{0\text{–}10\text{ or }30\,cm}) \times 0.05\} \quad (4.2)$$

where MCρ is the SOC density for mineral soils; OMCρ is the SOC density for organo-mineral soils and 0.05 is the deduction factor for organo-mineral over mineral soils from the IPCC DCF-derived fraction of SOC density.

The IPCC DCF-derived fraction of SOC density ($t\,C\,ha^{-1}$) was multiplied by the corresponding CF for the two soil layers (0–10 cm and 0–30 cm only) and soil categories (organo-mineral and organic) under grassland, rough grazing and grassland/tillage to achieve the corrected change over the estimation period (1990–2014).

4.2.3 Statistical analyses

The coefficient of determination (R^2) and coefficient of variation (CV) were used to compare the extent of any relationship and the degree of uncertainty for variables, respectively. The indices used were mean square error (MSE) and root mean square error (RMSE). Statistical analyses were performed in Microsoft Excel (2013) and JMP version 13.1 (SAS Inc., Cary, NC). ArcGIS version 10 (ESRI, Dublin) was used for overlaying maps and geoprocessing of data.

4.3 Results

4.3.1 Refined depth distribution models and pedotransfer functions

Based on the EPA's requirements and UNFCCC reporting obligations, methodologies and models for the estimation of SOC density/stock changes (in terms of source or sink; Tier 2 approach) in agricultural LULUC categories were developed. Emphasis was given to arable/tillage land and grassland, as well as their rotations, including grassland/rough grazing on organic soils/peatlands under cultivation. The soil types were mainly categorised as mineral, organo-mineral (degraded and non-degraded) and organic (degraded and non-degraded) soils under agriculture. This builds on previous work (Khalil *et al*., 2013b), although we reprocessed the original databases, including the estimated SOC densities/stocks and PTFs. The refined DDMs and PTFs for common soil types, key land covers and ISTs are provided in Tables 4.3 and 4.4, respectively.

The non-linear (exponential for mineral and organo-mineral soils; natural logarithmic for organic soils) DDMs were redeveloped using data from Khalil *et al.* (2013b). The soil depth ratio functions fitted well for all soil types (mineral, organo-mineral and organic) and the corresponding IST categories (e.g. acidity and drainage classes) and agricultural land uses (grassland, rough grazing and tillage), with the R^2 value and CV ranging from 0.54 to 1.00 and from 9% to 63%, respectively. The k values (scale constant, cm^{-1}) differed between mineral and organo-mineral soils (–0.025 to −0.042) within or between land uses. The values differed widely for organic soils, with non-degraded soils ranging from −0.066 to −0.164, and degraded soils ranging from 0.269 to 1.352.

The soil type-specific and land use-specific empirical equations (exponential) were redeveloped using data from Khalil *et al*. (2013b) to estimate bulk density from the PTFs (SOC). The k values, which varied between the soil types and land uses, ranged from −0.031 to −0.260, and the R^2 value varied from 0.67 to 0.99. Statistical evaluation of the models for the prediction of bulk density from SOC was also performed. Irrespective of soil types and land uses, the MSE was $\leq 0.028\,g\,cm^{-3}$ and the RMSE was $\leq 0.166\,g\,cm^{-3}$.

4.3.2 Key land uses and soil categories

The derived land uses were grassland, rough grazing and tillage and their rotations (grassland/rough grazing, grassland/tillage and rough grazing/tillage). Soils were categorised as (1) mineral (SOC < 10%), (2) organo-mineral (SOC 10–20% and > 20% at a depth of < 30 cm; degraded and non-degraded) and (3) organic (SOC > 20% and 10–20% at a depth of > 30 cm; degraded and non-degraded). The degraded and non-degraded classifications were used only to develop models to take account of the loss of SOC from surface layers for reasons other than severe degradation/erosion. This was to minimise the error in the estimations, as the presence of highly degraded soils is thought to be negligible under Irish conditions.

The preliminary compilation of the LPIS (2000–2014) and other databases resulted in 13 agricultural land use classes and their rotations. However, rough grazing in rotation with grassland and tillage was limited and the grassland/rough grazing rotation was merged with grassland and the rough grazing/tillage rotation was merged with grassland/tillage. There were therefore nine key agricultural land use classes on mineral, organo-mineral and organic soils (Figure 4.2): (1) grassland – mineral soil; (2) grassland – organo-mineral soil; (3) grassland – organic soil; (4) rough grazing – mineral soil; (5) rough grazing – organo-mineral soil; (6) rough grazing – organic soil; (7) tillage – mineral soil; (8) rotation grassland/tillage – mineral soil; and (9) rotation grassland/tillage – organo-mineral soil.

Analyses indicate that grassland represented the major share (79%) of Irish land uses and was dominant on mineral soils (55%), followed by organo-mineral soils (14%). Grassland/tillage rotations occurred mainly on mineral (9%) and organo-mineral (2%) soils, and rough grazing occurred mainly on organo-mineral and organic soils (7%). Tillage on mineral soils represented only 10% of the total agricultural land use.

Table 4.3. Depth distribution models for the estimation of SOC concentrations across soil depths for ISTs and key agricultural land covers in Ireland

Common soil type	Level of degradation	Major land cover	Acidity	Drainage class	IST	DDMs, x = SOCz10[a]	R^2	CV (%)
Mineral soil (SOC < 10%)	Non-degraded	Grassland	Non-calcareous	Well	AminDW, AminSW	$y = 1.4002e^{-0.035x}$	1.0000	30
				Poorly	AminPD (+AminSP)	$y = 1.3661e^{-0.034x}$	0.9998	31
			Calcareous	Well	BminDW, BminSW	$y = 1.3719e^{-0.035x}$	0.9999	33
				Poorly	BminPD	$y = 1.3654e^{-0.034x}$	0.9998	26
		Tillage	Non-calcareous	Well	AminDW, AminSW	$y = 1.5647e^{-0.029x}$	0.9947	29
				Poorly	AminPD	$y = 1.5195e^{-0.026x}$	0.9928	34
			Calcareous	Well	BminDW, BminSW	$y = 1.5328e^{-0.03x}$	0.9966	63
				Poorly	BminPD	$y = 1.5055e^{-0.025x}$	0.9920	17
Organo-mineral soil (SOC 10–20% and > 20% at < 30 cm depth)	Non-degraded (SOC > 20% at < 30 cm depth)	Rough grazing, grassland, tillage	Non-calcareous	Mixed, poorly major	AminSRPT (AminPDPT, AlluvMIN, AminPD, AminDW, AminSW)[b]	$y = 1.5652e^{-0.042x}$	0.9999	09
			Calcareous	Mixed, well major	BminPDPT (BminDW, BminPD, BminSW)[b]	$y = 1.6084e^{-0.041x}$	0.9996	10
	Degraded (SOC 10–20% at < 30 cm depth)	Grassland, rough grazing, tillage	Non-calcareous	Mixed, poorly major	AminPDPT, AminSRPT (AminPD, AminDW,[b] AlluvMIN?); if SOC_{10cm}: 10–20% (y1)/< 10% (y2)	$y1 = 2.3718e^{-0.038x}$;	0.9703	27
						$y2 = 3.5709e^{-0.035x}$	0.8843	27
			Calcareous	Well	BminPDPT, BminSRPT, (BminDW, BminSW);[b] if SOC_{10cm}: 10–20% (y1)/< 10% (y2)	$y1 = 2.7101e^{-0.037x}$	0.9485	10
						$y2 = 4.9308e^{-0.031x}$	0.7630	12
Organic soil (SOC > 20% and 10–20% at > 30 cm depth)	Non-degraded (SOC > 20% at > 30 cm depth)	Rough grazing, grassland, tillage[c]	Non-calcareous	Undefined	Cut	$y = -0.164\ln(x) + 1.4431$	0.9217	38
				Undefined	BkPt	$y = -0.066\ln(x) + 1.2306$	0.5798	13
	Degraded (SOC 10–20% at > 30 cm depth)	Rough grazing, grassland, tillage	Non-calcareous	Undefined	Cut = if SOC_{10cm}: 10–20%	$y = 0.2692\ln(x) + 0.3866$	0.5347	35
				Undefined	BkPt = if SOC_{10cm}: 10–20%	$y = 0.4357\ln(x) - 0.0383$	0.6080	12
				Undefined	Cut = if SOC_{10cm}: < 10%	$y = 1.1682\ln(x) - 1.0111$	0.6838	36
				Undefined	BkPt = if SOC_{10cm}: < 10%	$y = 1.3518\ln(x) - 1.6659$	0.7232	13

[a]SOC_{z10} = SOC concentration (%) at a 10-cm soil depth; y = SOC concentration (%) at a desired depth (> 10 cm).

[b]The ISTs should correspond mainly to AminPDPT, AminSRPT, BminPDPT and BminSRPT, but the other mineral soils under ISTs found to represent organo-mineral soils here may also be considered for estimation of SOC concentrations using the models where feasible/applicable.

