



Research article

Field scale estimates of soil carbon stocks on ten heavy textured farms across Ireland

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ABSTRACT

The world's soils store vast amounts ($\approx 2,500$ GT) of Carbon which acts as a vital sink to counterbalance the effects of increasing atmospheric carbon dioxide. There have been fruitful efforts to quantify soil Carbon stocks at national scales, which are required for policy level decisions but lack the high resolution required to support farm specific decisions. It is hypothesised that farm scale evaluations of soils can provide insight that is masked in national scale studies and can allow for spatially explicit management approaches to optimise soil Carbon storage and sequestration, such that it can be prioritized within profitable production systems. The objective of the present study was to estimate Carbon stocks on a range of heavy textured soils at field and farm scale and to quantify Carbon storage relative to national scale estimates. Ten grassland dairy farms (mean area of 52.2 Ha) were surveyed, sampled and classified to determine soil types and quantify soil Carbon stores. The level of Carbon present (mean: 346.0 T/Ha) at these sites was greater than previous averages on such soils quantified at national scale (by a factor of 1.1–3.9 depending on soil type). Furthermore, if Carbon saturation potential was realised, the amount of Carbon stored could be increased by an average of 792.1 T/Ha in each profile (from 346.0 to 1138.1 T/Ha). Current management has fostered the retention of large stores of soil Carbon on such soils/farms which co-exist within highly productive farm systems. As there is a societal demand to retain and enhance soil carbon stores to mitigate climate change, high Carbon soils should be identified and, under appropriate policies, commodified to offer a direct incentive to retain soil Carbon. The value of this resource should be recognised and policies to ensure a spatially explicit approach for soil Carbon management should be adopted.

1. Introduction

The soils of the world store a vast amount of carbon (C), holding more than the combined totals stored in vegetation and the atmosphere (Swift, 2001; Scharlemann et al., 2014). Takes long periods to build up, and when held in soils for a relatively long period as part of the terrestrial C cycle is said to be sequestered by the soil. The estimated total amount of C stored in soils is approximately 2,500 gigatonne (GT), relative to 560 GT found in living plants and animals and 800 GT in the atmosphere (Lal, 2004; Oelkers and Cole, 2008; Ontl and Schulte, 2012). This C storage pool provides an important sink to counterbalance and negate against the effects of increasing levels of carbon dioxide (CO₂) in the atmosphere (Bossio et al., 2020). Current and future strategies related to land management should be informed by the relative amounts of C stored in different soil types and indeed their capacity to build C. National (Government of Ireland, 2019) and European level policy

(European Commission (EC), 2016) is now better aligned with international IPCC accounting, so that the 2030 European Union Climate and Energy Framework integrates greenhouse gas (GHG) emissions and removals from Land Use, Land Use Change and Forestry (LULUCF). This allows C sinks to be included in national inventories under proportional "flexibilities", determined at member states level. This creates a demand for land management plans aimed at maximising the off-setting potential of the land (Schulte et al., 2016).

The organic component of a soil includes any plant or animal material that is returned to the soil and goes through a process of decomposition (Bot and Benites, 2005). A high level of SOM or SOC is known to benefit soils and their functionality in a number of facets. Increased levels of SOM are linked to improved soil aeration, enhanced soil biodiversity and a resistance to soil compaction. High SOM content is also linked to better crop nutrition, soil structure, water retention and ease of cultivation and its decline is generally reflected in a decline in

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overall soil health and quality (Van-Camp et al., 2004). While a number of GHGs are contributing to climate change, CO₂ has the greatest effect due to the significant increases in recent times (Ontl and Schulte, 2012). Atmospheric CO₂ levels have increased from approximately 280 parts per million (ppm) in 1850, prior to industrialisation, to approximately 412 ppm today (Buis, 2019). It is estimated that two-thirds of this increase in atmospheric CO₂ is attributable to the burning of fossil fuels, with the remainder due to SOC loss due to land use change (Lal, 2004). Carbon dioxide levels are now higher than at any point in the past 800,000 years and if current trends continue, atmospheric CO₂ is projected to exceed 900 ppm by the end of this century (Lindsey, 2018). Thus the importance of SOM is further enhanced as a C store and efforts to understand and quantify the value of soils in potential climate change mitigation measures continues. Detailed quantifications of soil C stores at multiple scales are called for.

