Geoderma Regional 32 (2023) e00615

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Soil organic carbon stocks by soil group for afforested soils in Ireland

Caren Jarmain [a,b], Thomas Cummins [c], Antonio Jonay Jovani-Sancho [d,e], Tim Nairn [f], Alina Premrov [g,h], Brian Reidy [i], Florence Renou-Wilson [j], Brian Tobin [k,l], Kilian Walz [a], David Wilson [m], Kenneth A. Byrne [a,*]

[a] Department of Biological Sciences, School of Natural Sciences, University of Limerick, Ireland
[b] Centre for Geographical Analysis, Department of Geography and Environmental Studies, University of Stellenbosch, South Africa
[c] UCD School of Agriculture and Food Science, University College Dublin, Ireland
[d] UK Centre for Ecology and Hydrology, Environment Centre, Wales, United Kingdom
[e] School of Biosciences, University of Nottingham, Loughborough LE12 5RE, United Kingdom
[f] SWS Forestry, Ireland
[g] ICARUS, Department of Geography, Maynooth University, Ireland
[h] Botany Discipline, School of Natural Sciences, Trinity College Dublin, Ireland
[i] National Parks & Wildlife Service, Ireland
[j] School of Biology and Environmental Science, University College Dublin, Ireland
[k] UCD Forestry, School of Agriculture and Food Science, University College Dublin, Ireland
[l] UCD Earth Institute, University College Dublin, Ireland
[m] Earthy Matters Environmental Consultants, Ireland

ARTICLE INFO

Keywords:
Soil organic carbon stocks
Forest floor litter
Forestry
Republic of Ireland
World Reference Base
Histosols
Leptosols
Gleysols
Gleys
Podzols
Stagnosols
Phaeozems
Umbrisols
Luvisols
Cambisols
Fluvisols
Regosols
Organo-mineral soils

ABSTRACT

Forest ecosystems are recognised as Natural Climate Solutions because forest soils are such important carbon stores, containing almost half of the total soil organic carbon of terrestrial ecosystems. Here we present the results of a synthesis of soil carbon stocks by World Reference Base soil group, and forest litter carbon stocks for afforested soils in the Republic of Ireland. We report soil carbon stocks of mineral soils separately from organo-mineral soils. We estimated mean soil carbon stocks in a 100 cm deep mineral soil to be between 162 ± 87 t C/ha (Gleysols) and 416 ± 0 t C/ha (Umbrisols, $n = 1$), and between 173 ± 65 t C/ha (Phaeozems) and 602 ± 226 t C/ha (Regosols) in a 100 cm deep organo-mineral soil; both less than the estimated soil carbon stocks in organic soils (Histosols): 645 ± 222 t C/ha. The entire soil carbon stocks in mineral Leptosols (100 ± 0 t C/ha, $n = 1$), Stagnosols (144 ± 39 t C/ha), Luvisols (159 ± 52 t C/ha) and Fluvisols (231 ± 0 t C/ha, n = 1) was contained in the upper 50 cm of soil. Based on a 100 cm deep soil, Histosols hold 1.6–4 times the amount of soil C than mineral soils and 1.1–3.7 times the amount in organo-mineral soils for the same profile depth. Certain mineral (e.g. Umbrisols) and organo-mineral soils (e.g Gleysols, Regosols) contain substantial soil carbon stocks relative to Histosols. We found considerable soil carbon stocks below 30 cm depth, which highlights the importance of depth extent for cumulative soil carbon stocks estimates. The upper third of the 100 cm profile contained 33% (Histosols) to 70% (Luvisols) of the soil carbon stocks and the upper half of a 100 cm profile contained the entire soil carbon stocks for Leptosols, Stagnosols, Luvisols and Fluvisols and organo-mineral Leptosols. Unfortunately, there were few samples available for mineral Leptosols, Umbrisols, Luvisols and Fluvisols, and the organo-mineral Stagnosols and Regosols, which precludes the drawing of conclusions for these groups. Relative to the soil carbon stocks, we found low mean forest litter stocks: 4.1 ± 5.5 t C/ha, 4.8 ± 3.3 t C/ha and 2.7 ± 2.9 t C/ha for broadleaf, coniferous and mixed forests respectively. Few exceptions existed for individual sites: 22.7 and 131.3 t C/ha for broadleaf forests. Our results are evidence that soil carbon stocks in mineral, organo-mineral and organic soils need to be protected, appropriately managed, and enhanced to be beneficial for greenhouse gas mitigation. Assessments are needed to identify which soil-site-management practice combinations risk soil carbon stock depletion. The large range observed in soil and litter carbon stocks stresses the importance of adequately accounting for soil group differences when GHG inventories are compiled. The synthesised dataset will contribute to improved SCS estimation for afforested lands in Ireland.

* Corresponding author at: Science and Education Building, Department of Biological Sciences, School of Natural Sciences, University of Limerick, Ireland.
E-mail address: ken.byrne@ul.ie (K.A. Byrne).

https://doi.org/10.1016/j.geodrs.2023.e00615
Received 31 March 2022; Received in revised form 1 December 2022; Accepted 24 January 2023
Available online 9 February 2023

1. Introduction

The soil organic carbon stock (SCS) is the largest carbon (C) pool in the terrestrial ecosystem (Scharlemann et al., 2014). In the global terrestrial C pool, 74% of the C is stored in the soil (top and subsoil) and a further 26% in plant biomass (Scharlemann et al., 2014). Forest soils alone store almost half of the total soil organic C of global terrestrial ecosystems (Mayer et al., 2020). Griscom et al. (2017) list forest ecosystems as one of several natural climate solutions (NCS), which is seen as an additional 'land stewardship action' (Cook-Patton et al., 2021). Moreover, NCS can use various pathways (protection, restoration and management) to increase C storage and/or avoid greenhouse gas (GHG) emissions (Cook-Patton et al., 2021).

Within forest ecosystems, the soil organic carbon (SOC) stocks are determined by factors related to the soil (parent material, humus form, depth), climate (temperature, rainfall), forest (type, tree species, litter quantity and quality) and management (past and present) (De Vos et al., 2015). Carbon inputs include forest surface litter and woody debris deposition, moss litter inputs, belowground root-litter production, and root exudates; C losses include decomposition, erosion or leaching from the soil profile, and management removals. Management activities influence SCS by altering the rates of input or release of C from soils (Jandl et al., 2007; Mayer et al., 2020). The forest floor (surface litter decomposition) supplements SCS and forms an integral part of the forest soil (Vanguelova et al., 2013). Several large-scale studies have highlighted the impact of soil type on SCS (Batjes, 2002; Vanguelova et al., 2013; Batjes, 2014; De Vos et al., 2015). For example, organic soils hold a disproportionately large amount of SCS and estimates by Vanguelova et al. (2013) have shown that afforested organic soils can store almost four times that of mineral soils. For the Republic of Ireland (hereafter, Ireland), Renou-Wilson et al. (2022) have shown that peatlands store 2216 Mt of C or twice as much C as in mineral soils (estimated at c. 1153 Mt for the 0–50 cm layer by Xu et al. (2011)), which is the bulk of the store for these soils and would thus represent 2/3 of the total national SCS. The permanence of the soil C store is key to avoiding emissions from decomposition (Vanguelova et al., 2013) and hence SCS should be maintained and increased where possible (Scharlemann et al., 2014).

In the long-term, mineral soils are expected to be neither sinks nor sources of atmospheric C (Agren et al., 2007; De Vos et al., 2015). Studies have shown that, in some instances, increased forest C stocks are linked to management changes, such as increased rotation length (Lorenz and Lal, 2009; Lundmark et al., 2018) and management intensity (Patton et al., 2022). The sustainable management of forests can increase the amount of C contained in the vegetation, soil, and hence the ecosystem C sink (Batjes, 2002; Lorenz and Lal, 2009; Mayer et al., 2020). However, forest management practices that expose or disturb the soil can stimulate C losses (Vanguelova et al., 2013; Mayer et al., 2020). Climate change can increase or decrease C sequestration rates in forest ecosystems (Lorenz and Lal, 2009; De Vries and Posch, 2011): increased growth (McMahon et al., 2010) and hence litterfall; increased soil temperature and increased decomposition rate (Davidson and Janssens, 2006; Keenan, 2015; Glassman et al., 2018), while management changes (fire protection, harvesting intensity) in a changing climate will alter the forest ecosystem C balance (Lorenz and Lal, 2009; Keenan, 2015; Patton et al., 2022).

There is a continued interest in accurately quantifying SCS (Jandl et al., 2014) and understanding the drivers of SCS change over time (Eaton et al., 2008), due to the extent of SCS and the fact that it is the most uncertain component in the forest C budget. The difficulty in distinguishing forest litter from the soil (organic and mineral layers) adds to the uncertainty in the SCS estimation and reporting. SCS is not measured routinely in forest inventories (Vanguelova et al., 2013), therefore this data scarcity often prevents the estimation of a regional or national-scale SCS or its spatial distribution (Xu et al., 2011). In Ireland, Tomlinson (2005) performed the first country-level assessment of C stocks in Irish soils, combining the General Soil Map of Ireland from Gardiner and Radford (1980) and county soil maps. Tomlinson (2005) presented SCS by soil groups and dominant land cover for the observed soil profile and CORINE land cover data (O'Sullivan, 1994). The extent and depth of peat types were taken from representative peat soil profiles and one average value for the different peat types was used (Hammond, 1981). Eaton et al. (2008) proceeded by combining CORINE land cover data with published SCS data from other countries (England, Wales and Northern Ireland) to estimate SCS for Ireland to a 100 cm depth. Eaton et al. (2008) also reported SCS by land use, but not by soil group, except for organic soils. Xu et al. (2011) combined datasets to provide a country-level estimate of SCS for Ireland, distinguishing between land uses and soil depths but not between soil groups. More recently, the Irish Soil Information System (SIS) project produced an indicative SCS map for Ireland (Creamer et al., 2016). Here, single-pit soil-series profile data were combined with measured and modelled bulk density (BD) values, to provide SCS values to 50 and 100 cm depths by soil association. The 50 cm dataset had been validated but due to a lack of data, the 100 cm map could not be validated (Creamer et al., 2016). Recently, Saunders et al. (2022), as part of the SOLUM project, integrated soil, land use, climate and management information to improve Tier 2 SCS estimates, focusing on land use change scenarios.

Several country-specific and regional studies (Batjes, 2002; Vanguelova et al., 2013; De Vos et al., 2015; Armolaitis et al., 2021; Osipov et al., 2021) have reported SCS according to World Reference Base for Soil Resources (WRB) Reference Soil Groups (IUSS, 2015; WRB, 2022) for afforested soils and other land uses. These studies documented the changes in BD, SOC concentrations and SCS over the soil profile depth for organic, mineral and Histic mineral soils and showed the ranges in SCS by WRB soil group. These authors also estimated the forest litter C stocks.

Such synthesis of knowledge on SCS and litter C stocks, linked to a soil group, is useful in informing the National GHG Inventories that are submitted annually to the United Nations Framework Convention on Climate Change (UNFCCC). It is particularly relevant for the reporting of GHG emissions by sources and GHG removals by sinks, resulting from Land Use, Land Use Change and Forestry (LULUCF) activities. As part of the Kyoto Protocol and Paris Agreement, activities such as afforestation, reforestation, deforestation and forest management must be reported annually (Duffy et al., 2021). The calculation of C stocks and flows for organic and mineral soils are treated differently (IPCC, 2006; IPCC, 2019). For organic soils, emission factors are applied, whereas, for mineral soils, SCS according to soil group are calculated. In Ireland, for GHG reporting organo-mineral soils are separated from mineral soils (Duffy et al., 2021) and emission factors corrected for depth, are applied.

This paper summarises BD, SOC and SCS over the observed soil profile depth for afforested land in Ireland and assigned to WRB soil groups. Both published and unpublished data sources are assimilated and summarised. We distinguish between organic, mineral and organo-mineral soils and report the forest litter per forest type separately. The publication shows the importance of separating mineral soils rich in organic material from typical mineral soils and summarises the distribution of SCS over the profile per WRB. We establish relationships between BD and SOC, and SCS over depth for the respective WRB soil groups. In this publication, the contribution of soil inorganic carbon (SIC) to the total SCS of mineral and organo-mineral soils is not considered due to a lack of data.

2. Materials and methods

2.1. Definitions

For this paper, we applied definitions by WRB (2022) and USDA (2014) for soil and plant litter. In addition, we reference Duffy et al. (2021) to highlight soil definitions specific to the Republic of Ireland used in the context of Ireland's National Inventory Report (NIR).

WRB (2022) defines the litter layer as "a loose layer that contains >

90% (by volume, related to the fine earth plus all dead plant remnants) recognisable dead plant tissues (e.g. undecomposed leaves)." Litter is characterised by the soil consistency term "loose" and includes coarse organic fragments (in the 2–100 mm size range). Moreover, WRB (2022) does not regard litter as part of the soil and separates it from the soil organic layers, similar to Creamer and O'Sullivan (2018).

Most soils contain fractions of both mineral material and organic material but are dominated by one or the other (USDA, 2014). In simple terms, organic material is distinguished from mineral material based on the mass proportion of SOC, with organic material having $\geq$ 20% SOC (WRB, 2022). Organic layers — of any thickness or in any sequence or position in the profile — consist of organic material; all other soil material is mineral material, and all other soil layers are mineral soil layers. Organic layers are designated as O when formed under unsaturated conditions (for $>$ 30 days/year) and H when formed in saturated conditions (for $>$ 30 days/year), even if subsequently dried due to drainage. H layers may be referred to as peat.

Below the litter layer (where present), further layers of forest-derived O material are typically found in forests. These terrestrial O horizons tend to demonstrate distinct layering and increasing decomposition state with depth, and with thicknesses of zero to a few tens of cm. WRB (2022) qualifies these as soil horizons with horizon designations of Oi, Oe and Oa, respectively; representing decomposition states that are *i*nitial, interm*e*diate, and *a*dvanced. Sources cited in this paper (Vanguelova et al., 2013; De Vos et al., 2015) often use other nomenclature for the forest-derived material (layers L, F and H or OL, OF and OH): where L or OL, is mostly identifiable material derived from litter; F or OF, *fermented* material where decomposition is clear but plant residues can still be distinguished, and H or OH, the *humified* material where decomposition has progressed substantially (De Vos et al., 2015). The abbreviations L, F and H are broadly equivalent to litter+Oi, Oe, and Oh horizons, respectively.

WRB (2022) defines the soil surface or 0 cm level as the top of all soil layers, including both organic (O and H) and mineral layers, and below the litter (which is not regarded as soil). Some data sources referenced here used a different convention to define this 0 cm level. All data sources used in this study have been standardised according to the WRB definition.

In Ireland, extensive areas have been afforested since the 1990s (Black et al., 2008; Byrne, 2014) often with artificial drainage; afforestation reduced the effective precipitation due to forest canopy interception (Aherne et al., 1999) and increased evapotranspiration (Farrell, 1985). Where organically rich soils were artificially drained, authors reported a reduced thickness or subsidence of H layers attributable to decomposition and dewatering (Farrell, 1985; Titus and Malcolm, 1991; Anderson et al., 1992; Byrne and Farrell, 1997; Shotbolt et al., 1998).

Where a soil has both organic and mineral horizons, USDA (2014) advises that the relative thickness of the organic and mineral soil materials are considered when distinguishing organic soils from mineral soils. Within the context of forest soil subsidence due to drainage, in this study, we applied the definitions used in the NIR of Ireland (Duffy et al., 2021) where the thickness of the organic (H) layer is used to distinguish organic from organo-mineral soil. In this specific context, we regard forest soils with H layers summing to $\geq$30 cm as representing undrained pre-afforestation Histosols (for which a 40 cm thickness is often applied as per Creamer and O'Sullivan (2018); WRB (2022)); and forest soils with H layers summing to $<$30 cm as representing undrained pre-afforestation organo-mineral soils which are by definition mineral soils. Organo-mineral soils are equivalent to peaty mineral soils, also referred to as the Histic subgroups of mineral Soil Great Groups e.g. Histic Podzols and Histic Gleysols (Simo et al., 2008; Vanguelova et al., 2013; Reidy et al., 2014; Creamer and O'Sullivan, 2018). It should be emphasised that this approach has no effect on the C stocks reported to 30 cm or greater depths. The approach used in the NIR is consistent with this, applying a 30 cm thickness criterion to distinguish soils reported for C stock change from those Histic subgroups and Histosols, all reported using emission factors (Duffy et al., 2021). Authors should consult WRB (2022) or USDA (2014) for a detailed definition of organic and mineral soils.

