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RESEARCH ARTICLE

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The soil organic carbon: Clay ratio in North Devon, UK: Implications for marketing soil carbon as an asset class

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Abstract

Building up stocks of agricultural soil organic carbon (SOC) can improve soil conditions as well as contribute to climate change mitigation. As a metric, the ratio of SOC to clay offers a better predictor of soil condition than SOC alone, potentially providing a benchmark for ecosystem service payments. We determined SOC:clay ratios for 50 fields in the North Devon UNESCO World Biosphere Reserve using 30 cm soil cores (divided into 0–10 cm and 10–30 cm depth samples), with soil bulk density, soil moisture and land-use history recorded for each field. All the arable soils exceeded the minimum desirable SOC:clay ratio threshold, and the ley grassland soils generally exceeded it but were inconsistent at 10–30 cm. Land use was the primary factor driving SOC:clay ratios at 0–10 cm, with permanent pasture fields having the highest ratios followed by ley grass and then arable fields. Approximately half of the fields sampled had potential for building up SOC stock at 10–30 cm. However, at this depth, the effect of land use is significantly reduced. Within-field variability in SOC and clay was low (coefficient of variation was ~10%) at both 0–10 cm and 10–30 cm, suggesting that SOC:clay ratios precisely characterized the fields. Due to the high SOC:clay ratios found, we conclude that there is limited opportunity to market additional carbon sequestration as an asset class in the North Devon Biosphere or similar areas. Instead, preserving existing SOC stocks would be a more suitable ecosystem service payment basis.

KEYWORDS

carbon sequestration, land use, soil clay content, soil organic carbon, soil structure

1 | INTRODUCTION

Reducing carbon emissions to the atmosphere and sequestering the excess carbon (C) already present is key to limiting the extent of human-induced climate change. Several potential global stores, including biota, oceans and soils, have the potential to sequester carbon from the atmosphere (Friedlingstein et al., 2022). Globally, soils are estimated to contain approximately 1500 Gt of soil organic carbon (SOC) in the top one metre of their profiles which is more than in the earth's atmosphere and biota combined (Batjes, 1996). SOC concentration (grams of SOC per kg of soil dry mass) is also a key driver of soil health (Lal, 2016) and is often strongly correlated with multiple soil properties and functions such as aggregate stability (Abiven et al., 2009; Six et al., 2004), hydrological properties, hydraulic conductivity (Jeffrey, 1970), penetration resistance (Stock & Downes, 2008), nutrient transformation and supply and the buffering of pollutants (Baldock & Skjemstad, 1999). However, since the onset of modern intensive agricultural practices, SOC has significantly decreased by a cumulative amount exceeding 100 Gt (Lal, 2018; Sanderman et al., 2017). Most cropland mineral soils have lost 30%–50% of their SOC stocks (tonnes of SOC per ha) in upper (0–30 cm) soil layers relative to their native condition (Davidson & Ackerman, 1993). Similarly, overgrazed and poorly managed grasslands may be depleted in SOC when compared to well managed or native grasslands (Conant et al., 2016). At present, approximately 45% of global soils are utilized for some form of agriculture (Paustian et al., 2019), highlighting the significant global potential for continued losses or future C sequestration.

The concept of complexed organic carbon (COC) was introduced by Dexter et al. (2008) and is carbon bound to clay in aggregates within a soil which is protected from mineralization, thereby forming long-term stores. It was found that the relative proportions of SOC and clay within a soil were a better predictor of its physical properties (bulk density, water retention characteristics and clay dispersibility) than SOC or clay content considered individually. Dexter et al. (2008) showed that the SOC:clay ratio of 1:10 marked an approximate capacity for SOC protection by clay as COC; representing a possible upper limit on the amount of SOC which is protected from decomposition within a soil. Johannes et al. (2017) compared the SOC:clay ratio with visible structural quality on Swiss Cambi-Luvisols and found that an increased soil quality score was associated with a higher ratio. Threshold values were proposed based upon these observations of: >1:8 for 'very good' structure; 1:8–1:10 as 'good' structural quality which can be aimed for even with tillage; 1:10–1:13 for soils requiring improvement and <1:13 for soils likely to be in a 'poor' physical condition (Johannes et al., 2017). Prout et al. (2021) compared data retrieved for the initial sampling (1978–1983) undertaken for the National Soil Inventory of England and Wales, covering 3809 sites under arable land, grassland and woodland, with these proposed thresholds. It was found that 38.2%, 6.6% and 5.6% of arable, grassland and woodland sites, respectively, had ratios suggesting 'degraded' soil. This index therefore represents one pragmatic way of benchmarking agricultural soils of different textures, given that a soil with a high clay content is expected to have higher potential to store C than a sandy soil.

Given the vital need to increase and conserve SOC, convincing farmers of the need to implement best management measures is a fundamental requirement. Mattila et al. (2022) found that farmers in Finland were most likely to implement measures which had high co-benefits for both soil structure and productivity, such as cover crops, nutrient-rich amendments and grassland management. Due to the significant economic costs associated with some best management measures recommended by current policies (Collins et al., 2016), financial incentives may be required to achieve higher uptake rates (Crabtree et al., 1999; Fish et al., 2003). Here, converting 'intangible' soil assets to new revenue streams could help financially transform farming in some regions and provide significant environmental co-benefits at the same time. Both government programmes and voluntary schemes funded by private companies can financially incentivize SOC sequestration, with the latter source of funding being more common in practice (Paustian et al., 2019; von Unger & Emmer, 2018). Here, carbon credits or certificates are sold for the implementation of farming practices aimed at sequestering additional CO_2 (Amelung et al., 2020). However, to tie payments to soil status properly, it is necessary to benchmark the current C stored within a field and its capacity for improvement. The national-scale evaluation of soils in England and Wales by Prout et al. (2021) using the SOC:clay ratio provides a new opportunity to benchmark soils using a method that accounts for natural variability in achievable SOC values due to soil clay content as well as providing a national-scale data set to which soils in individual fields can be compared. The study reported herein applied the SOC:clay ratio in selected fields with different land uses and management practices in the North Devon Biosphere region in the UK. This ratio has not been applied previously or intensively to fields within a local region in an attempt to benchmark SOC. The North Devon Biosphere aims to implement the United Nations Sustainable Development Goals in large part through encouraging good land management and ensuring a healthy soil condition and high carbon storage. The specific objectives of the work reported here were to assess the SOC concentrations in the context of clay and total SOC stocks in representative fields covering both grassland and arable land uses and a range of soil types and management practices; to assess factors controlling SOC; to explore the use of the SOC:Clay ratio as a means of benchmarking fields in the North Devon Biosphere. We also considered how Devon soils fit into the national picture of SOC and clay.