Soils vary in their capacity to act as a C sink for climate change mitigation and this requires C management strategies that are differentiated by soil type (Schulte et al., 2016). Organic soils where production exceeds decomposition can result in C sequestration which can exert a global cooling effect over millennia (Frolking and Roulet, 2007). In Ireland, organic soils are estimated to contain the majority of current SOC stock, and the importance of maintaining and managing these soils, including targeting hotspots of organic rich soils that have been drained for agricultural production, has been highlighted (Paul et al., 2018). In addition to organic rich soils, soils that are subject to clay illuviation and stagnic features are found to be associated with a pool of stable C at depth within microaggregates (<250 µm) in Irish grassland soils (Torres-Sallan et al., 2017). Simo et al. (2019) utilised a national soil survey to look beyond the standard 30 cm depth and assess the potential for deeper stores of soil C. While a national level assessment offers insights at that scale, a differentiated approach to soil management is necessary at local scale to mitigate climate change at a practical level, and assess scale effects on C estimation (Malone et al., 2018; de Gruijter et al., 2018). The next step (as in the present study) is to examine C reserves at field scale and in areas that are dominated by imperfectly or poorly drained soils. Grassland farms on these soils account for approximately 0.96 million Ha of the 3.18 million Ha (30%) of managed grassland in Ireland (O'Sullivan et al., 2015) while overall, some (50%) of the total land area is classified as imperfectly or poorly drained (Paul et al., 2018).

Soil quality is defined by the physical, chemical and biological capacity of a soil to perform its general functions such as primary productivity, biomass production, water filtration, C sequestration, nutrient cycling and as a habitat for biodiversity (Blum, 2005; Bouma, 2014; Rabot et al., 2018). Where quality is low or becomes degraded, a soils ability to perform some or all of these functions may be compromised. As such, the long-term stability of C stores may be compromised. A picture of spatial SPQ values on a farm will allow for an assessment of soil condition/management and help assess potential for long term stability of C stores (Bondi et al., 2020).

Poorly or imperfectly drained soils will generally have a much greater propensity towards excess soil moisture, higher proportions of SOM and are typically subject to lower intensity of production than freely drained soils. Such soils are used for grazing livestock (dairy and beef production) and in-practice; there is an increased likelihood of shallow soil damage during grazing events, a shorter grazing season, reduced resource efficiency and lower farm profitability than farms on freely drained soils (Shalloo et al., 2004; Tuohy et al., 2018). Many of these soils are C rich (Ostle et al., 2009; Paul et al., 2018), however, the amount of C stored across a range of such soils has not been quantified beyond shallow depths or at field scale.

The objective of the present study was to estimate soil C stocks on a range of heavy textured soils at field and farm scale and to establish the level of C stored relative to national scale estimates and to C saturation estimates. An understanding of the amount of C stored in these soils and their potential for further C sequestration is vital to assess their

contribution as a C sink, their potential for increased storage and in establishing strategies and management practices to maintain and perhaps increase this C storage pool.

2. Materials and methods

2.1. Study sites

A total of 10 study sites were selected for the current study. The farms are located throughout Ireland and operate as grassland, dairy farms with an average size of 52.2 Ha. Mean annual rainfall across sites is 1259 mm (min 982 mm – max 1757 mm) (Table 1).

2.2. Field work

A comprehensive high resolution soil survey of each farm was carried out following the exact protocol of the Irish Soil Information System (SIS)(Creamer et al., 2014). This enabled soils to be classified on each farm and an associated soil archive and database to be generated.

Initially an auger survey was carried out on each farm, involving an auger bore on average every hectare to investigate the soil physical features. In practice, more or less augers were used based on landscape complexity. Their resulting distribution was an even coverage across each farm (Fig. 1). The Dutch auger was driven into the soil to a depth of 1 m if possible. The soil features were described and recorded. Horizon type, depth, texture, colour, mottling, structure, roots and stones were recorded along with many more physical attributes detailed in the SIS soil profile handbook (Simo et al., 2014). Soil type and drainage class (Schulte et al., 2015) were assigned. Thereafter a number (3–4) of representative soil profile pits were excavated using the auger survey as a guide to represent the dominant soils on each farm. These pits were 1–2 m in depth and allowed for detailed description of soils. Each soil horizon identified was sampled to allow for further laboratory analysis. In total 34 test pits were excavated and 122 distinct horizons were identified and sampled. This survey produced high resolution soils maps and detailed soil classifications of every soil subgroup on each farm. The study sites were categorised as mineral, humic or organic, similar to the distinctions drawn by (Paul et al., 2018). Soils were defined as per SIS (Creamer et al., 2014); Organic/peat soils possess an organic layer with at least 20% soil organic carbon (SOC) and a minimum thickness of 40 cm. In humic soils, the key feature is an A horizon with significantly more organic matter than mineral matter, with minimum thickness of 7.5 cm. SOC content is lower, but at least 3.5–6.0% (depending on the clay content) (Creamer et al., 2014). Organic/Peat soils belong to the peat association (1XX), while humic soils were those described with the “Humic” diagnostic feature (Simo et al., 2014) with final classification determined following laboratory analysis. All other soils were classed as mineral.