2.2. Ireland: Climate and forestry

Ireland has a maritime climate (Cfb) according to the Köppen classification system (Beck et al., 2018), characterised by mild summers and cool winters, based on the 1981–2010 reference period. It has a relatively small mean annual temperature range (9–10 °C); upland areas are significantly cooler (Walsh, 2012). Mean daily summer temperatures range from 17 to 19 °C. The mean annual rainfall for Ireland is 1230 mm (Walsh, 2012) but ranges from 750 to 1000 mm in midland and eastern areas, to 1000–1400 mm elsewhere. Rainfall over 2000 mm/year falls in mountainous regions (Creamer and O'Sullivan, 2018).

Its maritime climate makes Ireland ideal for forestry. For instance, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) has shown increased timber productivity in Ireland when compared to other European countries (Green et al., 2007). The mild climate and high rainfall are favourable for the accumulation of soil organic matter (SOM) as they encourage plant litter production, while microbial decomposition is low (Creamer and O'Sullivan, 2018).

In 2019, forest cover was 776,650 ha or 10.9% of the land area of Ireland (Duffy et al., 2021). European Forest Type (EFT) species classes found include Coniferous (65.7%), Broadleaf (20.6%) and Mixed types (13.7%). Sitka spruce is the dominant species (51.1%), followed by the group 'Other pines' (mainly lodgepole pine, *Pinus contorta* Dougl.) (9.6%) and Other Short Living (OSL) broadleaves (7.9%) (Duffy et al., 2021). Ireland plans to increase the area under forestry at a rate of about 8,000 ha/year (Ireland, 2019). Under the recently published Climate Action Plan, there is a need for increased afforestation to achieve longer-term (2050 and beyond) national climate neutrality (Ireland, 2019). This assumes that the maintenance of existing forests and the establishment of additional forest ecosystems (natural or plantation), especially hardwood species, and on low-C soils, offers C sequestration potential in the long term (Creamer and O'Sullivan, 2018).

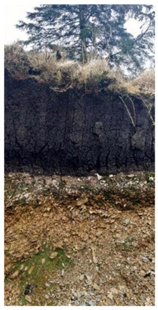
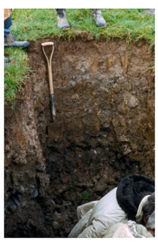
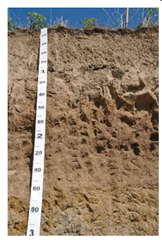
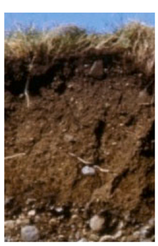
2.3. Ireland: Soils

Soils in Ireland are relatively young and have formed since the last ice age approximately 15,000 years ago (Creamer and O'Sullivan, 2018). The soil parent materials are broadly grouped into solid bedrock geology and subsequently reworked glacial geology, with glacial deposits accounting for most parent materials. High effective rainfall and subsequent leaching and gleying have strongly influenced soil development (Creamer and O'Sullivan, 2018). Histosols occur in broad topographic basins of the midlands as fen peats and raised bogs, and as climatic blanket peats in upland and Atlantic areas with frequent rainfall over slowly-weathering substrates. Histosols in most areas are highly modified by drainage and excavation for domestic and industrial fuels.

Most afforested areas are on mineral soils (60.8%) with the remaining area on Histosols (peats) (DAFM, 2018). Forests can also be found on Stagnosols, Gleysols, Podzols, Cambisols, Leptosols and Luvisols (Creamer and O'Sullivan, 2018; DAFM, 2018; Duffy et al., 2021), and smaller areas of Phaeozems, Umbrisols, Fluvisols and Regosols (Table 1). See WRB (2022) for definitions of these groups.

Duffy et al. (2021) calculated C stock changes in afforested areas in Ireland by four generalised mineral-soil groups consisting of several WRB soil groups having broadly similar SOC established as Tier 2 SOC_{ref} values (Simo et al., 2008; IUSS, 2015). For the NIR, organic soil has a thickness of $\geq$ 30 cm, with $>$ 20% SOC, and is distinguished from organo-mineral soils, where the sum of organic layers is $<$ 30 cm thick (Duffy et al., 2021). Stock change is estimated on mineral soils, and emission factors are reported for organo-mineral and organic soils (Duffy et al., 2021).

Table 1
Afforested soil groups found in Ireland as part of this study, according to the World Reference Base classification with typical horizons (IUSS, 2015; WRB, 2022) and soil great groups according to the Ireland classification system (Reidy et al., 2014). Soils are separated according to soil organic carbon (SOC) and depth into organic (^{O}), mineral (^{M}) or organo-mineral ($^{O\text{-}M}$) soils. *indicates the potential presence of an organic layer in mineral soil.

WRB RSG	**HISTOSOLS (HS)** ^{O}	**LEPTOSOLS (LP)** $^{M,\ O\text{-}M}$	**GLEYSOLS (GL)** $^{M,\ O\text{-}M}$	**PODZOLS (PZ)** $^{M,\ O\text{-}M}$
Description	Soils with thick organic layers	Soils with limitations to root growth	Groundwater-affected soils	Subsoil accumulation of iron oxide
				
Photo credit	C. Jarmain	T. Cummins	C. Jarmain	T. Cummins
Example horizons	Oi-Oa-E-Bs-C	Oi-Oe-Ah-R// Oi-Ah-CBw-C*	Ah-Bl-Br-Cr//Ah-Br-Cr// Ah-Bl-C*	Oi-Oe-Oa-AhE-E-Bhs-Bs-C//Oi-Oe-Oa-AhE-E-Bhs-BsC-C*
Great Soil Group(s), Ireland system	Ombrotrophic peats, Minerotrophic peats	Lithosols, Rendzina	Groundwater Gleys	Podzol, Brown Podzolics
WRB RSG	**STAGNOSOLS (ST)** $^{M,\ O\text{-}M}$	**PHAEOZEMS (PH)** $^{O\text{-}M}$	**UMBRISOLS (UM)** ^{M}	**LUVISOLS (LV)** ^{M}
Description	Stagnant water due to structure or texture	Pronounced accumulation of organic matter in mineral topsoil	Dark topsoil in low-base-status soil	Clay accumulation at depth
				
Photo credit	R.F. Hammond	Public domain	Public domain	R.F. Hammond
Example horizons	Ah-Bg-C//Oi-Ah-Eg-Btg-C*	Ah-C//Ah-Bw-C*	Ah-C//Oi-Ah-Bw-C	Ah-E-Bt-C
Great Soil Group(s); Ireland system	Surface water Gleys			Luvisols, Grey brown Podzolic
WRB RSG	**CAMBISOLS (CM)** ^{M}	**FLUVISOLS (FL)** ^{M}	**REGOSOLS (RG)** $^{O\text{-}M}$	
Description	Soils with moderate weathering	Stratified sediments	No significant profile development	
				
Photo credit	R.F. Hammond	T. Cummins	A. Jordán	
Example horizons	Ah-Bw-C//Oi-Oe-Ah-Bw-C	Ah-C1-2C2 - 3C3	A-C//Ah-C*	
Great Soil Group(s), Ireland system	Brown Earths	Alluvial Gley	Regosols	

2.4. *Data reviewed for this study*

No new field data were collected for this paper; instead, existing data were assimilated. We focussed on measured and not modelled data: sampling depth, SOC, BD, SCS and litter C stocks. Most data were extracted from publications (published and in preparation), but where possible, the source (raw) data were obtained from authors and subsequently combined (Table 2). We aggregated data for different depth intervals, by WRB soil group (IUSS, 2015; WRB, 2022) and separated mineral soils from organo-mineral soils based on SOC values in the upper 30 cm. Where necessary, we resampled the soil depth and soil 0 cm level, according to the definitions for soil and litter in section 2.1. The quality of the unpublished datasets was evaluated, and a few data points were excluded; the remainder was included as found. Our approach was to aggregate data across comparable methodological categories to allow comparison of forest litter C stocks as well as fixed-depth and whole-soil SCS.

Data from 18 studies and 241 sites were considered, and an additional 106 Histosol soil sampling depth data points were included (Table 2). Sites were well distributed across Ireland (Fig. 1). Data from 11 WRB soil groups are presented (Table 2): 1 organic soil type (Histosols), 8 mineral soil types (Leptosols, Gleysols, Podzols, Stagnosols, Umbrisols, Luvisols, Cambisols, Fluvisols) and 6 organo-mineral soils (Leptosols, Gleysols, Podzols, Stagnosols, Phaeozems, Regosols). Most data points were recorded for Histosols, Podzols and Cambisols (Fig. 2). Data from afforested coniferous, broadleaf, mixed and other (evergreen *Eucalyptus* or unspecified) forests were considered, with coniferous forests being dominant (Fig. 2).

Table 2
Summary of data sources considered for this paper. Data references and details on WRB soil groups and forest types (EFT) per study are shown. The sampling methodology used is also summarised. O, M and O-M refer to organic, mineral and organo-mineral soils; HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols. EFT considered were Broadleaf (B), Coniferous (C), Mixed (M) and Other (OTH). Litter includes fine woody debris (FWD) where not separated. An ✘ indicates no sample data were available; H/Ly refers to the sampling interval – horizon or fixed layer; F/R/A/P/S refers to the sampling method – Frame, Ring, Auger, Soil Pit or split tube sampler; SOM/SOC refers to soil organic matter (SOM) or soil organic carbon (SOC) estimated, with SOC* indicating that SOC was derived from SOM using a conversion factor. LOI/DC refers to the method used to determine SOC/SOM — loss of ignition or dry combustion; and CF indicates whether coarse fragments were considered (✓) or not (✘). † indicates sites where only depth data were used.

	SITES AND SOIL GROUPING		FOREST TYPE	LITTER AND SOIL SAMPLING						
Publication and/or Data Reference	Sites (n)	O/M/O-M with WRB	B/C/M/OT	Litter	Interval H/Ly	F/R/A/P/S	SOM/SOC	LOI/DC	CF ✓✘	Data level
Clancy (2018)	10	M (GL, PZ, ST, CM, FL)	C	✘	Ly	P, R	SOM, SOC*	LOI	✓	Publication
Clancy et al. (2015)	7	O-M (PZ); M (PZ)	B, OTH	✘	H	R, A	SOM, SOC*	LOI	✓	Publication
Creamer et al. (2014); Data reference: Teagasc and University (2014)	11	M (LP, GL, PZ, CM); O-M (PZ)	B, OTH	L (1)	H	R	SOM, SOC*	LOI	✘	Raw
Jarmain et al. (2022) and Premrov et al. (2018)	61	M (CM); O- M (LP, GL, PZ, PH)	B, C, M	✘	H	F, R, A	SOM, SOC	LOI, DC	✓	Raw
Jovani-Sancho et al. (2017a)	1	M (CM)	M	✘	Ly	R, P	SOM, SOC*	LOI	✓	Publication
Jovani-Sancho et al. (2017b)	2	O (HS)	C	✘	Ly	A	SOC	DC	✘	Publication
Jovani-Sancho et al. (2018)	8	O (HS)	C	✘	Ly	F, A	SOC	DC	✘	Publication
Jovani-Sancho et al. (2021)	8	O (HS)	C	L (8)	Ly	F, A	SOC	DC	✘	Raw
Kiely et al. (2009); Data reference: Kiely and Carton (2008)	9	O (HS); M (PZ, ST, LV); O-M (PZ)	B, C	✘	Ly	R, A	SOC	DC	✘	Raw
Green et al. (2007)†	72†	O (HS)	C	✘		A	✘	✘		Raw
Hiederer and Durrant (2010); Hiederer et al. (2011)	36	O (HS); M (GL, PZ, UM, CM); O-M (GL, PZ, ST, PH)	C	L (3)	Ly	R, A, P	✘	✘	✓	Raw
Nieuwenhuis et al. (2012); Data reference: Reidy et al. (2022)	27	M (GL, PZ, CM); O-M (GL, PZ)	B, C, M	L (27)	Ly	F, R, A	SOC	DC	✓	Raw
Renou-Wilson et al. (2010)†	34†	O (HS)	B	✘	✘	A	✘	✘	✘	Raw
Rigney (2016)	1	O (HS)	C	✘	Ly	A	SOC	DC	✘	Publication
Walz et al. (2022)	10	O (HS)	C	✘	Ly	A	SOC	DC	✘	Raw
Wellock et al. (2011a)	21	M (PZ, ST, CM)	B, C, M	L + FWD (21)	Ly	F, R, A	SOC	DC	✓	Publication
Wellock et al. (2011b)	24	O (HS)	C	✘	Ly	A, R	SOC	DC	✓	Publication
Wellock et al. (2014)	5	M (CM)	B	L (5)	Ly	F, R, A	SOC	DC	✓	Publication

The assimilated data were heterogeneous in terms of sampling design and method and included varying levels of site variation for the respective soil parameters. The original data were reported in layer intervals (fixed or variable) or by horizons (Table 2), with irregular depth intervals indicated for the latter. Details on sampling methods (depth sampled, methods used, repetitions) and profile depth sampled were determined by the scope of the individual study.

BD, defined as the mass of oven-dry soil divided by the total soil volume, is often assessed using samples taken from intervals or soil horizons, using coring rings (e.g. 100 cm^3), an auger or split tube sampler, or by excavation or quantitative pit methods (Al-Shammary et al., 2018). In Histosols, soil cores for BD are often taken with a Russian peat corer or a split tube sampler (e.g. Eijkelkamp Agrisearch Equipment BV, Netherlands). In the studies considered, all these methods were employed to extract soil samples to determine BD (Table 2). Where coarse rock fragments (CF) are present, sampling with coring rings is often not possible, especially where CF larger than the diameter of the cores is present. Moreover, CF may cause a soil volume dilution effect and UNFCCC reporting requires that SCS be corrected for CF (IPCC, 2006; IPCC, 2019). Several studies accounted for CF (Table 2).

Soil samples taken with coring rings, or a peat corer, are also used to determine SOM and/or SOC. The Walkley-Black (WB) and dry combustion (DC) methods are widely used to determine SOC directly and the Loss of ignition (LOI) method is employed to determine SOM (Roper et al., 2019), which can then be converted to SOC using a conversion factor, such as the Van Bemmelen factor (1.724) (Minasny et al., 2020). Study-specific SOM/SOC conversion factors, as used by Renou-Wilson et al. (2022) for peat soils in Ireland (1.59), also exist. Our review showed that both the DC and LOI methods were used (Table 2): DC to determine SOC directly and LOI to determine SOC indirectly from SOM estimates. The SOM/SOC conversion factor was typically not specified.

Our approach was to summarise available SCS (t/ha) but where raw data was provided, SCS was calculated from available BD (g/cm^3), CF (fraction) and SOC (%) data for individual (*i to k*) soil layers or horizon thicknesses (z in cm), and a conversion factor (100), which are then summed to give a profile SCS estimate (IPCC, 2006) (eq. 1).

$$SCS = \sum_{i=1}^{k} (BD_i) \times (SOC_i) \times (z_i) \times (1 - CF_i) \times 100 \tag{1}$$

Forest litter is often sampled over a fixed area (e.g. square plot or circular frame) as was done in the studies reviewed (Table 2). Litter mass and the OC concentration are used to estimate litter stocks as described by De Vos et al. (2015). Like SCS, our approach was to summarise available litter stock data (Litter or Litter + FWD) and present it by WRB reference soil group and forest type. FWD refers to fine woody debris.

2.5. Data standardisation, stratification and extrapolation

Available afforested SCS data for Ireland were heterogeneous, especially in terms of the sampling depth and interval at which the data were reported. This heterogeneity made data summaries and comparisons challenging. Consequently, this diverse dataset was transformed and summarised to make fixed-interval comparisons possible.