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted in the North Devon UNESCO World Biosphere Reserve which covers over 30% of the county of Devon in the southwest of the UK. As part of implementing the United Nations Sustainable Development Goals, a natural capital marketplace was launched in April

2022 where farmers have a route to market for the sale of C credits in return for beneficial actions such as tree planting, peatland restoration and habitat improvement in the Biosphere (North Devon Biosphere, 2022). Over 90% of farms in the biosphere currently depend on the Basic Payment Scheme to remain financially solvent. Therefore, by adding SOC as a marketable asset, a new revenue stream can potentially be made available to farmers in return for environmental goods and services provided.

North Devon experiences high mean annual rainfall of 960 mm at Chulmleigh in its centre (Climate-data.org, 2022). The geology of the area is primarily shale and sandstone Culm measures, laid down in the Carboniferous period (Figure 1). Soils over the Culm measures are often

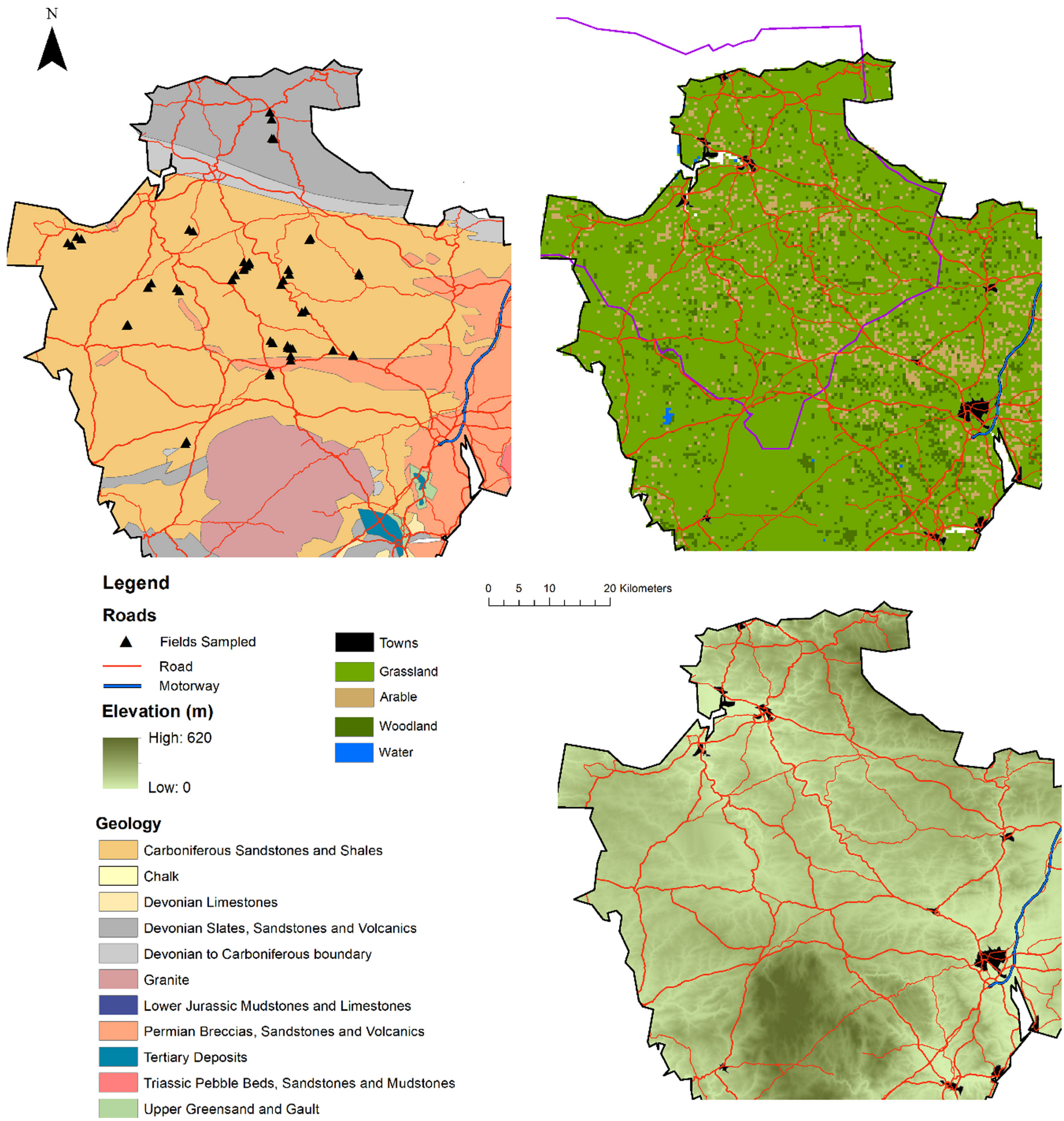

FIGURE 1 North Devon Biosphere boundary: the geology of Devon, data produced using data from the British Geological Survey; its land use, data from the Crop Map of England 2018; elevation from an Ordinance Survey 50 m DEM; the locations of fields sampled (Rural Payments Agency, 2020).

acidic, poorly drained and waterlogged. Over these soils, Culm grasslands (Rhôs pasture) form, which are important for biodiversity, and both water and C storage. Permian volcanic outcrops are present in the east and in a narrow horizontal strip through the centre of the area. Soils over this geology are characteristic 'redlands' due to their deep red colour. These soils of the Crediton association have a coarser, medium sandy silt loam texture, compared with clays or clay loams over other rock types (Table S1; Cranfield University, 2023). Land use is predominantly grassland for cattle and sheep grazing; however, cultivated fields for crop production are also common in areas where the topography is flatter such as on watersheds between river valleys. Arable land use covers approximately 8.9% of the biosphere and approximately two thirds of this is used for cereal production, with one third used for fodder crop production (Devon County Council, 2022).