Table 1
Information for various study sites.

Site	Size	Northing	Westing	Elevation ASL	Average annual precipitation (1981–2010)
	Hectare	Degree	Degree	m	mm
1	33.7	52°36'	08°01'	105	982
2	52.1	52°28'	09°33'	8	1095
3	70.0	51°59'	08°56'	231	1757
4	49.9	51°12'	09°08'	233	1622
5	47.3	52°44'	09°30'	9	1185
6	60.6	52°27'	09°19'	139	1320
7	71.0	52°13'	09°28'	36	1298
8	55.4	54°06'	09°17'	15	1162
9	51.5	53°57'	07°11'	180	1093
10	30.3	54°09'	07°02'	115	1079

*ASL =above sea level.



Fig. 1. Extent of auger survey at Site 7.

The 34 test pits excavated uncovered a range of soil types representing 11 different soil subgroups of a potential 56 identified in the Irish soil classification system (Creamer et al., 2014). The most common soil subgroup uncovered was the Typical Surface-water Gley (11 incidences) followed by Typical Alluvial soils (5 incidences) and Typical Brown Earths (4 incidences). The complimentary auger survey was used to establish the extent of each soil subgroup on the surveyed farms. In total 521.8 Ha were included in the auger survey. The most dominant soil subgroups on each farm were selected for more detailed analysis using test pits, as such, 368.7 Ha (or 70.6%) was represented by soil subgroups detailed from test pit analysis.

2.3. Soil physical properties

Soil texture (sand, silt, clay) was quantified for each horizon from samples collected. Each sample was dried and sieved (2 mm aperture) and a 250 g sub-sample was collected and sent for analysis (sieving and pipette sedimentation method; NRM Laboratories, Bracknell, UK). The B_d for each horizon was calculated using standard methods with 3 stainless steel cores having a volume of $9.82 \times 10^{-5} \text{ m}^3$ collected at each horizon. In some cases (21 of 122 horizons identified) it was not possible to collect samples for B_d measurement due to high proportion of stones present. Soil B_d was calculated for these horizons using pedotransfer functions developed by (Reidy et al., 2016) for Irish soils as used also by (Simo et al., 2019) to allow for accurate estimation of C stocks for each horizon (Lobsey and Viscarra Rossel, 2016).

2.4. Soil physical quality

To examine the state of the SPQ of the soils on each farm the static soil physical quality was estimated using the limits derived from (Fenton et al., 2017) for Irish soils i.e. horizons with $>6\%$ SOC and B_d values $< 1 \text{ g cm}^3$ were not included for S-index (S_i) estimation. In addition, the S-Index does not perform well on excessively drained soils. An indirect approach of the S-index of Dexter (2004) which utilises horizon specific soil hydraulic data from the soil water retention curve (SWRC), derived from texture (sand, silt, clay%) and B_d data was inputted into the H3 pedotransfer model of Rosetta (Schaap et al., 2001). The S_i is calculated as per Eq (1).

$$S_i = -n \left(\frac{\theta_s - \theta_r}{B_d} \right) \left[\frac{2n-1}{n-1} \right]^{\left[\frac{1}{n-2} \right]} \quad (1)$$

where, n is the SWRC shape parameter, θ_s and θ_r are the saturated and residual water contents. The value of S_i derived from Eq. (1) is always negative; therefore its absolute value is reported. The S-index range is described as follows: $S_i > 0.050$ indicates a “very good” SPQ; $0.050 \geq S_i > 0.035$ indicates a “good” SPQ; $0.035 \geq S_i > 0.020$ indicates a “poor” SPQ; and $0.020 \geq S_i$ indicates a “degraded” or “very poor” SPQ (Dexter, 2004). In terms of management effects on SPQ only the surface horizons (to 30 cm approx.) are considered where a higher B_d is more typically associated structural damage due to management practices and not inherent soil properties.

2.5. Soil carbon stocks and saturation

The SOM content was measured from another 250 g sub-sample (Brookside Laboratories, OH, USA) using the loss on ignition at 360°C method. Soil organic carbon content (%) was calculated as $\text{OM} * 0.581$. Total SOC in each horizon (OCh ; T Ha^{-1}) was calculated as per Eq (2) (Schrumpf et al., 2011; Simo et al., 2019) with successive horizons added together to calculate the C stock for each profile.

$$\text{OCh} (\text{T Ha}^{-1}) = \text{SOC} (\%) * B_d (\text{g cm}^{-3}) * \text{Horizon thickness (cm)} \quad (2)$$

The total C stock on each farm was then calculated as OCh for each soil profile multiplied by the number of mapped hectares for each soil type. The SOC content of each mineral horizon was compared with the SOC saturation model for Irish soils developed by (Kiely et al., 2017) to establish the potential for additional C storage in each soil profile. The C saturation in Irish soils is calculated as per Eq (3).

$$C_{\text{sat}} = 0.90 \times (\text{silt} + \text{clay}) + 10.59 \quad (3)$$

Where C_{sat} represents the organic C saturation level (g C kg^{-1}) and silt + clay represents the mass proportion of fine particles ($\text{g } 100 \text{ g}^{-1}$ soil).