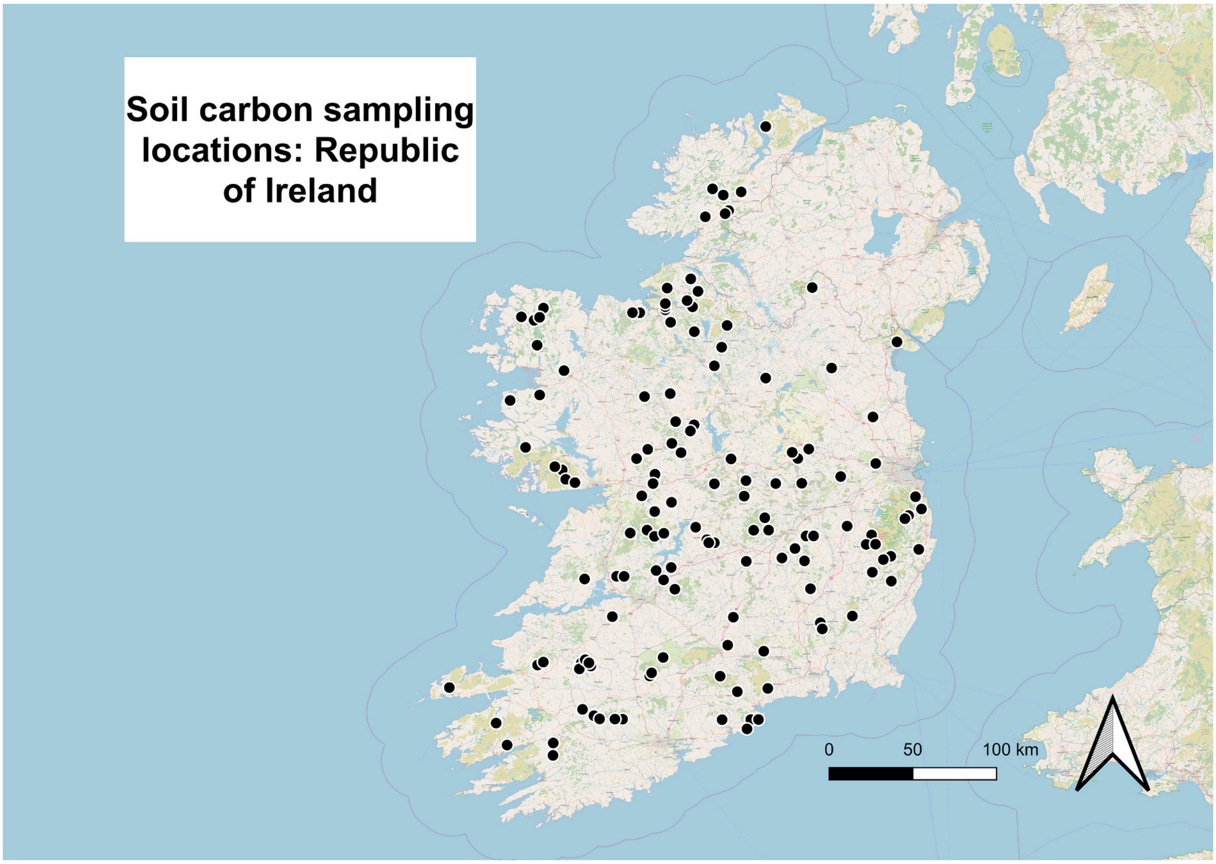


Fig. 1. Soil carbon sampling locations within the Republic of Ireland, considered in this publication, are shown by black dots. Openstreetmap (OSM) data are shown in the background.

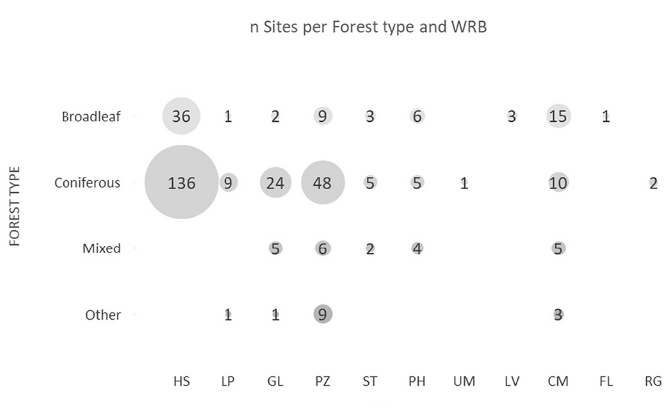


Fig. 2. Number of sites (n) considered according to forestry type and WRB soil group. The value inside the bubble presents n per forest type–WRB combination. Broadleaf refers to broadleaf forests, mixed to a mixture of coniferous and broadleaf forests and other, to other evergreen species or species not specified. Sites with only depth data are not included. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols.

1. In the first step, the datasets were extracted from publications and database spreadsheets according to the documented sampling intervals and each site was assigned a unique ID. Then, SOC, BD, CF and SCS were assigned to the specific sampling depth or interval.
2. In the second step, where data was presented by interval or horizon, the SOC and BD values were assigned to each centimetre (cm) within that interval or horizon (depending on the dataset), using the original sampling interval data as a reference. For SCS, a per-cm SCS was first calculated by dividing the interval/horizon SCS value by the thickness of the layer (SCS/z according to eq. 1). This per-cm SCS value was then assigned to each cm within that interval, but only for depths 0–200 cm. For depths below 200 cm, an SCS value per 50 cm interval was calculated (instead of per-cm). For BD and SOC, the cm-values remained constant between two intervals/sampling depths. The following assumptions were made: (a) BD and SOC values were representative of a specific depth interval/horizon and were, therefore, constant over that sampling interval, and (b) SCS increased linearly over depth between two sampling intervals. Linear interpolation is preferred here to higher-order functions given the expectation that the unknown physical sample size is large relative to the layer thickness, that it better represents the middle than the boundaries, and to avoid spurious precision.
3. In the next step, where needed, the soil 0 cm level was adjusted according to the definitions in section 2.1, so that 0 cm was at the surface of the uppermost organic horizon and below the loose litter layer. 'New' soil depths were subsequently calculated for the entire profile.
4. In the final step, the BD, SOC and SCS data were summarised to new standardised intervals using Microsoft Excel pivot tables. Two sets of intervals were considered: (a) sequential: 0–10, 10–30, 30–50, 50–100, 100–200, 200–300, 300–400, 400–500 and 500–600 cm and (b) specific profile depths: 0–30, 0–50, 0–100, 0–200, 0–300, 0–400, 0–500 and 0–600 cm. The SCS for each of the intervals were calculated as the sum of the per cm-SCS for the specified interval. Where the soil profile sampling depth did not extend to the next sampling interval, e.g. it was sampled to 80 cm instead of 100 cm, and bedrock was not reached, the SCS values were infilled using the per-cm SCS values from the preceding layer. Here we assumed that

the per cm-SCS from e.g. 50–80 cm depth remained constant for the additional depth (e.g. 80–100 cm) and the per cm-SCS was further accumulated over that depth. The BD and SOC values in the additional depth interval remained equal to that in the preceding depth interval. The above steps were performed on each dataset with disparate depth information.

All calculations were performed in Microsoft Excel using the VLookup function, together with the infill function in Excel Tables, and Pivot tables.

3. Results

3.1. Soil sampling depth

The variation in sampling depth for the sites considered is shown in Fig. 3. Soil sampling depth rather than profile depth was documented. Histosols were sampled to the greatest depth (Fig. 3a), with several profiles sampled beyond 200 cm; the mean sampling depth was 85 cm. Sampling depths of <30 cm were recorded for industrial cutaway peatlands (Histosols).

The mean sampling depth of mineral Leptosols and Stagnosols was shallow (22 and 34 cm, respectively), while Gleysols, Podzols and Cambisols were sampled to greater depths (Fig. 3b). The mean sampling depth for the organo-mineral Leptosols was 35 cm, less than the mean sampling depths for other organo-mineral WRB soil groups: 61–81 cm (Fig. 3c).

3.2. Bulk density over depth

The changes in mean BD values over depth for the different afforested WRB soil groups are shown in Fig. 4 and Table 3. In general, BD values increased with depth for mineral and organo-mineral soils, the exceptions being the mineral Podzols and the organo-mineral Leptosols,

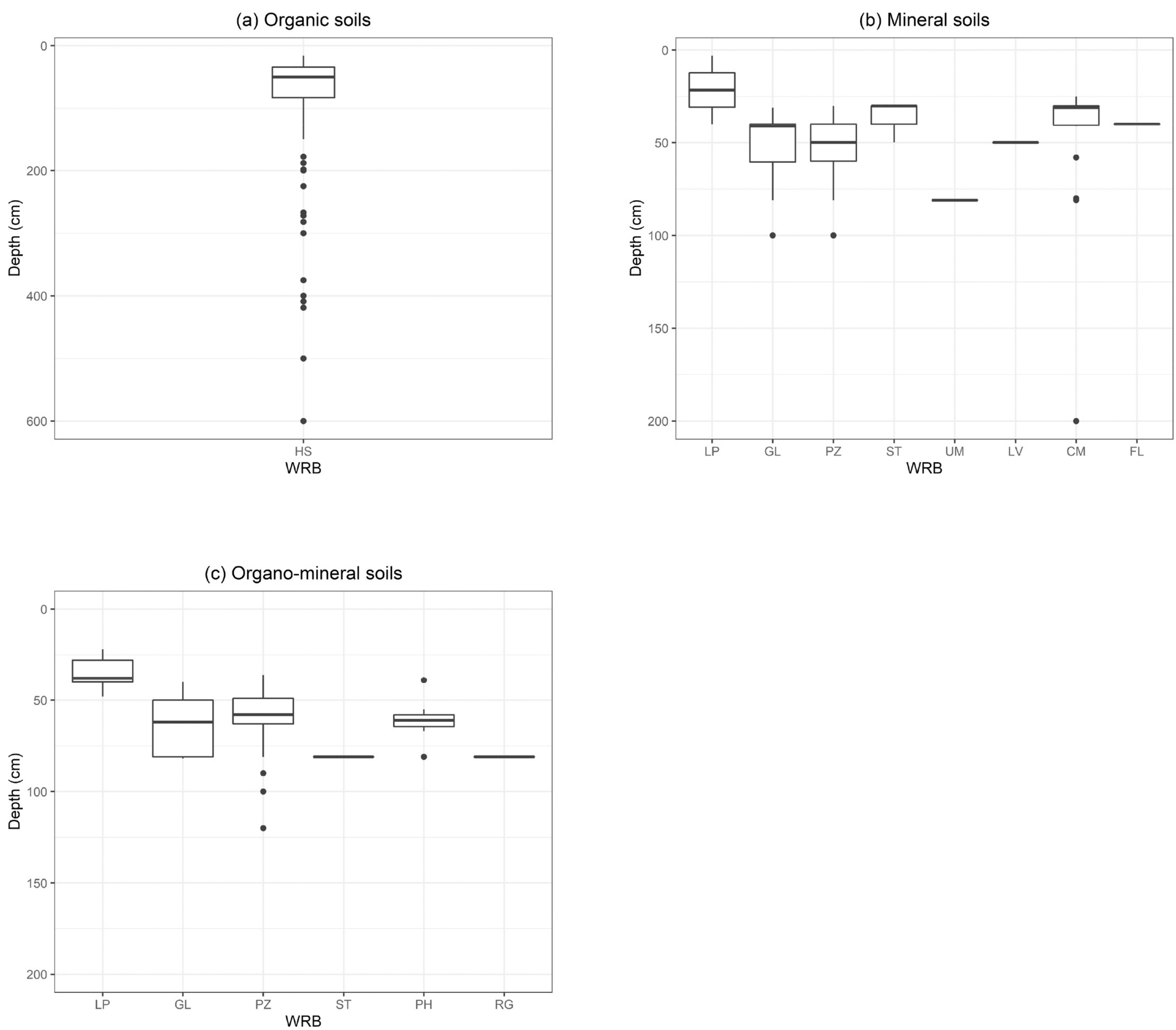


Fig. 3. Sampling depth (cm) by WRB soil group for (a) organic, (b) mineral, and (c) organo-mineral soils. Graphs show the distribution of data into quartiles with the bottom and top of the box showing the 1st and 3rd quartiles. The middle horizontal line shows the 2nd quartile (median). Lines extending vertically indicate the variability outside the upper and lower quartiles, and the points (·) outside those lines are considered outliers. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols.

where there was a decrease in BD at 50 and 100 cm, respectively. For Histosols, BD increased up to 100 cm depth, whereafter the BD values decreased. The BD values for Histosols were distinctly lower than other soil groups and the mean BD increased from 0.15 g/cm^3 in the upper 10 cm to 0.27 g/cm^3 at 100 cm, whereafter it decreased to 0.13 g/cm^3 at 400 cm (Fig. 4a, Table 3).

In contrast, the BD values for mineral soils were much greater (Fig. 4b, Table 3). For example, the BD value for Gleysols increased from 0.64 to 1.56 g/cm^3 in the upper 100 cm. Mean BD values for organo-mineral soils in the 0–10 cm layer were intermediate between BD values for organic soils and mineral soils: 0.15–0.89 g/cm^3 (Fig. 4c, Table 3). The mean BD values of organo-mineral soils at greater depths (> 50 cm) were comparable to those of mineral soils (Table 3).

3.3. Soil organic carbon concentration over depth

SOC values in the 0–30 cm layer of soil, by definition (section 2.1) differentiate organic, mineral and organo-mineral soils: organic soils have SOC ≥ 20% throughout this depth and below, mineral soils have SOC values <20% in this depth, and organo-mineral soils SOC ≥ 20% in any part of this layer. This study showed mean SOC values for Histosols of 50.2% and 49.7% in the 0–10 and 10–30 cm intervals (Fig. 5a, Table 4), respectively; below this depth, the mean SOC decreased from 49.7% to 44.5% (30–100 cm layers) and then increased to and remained at >50% below 100 cm soil depth.

For mineral soils, the SOC values decreased with depth (Fig. 5b), with mean SOC values in the 0–10 and 10–30 cm layers, greater in Leptosols and Umbrisols (< 15.3%) than in the other mineral soils (< 8%) (Fig. 5b). Mean SOC values do not reflect the elevated SOC values reported in some individual mineral-soil profiles (Gleysols, Podzols, Umbrisols), as indicated by the range maxima (Table 4).

Mean SOC values in the upper 10 cm of organo-mineral soils exceeded 20%, with the exceptions of Podzols (19.8%) and Phaeozems (8.1%) (Fig. 5c, Table 4). Few of the Phaeozems samples considered had thin organic layers (a few centimetres) with high SOC values that were not reflected in the mean SOC values. Except for the organo-mineral Regosols, the SOC values in all other organo-mineral soils were substantially reduced below 10 cm depth (to SOC < 11%) (Fig. 5c, Table 4).

3.4. Soil organic carbon concentration and bulk density relationship

When considering data from all depths and organic, mineral and organo-mineral soils, we found an exponential relationship between BD and SOC ($R^2 = 0.90$) (Fig. 6a). When splitting the data into groups, the best fits between BD and SOC for mineral soils and organic (Histosols) soils were second-order polynomials ($R^2 = 0.49$ and $R^2 = 0.82$, respectively) (Fig. 6b, d), and for organo-mineral soils, an exponential relationship ($R^2 = 0.77$) (Fig. 6c). For individual organo-mineral soil groups, exponential relationships were observed between BD and SOC ($R^2 > 0.71$, Fig. 6e–h). Poor BD-SOC relationships were found for several mineral soils ($R^2 < 0.35$, Fig. 6e, g, h), except for Gleysols ($R^2 = 0.81$, Fig. 6f) and Cambisols ($R^2 = 0.60$, Fig. 6i).

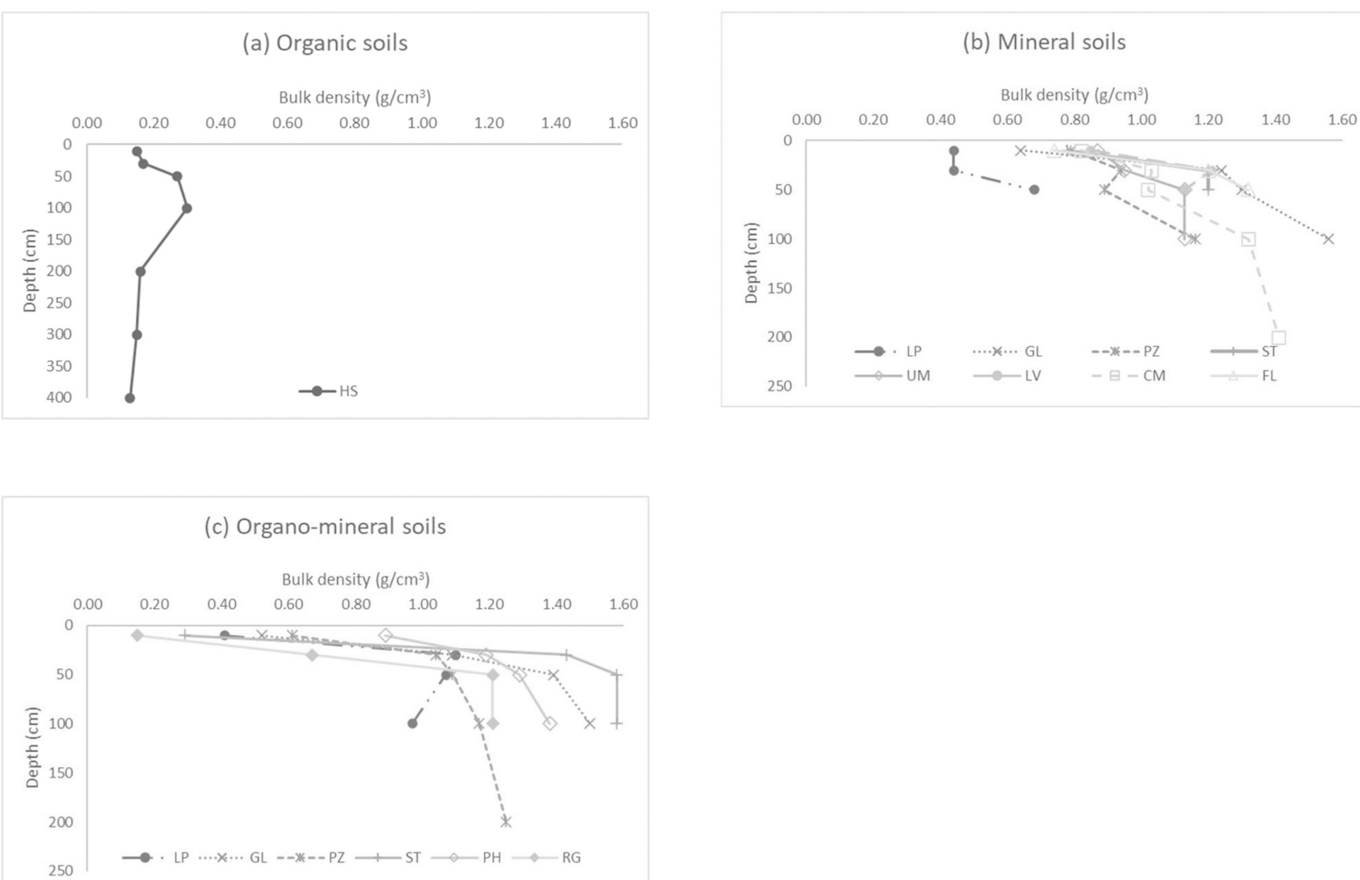


Fig. 4. Mean bulk density (BD: g/cm^3) of WRB soil groups for depth intervals (cm). Data is shown separately for (a) organic, (b) mineral, and (c) organo-mineral soils. Depth intervals were: 0–10, 10–30, 30–50, 50–100 and 100–200 cm. Note: Some BD data extrapolated from the original maximum sampling depth (e.g. 150 cm) to the next depth interval (e.g. 100–200 cm) are included. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols. All data shown are for afforested soils.