2.2 | Field sampling

Fifty fields spread over twenty-five farms were sampled for this project. The farms were selected based on their location in North Devon, with the overarching aim to sample locations spread across the entirety of the study area with different land uses, farm structures, management practices and soil types (Figure 1). Each farmer approached was asked to identify two contrasting fields for sampling based upon one being arable or temporary grass ley and one being long-term permanent grassland. Where both land uses were not available, the farmers were asked to select either fields with contrasting management practices they viewed as being particularly relevant to this study or their most and least productive fields. The farmers were asked for a land-use history for each field, as well as for details of any land management practice they are undertaking, which may affect SOC (Table S2). In each field, five sets of five cores were collected using a gauge corer of 2 cm internal diameter and 1 m length, according to suggested best practice (Farm Net Zero, 2021). Each set of five cores were collected in a cross pattern with a sample collected at each point of the cross and one in the centre, representing a 100 m^2 circular area. The crosses were oriented to the north with the northern core 5.6 m from its centre, the east 2.8 m, the south 4.9 m and west 4 m they were oriented in this way so that future sampling could locate the same points (Gashu et al., 2021). The cores were retrieved to a depth of 30 cm and divided into two sections: 0–10 cm and 10–30 cm. A depth of 30 cm was selected as it is a typical depth of tillage in agricultural fields in the UK. All five samples from each depth were bulked into a single bag forming a composite sample with a total of 500 bulked samples collected across all farms (Farm Net Zero, 2021). This sampling method was used to ensure that a representative sample from a particular area of a field was obtained, and the sampling area was georeferenced. Five of these crosses were sampled in each field distributed on the points of a W-shape which was positioned to sample as large an area of the field as possible while avoiding land within 10 m of the field margins or any tracks, drinking troughs or visibly disturbed soil. This sampling method aimed to replicate the conventional W method for soils within a field (Farm Net Zero, 2021). At the northern and southern points of the first cross, bulk density samples were retrieved using a ring of 5 cm internal diameter and 5 cm length and soil depths of 2.5–7.5 cm and 17.5–22.5 cm.

2.3 | Laboratory analysis

The bulked core samples collected were initially dried at 30°C in a fan-assisted oven and were subsequently gently disaggregated and homogenized by hand, using a pestle and mortar, before being sieved to <2 mm through a stainless-steel mesh to remove any coarser soil particles and roots. The samples were sent to NRM laboratories for clay analysis using the pipette method (Gee & Bauder, 1986). A subsample of each bulked sample was also finely ground and homogenized using a pestle and mortar for C analysis.

Total C and δ^{13}C concentrations were measured using a Carlo Erba NA2000 analyser and a SerCon 20–22 isotope ratio mass spectrometer. While a δ^{13}C measurement is not strictly required for this research it is provided as a by-product of the C analysis and can provide a useful indicator of the presence of inorganic carbonates, which the values of between −27 and −32 indicated were not present in the soils sampled (Leavitt et al., 2009). Between 10 and 60 mg of the prepared samples was packed into pure tin capsules and sealed for analysis. The mass analysed was dependent upon the C content of the sample and need to achieve values within the instruments range of detection. Wheat flour (IA-R001 from Iso-Analytical, Crewe, UK; 40.2% C and −26.43 δ^{13}C) calibrated against IAEA-CH6 for C by Iso-Analytical, Crewe, UK was used as a reference standard. As an additional test for inorganic carbonates, one sample from each field was washed using hydrochloric acid and re-analysed after any inorganic carbonates had been destroyed. Here, a strong correlation between the acid washed and unwashed samples indicated that no significant quantities of mineral carbonates were present and that the C measured was almost all SOC (Figure S1).

The bulk density samples were initially weighed wet before being oven dried at 60°C until they reached a constant weight. The dry weight was subtracted from the wet weight to calculate the percentage soil moisture. The dry mass was divided by the volume of the sampling cylinder to calculate the dry bulk density of the sample. Where any stones (> approximately 5 mm diameter) were found in the samples, their mass and volume were subtracted from the final bulk density value.

2.4 | Data analysis

SOC stocks were calculated using Equation 1 and were and compared between land uses. Any outlying results for a land use were examined in the context of the land management history of the field. The mean proportion of the total 0–30 cm SOC stock distributed in the 0–10 cm and 10–30 cm depths was then calculated. SOC concentration was then plotted against clay content for the two depths along with the thresholds established by Johannes et al. (2017). Fields failing to achieve or significantly exceeding the thresholds were examined in the context of soil moisture and land management history.

$$SOCs = SDD * SOCc * depth * 100$$

where: SOCs = SOC stocks ($t\,ha^{-1}$), SDD = Soil dry density ($kg\,m^{-3}$), SOCc = soil carbon content ($g\,kg^{-1}$), depth = depth of sampling (m).

For SOC:clay to act as a metric for benchmarking soils in the biosphere a reasonably low within-field variability is necessary. Therefore, the standard deviation and coefficient of variation of the five bulked samples in each field were calculated. All graphs were created using R version 4.1.1 and ggplot2 version 3.4.0.

2.5 | National soil inventory of England and Wales

Data from the National Soil Inventory of England and Wales (NSI) were received from Cranfield University (www.landis.org.uk; Proctor et al., 1998). The NSI was sampled on a 5 km grid of the land area at a depth of 0–15 cm, with analysis of soil chemistry, as well as records of some site characteristics (including broad land-use class). Data from the first sampling for the NSI (sampled in years 1978–1983) were selected using the following criteria: land use (arable, ley grassland or permanent grassland) and clay ($>0\,g\,kg^{-1}$). Data were excluded if classed as peat in the major soil group classification or if peat was recorded in the description of soil texture. Soils located in Devon from this subset of the NSI were identified for comparison with the North Devon study area samples. Prout et al. (2021) excluded statistical outliers in SOC/clay, but they have been included in this analysis to provide a more complete comparison of soils within Devon.

3 | RESULTS

3.1 | Total SOC stocks

The total SOC stocks in the top 30 cm of the soil profile were significantly affected by land use ($p < .05$, Kruskal–Wallis H-Test; Table 1; Table S2). Mean SOC stocks for fields under each land use were in the order: arable < ley < permanent pasture (PP). Overall, there was no consistent link between land management practices other than land use and C stocks. There was also no significant correlation ($p > .05$) between the number of years that a field has been used as PP and its total SOC stock.

The mean percentage of the SOC stock in the 0–10 cm depth relative to the total 0–30 cm stock of the sampled profiles was 34.5% for arable (2.5% standard deviation), 36.7% for ley (2.6% standard deviation) and 39.5% for PP (5.8% standard deviation). This indicates a fairly homogenous SOC distribution throughout the soil profile with some enrichment in the top 10 cm in ley and greater enrichment in PP. Most of the total SOC stock was stored at the 10–30 cm depth where more of the soils mass was located (mean bulk density for all land uses 0.96 at 0–10 cm and 1.19 $g\,cm^{-3}$ at 10–30 cm).