[c]Tillage as land cover was found under non-degraded organic soils but can generally be avoided, as tillage practices are not common on peaty soils. Depth of SOC for OM-O soils: > 30 cm drained and > 50 cm undrained.

Source: adapted from data generated by Khalil *et al.* (2013b).

Table 4.4. Pedotransfer functions for the estimation of soil bulk density across soil depths for ISTs and key agricultural land covers in Ireland

Common soil type	Level of degradation	Major land cover	Acidity	Drainage class	IST	y = PTF, x = SOCz[a]	R^2	SSE	MSE	RMSE
Mineral soil (SOC < 10%)	Non-degraded	Grassland	Non-calcareous	Well	AminDW, AminSW	$y=0.7468+0.6559e^{-0.260x}$	0.70	9.290	0.011	0.105
				Poorly	AminPD(+AminSP)	$y=0.2882+1.1420e^{-0.106x}$	0.90	1.644	0.003	0.056
			Calcareous	Well	BminDW, BminSW	$y=0.5041+0.8982e^{-0.146x}$	0.92	1.487	0.002	0.047
				Poorly	BminPD	$y=-0.0275+1.4995e^{-0.083x}$	0.99	0.001	<0.001	0.003
		Tillage	Non-calcareous	Well	AminDW, AminSW	$y=0.4827+0.9227e^{-0.153x}$	0.80	0.091	0.002	0.049
				Poorly	AminPD	$y=0.9302+0.6003e^{-0.209x}$	0.99	0.004	<0.001	0.010
			Calcareous	Well	BminDW, BminSW	$y=-0.0154+1.6219e^{-0.125x}$	0.99	0.001	<0.001	0.003
				Poorly	BminPD	$y=-0.0977+1.6157e^{-0.063x}$	0.99	<0.001	<0.001	0.003
Organo-mineral soil (SOC 10–20% and > 20% at < 30 cm depth)	Non-degraded (SOC > 20% at < 30 cm depth)	Rough grazing, grassland	Non-calcareous	Mixed, poorly major	AminSRPT (AminPDPT, AlluvMIN, AminDW, AminSW, AminPD)[b]	$y=0.2170+1.0763e^{-0.080x}$	0.76	2.043	0.028	0.166
		Rough grazing, grassland	Calcareous	Mixed, well major	BminPDPT, BminSRPT (BminDW, BminSW, BminPD)[b]	$y=0.1067+1.4473e^{-0.072x}$	0.99	<0.001	<0.001	0.003
	Degraded (SOC 10–20% at < 30 cm depth)	Grassland, rough grazing	Non-calcareous	Mixed, poorly major	AminPDPT, AminSRPT (AminDW, AminSW, AminPD, AlluvMIN)[b]	$y=0.2012+1.1592e^{-0.081x}$	0.67	8.037	0.028	0.166
		Grassland	Calcareous	Well	BminPDPT, BminSRPT (BminDW, BminSW)[b]	$y=0.3749+0.9901e^{-0.119x}$	0.89	1.191	0.005	0.071
Organic soil (SOC > 20% and 10–20% at > 30 cm depth	Non-degraded (SOC > 20% at > 30 cm depth)	Rough grazing, grassland tillage[c]	Non-calcareous	Undefined	Cut	$y=0.1235+2.5048e^{-0.085x}$	0.75	0.190	0.003	0.053
		Tillage,[c] rough grazing, grassland		Undefined	BkPt	$y=0.1437+5.7679e^{-0.121x}$	0.83	0.251	0.002	0.048
	Degraded (SOC 10–20% at > 30 cm depth)	Rough grazing grassland	Non-calcareous	Undefined	Cut	$y=-0.0751+1.5674e^{-0.042x}$	0.91	0.293	0.011	0.104
		Rough grazing grassland		Undefined	BkPt	$y=-0.2125+1.7592e^{-0.031x}$	0.87	0.341	0.014	0.119

[a]SOC_z = SOC concentration (%) at a desired depth.

[b]The ISTs should correspond mainly to AminPDPT, AminSRPT, BminPDPT and BminSRPT, but the other mineral soils under ISTs found to represent organo-mineral soils here may also be considered for estimation of bulk density using the models where feasible/applicable.

[c]Found these categories under tillage but can generally be avoided, as tillage practices are not common on peaty soils.

SSE, sum of squared error.

Source: adapted from data generated by Khalil *et al*. (2013b).

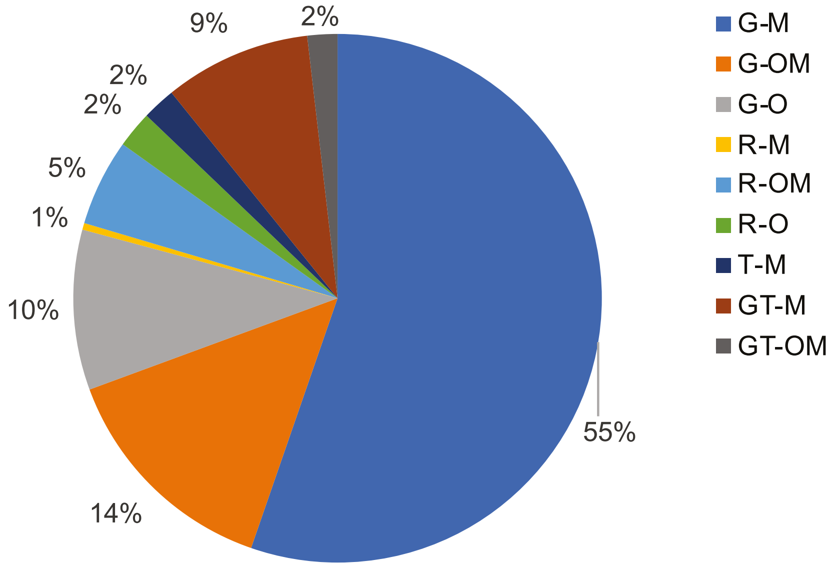


Figure 4.2. Estimated (%) distribution of key agricultural land uses and their rotations across soil types categorised by organic carbon ranges derived from the LPIS (2000–2014) and the NSDB (490 of 1310 sampling/grid points) for Ireland. G-M, grassland – mineral soil; G-O, grassland – organic soil; G-OM, grassland – organo-mineral soil; GT-M, grassland/tillage rotation – mineral soil; GT-OM, grassland/tillage rotation – organo-mineral soil; R-M, rough grazing – mineral soil; R-O, rough grazing – organic soil; R-OM, rough grazing – organo-mineral soil; T-M, tillage – mineral soil. Reprinted from *Geoderma*, Vol. 322, Khalil, M.I. and Osborne, B.A., Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland, 172–183, 2018, with permission from Elsevier.

4.3.3 SOC density, its historical changes and the net gains and losses

Irrespective of land use and soil layer, there were significant variations in SOC densities among the three soil categories, with the highest density being in organic soils, followed by organo-mineral and mineral soils (Figure 4.3). For the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers, the SOC densities for 2006 were highest (75–101, 225–307 and 425–1080 t C ha^{-1}, respectively) for rough grazing, grassland and grassland/tillage on organic and organo-mineral soils, and lowest for tillage on mineral soils (30, 80 and 142 t C ha^{-1}, respectively). Considering the 0- to 10-cm layer, the average SOC density was highest for rough grazing (86 t C ha^{-1}) and grassland (72 t C ha^{-1}) on organic soils than for the other land uses (30–58 t C ha^{-1}), with the lowest SOC density for tillage. Similar trends were observed for the 0- to 30-cm layer, with values of 215–242 t C ha^{-1} for rough grazing compared with 80–162 t C ha^{-1} for grassland on organic soils. For the 0- to 100-cm layer, the weighted average SOC density was estimated to be significantly higher for rough grazing (614 t C ha^{-1}) and grassland (562 t C ha^{-1}) than for grassland/tillage (194 t C ha^{-1}) and tillage (142 t C ha^{-1}).

Following the calculation of SOC densities for 2006, historical changes across agricultural land uses and soil types were estimated through backwards (from 2006 to 1990) and forwards (from 2006 to 2014) calculations, using the two-phase (exponential 3P) models developed (see Table 4.1). The SOC densities in 1990 were considered to be the first equilibrium states and the two-phase models provided two separate gain or loss processes for SOC, i.e. faster during the initial phase and slower during later periods (Figure 4.4).