Table 3
Bulk density (BD: g/cm^3) over soil depth intervals (cm) by WRB soil group. Data is shown separately for organic, mineral or organo-mineral soils. Count (n), average (AVE), standard deviation (SD), and range (minimum to maximum) in BD values are shown. NA indicates data were not available or could not be calculated. Note: This includes some data extrapolated from the original maximum sampling depth (e.g. 150 cm) to the next depth interval (e.g. 100–200 cm). HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols.

			BD (g/cm^3)							BD (g/cm^3)			
GROUP	WRB	Depth (cm)	n	AVE	SD	Range	GROUP	WRB	Depth (cm)	n	AVE	SD	Range
O	HS	10	35	0.15	0.07	0.06–0.36	M	FL	10	1	0.74	NA	0.74–0.74
O	HS	30	35	0.17	0.12	0.08–0.75	M	FL	30	1	1.20	NA	1.20–1.20
O	HS	50	35	0.27	0.31	0.08–1.19	M	FL	50	1	1.32	NA	1.32–1.32
O	HS	100	25	0.30	0.34	0.08–1.19	O-M	LP	10	9	0.41	0.28	0.06–0.93
O	HS	200	8	0.16	0.03	0.11–0.19	O-M	LP	30	9	1.10	0.35	0.59–1.79
O	HS	300	5	0.15	0.03	0.11–0.18	O-M	LP	50	6	1.07	0.40	0.59–1.79
O	HS	400	1	0.13	NA	0.13–0.13	O-M	LP	100	2	0.97	0.38	0.59–1.36
M	LP	10	1	0.44	NA	0.44–0.44	O-M	GL	10	17	0.52	0.45	0.08–1.58
M	LP	30	1	0.44	NA	0.44–0.44	O-M	GL	30	17	1.09	0.46	0.19–1.66
M	LP	50	1	0.68	NA	0.68–0.68	O-M	GL	50	17	1.39	0.35	0.66–1.95
M	GL	10	11	0.64	0.18	0.25–0.94	O-M	GL	100	13	1.50	0.28	0.95–1.95
M	GL	30	11	1.24	0.20	0.97–1.61	O-M	PZ	10	43	0.61	0.33	0.07–1.34
M	GL	50	11	1.30	0.24	0.97–1.86	O-M	PZ	30	43	1.04	0.43	0.21–1.70
M	GL	100	3	1.56	0.27	1.20–1.86	O-M	PZ	50	43	1.09	0.40	0.28–1.70
M	PZ	10	23	0.79	0.26	0.15–1.41	O-M	PZ	100	30	1.17	0.39	0.23–1.70
M	PZ	30	23	0.94	0.28	0.23–1.48	O-M	PZ	200	1	1.25	NA	1.25–1.25
M	PZ	50	22	0.89	0.42	0.01–1.73	O-M	ST	10	1	0.29	NA	0.29–0.29
M	PZ	100	12	1.16	0.33	0.34–1.73	O-M	ST	30	1	1.43	NA	1.43–1.43
M	ST	10	3	0.78	0.13	0.61–0.94	O-M	ST	50	1	1.58	NA	1.58–1.58
M	ST	30	3	1.20	0.23	0.87–1.39	O-M	ST	100	1	1.58	NA	1.58–1.58
M	ST	50	3	1.20	0.22	0.90–1.41	O-M	PH	10	15	0.89	0.29	0.19–1.28
M	UM	10	1	0.87	NA	0.87–0.87	O-M	PH	30	15	1.19	0.23	0.81–1.45
M	UM	30	1	0.95	NA	0.95–0.95	O-M	PH	50	15	1.29	0.26	0.81–1.76
M	UM	50	1	1.13	NA	1.13–1.13	O-M	PH	100	14	1.38	0.18	0.92–1.76
M	UM	100	1	1.13	NA	1.13–1.13	O-M	RG	10	2	0.15	0.04	0.12–0.19
M	LV	10	3	0.85	0.15	0.69–1.05	O-M	RG	30	2	0.67	0.52	0.15–1.19
M	LV	30	3	1.21	0.17	0.97–1.34	O-M	RG	50	2	1.21	0.24	0.97–1.45
M	LV	50	3	1.13	0.28	0.74–1.37	O-M	RG	100	2	1.21	0.24	0.97–1.45
M	CM	10	22	0.82	0.17	0.36–1.19							
M	CM	30	22	1.03	0.25	0.49–1.48							
M	CM	50	16	1.02	0.27	0.49–1.54							
M	CM	100	6	1.32	0.15	1.06–1.54							
M	CM	200	1	1.41	0.00	1.41–1.41							

3.5. Soil organic carbon stocks over depth

SCS for individual samples considered in this study varied with depth and WRB soil group (Fig. 7). SCS is based on soil samples taken at various depths (Fig. 3), either by depth interval or horizon (Table 2). Fig. 7 shows SCS where the interval/horizon SCS was converted to a centimetre or interval step increase (see section 2.5).

SCS estimates from individual sites (Fig. 7) are summarised for fixed intervals in Table 5. Soil profile depths sampled were variable, hence SCS were determined to various depths, for example, SCS was determined only to 50 cm for Leptosols, Stagnosols, Luvisols and Fluvisols, but SCS below 200 cm were also shown for Histosols. SCS estimates for organic soils (Histosols) are included intentionally; to highlight the comparative importance of SCS in certain mineral and organo-mineral soils.

In the 0–10 cm layer, the mean SCS of Umbrisols was 111 t C/ha, greater than the mean SCS value for all the other WRB soil groups (30–81 t C/ha). The 0–10 cm layer contained between 5% (Histosols) and 30% (mineral Leptosols) of the SCS of the entire soil profile considered (Table 5). Considering the SCS in a 0–30 cm profile, the mean SCS value was <100 t C/ha for mineral Leptosols, in the 100–200 t C/ha range for several mineral soils (Gleysols, Podzols, Stagnosols, Luvisols, Cambisols, Fluvisols) and organo-mineral soils (Leptosols, Podzols, Stagnosols, Phaeozems), and > 200 t C/ha for Histosols, mineral Umbrisols and organo-mineral Gleysols and Regosols. The 0–30 cm layer contained on average 60% of the profile SCS, or between 14% (Histosols) and 91% (mineral Leptosols), which indicates the variable importance of that part of the soil profile.

The SCS range in a 0–30 cm profile was often large (> 250 t C/ha): Histosols (97–467 t C/ha), mineral Podzols (37–307 t C/ha), organo-mineral Gleysols (80–594 t C/ha) and Podzols (35–395 t C/ha). Maximum SCS values in the 0–30 cm layer that exceeded 300 t C/ha (Table 5) were found in the Histosols, mineral Podzols and organo-mineral Gleysols, Podzols and Regosols. The SCS values in this layer exceeded the forest litter stocks for all WRB soil groups, except for one outlier (mineral Leptosols) (Table 5).

The SCS in a 50 cm soil profile had mean values between 100 and 475 t C/ha. The mean SCS values in mineral Umbrisols, organo-mineral Gleysols and Regosols, and Histosols were > 300 t C/ha. The range in SCS was often substantial: for example, Histosols (162–658 t C/ha), organo-mineral Gleysols (95–896 t C/ha), Podzols (46–644 t C/ha) and Regosols (272–678 t C/ha) (Table 5). Excluding Histosols, the 0–50 cm layer contained 70–100% of the profile SCS.

Mean SCS increased further when a profile of 100 cm was considered, with an additional 17 to 127 t C/ha in the extra 50 cm soil depth (excluding Histosols with an additional 296 t C/ha). The greatest mean SCS value was found with Histosols (645 t C/ha), followed by organo-mineral Regosols (602 t C/ha) and mineral Umbrisols (416 t C/ha), contrasted against mean SCS < 200 t C/ha for mineral Gleysols and organo-mineral Phaeozems. A substantial range in SCS was observed for Histosols and organo-mineral Gleysols, Podzols and Regosols, with maximum stocks of 1437, 861, 694 and 828 t C/ha, respectively

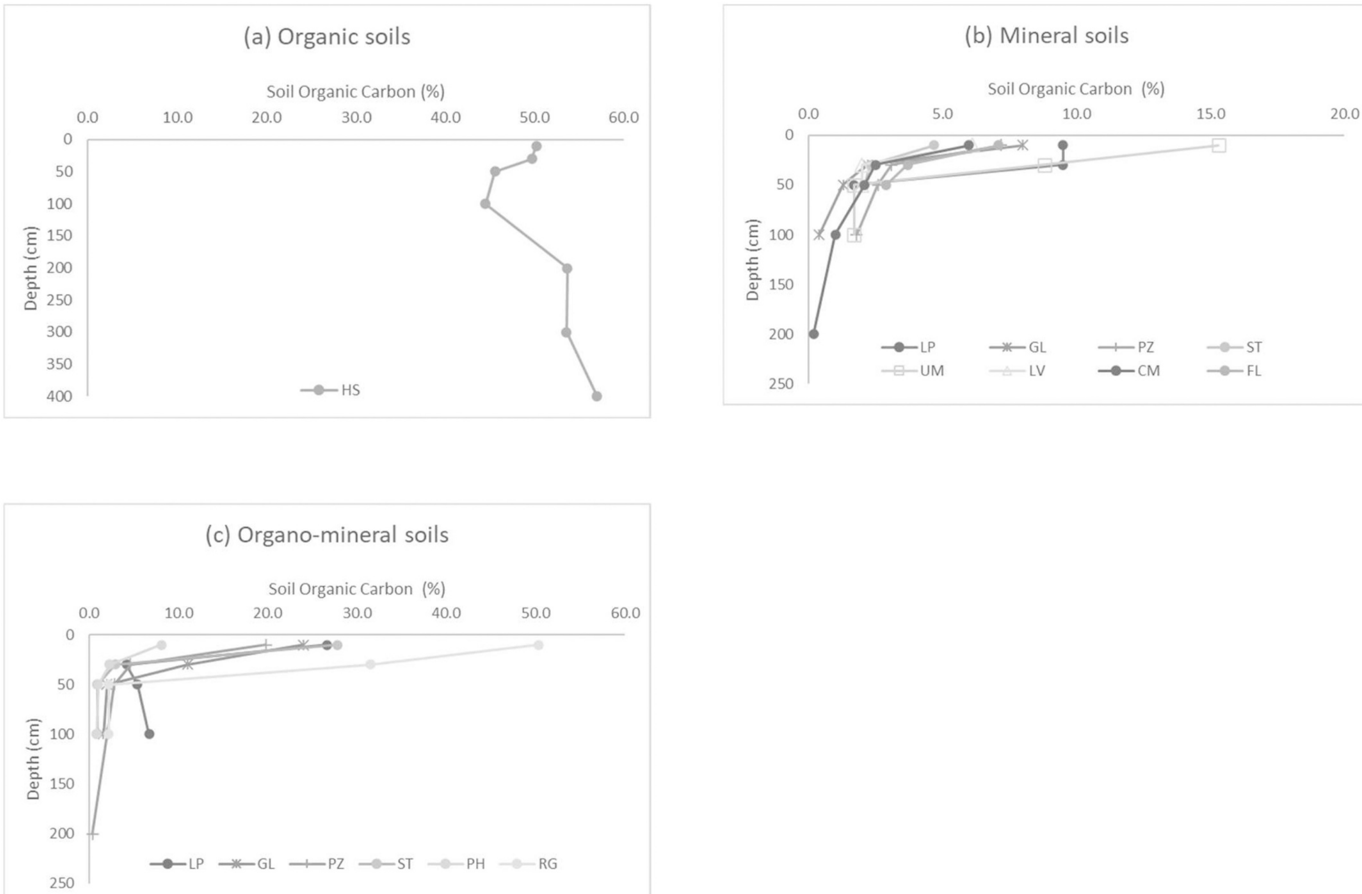


Fig. 5. Soil organic carbon (SOC: %) of WRB soil groups for depth intervals (cm). Data is shown separately for (a) organic, (b) mineral, and (c) organo-mineral soils. Depth intervals were: 0–10, 10–30, 30–50, 50–100 and 100–200 cm. Note: Some SOC data extrapolated from the original maximum sampling depth (e.g. 150 cm) to the next depth interval (e.g. 100–200 cm) are included. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols. All data shown are for afforested soils.

(Table 5). A substantial amount of SCS was stored beyond 100 cm (Table 5) in Histosols, with SCS increasing with increased soil depth. The mean SCS value in the upper 100 cm layer of Histosols was 645 t C/ha, which increased to 1556 t C/ha in the 600 cm profile (Table 5).

Linear and exponential trend or regression lines were fitted to the mean SCS increases over depth (Fig. 8), based on SCS from the 0–30, 0–50 and 0–100 cm soil profiles. A linear trend line ($y = 0.16\ x - 6.20$) applied to Histosols yielded the highest R^2 value (1.00); an exponential trend line only yielded a slightly lower R^2 value (Fig. 8a). Exponential trend lines fitted to mineral Gleysols, Podzols, Umbrisols and Cambisols yielded R^2 values that exceeded 0.90 (Fig. 8b) and exponential trend lines fitted to organo-mineral Gleysols, Podzols, Phaeozems and Regosols yielded R^2 values that exceeded 0.94 (Fig. 8c).

3.6. Forest litter stocks

Forest litter stocks considered in this study ranged between 0.2 and 22.7 t C/ha (Fig. 9, Table 5), with an outlier of 131.3 t C/ha. Forest litter stocks varied with WRB soil group and forest type (Fig. 9a): the greatest mean value recorded was for mixed forest on Podzols (11 t C/ha) followed by coniferous forest on Histosols (7 t C/ha) (Fig. 9a, Table 5). Mean forest litter stocks estimated for the respective forest types (4.1 ± 5.5 t C/ha, 4.8 ± 3.3 t C/ha and 2.7 ± 2.9 t C/ha for broadleaf, coniferous and mixed forests respectively), do not reflect the elevated values reported at individual sites (Fig. 9). The broadleaf litter C stock outlier (131.3 t C/ha on mineral Leptosols) is omitted from Figs. 9a&b and the statistics presented above. Note, occasionally FWD was inseparable from litter stocks and hence was reported with litter.

4. Discussion

4.1. Consistency of data sampling and reporting

Our understanding of C stocks and stock changes and the accuracy of the estimates is dependent on the consistency in (a) distinguishing between different C pools (e.g. soil and forest litter), and (b) methodologies applied to determine C stocks. Unfortunately, as found in this study, much SCS information is collected (measured and estimated) as part of (often budget-constrained) research projects, and not as part of country-wide or regional surveys, inventories or long-term monitoring networks, which often results in deviations in methodologies. For example, different strategies are followed for sampling a soil profile, whether by soil horizon or a variable fixed depth interval (anything from 5 to 30 cm) depending on the focus of the study. In some instances, the entire effective profile is sampled, while in other cases, a fixed depth (typically 30, 50 or 100 cm) is sampled. Understandably, it is not possible to collect all data at the same intervals, but harmonisation or standardisation would be useful, especially in reporting, and if repeat sampling in long-term monitoring is to be achieved.