While mean SOC concentrations at 0–10 cm and 10–30 cm depths were correlated with each other, this was only with a low r^2 of 0.29 ($p < .05$), suggesting that there were different environmental factors controlling SOC at

			Percentiles			
	n	**Median**	**5th**	**25th**	**75th**	**95th**
Arable	6	91.71	80.52	83.36	100.27	80.52
Ley	10	113.41	85.12	96.2	139.01	85.12
Permanent pasture	34	119.81	84.63	106.46	136.47	84.63

TABLE 1 Total SOC stocks ($t\,ha^{-1}$) within the top 30 cm of the sampled soil profiles.

the two depths. Clay contents at 0–10 cm and 10–30 cm were significantly linearly correlated with an r^2 of .77.

3.2 | SOC:Clay ratio

3.2.1 | 0–10 cm depth

When benchmarking the sampled fields against the SOC:clay ratio thresholds proposed by Johannes et al. (2017), all PP fields apart from two, had a ratio exceeding the maximum 1:8 threshold (Figure 2). The two fields which failed to reach this ratio were still within the good category with a ratio above 1:10, which means they were not atypical of PP fields nationally (Prout et al., 2021). The arable soils exceeded the 1:13 threshold and were mostly close to the 1:10 threshold (above and below) which represents an approximate maximum for SOC protection by mineral interaction. The ley soils mostly exceeded the 1:10 threshold except for two points which were still

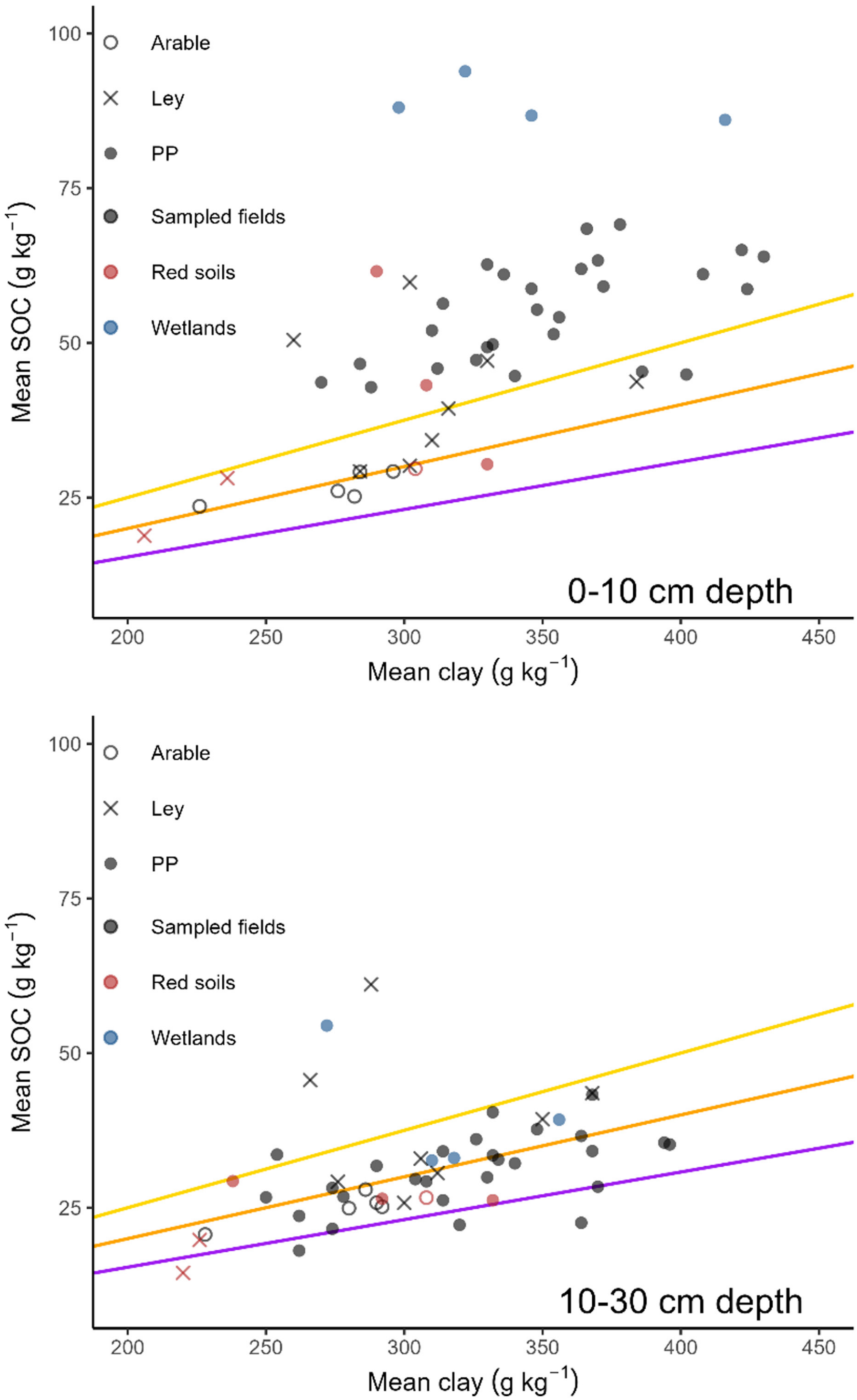

FIGURE 2 SOC and clay at 0–10 cm depth (top) and 10–30 cm depth (bottom) with lines representing SOC:clay thresholds of 1:8 (gold), 1:10 (orange) and 1:13 (purple).

above the 1:13 threshold. For context, 38.2% of arable fields in England and Wales, 15.0% of ley fields and 6.6% of PP fields had soils which were below the 1:13 threshold (Prout et al., 2021), emphasizing the good condition of soils in the North Devon Biosphere. Most non-wetland PP fields had a SOC concentration between approximately 40 and 70 $g\,kg^{-1}$ (mean 58.54 $g\,kg^{-1}$). Concentrations in arable and ley fields were lower with means of 27.09 $g\,kg^{-1}$ and 37.40 $g\,kg^{-1}$, respectively.

A correlation was found between SOC concentration and clay content (r^2 of .30). However, this may have been confounded by land use due to arable fields being positioned on lighter texture soils, perhaps by choice for freer drainage (Figure 2). Taking each land use separately, correlations of SOC and clay were variable with r^2 values for arable, ley and PP (once wetlands were removed) of 0.68, 0.21 and 0.28, respectively. Fields under PP management generally had SOC:clay values above the 1:8 threshold and therefore were likely to have SOC in excess of mineral interaction. Soil water content was a possible controlling factor of SOC, rather than clay content, for these fields as the four fields containing vegetation indicative of wetlands (e.g. rushes) identified in blue in Figure 2 had significantly higher SOC concentrations than other fields. There did not appear to be a particularly strong grouping or trend for redland soils with possible confounding effects from land use and soil texture.