3. Results

3.1. Spatial distribution of soil subgroups across the farms

The dominant soil subgroups in terms of area represented are Typical Surface-water Gleys (89.5 Ha), Stagnic Luvisols (53.8 Ha), Stagnic Brown Earths (48.9 Ha) and Alluvial Soils (41.0 ha). The soils at the study sites were found to be 70.9% mineral, 20.8% humic and 8.3% organic. As soil associations were described in the auger survey, these proportions refer to the full area considered in the study and not just the subset of those sites represented by test pits. Drainage class at field scale

showed 39.9% of fields to be poorly drained, 26.1% to be imperfectly drained, 25.0% to be moderately drained and just 9.0% to be well drained, this varied with soil type (Table 2).

3.2. Soil physical properties

Soil texture analysis showed content of sand, silt and clay ranged from 7 to 88%, 8–67% and 4–47%, respectively (Table S1). Soil B_d ranged from 0.10 (Peat Soil) to 1.87 g cm⁻³ including those measured directly (n = 101) and those calculated by pedotransfer function (n = 21) as per Reidy et al. (2016), (Table S1).

3.3. Soil physical quality

The S_i values whilst including all soil horizons and depths ranged from 0.003 to 0.081. A total of 42 of 122 horizons surveyed did not meet the limits set out for S_i estimation i.e. horizons with >6% SOC and/or B_d values < 1 g cm⁻³. Of the remaining 80 horizons SPQ indices of Very Poor, Poor, Good and Very Good were recorded for 41, 18, 5 and 16 incidences each, respectively. When disaggregated at horizon level, the mean S_i value for A (11 of 30 meeting criteria for estimation), B (23 of 31) and C (44 of 49) horizons was 0.040 (Good), 0.020 (Very Poor) and 0.027 (Poor), respectively.

3.4. Carbon stocks and saturation level

The results highlight a strong variability in C stocks with a range of 170.9 T/Ha (Site 1 - Typical Surface Water Gley) to 748.4 T/Ha (Site 2 - Ombrotrophic Peat) (Table 3). Furthermore, a strong variability was found not only between but within soil subgroups, having multiple profiles surveyed across study sites. For example, SOC stored in Typical surface-water Gleys ranged from 170.9 T/Ha (Site 1) to 459.3 T/Ha (Site 2) while SOC stored in Alluvial soils ranged from 254.6 T/Ha (Site 9) to 645.0 T/Ha (Site 5), (Table 4). The mean SOC content in O, A, B and C horizons was 29.5%, 5.8%, 1.8% and 0.9% respectively (Fig. 2).

The mean proportion of fine soil particles (silt + clay) in A, B and C horizons at these sites was 65.3%, 67.3% and 63.2%, respectively. As such, the mean saturation level of organic C in these soils (Kiely et al., 2017) is 6.9, 7.1 and 6.8% and is significantly greater than the levels stored currently (Fig. 3). If saturation potential was realised, the amount of C stored could be increased by an average of 792.1 T/Ha in each profile (from 346.0 to 1138.1 T/Ha). The majority of this potential exists in B and C horizons.

4. Discussion

The global mission to reduce the impacts and drivers of climate change is seeing more focus now on the role of soils in sequestering terrestrial stores of C. Changes in the policy environment along with an urgent demand to mitigate climate change have generated a demand to optimise the off-setting potential of the land (Schulte et al., 2016). C sinks can contribute to GHG emission reductions from agriculture from 2021 and the maintenance of, and potential for increase in, soil C storage will need to form part of a fully integrated approach to emission reductions that views land use and management in light of this changed circumstance.

Table 2
Drainage class by soil type across all sites.

Soil type	Drainage Class (%)			
	Poor	Imperfect	Moderate	Well
Mineral	29.2%	23.3%	34.8%	12.7%
Humic	70.1%	28.9%	1.0%	0.0%
Organic	57.5%	42.5%	0.0%	0.0%
All	39.9%	26.1%	25.0%	9.0%

Table 3
The rate and amount of soil carbon stored by each soil subgroup for all study sites. The number of profiles excavated and sampled was 3 or 4 per site depending on soil variability at each site. Soil subgroups are listed in order of prevalence at each site.