Several authors agree on the importance of data sampling and analysis standardisation and harmonisation. De Vos et al. (2015) provided an example at the European level where the sampling and analysis

Table 4
Soil organic carbon (SOC: %) over different soil depth intervals (cm) by WRB soil group. Average (AVE), standard deviation (SD), number of samples (n) and range (minimum to maximum) in SOC are shown. NA indicates data were not available or could not be calculated. Note: This includes some data extrapolated from the original maximum sampling depth (e.g. 150 cm) to the next depth interval (e.g. 100–200 cm). Data is shown for organic (O), mineral (M) and organo-mineral (O-M) soils. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols.

			SOC (%)							SOC (%)			
GROUP	WRB	Depth (cm)	n	AVE	SD	Range	GROUP	WRB	Depth (cm)	n	AVE	SD	Range
O	HS	10	35	50.2	6.8	28.1–56.1	M	FL	10	1	7.1	NA	7.1–7.1
O	HS	30	35	49.7	11.9	13.2–58.7	M	FL	30	1	3.7	NA	3.7–3.7
O	HS	50	35	45.6	18.5	1.3–59.6	M	FL	50	1	2.9	NA	2.9–2.9
O	HS	100	25	44.5	20.4	1.3–59.5	O-M	LP	10	9	26.6	17.3	4.1–50.5
O	HS	200	8	53.7	5.6	40.8–59.7	O-M	LP	30	9	4.2	3.7	0.7–11.2
O	HS	300	5	53.6	3.3	50.1–59.7	O-M	LP	50	6	5.4	4.0	0.7–11.2
O	HS	400	1	57.0	NA	57.0–57.0	O-M	LP	100	2	6.7	4.5	2.2–11.2
M	LP	10	1	9.5	NA	9.5–9.5	O-M	GL	10	17	24.0	15.3	0.8–56.8
M	LP	30	1	9.5	NA	9.5–9.5	O-M	GL	30	17	11.0	13.0	0.6–51.9
M	LP	50	1	1.7	NA	1.7–1.7	O-M	GL	50	17	2.0	2.0	0.3–7.9
M	GL	10	12	8.0	4.2	2.4–18.9	O-M	GL	100	13	1.6	2.0	0.3–7.9
M	GL	30	12	2.2	1.1	0.3–4.4	O-M	PZ	10	43	19.8	15.8	0.9–51.9
M	GL	50	12	1.3	1.0	0.3–3.9	O-M	PZ	30	43	4.6	5.2	0.4–28.3
M	GL	100	3	0.4	0.1	0.3–0.5	O-M	PZ	50	43	2.8	2.9	0.3–17.4
M	PZ	10	23	7.2	3.8	0.3–15.8	O-M	PZ	100	30	2.0	2.0	0.3–7.8
M	PZ	30	23	3.1	1.7	1.0–6.2	O-M	PZ	200	1	0.4	NA	0.4–0.4
M	PZ	50	22	2.6	1.3	0.4–5.4	O-M	ST	10	1	27.8	NA	27.8–27.8
M	PZ	100	12	1.8	1.5	0.3–5.4	O-M	ST	30	1	2.9	NA	2.9–2.9
M	ST	10	3	4.7	1.5	3.2–6.7	O-M	ST	50	1	0.9	NA	0.9–0.9
M	ST	30	3	2.3	1.3	0.8–4.0	O-M	ST	100	1	0.9	NA	0.9–0.9
M	ST	50	3	2.1	1.2	0.8–3.6	O-M	PH	10	15	8.1	8.9	2.7–31.6
M	UM	10	1	15.3	NA	15.3–15.3	O-M	PH	30	15	2.3	2.0	0.9–9
M	UM	30	1	8.8	NA	8.8–8.8	O-M	PH	50	15	1.0	0.8	0.3–3
M	UM	50	1	1.7	NA	1.7–1.7	O-M	PH	100	14	0.8	0.6	0.3–2.0
M	UM	100	1	1.7	NA	1.7–1.7	O-M	RG	10	2	50.3	3.3	47–53.6
M	LV	10	3	6.1	2.5	3.6–9.5	O-M	RG	30	2	31.5	9.1	22.4–40.5
M	LV	30	3	2.0	0.4	1.6–2.6	O-M	RG	50	2	2.2	NA	2.2–2.2
M	LV	50	3	2.0	0.4	1.6–2.6	O-M	RG	100	2	2.2	NA	2.2–2.2
M	CM	10	22	6.0	2.4	3.4–11.5							
M	CM	30	22	2.5	1.3	0.8–5.2							
M	CM	50	16	2.1	1.2	0.2–4.8							
M	CM	100	6	1.0	0.8	0.2–2.6							
M	CM	200	1	0.2	NA	0.2–0.2							

methodology had been standardised: the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests). Others point out certain challenges to standardisation: making regional comparisons, where various soil sampling and chemical analytical approaches were used, can be complex (Jandl et al., 2014); whether SIC and CF are included in SCS calculation may impact the accuracy of SCS (Scharlemann et al., 2014; De Vos et al., 2015). Vanguelova et al. (2013) highlight the importance of sampling depth and state that in many cases, the SCS estimations are limited to the topsoil, and the deeper layers are rarely considered (Zabowski et al., 2011). Similarly, stratification of sampling through a network of sampling sites is important to capture representative results and to improve our understanding of SCS (Batjes, 2002; Tomlinson, 2005; Vanguelova et al., 2013).

While authors are consistent in distinguishing loose fresh litter from soil layers and sampling accordingly, this has not always been expressed in clear definitions. WRB (2022) clearly distinguishes the soil organic layers from loose forest litter (section 2.1). ICOS (2021) defines organic layers as: '*undecomposed or partially decomposed litter, such as leaves, needles, twigs, moss, and lichens, which have accumulated on the surface; they may be on the surface of either mineral or organic soils, or at any depth below the surface if it was buried*', suggesting a combination of forest litter and soil O layers. ICOS (2021), similar to WRB (2022), separates the organic horizons into three layers: Oi: slightly decomposed plant material which is almost entire leaves and twigs; Oe, moderately decomposed plant material, which is fragmented plant parts still identifiable as twigs, leaves, buds, etc. and Oa, highly decomposed plant material, not identifiable; which differs somewhat from the organic layer definition above. In addition, when it comes to sampling, according to ICOS (2021), O-horizons are sampled by fixed area using a frame and the mineral soil is sampled from the upper mineral horizon (for both mineral and organo-mineral soils). Creamer and O'Sullivan (2018) separate the mineral horizons from the following organic horizons: peaty O horizon (accumulated under wet conditions or artificially drained), L (freshly deposited loose litter) and the F, H organic layers (partly decomposed and well-decomposed litter, respectively), highlighting that O horizons may overlay mineral horizons.

For NIR purposes, IPCC (2019) clearly defines organic soils as those with a minimum SOC of 12% that developed under poorly drained conditions characteristic of wetlands; all other soils are defined as mineral soils. IPCC (2006) includes '*live and dead fine roots and DOM within the soil, that are less than the minimum diameter limit (suggested 2 mm) for roots and dead organic matter (DOM)*', where they cannot be distinguished through empirical observation, as soil C, but groups dead wood and litter into one pool (DOM), which does not form part of the soil. Accordingly, litter includes the L layer as often defined in soil typologies.

Our review focused on afforested soils and combined and summarised BD, SOC, SCS and forest litter data from various publications and sources by WRB soil group and depth interval, and distinguishes organic, mineral and organo-mineral soils. Integrating dissimilar datasets in this way was challenging and every effort was made to apply the definitions used in this study consistently: to separate forest litter from the soil, and mineral from organo-mineral soils. But, due to differences in the definitions applied in the literature, direct comparisons to our forest litter C and SCS stocks were not always possible.

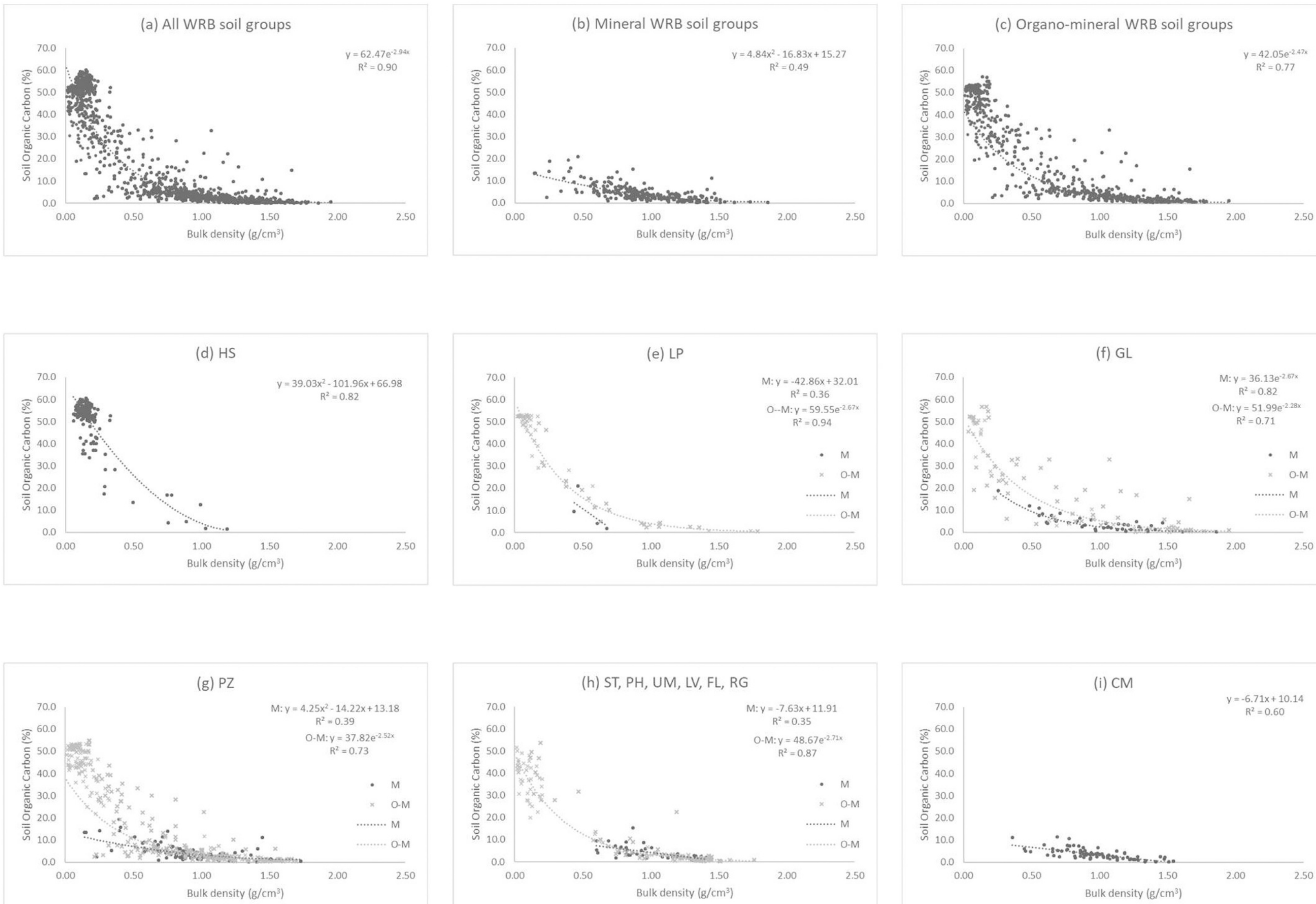


Fig. 6. Relationship between bulk density (BD: g/cm^3) and soil organic carbon (SOC: %) by WRB soil group considering data for all depths. Data is shown for organic (O), mineral (M) and organo-mineral (O-M) soils. Different regression relationships are fitted. For CM, a regression equation for mineral soils only, is shown. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols.

4.2. Soil organic carbon stocks by soil group

De Vos et al. (2015) following De Vries et al. (2000) showed that soil type is one of the most important factors (others include mean annual precipitation and temperature, pH–$CaCl_2$) to explain the differences in reported SCS for mineral soils. For Histosols, parent material has been shown to have the greatest influence (De Vos et al., 2015). Reporting SCS by soil group and land use, in this case for afforested areas, and especially contrasting SCS in organic soils against those in mineral and organo-mineral soils, holds great value in showing SCS extent, potential and vulnerabilities of all soil types. Data from several sources are discussed below.

The SCS for most afforested soils in Ireland, presented in the previous sections by comparative WRB soil groups, exceeds the IPCC LULUCF default or SCS_{ref} values (IPCC, 2006; IPCC, 2019) as well as those estimates from the UK (Vanguelova et al., 2013), a Europe–wide study (De Vos et al., 2015), a study from Lithuania (Armolaitis et al., 2021) and a study that considered data from 13 Central and Eastern European countries (Batjes, 2002) (Table 6). The exceptions were mineral Gleysols and Podzols, and Histosols, where the estimates from this study were comparable to the sources quoted in Table 6. Batjes (2002) did not differentiate between the various land uses considered.

Vanguelova et al. (2013) estimate that Histosols contained almost four times the amount of SCS of mineral soils and 1.5 times that of Histic Gleysols/Podzols, slightly lower than that calculated by De Vos et al. (2015) for the upper 100 cm depth (mineral soils 108 t C/ha vs. 578 t C/ha in Histosols). We showed that organic, mineral and organo-mineral soils all hold substantial SCS. In the upper 100 cm, based on average values, Histosols hold 1.6–4 times the amount of SCS in mineral soils and 1.1–3.7 the amount of SCS in organo-mineral soils for the same profile depth (Table 5, Table 6). The latter highlights the importance of SCS of certain mineral (e.g. Umbrisols) and organo-mineral soils (e.g Gleysols, Regosols), in comparison to Histosols.

In their paper, De Vos et al. (2015) showed SCS in the upper 100 cm in decreasing order: Histosols > Gleysols > Umbrisols > Cambisols > Luvisols > Stagnosols > Podzols > Regosols > Leptosols, whereas Vanguelova et al. (2013) reported the following order for mean SCS in the upper 100 cm: Histosols > Peaty Gleysols > Gleysols > Stagnosols > Podzols > Cambisols > Leptosols. We found a different trend: Histosols > Regosols$^{O\text{-}M}$ > Umbrisols^{M} > Gleysols$^{O\text{-}M}$ > Stagnosols$^{O\text{-}M}$ > Podzols$^{O\text{-}M}$ > Podzols^{M} > Leptosols$^{O\text{-}M}$ > Cambisols^{M} > Phaeozems$^{O\text{-}M}$ > Gleysols^{M}. The ^{M} and $^{O\text{-}M}$ refer to mineral and organo-mineral soils, respectively. This was dissimilar to another Irish study, where Tomlinson (2005) estimated SCS by soil group but did not discriminate between land use or specify the profile depth considered, so a direct comparison was not possible: Histosols (918 to 940 t/ha) > Podzols (229 t/ha) > Gleysols (144 t/ha) > Regosols > Cambisols > Leptosols (80 t/ha).