For the 0- to 10-cm and 0- to 30-cm layers, the SOC density changes (annual rates) as sinks were found to be significantly higher during the initial periods for grassland under organic and organo-mineral soils than for rough grazing, showing less variation with soil type, and becoming insignificant for all soil types in later years. Similar, but opposite, trends were observed for changes in SOC density as sources, with significantly higher losses from tillage under mineral soils than from grassland/tillage rotation under both mineral and

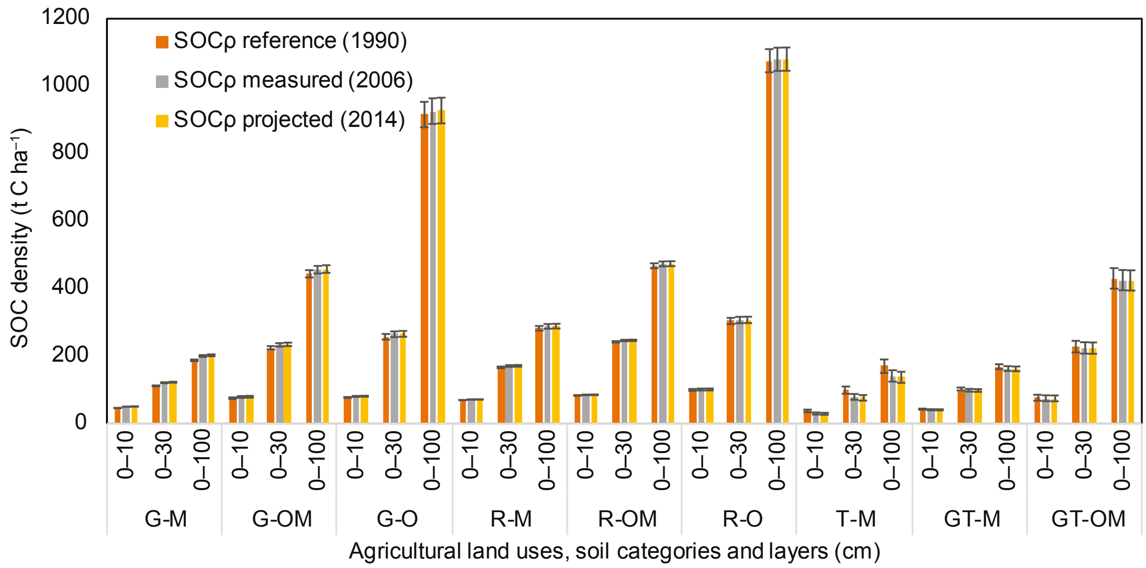


Figure 4.3. Estimates (corrected) of SOC density for 1990, 2006 and 2014 in three soil layers and types under major agricultural land uses. G-M, grassland – mineral soil; G-O, grassland – organic soil; G-OM, grassland – organo-mineral soil; GT-M, grassland/tillage rotation – mineral soil; GT-OM, grassland/ tillage rotation – organo-mineral soil; R-M, rough grazing – mineral soil; R-O, rough grazing – organic soil; R-OM, rough grazing – organo-mineral soil; T-M, tillage – mineral soil. Reprinted from *Geoderma*, Vol. 322, Khalil, M.I. and Osborne, B.A., Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland, 172–183, 2018, with permission from Elsevier.

organo-mineral soils. For the 0- to 100-cm layer, the SOC density changes as sinks were more similar, except for grassland under organic and organo-mineral soils, and the trends for tillage and grassland/tillage rotation were similar to those in the other two layers. Overall trends for sinks and sources were the same in later years, but the changes occurred at much lower rates.

Among agricultural land uses (except tillage), the corrected changes in SOC density showed no significant differences between the reference, measured and projected values within a soil layer (see Figure 4.3). For mineral soils, the reference values (1990) for the different layers (surface layer first) were estimated to be 46.63, 112.18 and 187.75 t C ha^{-1} for grassland; 69.99, 166.91 and 282.70 t C ha^{-1} for rough grazing; 37.93, 99.44 and 170.41 t C ha^{-1} for tillage; and 43.01, 103.00 and 168.88 t C ha^{-1} for grassland/tillage. Compared with mineral soils, significantly higher estimates were found for organo-mineral soils, with values varying from 75.51 to 468.02 t C ha^{-1}, depending more on soil depth than on land use. The tillage and grassland/tillage categories are not associated with organic soils; the estimated SOC densities in organic soils were 77.76, 257.62 and 915.99 t C ha^{-1} for grassland, and 100.2, 304.35 and 1075.60 t C ha^{-1} for rough grazing.

Compared with the reference values, significantly higher projected SOC densities for 2014 were estimated for grassland and rough grazing, except in the 0- to 100-cm layer for grassland on organo-mineral soils, grassland on organic soils and rough grazing on organic soils. Significant differences in SOC densities between 1990 and 2014 for tillage on mineral soils and grassland/tillage on mineral soils, except in the 0- to 100-cm layer, were also observed. The differences in SOC densities between 1990 and 2014 for tillage on mineral soils and grassland/tillage on mineral soils were similar and were significantly smaller than that for grassland/tillage on organo-mineral soils. Compared with the preliminary estimates using the IPCC DCFs, the corrected sum of SOC densities across land uses, soil categories and layers was 105.26 t C ha^{-1} lower for the reference year and 15.96 t C ha^{-1} higher for the projected year (data not shown). The fractional amount either increased or decreased with deeper soil layers, and the values for mineral soils in the 0- to 10-cm and 0- to 30-cm soil layers remained the same.

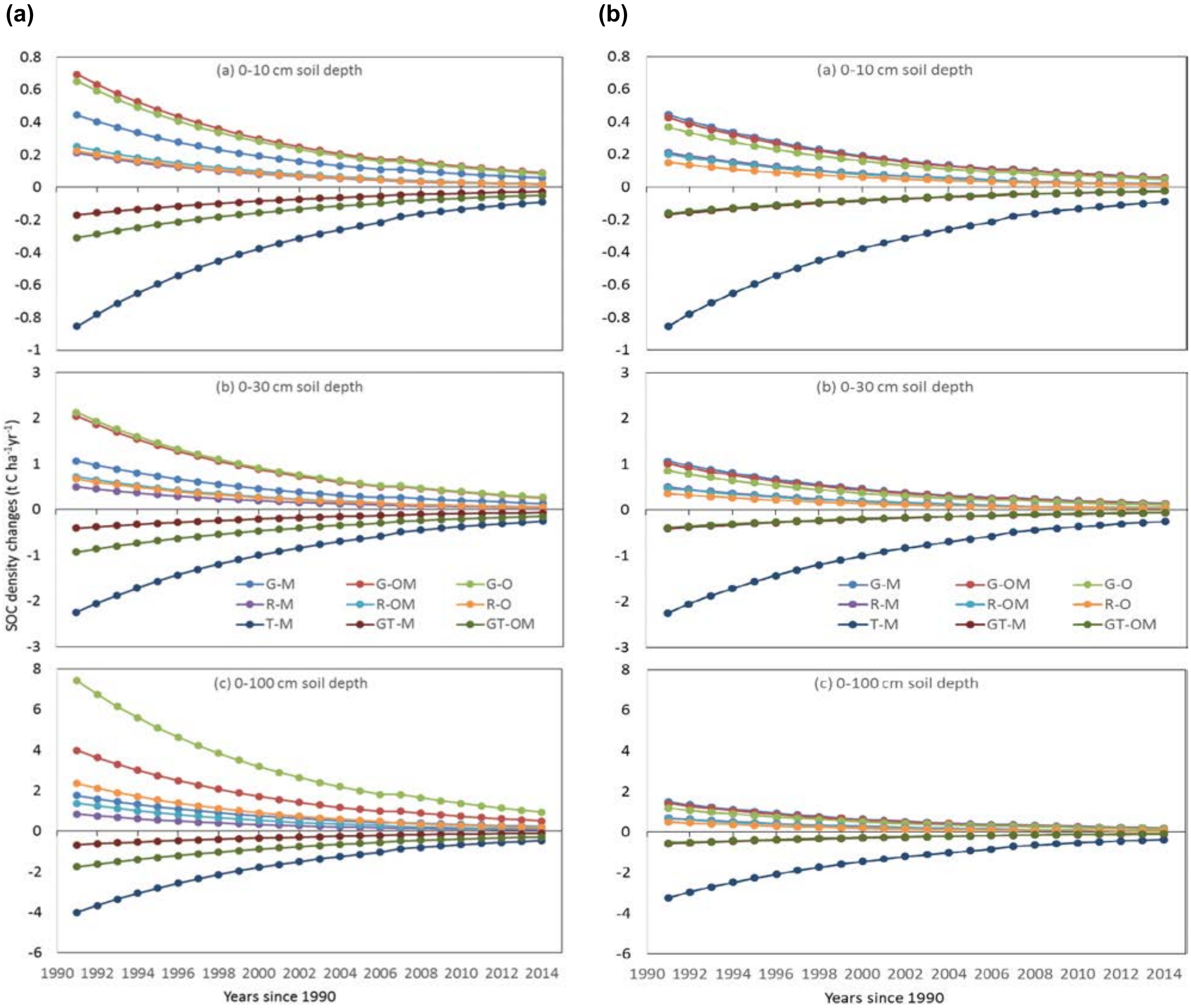


Figure 4.4. IPCC DCF-derived (a) and corrected (b) estimates of the rates of historical changes in SOC density for three soil layers and types under key agricultural land uses. G-M, grassland – mineral soil; G-O, grassland – organic soil; G-OM, grassland – organo-mineral soil; GT-M, grassland/tillage rotation – mineral soil; GT-OM, grassland/tillage rotation – organo-mineral soil; R-M, rough grazing – mineral soil; R-O, rough grazing – organic soil; R-OM, rough grazing – organo-mineral soil; T-M, tillage – mineral soil. Reprinted from *Geoderma*, Vol. 322, Khalil, M.I. and Osborne, B.A., Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland, 172–183, 2018, with permission from Elsevier.