3.2.2 | 10–30 cm depth

The threshold values used by Prout et al. (2021) to benchmark soils in England and Wales were tested at a shallower depth of 0–15 cm but, the interactions between SOC and clay are expected to still apply at a range of topsoil depths (Getahun et al., 2016). The thresholds are presented to determine whether the SOC concentrations have surpassed the 1:10 threshold relating to soil structure and physical protection of SOC (Figure 3). Only 7 of the 50 fields sampled were below the lowest 1:13 threshold suggesting that most of the soils were not structurally degraded. All arable fields, however, were below the 1:10 threshold, indicating that increased SOC storage would be possible at this depth. Half of the ten grass ley fields had SOC:clay above the 1:10 ratio indicating an improvement over arable land; however, 17 of the 34 PP fields failed to reach the threshold.

The three land uses did not have such a strong trend in differences of SOC concentration at 10–30 cm depth when compared to 0–10 cm depth, but there was still an effect of land use ($p < .05$, Kruskal–Wallis H-Test; Figure 3). Arable fields had the lowest median concentrations at both depths, but at 10–30 cm, the SOC concentrations of PP fields had dropped to a similar range as ley fields compared with the shallower depth. Of note is that three of the four wetland-type fields which had high SOC concentrations at 0–10 cm depth did not at 10–30 cm.

3.3 | Within-field variability

To establish the variability in SOC and clay concentrations within the individual fields, the concentrations recorded for the five crosses sampled were examined (Figure 4). At 0–10 cm depth, the mean standard deviation of SOC for the five crosses sampled was 6.0 $g\,kg^{-1}$ which was a mean coefficient of variation (COV) of 10.7% of the mean. Two outlying fields with the highest variability were both wetland-type fields. When these were removed, the mean standard deviation decreased to 4.8 $g\,kg^{-1}$ and mean COV to 9.60%. At 10–30 cm depth, the mean standard deviation was lower at 4.2 $g\,kg^{-1}$ although this equated to a higher mean COV of 13.2%. With the two outlying wetland sites removed, the standard deviation decreased to 3.7 $g\,kg^{-1}$ and COV to 11.82%. At this depth three additional outliers with a COV above 20% were found. The high variability here can be attributed to a shallow soil profile and the boundary of two different geological units within a field.

For clay content at 0–10 cm depth, variability was lower than that measured for SOC, with a mean standard deviation of 2.6% equating to a COV of 7.8%. Variability was similar at 10–30 cm depth, with a mean standard deviation of 2.36% and COV of 7.7%. Overall, the within-field variability in both SOC and clay content was low when compared to the differences observed between different fields. Variability in the SOC:clay ratio was found to be slightly higher than SOC considered alone at a mean COV of 11.1% at 0–10 cm depth and 15.23% at 10–30 cm depth.

3.4 | Devon soils in a national context

Soils sampled in Devon as part of the national sampling of the NSI had SOC and clay concentrations which were relatively central in the distribution of the data for each land use in the UK as a whole (Figure 5). Proportions of the sites with respect to SOC:clay thresholds (Table 2) showed that Devon soils under permanent grass were consistent with the full national results, soils under ley grass showed relatively fewer soils with SOC:clay ≥1/8, and more with SOC:clay between 1:13 and 1:10. Devon soils under arable management had a lower proportion of sites with SOC:clay <1:13 than the full national data set, but this was still higher than for grasslands. Therefore soils in North Devon might be expected to have a reduced risk of