Site	Soil 1				Soil 2				Soil 3				Soil 4				
	Soil Subgroup	Spatial Extent Ha	SOC T/Ha	T	Soil Subgroup	Spatial Extent Ha	SOC T/Ha	T	Soil Subgroup	Spatial Extent Ha	SOC T/Ha	T	Soil Subgroup	Spatial Extent Hectare	SOC T/Ha	T	Total Site SOC T
1	Typical Surface Water Gley	12.40	184.1	2282.8	Humic Surface Water Gley	2.99	448.3	1340.4	Typical Surface Water Gley	2.71	170.9	463.1	Brown Podzolic	3.49	301.4	1051.9	4086.4
2	Ombrotrophic Peat	19.93	748.4	14915.6	Typical Surface Water Gley	14.41	459.3	6618.5	Alluvial	9.94	309.9	3080.4	Brown Earth	3.10	413.9	1283.1	24614.5
3	Humic Brown Earth	20.67	179.6	3712.3	Brown Earth	10.57	368.2	3891.9	Humic Podzol	8.97	396.4	3555.7	Brown Earth	3.10	413.9	1283.1	11159.9
4	Stagnic Luvisol	24.73	363.3	8984.4	Brown Podzolic	6.52	334.4	2180.3	Alluvial	5.34	395.7	2113.0	Brown Earth	3.10	413.9	1283.1	14329.6
5	Alluvial	11.06	645.0	7133.7	Typical Surface Water Gley	5.71	215.6	1231.1	Typical Surface Water Gley	4.82	256.0	1233.9	Brown Earth	3.10	413.9	1283.1	10881.8
6	Stagnic Brown Earth	34.92	216.2	7549.7	Humic Surface Water Gley	10.64	589.2	6269.1	Humic Surface Water Gley	7.45	249.0	1855.1	Brown Earth	3.10	413.9	1283.1	15673.8
7	Stagnic Luvisol	29.11	358.5	10435.9	Typical Surface Water Gley	12.04	319.1	3842.0	Alluvial	7.33	441.6	3236.9	Typical Surface Water Gley	5.49	331.1	1817.7	19332.6
8	Brown Earth	12.35	257.8	3183.8	Luvisol	9.36	373.5	3496.0	Luvisol	8.79	326.4	2869.1	Typical Surface Water Gley	3.58	227.9	815.9	10364.7
9	Stagnic Brown Earth	13.98	317.2	4434.5	Typical Surface Water Gley	13.39	306.9	4109.4	Alluvial	7.34	254.6	1868.8	Typical Surface Water Gley	3.58	227.9	815.9	10412.6
10	Brown Earth	10.59	247.1	2616.8	Typical Surface Water Gley	8.41	284.7	2394.3	Typical Surface Water Gley	6.52	259.4	1691.3	Typical Surface Water Gley	3.58	227.9	815.9	6702.4

Table 4

Soil carbon stored by each soil subgroup classification across sites. Soils are listed in order of prevalence at study sites.

			Mean depth	Mean SOC	Min SOC	Max SOC	Mean SOC: Current Study amended ^a	Mean SOC: Simo et al., 2019*
	Incidences	Ha	cm	T/Ha	T/Ha	T/Ha		T/Ha
Typical Surface Water Gley	11	89.5	137	274.1	170.9	459.3	241.9	128.4
Stagnic Luvisol	2	53.8	147	360.9	358.5	363.3	319.4	108.9
Stagnic Brown Earth	2	48.9	112	266.7	216.2	317.2	240.1	124.4
Alluvial	5	41.0	140	409.4	254.6	645.0	271.9	166.0
Brown Earth	4	36.6	146	321.8	247.1	413.9	285.7	128.0
Humic Surface Water Gley	3	21.1	133	428.8	249.0	589.2	172.9	157.3
Humic Brown Earth	1	20.7	116	179.6	–	–	172.2	163.1
Ombrotrophic Peat	1	19.9	116	748.4	–	–	–	–
Luvisol	2	18.2	150	350.0	326.4	373.5	163.2	121.9
Brown Podzolic	2	10.0	102	317.9	301.4	334.4	312.5	137.2
Humic Podzol	1	9.0	160	396.4	–	–	178.2	125.3

^a Estimated values for these soil subgroups at 0–100 cm and neglecting Histic horizons (Soil Organic Carbon (SOC) > 20%).