For the 0- to 30-cm soil layer, the historical changes in SOC densities resulted in grassland and rough grazing being a sink (+) of carbon and tillage and grassland/tillage being a source (–) of carbon across soil types (Figure 4.5). The changes in SOC density values for grassland were significantly higher than those for rough grazing and the changes for tillage were significantly higher than those for grassland/tillage, for all soil types and layers. Regardless of soil category, the total carbon gain or loss over 25 years increased with the soil depth from 4.19 to 13.73 t C ha^{-1}, 1.73 to 5.68 t C ha^{-1}, −8.57 to −32.96 t C ha^{-1}, and −3.59 to −14.19 t C ha^{-1} for grassland, rough grazing, tillage and grassland/tillage, respectively. The overall corrected balance resulted in a carbon sequestration potential of 0.23 ± 0.03 t C ha^{-1} $year^{-1}$, 0.42 ± 0.05 t C ha^{-1} $year^{-1}$ and 0.53 ± 0.06 t C ha^{-1} $year^{-1}$ for the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers, respectively, irrespective of land use, management practice or inputs. Despite the use of the same default DCFs, particularly for the mineral and organo-mineral soil

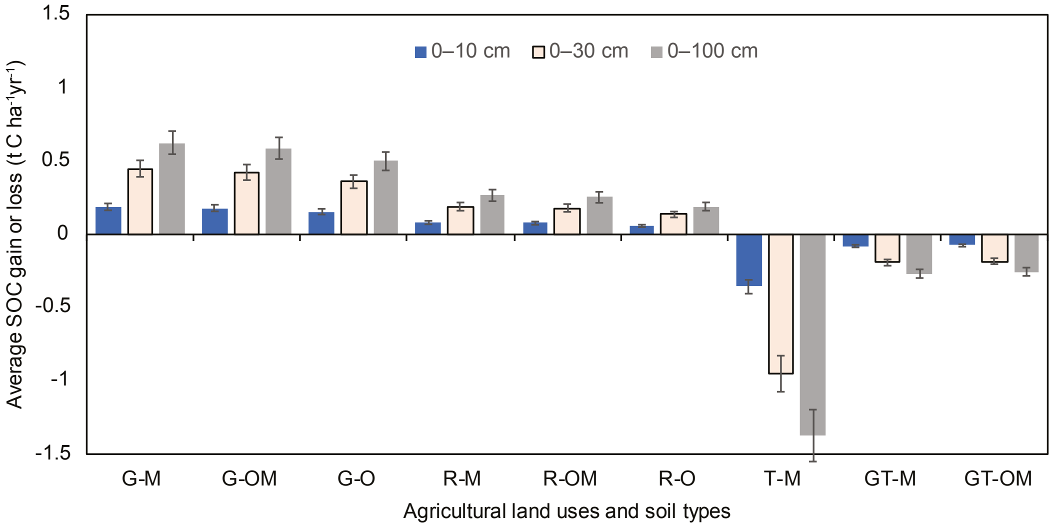


Figure 4.5. Estimates (corrected) of 25-year average changes in annual SOC density by mass per hectare and the overall annual sinks (± standard errors) in agricultural soils. G-M, grassland – mineral soil; G-O, grassland – organic soil; G-OM, grassland – organo-mineral soil; GT-M, grassland/tillage rotation – mineral soil; GT-OM, grassland/tillage rotation – organo-mineral soil; R-M, rough grazing – mineral soil; R-O, rough grazing – organic soil; R-OM, rough grazing – organo-mineral soil; T-M, tillage – mineral soil. Reprinted from *Geoderma*, Vol. 322, Khalil, M.I. and Osborne, B.A., Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland, 172–183, 2018, with permission from Elsevier.

categories, the preliminary estimates of SOC density increased by 0.92, 2.24 and 7.37 times in the three soil layers, respectively (data not shown), compared with the corrected estimates. Based on these preliminary results, the overestimations were minimised through assessment of the SOC density differences between mineral soils and organo-mineral plus organic soils within a land use and deducting these amounts from the respective soil category under a particular land use. This resulted in a final total balance of 0.29, 0.58 and 0.84 t C ha^{-1} year^{-1} for the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers, respectively. The corrected estimates provide SOC density differences across ISTs, land uses and soil categories over the previous 25 years, i.e. through backwards calculations to 1990 from 2006 and projections to 2014.

4.3.4 SOC stocks in Irish agricultural soils and the historical balance

In Ireland, the dominant land use is grassland, followed by tillage and rotations of grassland and tillage. Accordingly, grassland had a higher SOC stock in 2006, at 253, 675 and 1368 Tg for the 0–10, 0–30 and 0–100 cm soil layers, respectively, than the other land uses (Figure 4.6). Among the soil types, the major contribution to SOC stocks was from grassland on mineral soils, followed by grassland on organo-mineral and organic soils. After grassland, the next highest contribution was from rough grazing (42, 195 and 217 Tg, respectively) and the grassland/tillage (12, 29 and 50 Tg, respectively) rotation, with the lowest contribution from tillage (9, 25 and 44 Tg, respectively), and a similar contribution from rough grazing, grassland/tillage and tillage for mineral soils was found. Of the national total SOC stock, grassland contributed 66%, rough grazing contributed 27%, grassland/tillage contributed 4% and tillage contributed 3% (national totals 316, 838 and 1679 Tg for the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers, respectively).

The historical changes in SOC stocks for the 0- to 30-cm soil layer showed an initial sharp increase for grassland and rough grazing, and a decrease for tillage and grassland/tillage, after which the rate of change was found to be relatively small, irrespective of land use and soil type (data not shown). Similar to the SOC density balance, the corrected historical changes in SOC stocks resulted in grassland and rough grazing being a sink, and tillage and grassland/tillage being a source, across soil types (Figure 4.7). Over 25 years,

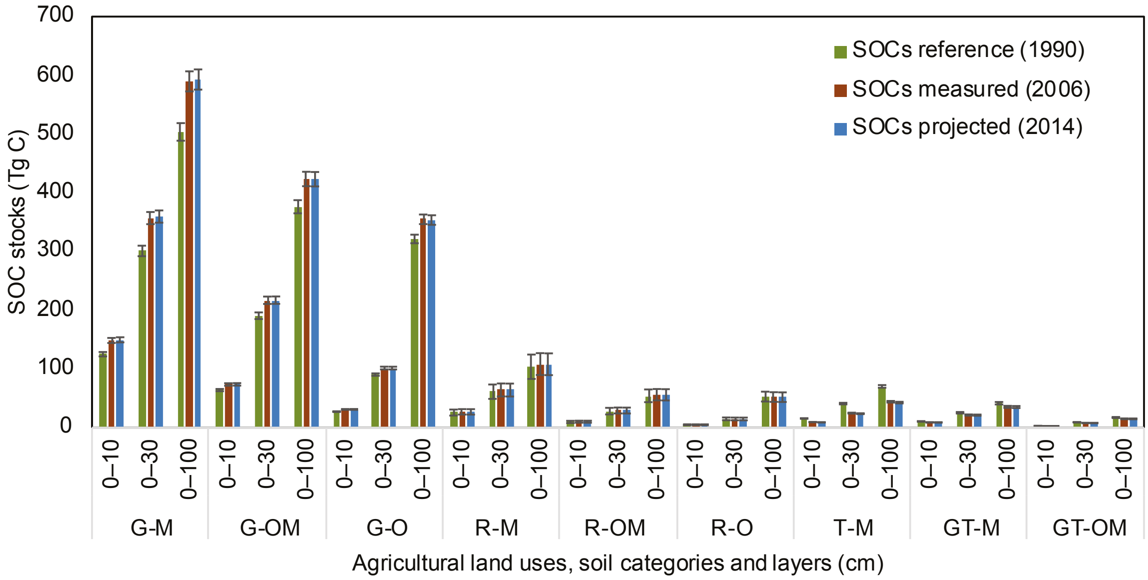


Figure 4.6. Grand totals and aggregated SOC stocks for 1990, 2006 and 2014 for the three soil types under key agricultural land uses. G-M, grassland – mineral soil; G-O, grassland – organic soil; G-OM, grassland – organo-mineral soil; GT-M, grassland/tillage rotation – mineral soil; GT-OM, grassland/tillage rotation – organo-mineral soil; R-M, rough grazing – mineral soil; R-O, rough grazing – organic soil; R-OM, rough grazing – organo-mineral soil; T-M, tillage – mineral soil. Reprinted from *Geoderma*, Vol. 322, Khalil, M.I. and Osborne, B.A., Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland, 172–183, 2018, with permission from Elsevier.