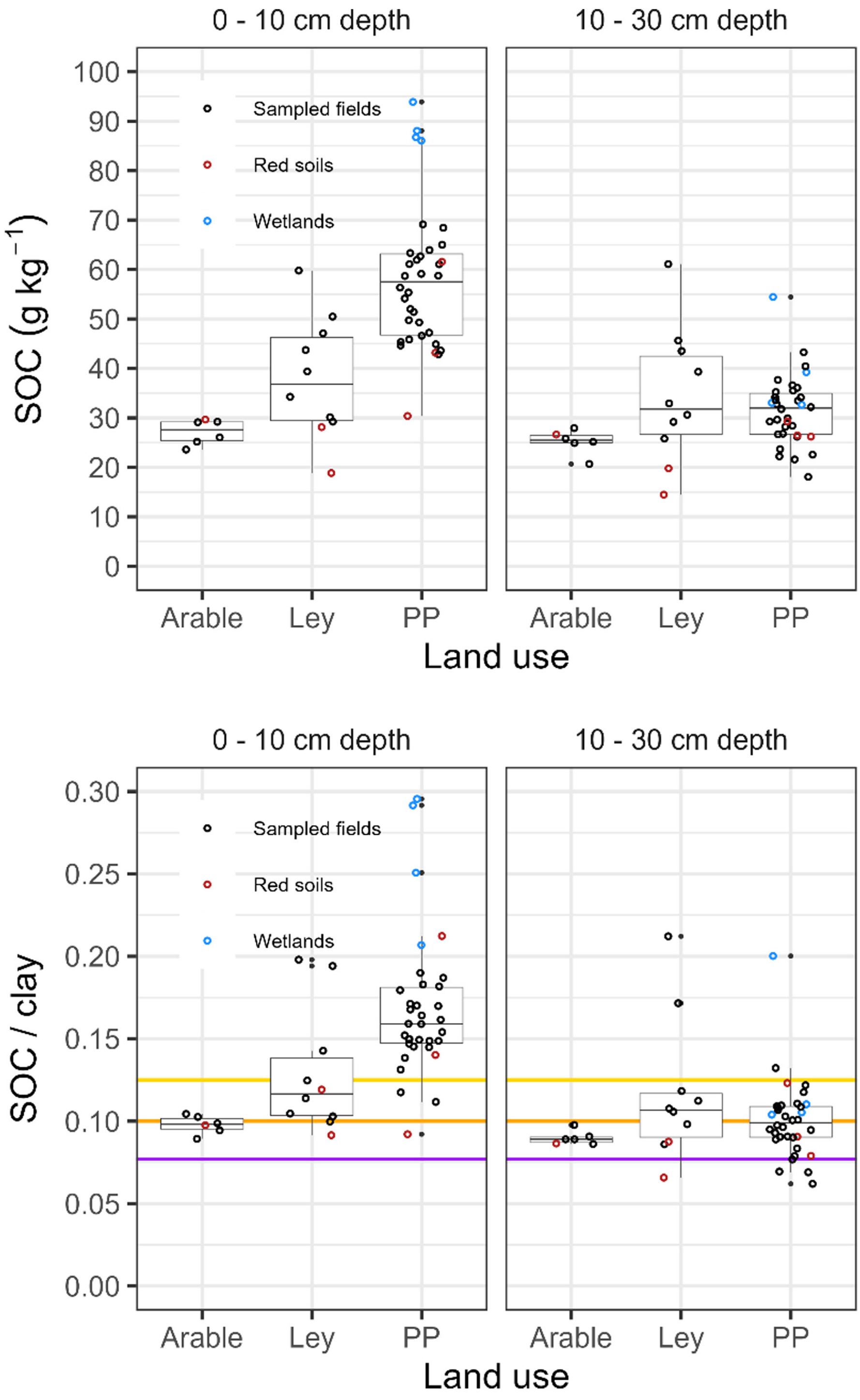

FIGURE 3 Boxplots of SOC concentration (top) and SOC/clay ratio (bottom) of the North Devon Biosphere fields summarized by land use and sampling depth. The SOC:clay thresholds (1:8, 1:10 and 1:13) are plotted at the corresponding decimal SOC/clay values. Open circle points show the data which each boxplot summarizes (randomly jittered on the x-axis for visibility). Black dot points are determined outliers of the distribution.

SOC:clay being <1:13 whether through farming practices or climatic effects.

The comparison of the North Devon Biosphere sampling with the NSI data was limited by the difference in sampling depth (0–10 cm vs 0–15 cm); however, the shallower data did not look out of place when overlayed (Figure 6). For the arable and ley soils, the data did not show a strong dilution effect with this difference in depth (considering the difference at 10–30 cm, Figure 3). While this sampling depth difference might have had a stronger impact for PP fields, the new data points fell in a similar range of SOC and clay to the NSI points.

4 | DISCUSSION

4.1 | Controls on SOC

It was evident from the results generated that, as found in previously published literature, land use was a major

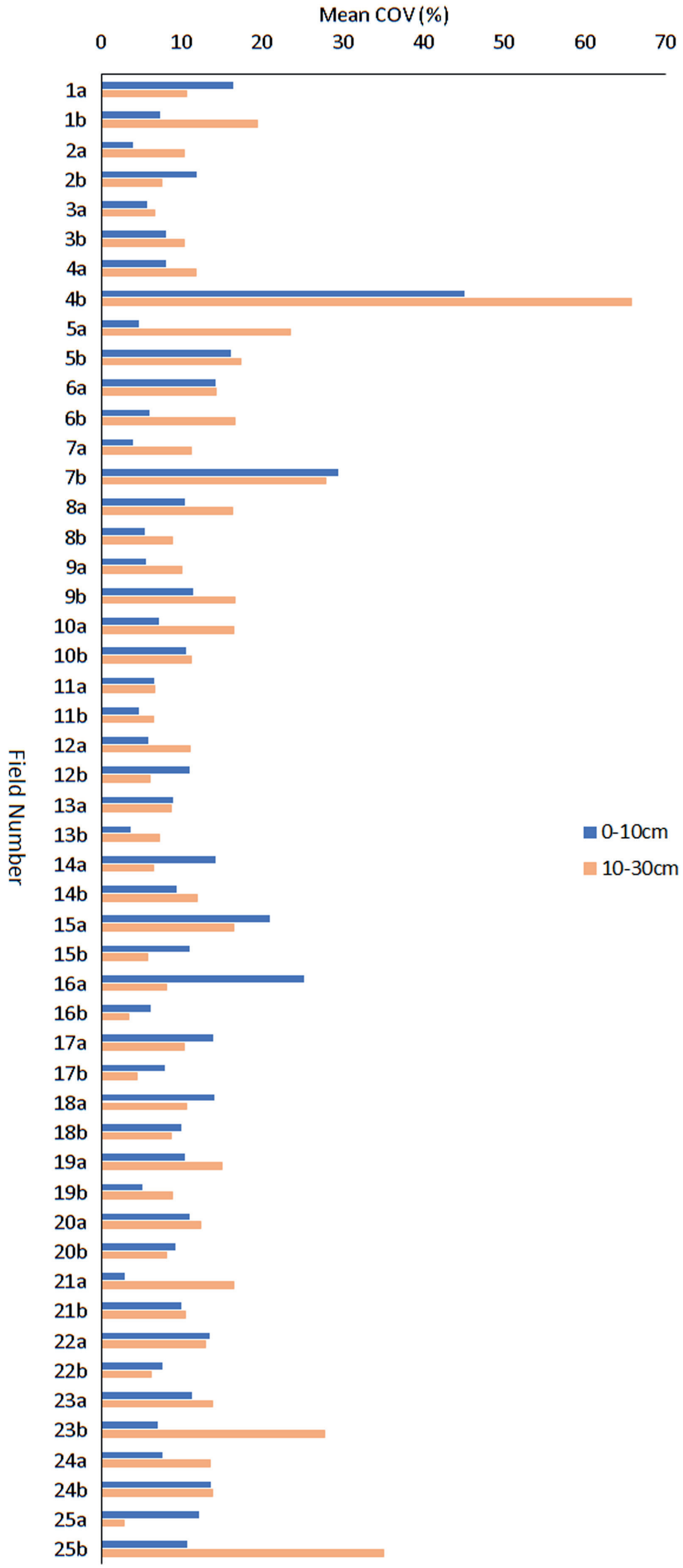

FIGURE 4 Mean coefficient of variation in SOC concentration between the five replicate bulked samples retrieved at 0–10 cm and 10–30 cm depths in each sampled field; field numbers refer to those described in Tables S1 and S2.

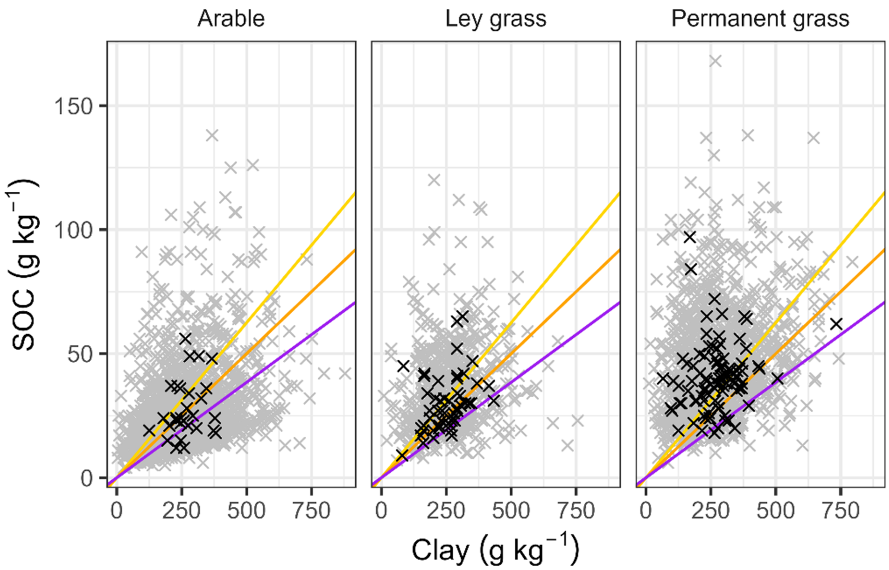

FIGURE 5 Data from the National Soil Inventory of England and Wales under specified land uses coloured by relation to the borders of Devon: within (black) or elsewhere (grey). Lines represent SOC:clay ratios of 1:8 (gold), 1:10 (orange), and 1:13 (purple).