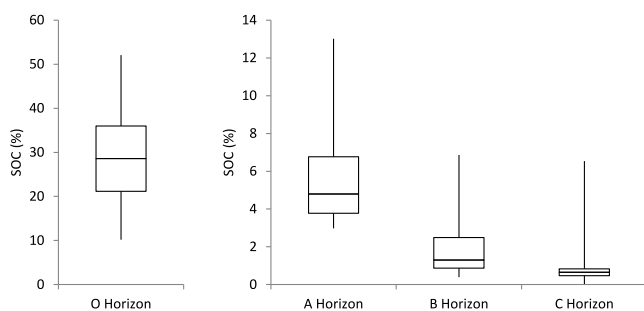


Fig. 2. SOC content (%) box and whisker plots for each horizon. Lower and upper box boundaries represent lower and upper quartiles, respectively, the line inside the box represents the median and the whiskers represent the range of values. Incidences of each horizon are O (n = 8), A (n = 30), B (n = 31) and C (n = 49).

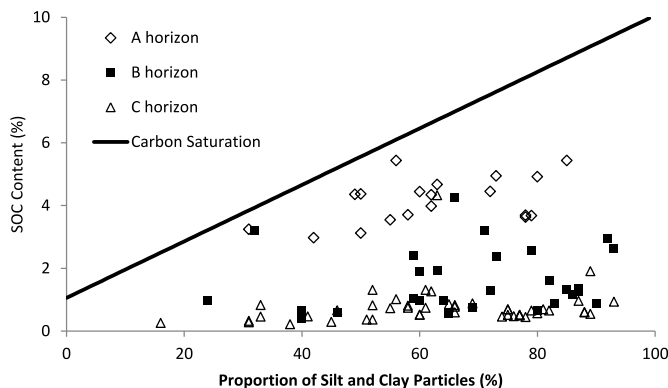


Fig. 3. Relationship between soil organic carbon content and the proportion of fine soil particles relative to the carbon saturation line (Kiely et al., 2017) for all soil horizons with <10% organic matter content differentiated by horizon type.

The estimates produced for the current study show significant storage of SOC in an array of soils types and depths. These grassland soils are shown to store significantly more C than mean estimates produced from a nationally representative survey previously completed (Simo et al., 2019), even when accounting for differences in survey depths and estimation methodology (i.e. Simo et al., 2019 focused on mineral soils and excluded soil horizons with >20% SOC due to high instability). This higher C store is due to higher relative amounts of organic C and shows the potential for much higher reserves of C (of the order of 1–4 times magnitude) when estimated at field scale when compared to more general mean values estimated across a range of locations with like soil types. This study provides a full estimate of the value that particular soils

may hold as C stores. Site 4, for example, is comprised of 24.73 Ha of Stagnic Luvisol, 10.01 Ha of Brown Podzolic and 5.34 Ha of Alluvial soils. The amount of C stored in these soils over such areas by the estimates established by Simo et al. (2019) is 4,952.9 Tonnes. Using the methods and resolution applied herein, a value of 14,329.6 Tonnes is calculated (Table 3).

Recent research shows that many soils are not C saturated, and therefore have the potential to sequester additional C from the atmosphere under appropriate management (Jones and Donnelly, 2004; Allard et al., 2007). The saturation level is determined by the properties of the fine mineral fraction of the soil (Beare et al., 2014) and additional capacity for C storage is determined as the difference between this saturation level and current storage. Studies have shown that there exists a high potential for additional soil C storage in many soils in France (Angers et al., 2011), Germany (Wiesmeier et al., 2014), New Zealand (McNally et al., 2017) and elsewhere (Chung et al., 2008; Castellano et al., 2015). While it is still a matter of debate whether all of this potential can be realised (Six et al., 2002; O'Rourke et al., 2015; Barré et al., 2017), or is potentially restricted by nutrient stoichiometry (Soussana et al., 2017; Van Groenigen et al., 2017), there are certainly gains to be made (Ricard and Viglizzo, 2020). A method to calculate the C saturation level of Irish soils has been developed (Kiely et al., 2017) which highlights an enormous potential for additional C to be stored in these soils, being bound to fine mineral particles. For the sites in the current study the average C content as a proportion of C saturation of A, B and C horizons was 77.4%, 21.5% and 10.1% respectively while the average difference between C storage and C saturation across soils surveyed was 792.1 T/Ha. Like most soils there is clear capacity for increased C storage.

The decreasing saturation at depth is consistent with research on Irish grassland soils, where an unsaturated pool of C at depth was associated with microaggregates in soils with argic and stagnic properties (Torres-Sallan et al., 2018). The longer OM stays in the system, the more it is transformed and stabilised in aggregates and bonded to the surface of minerals such as silt and clay (Six et al., 2002). Those that are biochemically recalcitrant have very long turnover times and low bioavailability (Zimmermann et al., 2007). Increasing C stocks in the soil C pools with the longest mean residence times (MRT) is the most promising for C sequestration (Dungait et al., 2012). In general, it is considered that turnover and concentration of SOC tend to be highest closest to the surface soil but tending to have a lower MRT. O horizons at study sites store an average of 310.0 T/Ha of C, relative to 150.5, 66.5 and 48.1 T/Ha in A, B and C horizons respectively. The greatest potential for increased C sequestration is typically in deeper horizons where reserves are lower and greater physical protection of C in microaggregates can increase the recalcitrance of C at depth (Torres-Sallan et al., 2018). While this offers a major opportunity, there are also many challenges due to the chemical nature of subsoils and storage potential uncertainty (Lorenz and Lal, 2005).