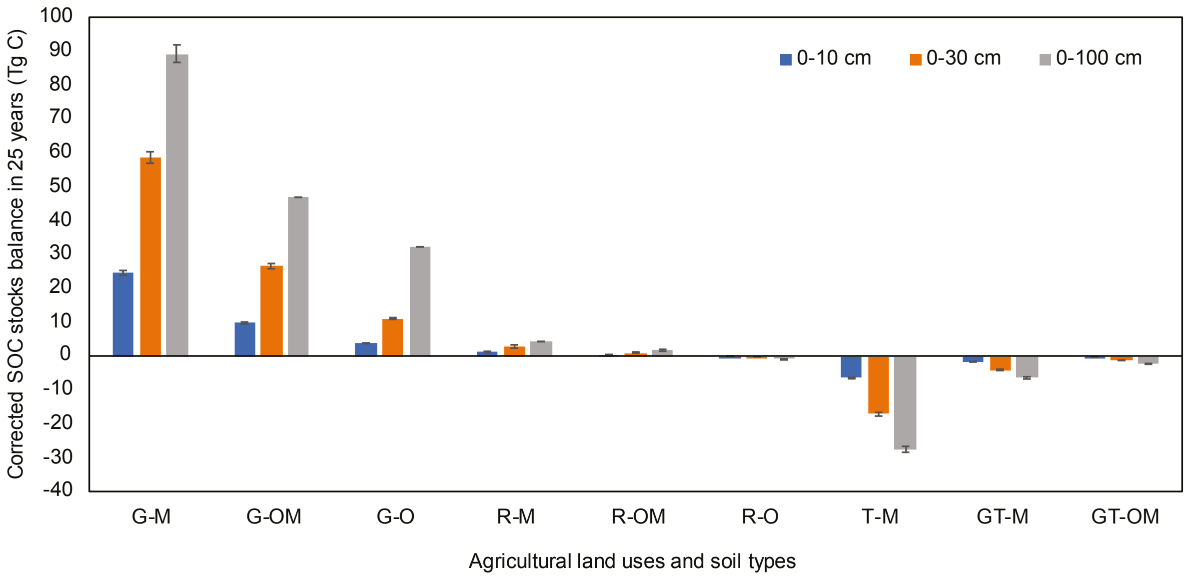


Figure 4.7. Gains and losses of SOC stocks for key agricultural land uses and their rotations over 25 years. G-M, grassland – mineral soil; G-O, grassland – organic soil; G-OM, grassland – organo-mineral soil; GT-M, grassland/tillage rotation – mineral soil; GT-OM, grassland/tillage rotation – organo-mineral soil; R-M, rough grazing – mineral soil; R-O, rough grazing – organic soil; R-OM, rough grazing – organo-mineral soil; T-M, tillage – mineral soil. Reprinted from *Geoderma*, Vol. 322, Khalil, M.I. and Osborne, B.A., Improving estimates of soil organic carbon (SOC) stocks and their long-term temporal changes in agricultural soils in Ireland, 172–183, 2018, with permission from Elsevier.

the changes in SOC stocks for grassland, rough grazing, tillage and grassland/tillage ranged from 38.0 to 168.3 Tg C, from 1.5 to 4.9 Tg C, from −6.5 to −27.6 Tg C and from −2.1 to −8.8 Tg C for the different soil layers. The overall annual gains in SOC stocks at the national level were 1.24, 3.09 and 5.48 Tg C in the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm soil layers, respectively.

4.4 Discussion

4.4.1 Improvement of depth distribution models and pedotransfer functions

Both DDMs and PTFs across key land cover categories considering GSGs have been developed previously (Khalil *et al*., 2013b). The current study refined these models and PTFs and considered key land use classes: disaggregated arable/tillage, grassland and rough grazing, as well as their rotations. The soil types were mainly categorised as mineral, organo-mineral (degraded and non-degraded) and organic (degraded and non-degraded) soils under agriculture, with subcategorisation according to ISTs to reduce uncertainty in the estimates.

The non-linear (exponential for mineral and organo-mineral soils; natural logarithmic for organic soils) DDMs refined using the data of Khalil *et al*. (2013b) were based on exponential functions only. The soil depth ratio functions fitted well for all soil types and land uses, with reduced uncertainty compared with the previous findings. The k (scale constant) values can be used to differentiate between soil types and land use types. This implies that the non-linear models can reliably estimate SOC content across soil depths for mineral, organo-mineral and organic soils under cultivation.

The improved soil type-specific and land use-specific empirical equations for estimating bulk density from PTFs (SOC) and the corresponding k values indicate that the approach clearly differentiates between the importance of the various land uses and soil types. The statistical evaluation of the models' predictability supports the findings, showing reasonably small MSE and RMSE values. Therefore, these models can be applied for each soil type within a land use, leading to small uncertainties in their estimates of emissions compared with the original models (Khalil *et al*., 2013b). Similar methodological approaches have been used and implemented elsewhere (e.g. Meersmans *et al*., 2009; Xu and Kiely, 2009).

4.4.2 Identification of key land uses and soil categories

Agricultural land use classes, management practices and soil types have variable impacts on soil carbon gains and losses, and several approaches were adopted to elucidate categories and subcategories of these variables. Although the LPIS and NSDB have a reasonably high spatial resolution, they have limitations in terms of providing detailed information on disaggregated land use classes in Ireland. In addition to the NSDB, which provides information on SOC content across land covers and soil types, ISTs, denoting acidity, drainage and other soil characteristics, were also used for development of the different methods/models. The preliminary compilation of the LPIS (2000–2014) and other databases resulted in 13 agricultural land use classes and their rotations. Rough grazing in rotation with grassland and tillage was limited and the grassland/rough grazing rotation was merged with grassland and the rough grazing/tillage rotation was merged with grassland/tillage. There were therefore nine key agricultural land use classes on mineral, organo-mineral and organic soils. Being able to identify grassland, rough grazing, tillage and their rotations, from the historical LPIS (2000–2014) data is an advantage compared with previous studies (e.g. Eaton *et al*., 2008, Xu and Kiely, 2009; Khalil *et al*., 2013b). On mineral soils, grassland most likely represents the major share of Irish land uses, followed by grassland/tillage and tillage, whereas on organo-mineral and organic soils rough grazing is predominant.

The approach used enabled different soil types to be categorised based on SOC content, including mineral, organo-mineral and organic soils. As in the IPCC approach, degraded and non-degraded classifications were used only to develop models to take into account the loss of SOC from surface layers from causes other than severe degradation/erosion, to minimise errors in estimations. This approach was found to be promising in terms of providing further details of the impact of land use change and other factors with reduced uncertainty, leading to more reliable estimates of SOC densities/stocks across agricultural land uses and soil types.

4.4.3 SOC density and changes in SOC density following the first equilibrium

Despite some variations within the key soil types across land uses, the improved models provide good estimates of SOC concentrations and therefore densities for different soil layers/depths. Several biophysical and climatic conditions regulate the degree of decomposition of and thereby organic carbon sequestration in soils and should be considered as important factors for long-term enrichment of SOC density and changes in SOC density (Meersmans *et al*., 2009; Smith *et al*., 2000). Accordingly, the current estimates of SOC density considered disaggregated land uses and soil types, including widely applicable categories such as mineral, organo-mineral and organic soils. The impact of the latter, particularly the presence of organo-mineral soils, was also identified in the previous study by Khalil *et al*. (2013b). Therefore, the IPCC default DCFs proposed in percentage rather than by weight for mineral soil were evaluated by splitting mineral soils into mineral and organo-mineral soils, considering the diverse SOC content of Irish agricultural soils, allowing corrections to be made.

The maps corresponding to the ISTs, NSDB and LPIS were overlaid and the outputs show some differences in SOC content; these are likely to be attributed to the mismatching of polygons/grid points between the databases. In this study, mineral soils and organic soils (particularly cutaway and blanket peatland – Bkpt) associated with mineral soils were separated, and the cutaway and Bkpt not under cultivation, i.e. peat soils, were removed to minimise accounting/representation errors in SOC densities. This also led to a higher level of disaggregation of SOC densities across agricultural land uses and soil depths. As in the previous study (Khalil *et al*., 2013b), the SOC density was significantly higher under rough grazing than under grassland and tillage, but the variability in SOC density among land uses and soil types was found to be smaller than that reported in previous work (Cannell *et al*., 1999; Khalil *et al*., 2013b), where soil depth (Chevallier *et al*., 2000) and SOC density in peats played a major role. The current study explicitly considered soil-specific estimations, particularly variable SOC concentrations, to split soils into three categories, and included the relevant properties affecting SOC gain or loss across agricultural land uses, to reduce the uncertainty arising from soil heterogeneity and the impacts of climate and vegetation.