Our study showed large standard deviations around the mean SCS for all the WRB soil groups presented (Table 5, Table 6), particularly for Histosols, mineral Podzols and organo-mineral Gleysols, Podzols and Regosols. Vanguelova et al. (2013) found SCS in organic soils more variable compared with mineral soils (with few exceptions), but that Histic Gleysols and Podzols exhibited the greatest variability in SCS despite a large number of representative plots. In our review, the small

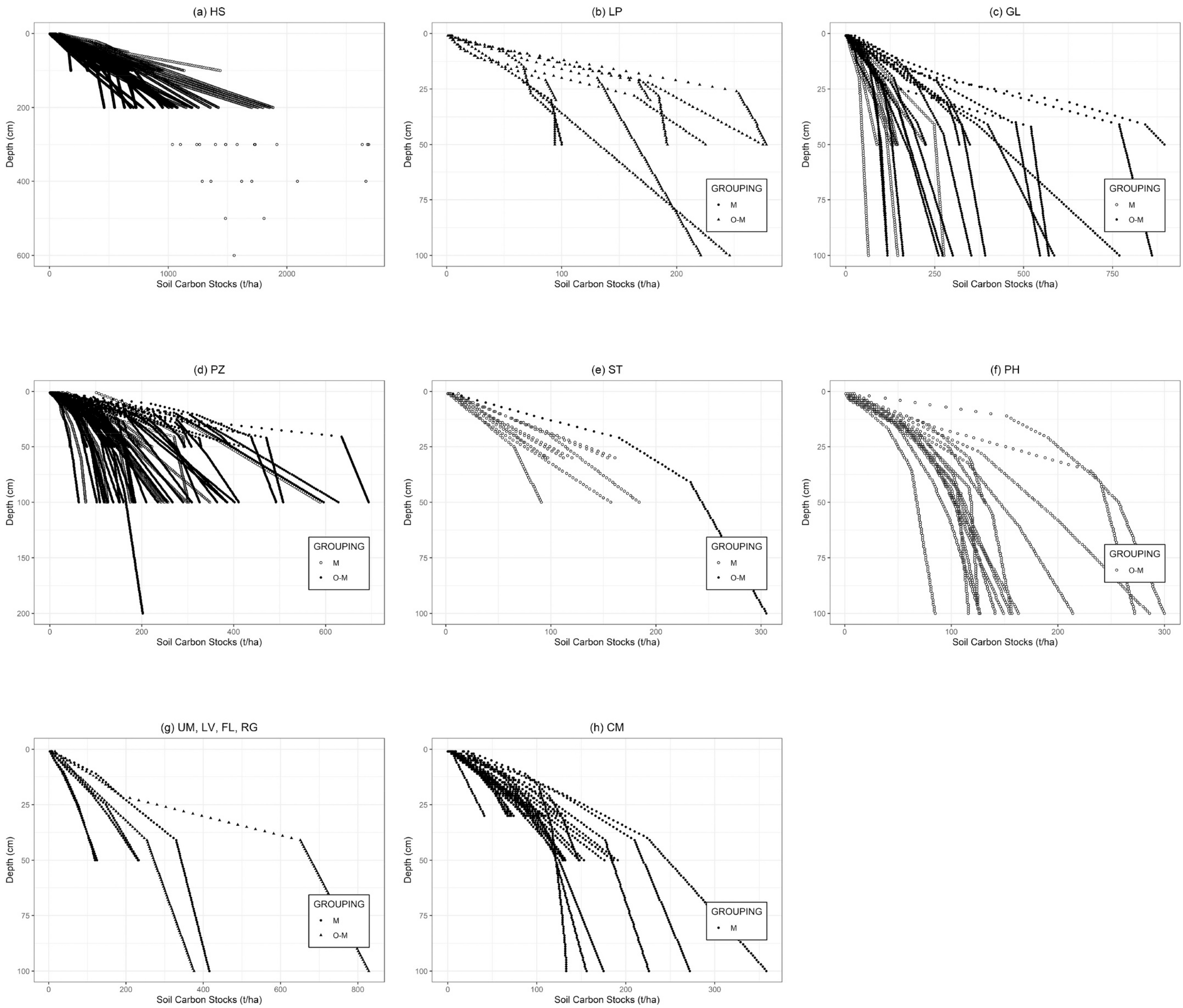


Fig. 7. Cumulative soil carbon stocks (SCS: t/ha) to sampled depth by centimetre or fixed-depth interval. Data is shown for individual sites by WRB soil group. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols. Graphs combine mineral (O) and organo-mineral (O-M) soils.

number of mineral Leptosols (1), Umbrisols (1), Luvisols (3), Fluvisols (1) and organo-mineral Stagnosols (1) and Regosols (2) precludes the drawing of conclusions for these groups.

4.3. SCS depth relationships

Vanguelova et al. (2013) showed the importance of the upper part of the soil profile for SCS. They reported that the upper quarter (0–20 cm) of their profile (80 cm) contained between 29% (Histosols) and 69% (Leptosols) of the total SCS, while the upper half of the soil (0–40 cm) stored between 58% (Histosols) and 100% (Leptosols), whereas other soil groups (Cambisols, Gleysols, Stagnosols, Podzols) stored 72 to 77% of the SCS in this part of the soil profile. They also showed that 43% of SCS of Histic Gleysols and Podzols were found in the upper quarter of the soil profile (80 cm). De Vos et al. (2015) confirmed global patterns in the vertical distribution of SCS reported for forest soils in the upper 30 cm of the soil: 55–65%. The exceptions were Histosols, which contained a small fraction (32%) and Leptosols, which contained all the SCS (95%) in the upper 30 cm of the soil profile.

In this study, we showed considerable SCS beyond 30 cm depth and the importance of depth extent for cumulative SCS. We observed that the upper third of the profile (0–30 cm of the 100 cm profile) contains between 33% (Histosols) and 70% (Luvisols) of the SCS; the upper half of the profile (0–50 cm of 100 cm) contains > 54% of the SCS: the entire SCS for Leptosols, Stagnosols, Luvisols and Fluvisols and organo-mineral Leptosols is found in this layer and > 70% for mineral Podzols, Umbrisols and Cambisols and organo-mineral Gleysols, Podzols and Phaeozems. We observed continuous SCS for Histosols with depth, with the deeper layers (100 to 600 cm) cumulatively storing about 2.4 times the amount of that in the upper 100 cm. WRB soil groups containing substantial SCS should be seen as priority NCS and protected and/or managed carefully to prevent C losses.

Using our review data, exponential relationships between SCS and depth were derived for mineral soils (R^2 = 0.90–1.00) and organo-mineral soils (R^2 = 0.94–1.00) (Fig. 8). A linear and an exponential relationship of SCS over depth were found for Histosols (R^2 = 0.99–1.00). Similarly, De Vos et al. (2015) established a logarithmic function for SCS changes over depth. They used the relationships to

Table 5
Soil carbon stocks (SCS: t/ha) per soil interval and total profile. Litter carbon (C) stocks (including fine woody debris, FWD) (t/ha). Data is shown per WRB reference soil group: average (AVE), standard deviation (SD), number of samples (n) and range (minimum to maximum) in SCS are shown. In addition, layer SCS as a percentage (%) of total profile SCS is shown. NA indicates data were not available or could not be calculated. Data is shown for organic (O), mineral (M) and organo-mineral (O-M) soils. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols. *The litter on mineral leptosols (131.1 t C/ha) presents an outlier.

			CARBON STOCKS (t/ha)								CARBON STOCKS (t/ha)				
GROUP	WRB	Depth (cm)	n	AVE	SD	Range	% of Prof	GROUP	WRB	Depth (cm)	n	AVE	SD	Range	% of Prof
O	HS	Litter	9	7	2	4–12	NA	M	CM	Litter	24	4	5	0.3–23	NA
O	HS	0–10	67	75	33	29–211	5	M	CM	0–10	31	44	15	16–81	20
O	HS	0–30	67	216	67	97–467	14	M	CM	0–30	31	103	27	41–177	47
O	HS	0–50	67	349	98	162–658	22	M	CM	0–50	16	159	37	121–247	72
O	HS	0–100	55	645	222	180–1437	41	M	CM	0–100	6	220	77	133–358	100
O	HS	0–200	26	1112	411	461–1884	71	M	CM	0–200	1	144	0	144–144	NA
O	HS	0–300	14	1712	551	1036–2689	110	M	FL	0–10	1	53	0	53–53	23
O	HS	0–400	6	1787	471	1287–2666	115	M	FL	0–30	1	155	0	155–155	67
O	HS	0–500	2	1645	162	1482–1807	106	M	FL	0–50	1	231	0	231–231	100
O	HS	0–600	1	1556	0	1556–1556	100	O-M	LP	0–10	9	55	21	24–81	24
M	LP	Litter	1	131*	0*	131–131*	NA	O-M	LP	0–30	9	155	56	79–257	67
M	LP	0–10	1	30	0	30–30	30	O-M	LP	0–50	7	195	65	94–278	84
M	LP	0–30	1	91	0	91–91	91	O-M	LP	0–100	2	233	12	221–246	100
M	LP	0–50	1	100	0	100–100	100	O-M	GL	Litter	4	5	2	3–7	NA
M	GL	Litter	7	1	0	0.3–2	NA	O-M	GL	0–10	17	75	31	28–130	18
M	GL	0–10	11	43	12	19–63	27	O-M	GL	0–30	17	243	139	80–594	60
M	GL	0–30	11	106	37	41–183	65	O-M	GL	0–50	17	349	221	95–896	86
M	GL	0–50	11	145	55	48–253	90	O-M	GL	0–100	13	408	232	117–861	100
M	GL	0–100	3	162	87	64–276	100	O-M	PZ	Litter	3	4	4	0.2–9	NA
M	PZ	Litter	12	5	4	0.2–14		O-M	PZ	0–10	43	69	38	19–199	24
M	PZ	0–10	29	53	28	20–158	22	O-M	PZ	0–30	43	169	96	35–395	59
M	PZ	0–30	29	122	54	37–307	50	O-M	PZ	0–50	43	216	132	46–644	76
M	PZ	0–50	23	171	75	44–388	70	O-M	PZ	0–100	30	286	166	63–694	100
M	PZ	0–100	12	243	133	78–588	100	O-M	PZ	0–200	1	202	0	202–202	NA
M	ST	Litter	6	2	1	0.2–3	NA	O-M	ST	0–10	1	77	0	77–77	25
M	ST	0–10	9	39	10	26–52	27	O-M	ST	0–30	1	195	0	195–195	64
M	ST	0–30	9	114	28	70–161	79	O-M	ST	0–50	1	244	0	244–244	80
M	ST	0–50	3	144	39	91–184	100	O-M	ST	0–100	1	305	0	305–305	100
M	UM	0–10	1	111	0	111–111	27	O-M	PH	0–10	15	43	26	24–137	25
M	UM	0–30	1	251	0	251–251	60	O-M	PH	0–30	15	105	42	56–213	61
M	UM	0–50	1	343	0	343–343	82	O-M	PH	0–50	15	134	52	68–257	77
M	UM	0–100	1	416	0	416–416	100	O-M	PH	0–100	14	173	65	85–300	100
M	LV	0–10	3	44	12	34–62	28	O-M	RG	0–10	2	81	16	65–97	13
M	LV	0–30	3	111	38	84–165	70	O-M	RG	0–30	2	291	105	186–396	48
M	LV	0–50	3	159	52	120–233	100	O-M	RG	0–50	2	475	203	272–678	79
								O-M	RG	0–100	2	602	226	376–828	100

extrapolate SCS below 80 cm. But, De Vos et al. (2015) noted that this function was unable to adequately represent strong vertical SCS variations among layers. De Vos et al. (2015) highlighted that most studies apply depth functions to SOC (Nakane, 1976; Odgers et al., 2012), although they suggested it is better to use SCS depth functions, which incorporate the effects of BD, CF and SOC into a single relationship.

4.4. Soil organic carbon, bulk density and depth relationships

Several authors have documented BD, SOC, and SCS data over soil profile depth (Batjes, 2002; Vanguelova et al., 2013; De Vos et al., 2015; Armolaitis et al., 2021), yet few have explored and documented the relationships between these soil properties (BD, SOC, SCS) and soil depth to infill or extrapolate SCS estimates. In reporting soil properties, few studies have discriminated between land use and soil groups. The discussion below relates to the relationships documented for afforested soils.

Our study corroborates other research findings that showed a decrease in SOC over depth and an increase in BD over depth in most mineral soils, but not in Histosols, mineral Podzols and organo-mineral Leptosols. De Vos et al. (2015) noted that the decrease in SOC is steeper than the relative increase of BD (and CF) with depth. Their results showed that SOC in mineral soils decreases exponentially with depth, a typical pattern for forest soils (Nakane, 1976). For Histosols, De Vos et al. (2015) showed a slight increase in SOC in Histosols from 10 to 40 cm, whereafter it decreased slightly. Our study showed the reverse: the SOC in Histosols first decreased slightly (10 to 100 cm), whereafter it increased to 600 cm. In our study, the mean BD at shallow depths (0–10 cm) ranged greatly between organic, mineral and organo-mineral soils. At greater depths (50–100 cm), except for Histosols and mineral Leptosols and Podzols, BD was between 0.97 g/cm^3 (organo-mineral Leptosols) to 1.58 g/cm^3 (organo-mineral Stagnosols). Mean BD values by Vanguelova et al. (2013) appear to be lower than those in our review, while they also noted little change over depth for Histosols, 0.16 to 0.17 g/cm^3, similar to that estimated by De Vos et al. (2015): 0.166 (upper 10 cm) to 0.142 g/cm^3 at 40–80 cm. Armolaitis et al. (2021) reported little variation in mean BD for different soil groups in the upper 30 cm, with values ranging between 0.8 (Cambisols) and 1.4 g/cm^3 (Arenosols).

We established exponential relationships between SOC and BD when considering all WRB soil groups ($R^2 = 0.90$) and considering organo-mineral soil groups only ($R^2 = 0.77$); and second-order polynomial relationship between SOC and BD for Histosols ($R^2 = 0.82$) and mineral soils ($R^2 = 0.49$) (Fig. 6). Exponential relationships between SCS and depth were derived for individual mineral soils ($R^2 = 0.35$–0.82) and organo-mineral soils ($R^2 = 0.71$–0.94) (Fig. 6). Similarly, Xu et al. (2011) established a logarithmic relationship between SOC and BD for soils in Ireland [$y = -0.312 \ln(x) + 1.329$; $R^2 = 0.90$; RMSE $= 0.14$]. Their relationship was developed by considering data from different depths, soil groups (mineral and organic), and land use. Vanguelova et al. (2013) showed a logarithmic relationship between BD and SOC, but according to SOC class and forest type, rather than soil group. They found R^2 values between 0.17 and 0.72 when considering data from all

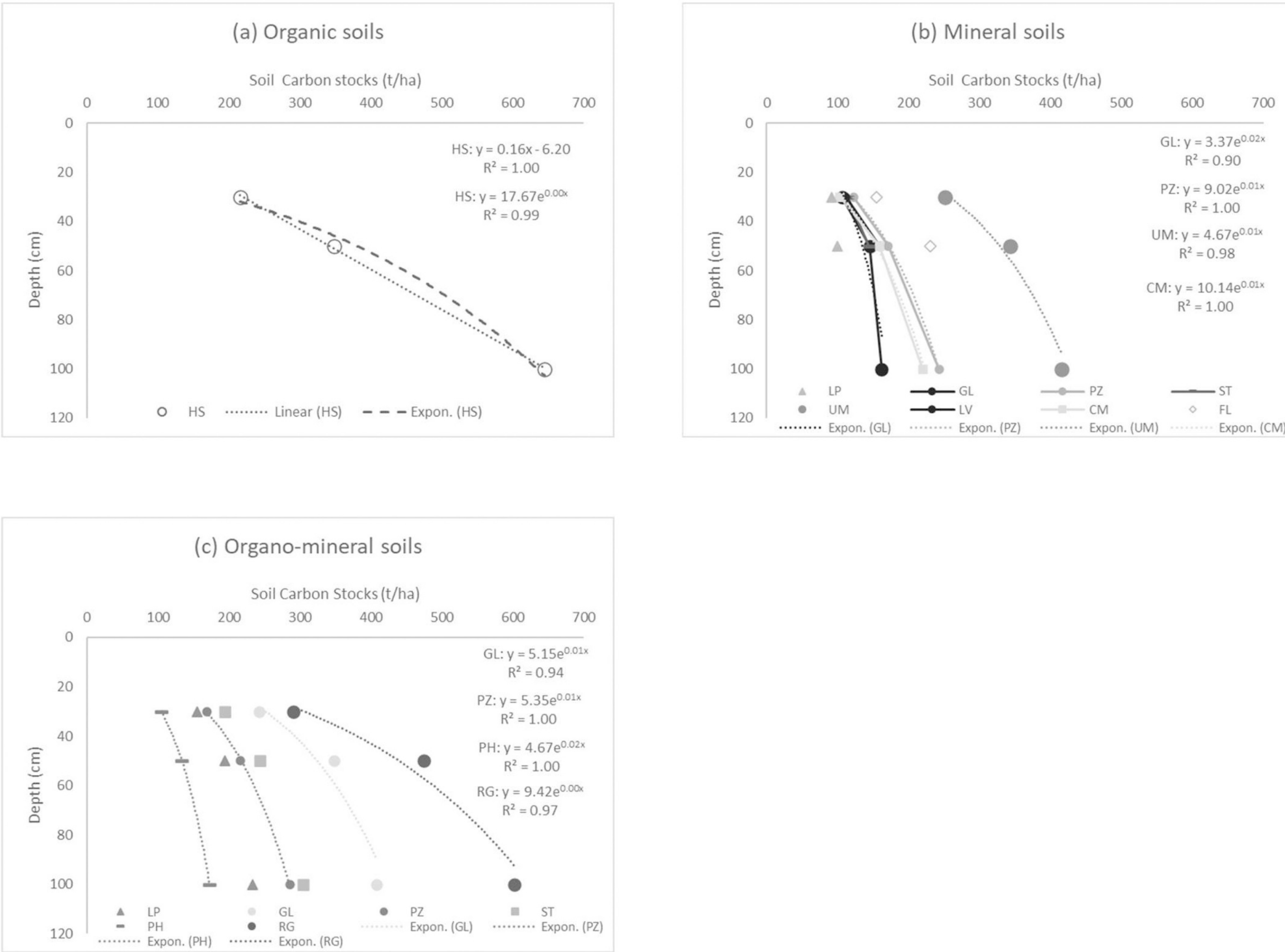


Fig. 8. Mean soil carbon stocks (SCS: t/ha/depth) at different soil depths (0–30, 0–50 and 0–100 cm) are shown for WRB soil groups. Data is shown separately for organic (O), mineral (M) and organo-mineral (O-M) soils. A linear and exponential trend line was fitted to Histosols (HS) and exponential trend lines to mineral Gleysols (GL), Podzols (PZ), Umbrisols (UM) and Cambisols (CM) and organo-mineral Gleysols, Podzols, Phaeozems (PH) and Regosols (RG). The mean SCS is also shown for Leptosols (LP), Stagnosols (ST), Luvisols (LV) and Fluvisols (FL).