Soil physical quality is seen to vary significantly with depth in the current study. Generally, in most soils, soil physical integrity is positively correlated with total SOC content (Herrick and Wander, 2018). A similar trend is observed herein with highest mean SOC content observed at Good and Very Good SPQ indices. Mean SOC content in horizons of each index was 1.2%, 1.0%, 1.5% and 1.8% for very poor, poor, good and very good indices respectively. Good S_i values for surface (A) horizons, those affected by land management; indicate good soil condition in general across study sites despite the potential vulnerability of these wetter soils to structural damage under traffic where poorly managed. This finding is consistent with a national study by Bondi et al. (2020). Given that the (deeper) soil horizons with the most potential for increased C storage are more likely to have poor soil quality, efforts at exploiting this potential will need to look at both building physical quality and soil C simultaneously. There are many on-farm tools now available to protect soil quality and in particular SPQ on grassland farms. For example, the visual soil evaluation tool specific to grassland called GrassVESS (Emmet-Booth et al., 2019) or the trafficking index for soil compaction management in grasslands (Bondi et al., 2020). The application of such tools to study sites and similar areas would allow for straightforward SPQ assessments on-farm by landowners and highlight which practices affect change and where improvements are required. A general increase in SPQ, particularly in those deeper horizons would offer the potential for corresponding increases in soil C storage.

The level of C storage in soils can be heavily impacted by management practices. These practices, by their nature, are most effective in surface layers but there is potential to have positive impacts to much greater depths. Generally surface (A) horizons are most responsive to changes in management, and can offer stable stores of C where SPQ is high, as in the current study. A number of methods to maintain/increase soil C storage have been documented; these include erosion control, grazing management, promotion/introduction of earthworms, introduction of grass varieties with deeper rooting properties, introduction of legumes, perennial pastures, addition of animal manures or composts (Chan, 2008), many of which will also be effective in improving yields and increasing resource efficiency. The addition of organic fertilizers and amendments has shown positive impacts in numerous studies (Chen et al., 2018; van Zwieten, 2018). Generally the conversion of cropland to grassland is known to improve soil C stocks (Conant et al., 2017) while precision grassland management can yield further improvements. The relative C storage levels of each part of these study sites, has clearly shown where current management is coinciding with high C storage levels and where improvements can be made. Such information is crucial to providing insight in to management effects and facilitating maintenance of and/or increase in C stores.

Artificial drainage of such soils is linked with C loss, particularly when the C rich organic and humic soils are drained to alleviate surface wetness and increase production potential and accessibility (Renou-Wilson et al., 2015; Nachimuthu and Hulugalle, 2016; Paul et al., 2018). Using the criteria of Mockler et al. (2013) artificial drainage for all poorly draining agricultural soils below 200 m and with a gradient lower than 12° can be assumed. As such, the vast majority of soils at study sites would be assumed to be artificially drained. In reality, the amount of area drained varies by farm and temporally as existing drainage systems come to the end of their lifespan and new systems are installed. At any one time it is estimated that approximately 25–50% of these sites are artificially drained with in-field subsurface systems, while they are all characterised by extensive networks of open drains which provide outfall for excess water being discharged from the farm area. The C rich organic (8.3% by area) and humic soils (20.8%), account for less area than the mineral soils (70.9%) but are storing larger volumes of C and as a result are more vulnerable to losses. Estimated annual C losses of up to 3.14 T/Ha are possible where these soils are subject to effective artificial drainage (O'Sullivan et al., 2015). The management of these soils with regard to drainage works will dictate to a large degree the amount of C that is stored in the long term, as well as related impacts of water table

manipulation (Clagnan et al., 2020). Artificial drainage of poorly drained mineral soils has positive effects on GHG emissions by reducing losses of Nitrous Oxide (N_2O), while for organic soils, the cessation of artificial drainage works and the rewetting of a proportion already drained is proposed (Lanigan et al., 2018). The identification and classification of C rich soils, as described herein, will be crucial in this regard. At study sites, 56.6% of poorly and imperfectly drained soils are mineral. Strategies will need to be outlined, which are suited to each particular soil type, to reduce losses and where possible rebuild C stores.