This study also observed significant variations in SOC densities among the ISTs, although the values were comparable to those found in the study by Khalil *et al*. (2013b). Importantly, the approach used can distinguish between the three soil categories, and the overlapping of organic and mineral soil types that was observed earlier has been removed. Unlike the previous study, tillage crops were found to be grown on mineral soils, and the errors associated with the GSM have also been removed. This includes the removal of errors associated with organo-mineral soils under all land covers near the surface layers, which were mostly evident in the previous analysis of rough grazing. Therefore, the models provide a precise estimate of SOC concentrations and therefore densities across soil depths. However, SOC densities were remarkably high in the grassland/tillage rotation on organo-mineral soils, in line with the previous study, and the errors, if any, associated with this need to be analysed through field investigations.

Importantly, it was observed that the SOC density under grassland was somewhat higher than that in the previous study (Khalil *et al*, 2013b). The increase was smaller for rough grazing and, for tillage, the SOC density was slightly lower. This indicates that the differences in SOC density values across land uses and soil type/categories compared with the previous study had no significant impact on overall estimates of national stocks. Similar variable estimations of SOC densities in Ireland have been reported in other studies (Bradley *et al*., 2005; Eaton *et al*., 2008; Xu and Kiely, 2009). The most likely reasons for the SOC density differences between this study and other studies are the use of varying data sources, the absence of land cover/use as variables, accounting errors in SOC contents with soil depth and the inclusion/exclusion of peats/peaty soils that were considered not to be under cultivation. The variations in SOC density in this study between grassland and tillage were similar to those observed by others (Liebens and Van Molle, 2003; Lettens *et al*., 2004; Meersmans *et al*., 2009, 2011). The findings provide for the first time an estimate of SOC density for grassland/tillage (rotation/ley) and the contribution of the rotation to increased SOC sequestration. The extent of carbon loss from tillage, with some recovery through rotation with grassland, implies that the sustainable use of agricultural soils that includes a crop rotation has the potential to sequester carbon (West and Post, 2002; Lal *et al*., 2011).

The empirical models provided good estimates of reference SOC density values for different soil layers and indicate that significant amounts of SOC can be stored in the deeper (30–100 cm) layers, in agreement with the earlier study by Khalil *et al*. (2013b). However, the estimated reference SOC density values for grassland and rough grazing indicated that they are a sink for carbon, unlike the previous study, whereas tillage (excluding the grassland/tillage rotation, which was not accounted for) was a source of carbon, although the estimates were broadly comparable to those in the earlier study. The overall trends for soil carbon gains or losses occurred at smaller rates, but the contributions of various land uses and soil types were evident. As stated earlier, the predictive models provided two separate gain (+) and loss (–) processes for SOC density, with rates of change across soil types and use categories. The rates of SOC density change, on average, decreased with the increase in soil depth according to the following order, as observed in the preliminary estimates: organic < organo-mineral < mineral soils. However, the CF changed the above order for organo-mineral and organic soils, with only a 4–6% (not significant) and 17–29% (significant) reduced rate of SOC density change, respectively, compared with mineral soils.

Although there were large differences in both the SOC concentrations and changes in SOC density among the different land use and soil categories, varying from significant gains to significant losses, combining all the land uses resulted in estimates of carbon sinks of 0.23, 0.42 and 0.53 t C ha^{-1} $year^{-1}$ for the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers, respectively, with relatively small uncertainties. This positive balance clearly relates to the significantly higher SOC concentrations for grassland and rough grazing in Ireland compared with tillage and grassland/tillage rotations. It has been observed that management techniques such as intensive grazing, application of manure, fertilisation, and the sowing of favourable forage grasses and legumes have the potential to augment SOC densities/stocks (Fornara *et al*., 2016).

Overall, reasonable estimates were obtained for SOC densities for 2006, and their historical changes, using exponential 3P models, considering all major agricultural land use classes and soil types. These models can also be applied to estimate SOC changes on a short-term basis (or annual basis), such as when reseeding grassland, referred to as temporary grassland, and for the rotation of grassland with other arable crops. The IPCC approach revealed highly variable impacts of land uses, management practices and input-related DCFs on SOC in mineral soils compared with organic soils (IPCC, 2006, 2014). In addition, this study revealed a discrepancy related to the use of a common IPCC default DCF (%) – this resulted in overestimation of carbon levels in soils having a high SOC content. We successfully separated organo-mineral from mineral soils to estimate the density of soils having contrasting SOC contents, i.e. the observation of a higher rate of SOC density change in organo-mineral (and also organic) soils than in minerals soils. This implies that the proportional distribution of land uses, management and other factors for the estimation of SOC and density/stock changes should be disaggregated across soil types based on SOC content, through weighted averages at national/regional levels and/or accounting by mass by area.

4.4.4 National SOC stocks and changes in SOC stocks

In this study, higher spatial resolution databases (LPIS and ISTs) were used to estimate total SOC densities and therefore stocks for the selected soil layers, covering disaggregated agricultural land covers/uses (tillage: full, reduced and no tillage; grassland/tillage rotation/temporary grassland/ley: full and reduced tillage; grassland: pasture, hay and silage; and rough grazing). Despite large variations in SOC density across land uses and soil types, the estimated national stocks showed no significant differences from the previous study, in contrast to other studies using the CORINE 2000 land cover areas. The estimated national SOC stocks in the three soil layers were found to be 6% for the 0- to 30-cm layer and 8% for the 0- to 100-cm soil layer, which are lower than the previous estimates of 888 and 1832 Tg using CORINE 2000 land cover areas (Khalil *et al*., 2013b) and slightly higher than the value estimated by others for the 0- to 100-cm soil layer (Eaton *et al*., 2008; Xu and Kiely, 2009).

The current study estimated the SOC stocks using 2006 CSO data, as the NSDB was based on soil data collected around 2006, instead of 2004, as used in the previous study (Khalil *et al*., 2013b).

Considering the variations in land use areas, the previous estimates of SOC stocks for the three reference layers were reduced by 18%, 23% and 32%, respectively. Importantly, this work took into account the variations found within the three soil categories (mineral, organo-mineral and organic under cultivation) and disaggregated land uses to some extent within a land cover. In Ireland, cattle grazing and silage under grassland are the dominant land uses, and the higher amount of SOC in rough grazing mainly under organo-mineral and organic soils was considered separately in this study, unlike others (Eaton *et al*., 2008; Xu and Kiely, 2009). On the other hand, the use of IPCC DCFs and the apportioning approach for all soil categories overestimated the overall annual gain in SOC at the national level by 11%, 18% and 38% compared with the corrected annual rate, which was 1.24, 3.09 and 5.48 Tg C in the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm soil layers. Considering the SOC in the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers and the Irish EPA report on the national estimates of GHG emissions in CO_2 equivalents (Duffy *et al*., 2017), we found a potential for carbon sequestration in agricultural soils in the 0- to 10-cm, 0- to 30-cm and 0- to 100-cm layers to offset 24%, 59% and 106%, respectively, of the total GHGs emitted from Irish agriculture.

The methodological approaches used in this work take into account the SOC variations across soil depths and factors that influence SOC gains or losses from a system, and the estimates are consistent with, although somewhat larger than, previous estimates. Therefore, the empirical models developed to estimate SOC stocks for disaggregated land use classes (except forestry) can be adopted to account for changes in the AFOLU sectors. However, it is worth noting that many variables – soil data based on interpolation/extrapolation across land uses, soil types and climatic conditions – trigger large uncertainties in estimates and that consistent standardised approaches are critically important for observing any changes. Moreover, the estimates of SOC stocks are consistent with historical changes when LPIS data are coupled with DCFs/EFs and related information on agricultural inputs, soil types and management practices. Generally, weather conditions may be considered to have an insignificant impact on SOC sequestration under Irish conditions. However, the same IPCC country-specific DCFs for both mineral and organo-mineral soils overestimated SOC densities/stocks for organo-mineral soils, as reported earlier (Khalil and Osborne, 2017). Although empirical models were developed to correct the estimates, the discrepancy related to IPCC default DCFs (proportion) needs to be considered in future research.

4.5 Conclusions

The improved DDMs and PTFs, as well as newly developed non-linear models, can be used for the estimation of SOC concentrations and therefore densities/stocks at national and regional levels. The higher spatial resolution databases (LPIS, ISTs and NSDB), coupled with empirical modelling and GIS approaches, have the potential to provide robust estimates of SOC densities/stocks for disaggregated agricultural land uses and soil types (Tier 2 development). The estimated baseline SOC densities can be used for ALULUC accounting and assessment of the offsetting potential, as stratified input data for incorporation in ecosystem models and for their verification, as well as for quantification and refinement of the land use- and soil-specific carbon sequestration capability. The data can also be used for mapping and for developing a widely applicable tool to estimate long-term changes in SOC densities/stocks, with the potential for estimating GHG emissions with further improvement. However, apportioning of land use and management-specific gains or losses of SOC (DCFs/EFs, even when country specific), as proposed by the IPCC and also the 4 per mille per year concept, may be a concern for obtaining precise estimates of SOC stocks and their temporal or spatial variability, particularly for soils with a high organic carbon content.