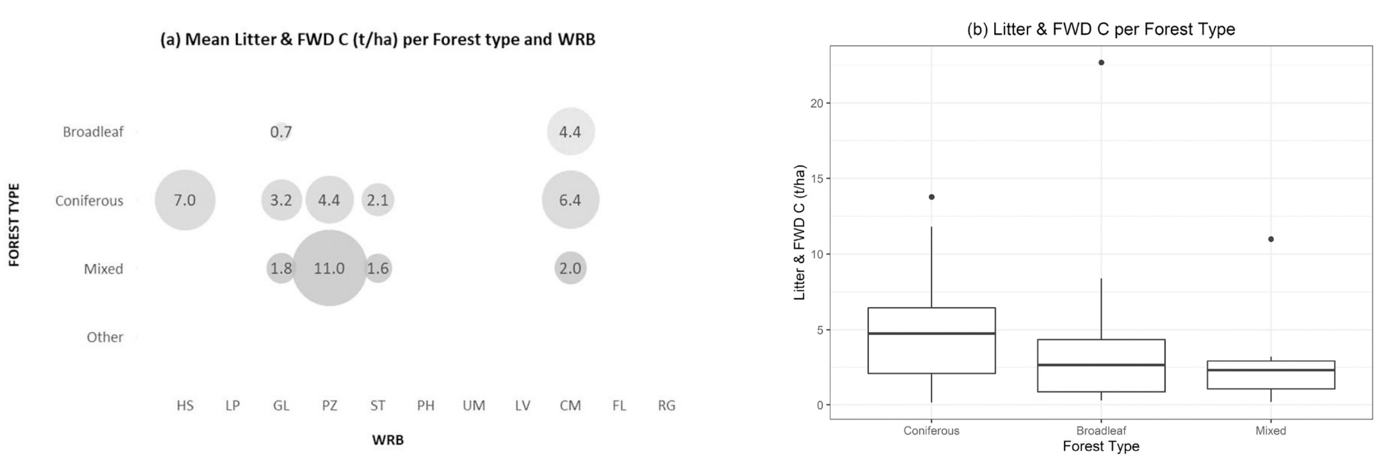


Fig. 9. Forest litter carbon (C) with fine woody debris (FWD) (t/ha) by (a) forest type-soil-group combination, and (b) forest type only. Identifiable loose litter includes FWD (diameter 2–10 mm) where not separated from litter. In (a) the value inside the bubble represents mean litter C (t/ha) per forest type-WRB matrix combination. Graph (b) show the distribution of data into quartiles with the bottom and top of the box showing the 1st and 3rd quartile. The middle horizontal line shows the 2nd quartile (median). Lines extending vertically indicate the variability outside the upper and lower quartiles, and the points (·) outside those lines are considered outliers. One substantial outlier is omitted from (a) and (b) (broadleaf forest on a mineral leptosol, 131 t/ha). Mineral and organo-mineral WRB soil types are shown together. HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols.

Table 6
Mean soil carbon stocks (SCS ± SD) in t/ha for afforested soils compiled in this study are shown by WRB soils group. IPCC reference soil carbon stocks (SCS_{ref}) in the upper 30 cm of soil of native vegetation are shown — from the original IPCC climate zone for Ireland (Cold temperate moist) (IPCC, 2006) and the updated IPCC climate zone C1 (Cool temperate moist) (IPCC, 2019). Mean SCS derived for afforested soils in Europe ($n = 3273$), Lithuania ($n = 167$), UK ($n = 166$) and central and eastern Europe ($n = 201–321$) are also shown with % standard deviation (SD) or % coefficient of variation (CV), where available. Note: Cambisols, Leptosols, Luvisols, Regosols, Stagnosols and Umbrisols are all high–activity–clay soils according to IPCC (2019); Podsols are spodic soils, Gleysols are wetland soils and Histosols are organic soils (IPCC, 2006; IPCC, 2019). *Refers to all organo-mineral soils from this review and † refers to hystic soils considered by Vanguelova et al. (2013). HS refers to Histosols, LP Leptosols, GL Gleysols, PZ Podzols, ST Stagnosols, PH Phaeozems, UM Umbrisols, LV Luvisols, CM Cambisols, FL Fluvisols and RG Regosols. NA indicates data was not available.

		SOIL CARBON STOCKS (t/ha)							
		SCS Ireland (This review)		SCS_{ref} (IPCC, 2006)	SCS_{ref} (IPCC, 2019)	SCS Europe (De Vos et al., 2015)	SCS Lithuania (Armolaitis et al., 2021)	SCS UK (Vanguelova et al., 2013)	SCS Central and Eastern Europe (Batjes, 2002)
WRB soil group	Depth (cm)	n	Mean ± SD	Mean	Mean ± % SD	Mean	Mean	Mean	Mean ± % CV
HS	0–30	67	216 ± 67	NA	NA	186	150	NA	221 ± 44
	0–100	55	645 ± 222	NA	NA	578	NA	539	729 ± 25
LP	0–30	1	91 ± 0	95	81 ± 5%	73	NA	NA	84 ± 92
	0–100	NA	NA	NA	NA	77.1	NA	108	152 ± 49
GL	0–30	11	106 ± 37	87	128 ± 13%	104	102	NA	114 ± 61
	0–100	3	162 ± 87	NA	NA	182	NA	173	173 ± 33
PZ	0–30	29	122 ± 54	115	128 ± 14%	52.8	92	NA	120 ± 187
	0–100	12	243 ± 133	NA	NA	104	NA	154	296 ± 146
ST	0–30	9	114 ± 28	95	81 ± 5%	65.3	NA	NA	NA
	0–100	NA	NA	NA	NA	106	NA	167	NA
UM	0–30	1	251 ± 0	95	81 ± 5%	95	NA	NA	NA
	0–100	1	416 ± 0	NA	NA	181	NA	NA	NA
LV	0–30	3	111 ± 38	95	81 ± 5%	68.9	96	NA	50 ± 57
	0–100	NA	NA	NA	NA	115	NA	NA	91 ± 46
CM	0–30	31	103 ± 27	95	81 ± 5%	71.4	118	NA	69 ± 73
	0–100	6	220 ± 77	NA	NA	121	NA	152	118 ± 51
FL	0–30	1	155 ± 0	NA	NA	NA	NA	NA	NA
	0–100	NA	NA	NA	NA	NA	NA	NA	NA
Histic LP, GL, PZ, ST, PH, RG*	0–30	87	174 ± 107	NA	NA	NA	NA	NA	NA
	0–100	62	295 ± 191						
Histic GL, PZ, ST†	0–30	61	203 ± 113						
	0–100	44	333 ± 194					362	

depth layers. Armolaitis et al. (2021) showed linear relationships between BD and SOC by soil group, but also by land use. For afforested soils, Armolaitis et al. (2021) found R^2 values of 0.36 to 0.49.

4.5. Forest floor litter

Several authors (Vanguelova et al., 2013; Bárcena et al., 2014; Batjes, 2014; De Vos et al., 2015) have shown that forest litter stocks are an important C pool and should not be neglected in forest C stock and flux calculations. The results from our review showed a smaller contribution of forest litter stocks of loose fresh litter, as defined by WRB and applied in this paper, relative to SCS, except for a few samples.

The forest floor comprises the most dynamic part of the forest SOC stock (Lal, 2005; De Vos et al., 2015), unfortunately, is often neglected in regional SCS estimates (Eswaran et al., 1993). For forest litter to accumulate and for stocks to increase with stand age, plant litter production needs to exceed decomposition rates (Zak et al., 1990; Thuille et al., 2000; Bárcena et al., 2014). Tree species differ in forest litter C stock assimilation due to differences in litter quality, which affect decomposition rates (Vesterdal and Raulund-Rasmussen, 2002; Vesterdal et al., 2012; Vesterdal et al., 2013; De Vos et al., 2015). Both De Vos et al. (2015) and Vesterdal et al. (2013) found that soil type and tree species are important factors in determining forest litter C stocks. Other studies, e.g. Bárcena et al. (2014), have found that factors, such as temperature, precipitation and soil properties, which vary across climatic zones, contribute towards the variation in forest litter C accumulation within the same forest type.

Vanguelova et al. (2013) highlighted the factors that impact litter decomposition (soil type, associated conditions, stand age, species mix and climatic conditions), which complicate direct comparisons between litter stock estimates. Similarly, as highlighted in section 4.1, the definition of forest litter is often ambiguous. Forest litter stocks considered in this study ranged between 0.2 and 22.7 t C/ha for individual sites, not including an outlier estimated at 131.3 t C/ha. The mean forest litter stocks estimated for the respective forest types was 4.1 ± 5.5 t C/ha (excluding the outlier), 4.8 ± 3.3 t C/ha and 2.7 ± 2.9 t C/ha for broadleaf, coniferous and mixed forests, respectively. Few authors separate loose litter stocks as defined by WRB (2022) from decomposing litter stocks (soil O horizon). Vanguelova et al. (2013) reported mean litter stocks (denoted OL) of 6.9 and 7.7 t C/ha for coniferous and broadleaf forests, respectively, within the range that we found here. Zerva and Mencuccini (2005) reported litter stocks (OL) for coniferous forests that were generally higher: 16.4 ± 0.8 t C/ha (12–year old stand) to 29.5 ± 6.3 t C/ha (40–year old stand). For comparison, according to IPCC (2006) the default forest litter stock value (Tier 1) for a cold temperate, moist climate (e.g. Ireland) is 16 t C/ha (range 5 to 31 t C/ha) in mature deciduous stands and 26 t C/ha (range 10 to 48 t C/ha) in mature coniferous stands. IPCC (2019) classifies the afforested area in Ireland as Temperate oceanic forest, for which no default litter C stock values are available. Several authors (Baritz et al., 2010; Bárcena et al., 2014; De Vos et al., 2015; Armolaitis et al., 2021) do not report forest litter stocks, as defined by WRB (2022), but instead, combine the C stocks contained in the soil O layers with stocks in the loose forest litter, and so could not be used for comparison.

5. Conclusion

This study presents the first synthesis of BD, SOC, SCS and forest litter stocks for afforested soils in Ireland, by WRB soil group and depth, separating organic, mineral and organo-mineral soils. Standardisation of C stock definitions, sampling, analysis and data reporting is key for the expansion of such databases. The assembly of disparate datasets will aid in robust data comparisons and improve the accuracy of SCS estimates and reporting, as well as our understanding of SCS and SCS changes.

Results that characterise the data by WRB soil group clearly show the large variation in SCS held in soils; also, the substantial SCS contained in Histosols and certain mineral and organo-mineral soils, specifically Gleysols, Podzols, Stagnosols, Umbrisols, Cambisols and Regosols. This emphasises the need to protect SCS in all soils to avoid soil greenhouse gas (GHG) emissions, and to gain the benefit of any C sequestration. Assessments are needed to identify which soil-site-management-practice combinations risk SCS depletion. The large range in SCS and litter stocks underlines the importance of adequately accounting for these soil differences when GHG inventories are compiled.

Our review further highlights the need for a detailed, high-resolution soil map and long-term soil monitoring network to adequately inform these inventories and account for the reported differences. The summarised data reported here should contribute to improved SCS estimation for afforested land in Ireland.

Declaration of Competing Interest

None

Data availability

The authors do not have permission to share data.

Acknowledgements

The authors would like to acknowledge all the authors whose work is cited in this paper for their research. We would like to thank their additional insights and shared data (often original/raw). This publication emanated from research supported in part by a Grant from Science Foundation Ireland under Grant number [SFI 20/SPP/3705], and the University of Limerick is acknowledged for making funding and resources available for this review. The authors are grateful to the Irish Environmental Protection Agency (EPA) for funding the AUGER: "peAtland properties inflUencing greenhouse Gas Emissions and Removals" Project (2015-CCRP-MS.30) under EPA Research Programme 2014–2020; the Department of Agriculture, Food and the Marine is acknowledged for funding the CForRep project (Grant Number: 11/C/205), and all other institutions that funded the research data included in this review are acknowledged for their financial support. The authors acknowledge Prof. Lars Vesterdal (University of Copenhagen) for comments made on a previous manuscript related to this work. The authors also acknowledge the reviewers for their rigorous review and suggestions, which significantly improved this manuscript.

References

Agren, G.I., HyvÖNen, R., Nilsson, T., 2007. Are Swedish Forest soils sinks or sources for CO_2: model analyses based on forest inventory data. Biogeochemistry 82 (3), 217–227 available: https://doi.org/10.1007/s10533-006-9064-0.

Aherne, J., Cummins, T., Farrell, E.P., 1999. Modelling soil water fluxes in a Norway spruce {*Picea abies* (L.) Karst.} stand at Ballyhooly, Co Cork. Irish Forestry 56 (2), 22–27.

Al-Shammary, A.A.G., Kouzani, A.Z., Kaynak, A., Khoo, S.Y., Norton, M., Gates, W., 2018. Soil bulk density estimation methods: a review. Pedosphere 28 (4), 581–596 available: https://doi.org/10.1016/s1002-0160(18)60034-7.

Anderson, A.R., Pyatt, D.G., Sayers, J.M., Blackwall, S.R., Robinson, H.D., 1992. Volume and mass budgets of blanket peat in the north of Scotland. Suo 43, 195–198.

Armolaitis, K., Varnagirytė-Kabašinskienė, I., Žemaitis, P., Stakėnas, V., Beniušis, R., Kulbokas, G., Urbaitis, G., 2021. 'Evaluation of organic carbon stocks in mineral and organic soils in Lithuania', *Soil use and management*. available:. https://doi.org/10.1111/sum.12734.

Bárcena, T.G., Kiær, L.P., Vesterdal, L., Stefánsdóttir, H.M., Gundersen, P., Sigurdsson, B. D., 2014. Soil carbon stock change following afforestation in northern Europe: a meta-analysis. Glob. Chang. Biol. 20 (8), 2393–2405 available: https://doi.org/10.1111/gcb.12576.

Baritz, R., Seufert, G., Montanarella, L., Van Ranst, E., 2010. Carbon concentrations and stocks in forest soils of Europe. For. Ecol. Manag. 260 (3), 262–277 available: https://doi.org/10.1016/j.foreco.2010.03.025.

Batjes, N.H., 2002. Carbon and nitrogen stocks in the soils of Central and Eastern Europe. Soil Use Manag. 18 (4), 324–329 available: https://doi.org/10.1111/j.1475-2743.2002.tb00248.x.