It is clear, that the management regimes in place at the study sites have co-existed with these relatively high soil C pools. There are a number of factors which may have influenced such a scenario. Average precipitation at the study sites is 1259 mm and ranges from 982 to 1757 mm. Generally soil C is expected to increase with precipitation, due its reducing/slowing effect on biological activity and association with higher productivity and greater volumes of plant litter inputs (Cole et al., 1993; Derner and Schuman, 2007), which increase the C input to soil. Several practices already inherent to the management of Irish grasslands are known to be positive in terms of increasing C sequestration potential (e.g. perennial pastures, incorporation of animal manures, little soil erosion), (Chan, 2008; Spink et al., 2010). While farms dominated by poorly draining soil can, in general, be seen as disadvantaged, previous studies have shown these particular farms consistently outperform similar farms in terms of productivity and profitability (Hanrahan et al., 2019). The current study shows them also to be successful at balancing relatively high outputs with good soil quality, in so much as can be influenced by management, and high soil C storage. Future development will need to ensure these often competing soil functions can continue to co-exist.

The sustainable management of such poorly drained soils requires a balance between primary productivity and agronomic output of the soils and other soil functions such as nutrient cycling, water purification, C sequestration and habitat provision. The optimisation of this balance is key to aligning production systems with wider obligations towards improved water quality, climate regulation and biodiversity. Such farms will require spatially explicit management approaches to optimise these functions for particular soils types such that they can be prioritized within profitable production systems. This spatially explicit management can only be realised with field scale interpretation/measurement of soil characteristics, which highlights the benefits of field scale soil mapping and presents a very pertinent use case of same. National scale studies are more pertinent in terms of extent and potential at national scale which is important for high level decision making but lack the high resolution at local scale to support farm specific decision support and targeted opportunities for agricultural soils towards GHG mitigation. This study has shown that even at farm scale, C reserves are not dispersed uniformly. At Site 6, 40% of Carbon reserves are found in a Humic surface water Gley covering 20% of the farm area, while at Site 5, a typical surface water gley occupies 23% of the farm area but accounts for just 11% of C stores.

The current study offers insight into high resolution field scale information on levels of C storage on managed grasslands on poorly drained soils which have been subject to numerous land drainage schemes. To build on this new insight, and overcome the primary limitation to the generalization of these results, future work needs to assess in greater detail how land use and management are driving C storage in practice, outside of the scope of this study in terms of soil type and land use, and to establish how best to utilise such information with regard to future management practices. Where land use is optimised there can be significant benefits but such optimisation requires a tailored approach (O'Sullivan et al., 2015). The current study should offer an outline for how a deeper understanding of soil characterisation and function at farm and field scale can assist in defining where and how such a tailored approach could be implemented and echoes calls for standardisation and widespread application of C stock measurement (Bispo et al., 2017). While such an insight offers much in terms of assessing C stores and

informing future management, we are limited by the lack of a temporal assessment of changes in C storage levels. An assessment of trends over time is vital in analysing management impacts, monitoring temporal variability and arresting detrimental practices that would undermine C stores.

5. Conclusion

This study examined soil C stocks at 10 sites throughout Ireland. The soils in this study contain considerable C stores, consistent with the soil types found. The availability of field scale data has shown greater C storage which is masked when using larger national scale averages and reinforces the requirement for localised studies across different land uses, farm enterprises and intensities at a similarly detailed scale to support focused opportunities to selectively manage soils according to their inherent properties. Comparisons with C saturation potential highlight further capacity for C storage in these soils. The importance of soil C stores cannot be overstated in terms of potential impacts on GHG emission reduction and cooperation with climate change policy. For the soils discussed herein, inherent conditions and current management have fostered the retention of large stores of soil C which co-exist within highly productive farm systems. The long term status of these C reserves cannot be guaranteed. There exists both a threat to these C stores, if management practices were to drastically change, and an opportunity to increase C stores towards saturation levels where high C soils can be identified and under appropriate policies, commodified to offer a direct incentive to retain soil C. For this to be achieved, the value of this resource will need to be recognised and policies to ensure a “right measure, right place” approach for soil C management will need to be adopted with bespoke management of each land parcel. Detailed assessments, such as that described herein will also need to be carried out periodically to continuously assess trends in soil C stores (Smith et al., 2020). A 5–10 year interval is recommended to assess SOC stock changes (Black et al., 2008). Such efforts could be included in the context of a broader soil monitoring network and could help balance the need for agronomic output with retention/build-up of soil C at farm and field scale.

Credit author statement

Pat Tuohy: Conceptualization, Methodology, Resources, Investigation, Data curation, Writing – original draft, Visualization, Lillian O Sullivan: Conceptualization, Methodology, Writing – review & editing, Owen Fenton: Conceptualization, Methodology, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2020.111903>.

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