The project tasks were designed to contribute to national assessment methodologies relating to the UNFCCC reporting requirements for carbon emissions and sinks, focusing on the impact of a range of soil types, land uses and management scenarios. This work was also aimed at providing an improved understanding of the consequences of land use change for the carbon cycle and for potential GHG mitigation and offsetting approaches. The end target was to provide a tool for the quantitative assessment of the consequences of different scenarios for carbon stocks and the GHG balance, but this was left unfinished because of time constraints. In addition to improved national inventory reporting, this project also provides a basis to build capacity in the understanding and application of model interfaces, and enable better-quality assessment of SOC densities/stocks, while also facilitating more accurate computations of carbon and nitrogen emissions and their projections and contributing to mitigation/offsetting options.

References

Abdalla, M., Wattenbach, M., Smith, P., Ambus, P., Jones, M. and Williams, M., 2009. Application of the DNDC model to predict emissions of N_2O from Irish agriculture. *Geoderma* 151: 327–337.

Abdalla, M., Jones, M., Ambus, P. and Williams, M., 2010. Emissions of nitrous oxide from Irish arable soils: effects of tillage and reduced N input. *Nutrient Cycling in Agroecosystems* 86: 53–65.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. and Cadisch, G., 2003. Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant Soil* 254: 361–370.

Bord Bia, 2016. *Sustainability Report 2016*. Bord Bia, Dublin.

Bord Bia, 2017. *Origin Green Ireland: Working with Nature*. Available online: https://www.origingreen.ie/what-is-origin-green/about-origin-green/ (accessed 2017).

Bradley, R.I., Milne, R., Bell, J., Lily, A., Jordan, C. and Higgins, A., 2005. A soil carbon and land use database for the United Kingdom. *Soil Use and Management* 21: 363–369.

Cannell, M.G.R., Milne, R., Hargreaves, K.J., Brown, T.A.W., Cruickshank, M.M., Bradley, R.I., Spencer, T., Hope, D., Billett, M.F., Adger, W.N. and Subak, S., 1999. National inventories of terrestrial carbon sources and sinks, the UK experience. *Climate Change* 42: 505–530.

Chadwick, D.R., Pain, B.F. and Brookman, S.K.E., 2000. Nitrous oxide and methane emissions following application of animal manures to grassland. *Journal of Environmental Quality* 29: 277–287.

Chen, D., Li, Y., Grace, P. and Mosier, A.R., 2008. N_2O emissions from agricultural lands: a synthesis of simulation approaches. *Plant Soil* 309: 169–189.

Chevallier, T., Voltz, M., Blanchart, E., Chotte, J.L., Eschenbrenner, V., Mahieu, M. and Albrecht, A., 2000. Spatial and temporal changes of soil C after establishment of a pasture on a long-term cultivated vertisol (Martinique). *Geoderma* 94: 43–58.

CSO (Central Statistics Office), 2012. *Census of Agriculture 2010 – Final Results*. Agriculture Register Section, CSO, Cork.

DAFM (Department of Agriculture, Food and the Marine), 2014. *AIM Bovine Statistics Report 2013*. DAFM, Dublin. Available online: https://www.agriculture.gov.ie/media/migration/animalhealthwelfare/animalidentificationandmovement/cattlemovementmonitoringsystem/AIMBOVINESTATISTICS2013050614.pdf (accessed 2016).

DAFM (Department of Agriculture, Food and the Marine), 2017. *Food Wise 2025: A 10-year Vision for the Irish Agri-Food Industry*. DAFM, Dublin. Available online: https://www.agriculture.gov.ie/media/migration/foodindustrydevelopmenttrademarkets/agri-foodandtheeconomy/foodwise2025/report/FoodWise2025.pdf (accessed 2017).

DCCAE (Department of Communications, Climate Action and Environment), 2017. *National Mitigation Plan.* Available online: http://www.dccae.gov.ie/documents/National%20Mitigation%20Plan%202017.pdf (accessed 5 May 2020).

Duffy, P., Hanley, E., Black, K., O'Brien, P., Hyde, B., Ponji, J. and Alam, S., 2016. *Ireland: National Inventory Report 2016. Greenhouse Gas Emissions 1990–2014 Reported to the United Nations Framework Convention on Climate Change*. Environmental Protection Agency, Johnstown Castle, Ireland.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Climate Change* 91: 317–334.

EC (European Commission), 2016. *Strategy for Agricultural Statistics 2020 and beyond and Subsequent Potential Legislative Scenarios*. Commission Staff Working Document: Impact Assessment. EC, Brussels.

EPA (Environmental Protection Agency), 2006. National soils map. Available online: https://data.gov.ie/dataset/national-soils-map; http://gis.epa.ie/arcgis/rest/services/EPAMapServices/Land/MapServer (accessed 2015).

EPA (Environmental Protection Agency), 2014. *Ireland's Greenhouse Gas Emission Projections: 2012–2030*. EPA, Johnstown Castle, Ireland.

FAO (Food and Agriculture Organization of the United Nations), 2015. *World Programme for the Census of Agriculture 2020. Volume 1: Programme, Concepts and Definitions*. FAO, Rome.

Fornara, D.A., Wasson, E-A., Christie, P. and Watson, C.J., 2016. Long-term nutrient fertilization and the carbon balance of permanent grassland: any evidence for sustainable intensification? *Biogeosciences* 13: 4975–4984.

Gal, A., Vyn, T.J., Micheli, E., Kladivko, E.J. and McFee, W.W., 2007. Soil carbon and nitrogen accumulation with long-term no-till versus mouldboard plowing overestimated with tilled zone sampling depths. *Soil & Tillage Research* 96: 42–51.

Harty, M.A., Forrestal, P.J., Watson, C.J., McGeough, K.L., Carolan, R., Elliot, C., Krol, D., Laughlin, R.J., Richards, K.G. and Lanigan, G.J., 2016. Reducing nitrous oxide emissions by changing N fertiliser use from calcium ammonium nitrate (CAN) to urea based formulations. *Science of the Total Environment* 563–564: 576–586.

Helgason, B.I., Janzen, H.H., Chantigny, M.H., Drury, C.F., Ellert, B.H., Gregorich, E.G., Lemke, R.L., Pattey, E., Rochette, P. and Wagner-Riddle, C., 2005. Toward improved coefficients for predicting direct N_2O emissions from soil in Canadian agroecosystems. *Nutrient Cycling in Agroecosystems* 71: 87–99.

Hennessy, T., Buckley, C., Cushion, M., Kinsella, A. and Moran, B., 2011. *National Farm Survey of Manure Application and Storage Practices on Irish Farms*. Teagasc, Athenry, Ireland.

Hennessy, T., Moran, B., Kinsella, A. and Quinlan, G., 2012. *Teagasc National Farm Survey Results 2012*. Agricultural Economics & Farm Surveys Department, Rural Economy and Development Programme. Teagasc, Athenry, Ireland.

Holland, J.M., 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. *Agriculture, Ecosystems & Environment* 103: 1–25.

Hyde, B., Carton, O. and Murphy, W., 2008. *Farm Facilities Survey – Ireland 2003*. Teagasc, Johnstown Castle, Ireland.

IPCC (Intergovernmental Panel on Climate Change), 1997. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. UK Met Office, Bracknell, UK.

IPCC (Intergovernmental Panel on Climate Change), 2006. *Agriculture, Forestry and Other Land Use. IPCC Guidelines for National Greenhouse Gas Inventories*. Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds). Institute for Global Environmental Strategies, Hayama, Japan.

IPCC (Intergovernmental Panel on Climate Change), 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds). Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 2014. *Climate Change 2013: The Physical Science Basis*. Working Group Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds). Cambridge University Press, Cambridge, UK.

Johnson, J.M.-F., Franzluebbers, A.J., Weyers, S.L. and Reicosky, D.C., 2007. Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution* 150: 107–124.

Khalil, M.I. and Inubushi, K., 2007. Possibilities to reduce rice straw-induced global warming potential of a sandy paddy soil by combining hydrological manipulations and urea-N fertilizations. *Soil Biology & Biochemistry* 39: 2675–2681.

Khalil, M.I. and Osborne, B., 2017. Coupling high spatial resolution data, GIS approaches and modelling for reliable estimates of SOC stocks and their historical changes in agricultural lands. *Proceedings of the. Global Symposium on Soil Organic Carbon*, Food and Agriculture Organization of the United Nations, Rome, 21–23 March, pp. 109–114.

Khalil, M.I., Rahman, M.S., Schmidhalter, U. and Olfs, H.W., 2007. Nitrogen-fertilizer induced mineralization of soil organic C and N in six contrasting soils of Bangladesh. *Journal of Plant Nutrition and Soil Science* 170: 210–218.

Khalil, M.I., Richards, M., Osborne, B., Williams, M. and Müller, C., 2013a. Simulation and validation of greenhouse gases and carbon stock in arable lands using the ECOSSE model. *Atmospheric Environment* 81: 616–624.

Khalil, M.I., Kiely, G., O'Brien, P. and Müller, C., 2013b. Organic carbon stocks in agricultural soils in Ireland using combined empirical and GIS approaches. *Geoderma* 193–194: 222–235.