Batjes, N.H., 2014. Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47, 151-163. Reflections by N.H. Batjes. Eur. J. Soil Sci. 65 (1), 2–3 available: https://doi.org/10.1111/ejss.12115.
Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Koppen-Geiger climate classification maps at 1-km resolution. Sci Data 5, 180214 available: https://doi.org/10.1038/sdata.2018.214.
Black, K., O'Brien, P., Redmond, J., Barrett, F., Twomey, M., 2008. The extent of recent peatland afforestation in Ireland. Irish Forestry 65 (1&2), 71–81.
Byrne, K.A., 2014. 'Current and future degradation risks to forest soils in Ireland. In: FORRISK International Workshop on 'Soil Degradation Risks in Planted Forests. Bilboa, 10 September 2014.
Byrne, K.A., Farrell, E.P., 1997. The impact of forestry on blanket peatland. In: Hayes, M. H.B., Wilson, W.S. (Eds.), Humic Substances, Peats and Sludges*: Health and Environmental Aspects.* Royal Society of Chemistry, pp. 262–277.
Clancy, M., 2018. Soil carbon stocks and life cycle analysis of short rotation forestry. unpublished thesis (PhD). University of Limerick.
Clancy, M.A., Jovani-Sancho, A.J., Cummins, T., Byrne, K.A., 2015. The need to disaggregate podzols and peaty podzols when assessing forest soil carbon stocks. Irish Forestry 72 (1&2), 16.
Cook-Patton, S.C., Drever, C.R., Griscom, B.W., Hardman, H., Kroeger, T., Pacheco, P., Raghav, S., Webb, C., Yeo, S., Ellis, P.W., 2021. Protect, manage and then restore lands for climate mitigation. Nat. Clim. Chang. 11, 1027–1034 available: https://doi.org/10.1038/s41558-021-01198-0.
Creamer, R., O'Sullivan, L., 2018. The Soils of Ireland. Springer, USA.
Creamer, R., Simo, I., Reidy, B., Carvalho, J., Fealy, R.M., Hallett, S., Jones, R., Holden, A., Holden, N., Hannam, J.A., Massey, P., Mayr, T., McDonald, E., O'Rourke, S., Sills, P., Truckell, I., Zawadzka, J., R.S, 2014. *Irish Soil Information System Synthesis Report*, Ireland: Environmental Protection Agency. available: http://erc.epa.ie/safer/reports.
Creamer, R.E., Simo, I., O'Sullivan, L., Reidy, B., Schulte, R.P.O., Fealy, R.M., 2016. Irish Soil Information System: Soil Property Maps (2007-S-CD-1-S1). Environmental Protection Agency, Ireland available: https://www.epa.ie/publications/research/land-use-soils-and-transport/research-204.php [accessed].
DAFM, 2018. Ireland's National Forest Inventory 2017. Government of Ireland, Ireland available: https://www.gov.ie/en/publication/823b8-irelands-national-forest-inventory/ [accessed].
Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440 (7081), 165–173 available: https://doi.org/10.1038/nature04514.
De Vos, B., Cools, N., Ilvesniemi, H., Vesterdal, L., Vanguelova, E., Carnicelli, S., 2015. Benchmark values for forest soil carbon stocks in Europe: results from a large scale forest soil survey. Geoderma 251-252, 33–46 available: https://doi.org/10.1016/j.geoderma.2015.03.008.
De Vries, W., Posch, M., 2011. Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900–2050. Environmental pollution (1987) 159 (10), 2289–2299 available: https://doi.org/10.1016/j.envpol.2010.11.023.
De Vries, W., Reinds, G.J., Van Kerkvoorde, M.S., Hendriks, C.M.A., Leeters, E.E.J.M., Gross, C.P., Voogd, J.C.H., Vel, E.M., 2000. 'Intensive monitoring of forest ecosystems in Europe technical report 2000', Technical Report 2000, p. 191.
Duffy, P., Black, K., Fahey, D., Hyde, B., Kehoe, A., Murphy, J., Quirke, B., Ryan, A.M., Ponzi, J., 2021. National Inventory Report 2021. Greenhouse Gas Emissions 1990–2019 Reported To The United Nations Framework Convention On Climate Change, 502.
Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P., Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. Clim. Chang. 91 (3), 317–334 available: https://doi.org/10.1007/s10584-008-9412-2.
Eswaran, H., Van Den Berg, E., Reich, P., 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57 (1) https://doi.org/10.2136/sssaj1993.03615995005700010034x available:
Farrell, E.P., 1985. Long-term study of Sitka spruce (Picea sitchensis (Bong.) Carr.) on lanket peat. 2. Water-table depth, peat depth and nutrient mineralisation studies. Irish Forestry 42, 92–105.
Gardiner, M.J., Radford, T., 1980. *Ireland, general soil map.* [map], sheet National Soil Survey of Ireland. An Foras Taluntais.
Glassman, S.I., Weihe, C., Li, J., Albright, M.B.N., Looby, C.I., Martiny, A.C., Treseder, K. K., Allison, S.D., Martiny, J.B.H., 2018. Decomposition responses to climate depend on microbial community composition. Proc. Natl. Acad. Sci. U. S. A. 115 (47), 11994–11999 available: https://doi.org/10.1073/pnas.1811269115.
Green, C., Tobin, B., O'Shea, M., Farrell, E.P., Byrne, K.A., 2007. Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (Picea sitchensis (Bong) Carr.). Eur. J. For. Res. 126 (2), 179–188 available: https://doi.org/10.1007/s10342-005-0093-3.
Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamaki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., Fargione, J., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. U. S. A. 114 (44), 11645–11650 available: https://doi.org/10.1073/pnas.1710465114.
Hammond, R.F., 1981. The Peatlands of Ireland : To Accompany Peatland Map of Ireland, 1978, Second edition. ed. FORAS TALUNTAIS, Dublin.
Hiederer, R., Durrant, T., 2010. Evaluation of BioSoil Demonstration Project Preliminary Data Analysis. European Commission Joint Research Centre Institute for Environment and Sustainability, Italy.
Hiederer, R., Michéli, E., Durrant, T., 2011. Evaluation of BioSoil Demonstration Project Soil Data Analysis. European Commission Joint Research Centre Institute for Environment and Sustainability, Italy.
ICOS, 2021. ICOS ecosystem instructions soil sampling and preparation for monitoring the soil organic carbon and nitrogen. Version 20211109.
IPCC, 2006. *2006* IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4. available: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html [accessed].
IPCC, 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. available: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ [accessed].
Ireland, G.O., 2019. Climate Action Plan 2019. available: https://www.gov.ie/en/publication/ccb2e0-the-climate-action-plan-2019/ [accessed].
IUSS, W.G., 2015. World Reference Base for Soil Resources 2014. Food and Agriculture Organization of the United Nations, Rome.
Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137 (3), 253–268 available: https://doi.org/10.1016/j.geoderma.2006.09.003.
Jandl, R., Rodeghiero, M., Martinez, C., Cotrufo, M.F., Bampa, F., van Wesemael, B., Harrison, R.B., Guerrini, I.A., Richter, D.D., Rustad, L., Lorenz, K., Chabbi, A., Miglietta, F., 2014. Current status, uncertainty and future needs in soil organic carbon monitoring. Sci. Total Environ. 468-469, 376–383 available: https://doi.org/10.1016/j.scitotenv.2013.08.026.
Jarmain, C., Byrne, K.A., Cummins, T., 2022. *CForRep Soil Organic Carbon over depth and per WRB soil group* [dataset].
Jovani-Sancho, A.J., Brosnan, S., Byrne, K.A., 2017a. Partitioning of soil respiration in a first rotation beech plantation. Biol. Environ. Proc. Roy. Irish Acad. 117B (2), 91 available: https://doi.org/10.3318/bioe.2017.09.
Jovani-Sancho, A.J., Cummins, T., Byrne, K.A., 2017b. Collar insertion depth effects on soil respiration in afforested peatlands. Biol. Fertil. Soils 53 (6), 677–689 available: https://doi.org/10.1007/s00374-017-1210-4.
Jovani-Sancho, A.J., Cummins, T., Byrne, K.A., 2018. Soil respiration partitioning in afforested temperate peatlands. Biogeochemistry 141 (1), 1–21 available: https://doi.org/10.1007/s10533-018-0496-0.
Jovani-Sancho, A.J., Cummins, T., Byrne, K.A., 2021. Soil carbon balance of afforested peatlands in the maritime temperate climatic zone. Glob. Chang. Biol. 27 (15), 3681–3698 available: https://doi.org/10.1111/gcb.15654.
Keenan, R.J., 2015. Climate change impacts and adaptation in forest management: a review. Ann. For. Sci. 72 (2), 145–167 available: https://doi.org/10.1007/s13595-014-0446-5.
Kiely, G., Carton, O., 2008. *SoilC - Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils: Data* [dataset].
Kiely, G., McGoff, N.M., Eaton, J.M., Xu, X., Leahy, P., Carton, O., 2009. SoilC – Measuring and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils. Environmental Protection Agency, Ireland available: https://eparesearch.epa.ie/safer/resource?id=8f7427d4-65d6-102c-9c91-0a68ec663af0 [accessed November 2021].
Lal, R., 2005. Forest soils and carbon sequestration. For. Ecol. Manag. 220 (1), 242–258 available: https://doi.org/10.1016/j.foreco.2005.08.015.
Lorenz, K., Lal, R., 2009. Carbon Sequestration in Forest Ecosystems, 1. Aufl. ed. Springer Netherlands, Dordrecht.
Lundmark, T., Poudel, B.C., Stål, G., Nordin, A., Sonesson, J., 2018. Carbon balance in production forestry in relation to rotation length. Can. J. For. Res. 48 (6), 672–678 available: https://doi.org/10.1139/cjfr-2017-0410.
Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.-P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Tamm review: influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. For. Ecol. Manag. 466, 118127 available: https://doi.org/10.1016/j.foreco.2020.118127.
McMahon, S.M., Parker, G.G., Miller, D.R., 2010. Evidence for a recent increase in forest growth. Proc. Natl. Acad. Sci. U. S. A. 107 (8), 3611–3615 available: https://doi.org/10.1073/pnas.0912376107.
Minasny, B., McBratney, A.B., Wadoux, A.M.J.C., Akoeb, E.N., Sabrina, T., 2020. Precocious 19th century soil carbon science. Geoderma Reg 22. https://doi.org/10.1016/j.geodrs.2020.e00306 available:
Nakane, K., 1976. An empirical formulation of the vertical distribution of carbon concentration in forest soils. Jpn J. Ecol. 26, 171–174.
Nieuwenhuis, M., Tobin, B., Gardiner, P., Olajuyigbe, S., Osborne, B., Saunders, M., Benanti, G., Bolger, T., Reidy, B., 2012. CARBIFOR II. Carbon sequestration by Irish forest ecosystems.
Odgers, N.P., Libohova, Z., Thompson, J.A., 2012. Equal-area spline functions applied to a legacy soil database to create weighted-means maps of soil organic carbon at a continental scale. Geoderma 189-190, 153–163 available: https://doi.org/10.1016/j.geoderma.2012.05.026.
Osipov, A.F., Bobkova, K.S., Dymov, A.A., 2021. Carbon stocks of soils under forest in the Komi Republic of Russia. Geoderma Reg 27, e00427 available: https://doi.org/10.1016/j.geodrs.2021.e00427.
O'Sullivan, G., 1994. Project Report, CORINE Land Cover Project (Ireland).
Patton, R.M., Kiernan, D.H., Burton, J.I., Drake, J.E., 2022. Management trade-offs between forest carbon stocks, sequestration rates and structural complexity in the central Adirondacks. For. Ecol. Manag. 525 https://doi.org/10.1016/j.foreco.2022.120539 available:
Premrov, A., Cummins, T., Byrne, K.A., 2018. Bulk-density modelling using optimal power-transformation of measured physical and chemical soil parameters. Geoderma 314, 205–220 available: https://doi.org/10.1016/j.geoderma.2017.10.060.

Reidy, B., Simo, I., Spaargaren, O., Creamer, R.E., 2014. Irish Soil Information System. Correlation of the Irish Soil Classification System to World Reference Base - 2006 System. *Final Technical Report 8*. Environmental Protection Agency, Ireland.
Reidy, B., Jarmain, C., Bolger, T., Tobin, B., 2022. (Unpublished) *Soil bulk density, carbon concentration and carbon stocks dataset*. In: [dataset].
Renou-Wilson, F., Pöllänen, M., Byrne, K., Wilson, D., Farrell, E.P., 2010. The potential of birch afforestation as an after-use option for industrial cutaway peatlands. Suo 61 (3–4), 59–76.
Renou-Wilson, F., Byrne, K.A., Flynn, R., Premrov, A., Riondato, E., Saunders, M., Walz, K., Wilson, D., 2022. Peatland Properties Influencing Greenhouse Gas Emissions and Removal. Environmental Protection Agency, Ireland.
Rigney, C., 2016. *Greenhouse gas emissions from rewetted peatland forests*, unpublished thesis.
Roper, W.R., Robarge, W.P., Osmond, D.L., Heitman, J.L., 2019. Comparing four methods of measuring soil organic matter in North Carolina soils. Soil Sci. Soc. Am. J. 83 (2), 466–474 available: https://doi.org/10.2136/sssaj2018.03.0105.
Saunders, M., Afrasinei, G.M., Zimmerman, J., Premrov, A., Black, K., Green, S., 2022. Soil Organic Carbon and Land Use Mapping (SOLUM). Environmental Protection Agency, Ireland.
Scharlemann, J.P., Tanner, E.V., Hiederer, R., Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag. 5 (1), 81–91 available: https://doi.org/10.4155/cmt.13.77.
Shotbolt, L., Anderson, A.R., Townsend, J., 1998. Changes to blanket bog adjoining forest plots at Bad a'Cheo, Rumster Forest, Caithness. Forestry 71, 311–324.
Simo, I., Creamer, R.E., Reidy, B., Jahns, G., Massey, P., Hamilton, B., Hannam, J.A., McDonald, E., Sills, P., Spaargaren, O., 2008. Irish Soil Information System', *EPA STRIVE Programme 2007-2013*, ((2007-S-CD-1-S1)), p. 88.
Teagasc and University, C, 2014. Irish National Soils Map 1, 250,000k, V1b [dataset].
Thuille, A., Buchmann, N., Schulze, E.-D., 2000. Carbon stocks and soil respiration rates during deforestation, grassland use and subsequent Norway spruce afforestation in the Southern Alps, Italy. Tree Physiol. 20 (13), 849–857 available: https://doi.org/10.1093/treephys/20.13.849.
Titus, B.D., Malcolm, D.C., 1991. Nutrient changes in peaty gley soils after Clearfelling of Sitka spruce stands. Forestry 64, 251–270.
Tomlinson, R.W., 2005. Soil carbon stocks and changes in the Republic of Ireland. J. Environ. Manag. 76 (1), 77–93 available: https://doi.org/10.1016/j.jenvman.2005.02.001.
USDA, S.S.S., 2014. *Keys to Soil Taxonomy Twelfth Edition*: United States Department of Agriculture Natural Resources Conservation Service.
Vanguelova, E.I., Nisbet, T.R., Moffat, A.J., Broadmeadow, S., Sanders, T.G.M., Morison, J.I.L., 2013. A new evaluation of carbon stocks in British forest soils. Soil Use Manag. 29 (2), 169–181 available: https://doi.org/10.1111/sum.12025.
Vesterdal, L., Raulund-Rasmussen, K., 2002. Availability of nitrogen and phosphorus in Norway spruce forest floors fertilized with nitrogen and other essential nutrients. Soil Biol. Biochem. 34 (9), 1243–1251 available: https://doi.org/10.1016/S0038-0717(02)00064-0.
Vesterdal, L., Elberling, B., Christiansen, J.R., Callesen, I., Schmidt, I.K., 2012. Soil respiration and rates of soil carbon turnover differ among six common European tree species. For. Ecol. Manag. 264 (JAN), 185–196 available: https://doi.org/10.1016/j.foreco.2011.10.009.
Vesterdal, L., Clarke, N., Sigurdsson, B.D., Gundersen, P., 2013. Do tree species influence soil carbon stocks in temperate and boreal forests? For. Ecol. Manag. 309, 4–18 available: https://doi.org/10.1016/j.foreco.2013.01.017.
Walsh, S., 2012. *Climatological note no.14. A summary of climate averages for Ireland. 1981-2010*, Ireland: Met Éiraenn. available: https://www.met.ie//climate-ireland/SummaryClimAvgs.pdf [accessed].
Walz, K., Renou-Wilson, F., Wilson, D., Byrne, K.A., 2022. AUGER project database: peatland properties influencing greenhouse gas emissions and removal. *Unpublished* [dataset].
Wellock, M.L., LaPerle, C.M., Kiely, G., 2011a. What is the impact of afforestation on the carbon stocks of Irish mineral soils? For. Ecol. Manag. 262 (8), 1589–1596 available: https://doi.org/10.1016/j.foreco.2011.07.007.
Wellock, M.L., Reidy, B., Laperle, C.M., Bolger, T., Kiely, G., 2011b. Soil organic carbon stocks of afforested peatlands in Ireland. Forestry (London) 84 (4), 441–451 available: https://doi.org/10.1093/forestry/cpr046.
Wellock, M.L., Rafique, R., La Perle, C.M., Peichl, M., Kiely, G., 2014. Changes in ecosystem carbon stocks in a grassland ash (Fraxinus excelsior) afforestation chronosequence in Ireland. J. Plant Ecol. 7 (5), 429–438 available: https://doi.org/10.1093/jpe/rtt060.
WRB, I.W.G., 2022. World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.
Xu, X., Liu, W., Zhang, C., Kiely, G., 2011. Estimation of soil organic carbon stock and its spatial distribution in the Republic of Ireland. Soil Use Manag. 27 (2), 156–162 available: https://doi.org/10.1111/j.1475-2743.2011.00342.x.
Zabowski, D., Whitney, N., Gurung, J., Hatten, J., 2011. Total soil carbon in the coarse fraction and at depth. For. Sci. 57 (1), 11–18.
Zak, D.R., Grigal, D.F., Gleeson, S., Tilman, D., 1990. Carbon and nitrogen cycling during old-field succession: constraints on plant and microbial biomass. Biogeochemistry 11 (2), 111–129 available: https://doi.org/10.1007/BF00002062.
Zerva, A., Mencuccini, M., 2005. Carbon stock changes in a peaty gley soil profile after afforestation with Sitka spruce (Picea sitchensis). Ann. For. Sci. 62 (8), 873–880 available: https://doi.org/10.1051/forest:2005078.