TABLE 2 Summary of the distribution of data with respect to SOC:clay thresholds for each land use in the National Soil Inventory of England and Wales (NSI), Devon sites from the NSI, and fields sampled in the North Devon Biosphere. NSI data were from samples collected at 0–15 cm depth. Data for North Devon Biosphere is for samples at 0–10 cm depth.

			% of n in SOC:clay range			
Dataset	**Land use**	***n***	**≥1:8**	**<1:8, ≥1:10**	**<1:10, ≥1:13**	**<1:13**
NSI						
	Arable	1744	31	13.4	18.8	36.8
	Ley grass	638	52.5	19.1	14.3	14.1
	Permanent grass	1422	69.8	13.6	10.7	5.9
NSI Devon						
	Arable	29	31	20.7	20.7	27.6
	Ley grass	52	36.5	19.2	38.5	5.8
	Permanent grass	94	61.7	23.4	8.5	6.4
North Devon Biosphere						
	Arable	6	0	33.3	66.6	0
	Ley grass	10	30	50	20	0
	Permanent grass	34	91.2	5.9	2.9	0

control on SOC (Lal, 2004; Pabst et al., 2016; Wright & Wimberly, 2013). Arable fields when ploughed conventionally will typically lose about 40%–60% of their SOC (Guo & Gifford, 2002). There was a 54% difference between the sampled arable field mean SOC concentration and that found in PP, falling within this published range of SOC losses. There was, however, little indication that land management practices, other than land-use change, were having a significant effect on SOC. While manure applications took place in many of the studied arable and ley fields, there was no clear trend in such applications causing higher SOC stocks. Maintaining two fields as grassland rather than as an arable rotation and the mixing of SOC deeper through the soil profile during regular ploughing and reseeding operations may, however, have driven the two highest SOC stocks in the 0–30 cm depth range. van Eekeren et al. (2008) found SOC 1.7 times higher after 3 years of arable cultivation when preceded by 3 years of grassland than without. It was also not possible to observe a clear impact of cover cropping within the collected dataset. However, Zhang et al. (2022) found a greater accumulation of microbial-derived C in mineral-associated SOC in fields containing mixed legume, grass and brassica compared with monocultures of grass and brassica indicating the significant potential of cover crops to increases SOC in arable systems. Therefore, a lack of effect of many of the possible land management measures within the dataset may be linked to legacy carbon stocks from when the fields were last grassland, or the effects of soil moisture driven by local topography.

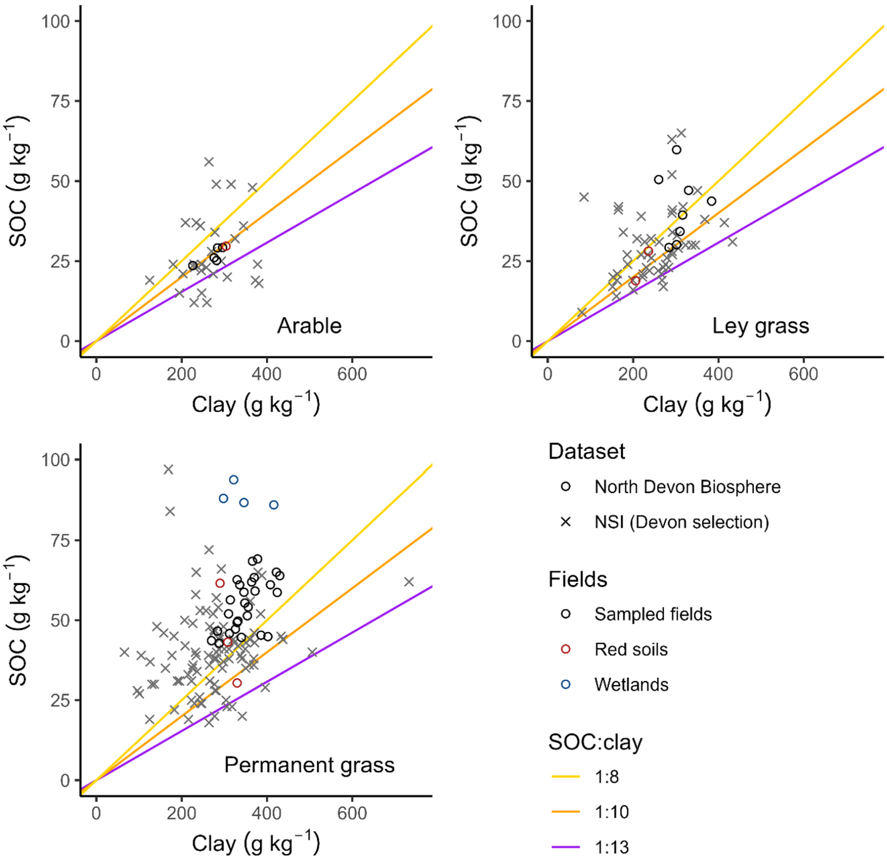

FIGURE 6 SOC and clay concentrations for data from fields sampled in the North Devon Biosphere (sampling depth 0–10 cm) and data for Devon soils from the National Soil Inventory of England and Wales (sampling depth 0–15 cm).

This study suggested that SOC in the 10–30 cm depth range was much less affected by land use than at 0–10 cm depth. It has been found in other studies that there is limited evidence of a significant change in SOC stocks under 30 cm depth associated with long-term arable or grassland land uses (Hopkins et al., 2009; Jenkinson, 1971; Poulton et al., 2003). Three fields with outlying high SOC concentrations at 10–30 cm depth were, however, found. Each of these fields had been ploughed or paraploughed (compacted layers are loosened at ~300 mm depth without significant soil inversion), possibly moving some SOC deeper through the soil profile. However, many other fields which had been ploughed did not show the same effect.