Khalil, M.I., Abdalla, M., Lanigan, G., Osborne, B. and Müller, C., 2016. Evaluation of parametric limitations in simulating greenhouse gas fluxes from Irish arable soils using three process-based models. *Agricultural Sciences* 7: 503–520.

Lal, R., 2004. Soil carbon sequestration impacts on global change and food security. *Science* 304: 1623–1627.

Lal, R., Delgado, L., Grofman, P., Millar, N., Dell, C. and Rotz, A., 2011. Management to mitigate and adapt to climate change. *Journal of Soil and Water Conservation* 66: 276–285.

Lettens, S., Van Orshoven, J., van Wesemael, B. and Muys, B., 2004. Soil organic and inorganic carbon contents of landscape units in Belgium derived using data from 1950 to 1970. *Soil Use and Management* 20: 40–47.

Li, D., Lanigan, G. and Humphreys, J., 2011. Measured and simulated N_2O emissions from ryegrass and ryegrass/clover swards in a moist temperate climate. *PLOS ONE* 6: e26176. https://doi.org/10.1371/journal.pone.0026176.

Liebens, J. and Van Molle, M., 2003. Influence of estimation procedure on soil organic carbon stock assessment in Flanders, Belgium. *Soil Use and Management* 19: 364–371.

Meersmans, J., van Wesemael, B., De Ridder, F. and Van Molle, M., 2009. Modelling the three-dimensional spatial distribution of soil organic carbon (SOC) at the regional scale (Flanders, Belgium). *Geoderma* 152: 43–52.

Meersmans, J., van Wesemael, B., Goidts, E., Van Molle, M., De Baets, S. and De Ridder, F., 2011. Spatial analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960–2006. *Global Change Biology* 17: 466–479.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., *et al*., 2017. Soil carbon 4 per mille. *Geoderma* 292: 59–86.

Oenema, O., Velthof, G.L., Yamulki, S. and Jarvis, S.C., 1997. Nitrous oxide emissions from grazed grassland. *Soil Use and Management* 13: 288–295.

Osborne, B., Saunders, M., Walmsley, D., Jones, M. and Smith, P., 2010. Key questions and uncertainties associated with the assessment of the cropland greenhouse gas balance. *Agriculture, Ecosystems & Environment* 139: 293–301.

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R. and Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Global Change Biology* 10: 155–160.

Smith, K.A., McTaggart, I.P., Dobbie, K.E. and Conen, F., 1998. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. *Nutrient Cycling in Agroecosystems* 52: 123–130.

Smith, P., Milne, R., Powlson, D.S., Smith, J.U., Falloon, P. and Coleman, K., 2000. Revised estimates of the carbon migration potential of UK agricultural land. *Soil Use and Management* 16: 293–295.

Soussana, J.-F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T. and Arrouays, D., 2004. Carbon cycling and sequestration opportunities in temperate grassland. *Soil Use and Management* 20: 219–230.

Tomlinson, R.W., 2005. Soil carbon stocks and changes in the Republic of Ireland. *Journal of Environmental Management* 76: 77–93.

UN (United Nations), 2015a. *Guidelines for Reporting Emissions and Projections Data under the Convention on Long-Range Transboundary Air Pollution*. ECE/EB.AIR/128. UNECE Information Service, Geneva.

UN (United Nations), 2015b. *Paris Agreement*. Available online: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (accessed 5 May 2020).

Venterea, R.T., Burger, M. and Spokas, K.A., 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. *Journal of Environmental Quality* 34: 1467–1477.

West, T.O. and Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal* 66: 1930–1946.

Wiesmeier, M., Poeplau, C., Sierra, C.A., Maier, H., Frühauf, C., Hübner, R., Kühnel, A., Spörlein, P., Geuß, U., Hangen, E., Schilling, B., von Lützow, M. and Kögel-Knabner, I., 2016. Projected loss of soil organic carbon in temperate agricultural soils in the 21st century: effects of climate change and carbon input trends. *Nature Scientific Reports* 6: 32525. https://doi.org/10.1038/srep32525

Xu, X. and Kiely, G., 2009. SOC stock and its distribution in the Republic of Ireland: estimate based on geostatistics and GIS techniques. Available online: https://www.ucc.ie/en/media/research/hydromet/Xu2.2009Presentation.pdf (accessed 2017).

Abbreviations

AAD	Agricultural activity data
AFOLU	Agriculture, forestry and other land use
AGRI-I	Agricultural Greenhouse Gas Research Initiative for Ireland
AIM	Animal identification and movement
ALULUC	Agricultural land use and land use change
Bkpt	Blanket peatland
CF	Correction factor
CH_4	Methane
CLRTAP	Convention on Long-range Transboundary Air Pollution
CO_2	Carbon dioxide
CoA	Census of Agriculture
CORINE	Co-ordination of Information on the Environment
CSO	Central Statistics Office
CV	Coefficient of variation
DAFM	Department of Agriculture, Food and the Marine
DCF	Density change factor (SOC)
DDM	Depth distribution model
EF	Emission factor
EPA	Environmental Protection Agency
ESRI	Economic and Social Research Institute
EU	European Union
FSS	Farm Structure Survey
FYM	Farmyard manure
GHG	Greenhouse gas
GIS	Geographic information system
GPGs	Good practice guidelines
GSG	General soil group
GSM	General Soil Map
ICBF	Irish Cattle Breeding Federation
IPCC	Intergovernmental Panel on Climate Change
ISIS	Irish Soil Information System
IST	Indicative soil type
LPIS	Land Parcel Identification System
LULUC	Land use and land use change
LULUCF	Land use, land use change and forestry
MSE	Mean square error
N_2O	Nitrous oxide
NFS	National Farm Survey
NIR	National Inventory Report
NSDB	National Soil Database
PTF	Pedotransfer function
R^2	Coefficient of determination
RMSE	Root mean square error
SAPM	Survey of Agricultural Production Methods
SDAS	Sustainable Dairy Assurance Scheme

SOC	Soil organic carbon
TCD	Trinity College Dublin
UCC	University College Cork
UCD	University College Dublin
UNFCCC	United Nations Framework Convention on Climate Change

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

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

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

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

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

Ár bhFreagrachtaí

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

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

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

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

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

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

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

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

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

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

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

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

EPA Research Report 325

Sourcing and Assessing Agricultural Activity Data for Modelling and National Estimates of Greenhouse Gases and Air Pollutants

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

Author: Mohammad Ibrahim Khalil

Identifying pressures

This project aimed to inform efforts at combating climate change as a core national priority in the pursuit of a sustainable, low-carbon economy in compliance with international obligations to reduce emissions of greenhouse gases (GHGs) and air pollutants and increase soil organic carbon (SOC) sequestration. It identifies practical approaches to the reporting requirements, as well as technological options for inclusion in mitigation policies, adaptation strategies and assessment. The EPA has the overall responsibility for the timely estimation and reporting of reactive gas emissions and their uncertainty and implementation of a quality assurance/quality control system. The use of more sophisticated models with high-resolution climatic, soil and other activity data, together with disaggregated emissions reporting, will be important to reduce uncertainty and introduce more flexibility into the inventories to better reflect mitigation measures.

Informing policy

Signatory nations to the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Long-range Transboundary Air Pollution (CLRTAP) have agreed to report their national emissions of GHGs and air pollutants annually using the Intergovernmental Panel on Climate Change (IPCC) and United Nations Economic Commission for Europe (UNECE) guidelines. This project aimed to identify improved methodologies for upscaling from site to national scales and to identify the reporting requirements for agricultural systems. This, in turn, can inform the development of measures under the Common Agricultural Policy and the rural development and environmental regulations and directives of the EU, which have a strong influence on agriculture and its impact on environmental variables and their indicators. These could have strategic importance for science, technology and innovation in Ireland and the improved environmental technologies required to cope with EU and international policies on emissions reductions and enhanced carbon sequestration. Future initiatives should include improving the collation of and access to measured/collected activity data to enable researchers and modellers to validate emerging models.

Developing solutions

This project aimed to supplement EPA activities focused on improving national inventory reporting/ National Atmospheric Inventory System reporting through the development of novel methodologies and computational protocols. This was undertaken as it is not possible to directly measure GHGs, atmospheric pollutants and SOC covering all agricultural lands and associated management practices, including the impact of land use/land cover change over large areas and for extended periods of time. This work sourced, collected and assessed agricultural activity data, analysed their uncertainty and developed proxies, leading to recommendations for filling some research gaps and for the improved estimation of emissions of GHGs and atmospheric pollutants. The use of a process-based model provides a potential solution for more robust emission accounting and reporting of SOC estimates with reduced uncertainty. The added advantages of this approach are a potential ability to simulate site-specific information at national and even global levels and to identify mitigation strategies and GHG offsetting mechanisms. However, further research is required to develop relevant methodologies/procedures and enhance model performance in collaboration with the EPA inventory team to improve inventory estimates and UNFCCC/UNECE reporting.

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/