4.2 | The SOC: Clay ratio

A generally low variability in SOC and clay was found within the individual fields sampled indicating that SOC:clay is likely to be practical to characterize at field scale in landscapes similar to North Devon. The SOC:clay ratio thresholds proposed by Johannes et al. (2017) were of assistance in determining that most fields had a good amount of SOC in relation to their clay contents and that these soils had 'free' organic matter beyond that stored in clay aggregates as they exceeded the threshold of 1:10 identified by Dexter et al. (2008). The mean SOC:clay ratios of soils with good or bad soil structure were established at 5–10 cm depth by Johannes et al. (2017). The soil cores collected in this study were collected at 0–10 cm and 10–30 cm and therefore the mean SOC:clay ratio for soil with 'good' and 'bad' structure are likely to be slightly different here than in the work of Johannes et al. (2017). However, there is still likely to be a positive relationship between SOC:clay ratio and soil structure. Therefore, strictly speaking it is the core that is classified as having 'good' or 'bad' structure rather than the soil, the location or the profile. Prout et al. (2022) suggested that the thresholds of >1:13, > 1:10 and >1:8 can be used as targets for arable, ley grass and permanent grass, respectively, in England and Wales. In our new dataset at 0–10 cm depth, higher ratios were found in almost all fields. This may suggest that soils in similar climate and landscape settings may more easily reach these targets without major changes to agricultural practices than soils in other settings. But, as Prout et al. (2022) showed, there could be declines in SOC:clay for all the land uses sampled here, especially at SOC:clay ratios greater than 1:8, which should warn against complacency. For example, many arable fields may not have been continuously cropped for decades allowing for some legacy carbon stores from their time as ley grassland to remain maintaining the 1:10 ratio. The ratio indicated some potential for greater SOC accumulation at 10–30 cm depth. However, as land use was not a major controlling factor on SOC at this depth, it may be difficult to achieve this increase in practice. The relatively strong concentration gradient for PP soils between 0–10 cm and 10–30 cm depths compared with arable and ley grass may be in part due to few, if any, disturbances to redistribute the SOC deeper under PP. However, rooting depth and grassland management may also promote deeper inputs of carbon.

4.3 | SOC as a marketable asset class

Two possible avenues can be considered for converting SOC to a marketable asset class. These are by increasing SOC concentrations or maintaining existing SOC. Linking payments to an action or change made by farmers may be more appealing to potential customers. However, within the new data set reported herein, there was limited evidence of a clear link between SOC and land management practices. Soil moisture, as the major control is mostly an intrinsic factor of the field which cannot be easily increased. However, allowing historically installed field drains, which are widespread in the UK, to degrade, may achieve an increase in soil moisture. As this action is site-specific, as field drains are only present in particular fields, land-use change is instead considered here as a more widely applied measure. An additional drawback to field re-wetting is that it may also increase nitrous oxide losses to the atmosphere (Banerjee et al., 2016). The new results from this study suggest that, in general, land use only has a small impact on SOC below 10 cm depth. Therefore, land-use practices are only likely to deliver significant benefits to the between 34.5% (arable) and 39.5% (PP) of 0–30 cm depth SOC stored in the top 10 cm of the soil. For context, over 50% of the total SOC stored in UK soils is in the top 30 cm of the soil (Natural England, 2015). However, a comparison to the wider national data set suggests that fields in North Devon are largely achieving and exceeding SOC concentrations which can be expected for their land uses at this 0–10 cm depth. The SOC:clay ratio indicated that there was greater potential for increasing long-term stores of SOC at the 10–30 cm depth; however, a reduced difference between SOC concentrations in different land uses at this depth suggested that achieving this outcome may be challenging.

Taking the differences between mean SOC stocks for the fields sampled, converting an arable field to PP would increase soil C stock by 28.42 t ha^{-1} and converting a ley field to PP would increase stock by 6.51 t ha^{-1}. Gains may, however, be smaller than this, given the lower clay content of the arable fields and their positioning on hilltops with lower soil moisture. The potential for gaining additional soil C is low when compared to the amount of SOC already stored in the fields of 94.87 t ha^{-1} for arable, 116.78 t ha^{-1} for grass ley and 123.29 t ha^{-1} for PP. Therefore, basing payments upon maintaining existing grassland may therefore deliver greater environmental benefits than land-use change given increasing climate change and food security pressures. This may be less appealing to potential customers; however, as it does not require any substantial additional actions to be taken by farmers and does not sequester substantial amounts of new atmospheric C. An alternative option may be the implementation of silvo-pasture due to the increased root-biomass associated with trees and its eventual contribution to SOC (López-Santiago et al., 2019). However, further research is required to quantify the potential increases to SOC associated with this farming system in landscapes such as North Devon.

5 | CONCLUSIONS

Within North Devon and possibly other areas with a similarly wet climate, long-term PP is clearly capable of supporting SOC concentrations greater than the limits imposed by clay content and the soils potential to complex organic C into aggregates. Arable land and ley grassland in the study area also generally had high SOC concentrations close to approximate limits for SOC–mineral interaction.

However, there is no clear pathway to achieving increases through land management given the limited impacts of most actions other than differences between land-use classes which were observed in the collected data set. Instead, there is greater potential for the loss of C through land-use change and marketing the preservation of existing SOC stores is likely to be of most benefit in the North Devon Biosphere. Therefore, as suggested in other research, policy goals to preserve C already stored in ecosystems deserve at least as much attention as efforts to sequester additional C using existing or new stores. This is especially important given the significant projected expansion of the global cropland area.

Overall, the SOC:clay ratio provides a pragmatic means to identify if soils are storing sufficient SOC that can be marketed as an asset to be preserved, or if they have potential to increase SOC stocks which can be monitored and then sold.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest related to the work presented in this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Abiven, S., Menasseri, S., & Chenu, C. (2009). The effects of organic inputs over time on soil aggregate stability – A literature analysis. *Soil Biology and Biochemistry*, *41*, 1–12. https://doi.org/10.1016/j.soilbio.2008.09.015

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*(1), 5427. https://doi.org/10.1038/s41467-020-18887-7

Baldock, J. A., & Skjemstad, J. O. (1999). Soil organic carbon/soil organic matter. In K. Peverill, D. Reuter, & L. Sparrow (Eds.), *Soil analysis – An interpretation manual* (pp. 159–170). CSIRO Publishing, Melbourne, Vic.

Banerjee, S., Helgason, B., Wang, L., Winsley, T., Ferrari, B. C., & Siciliano, S. D. (2016). Legacy effects of soil moisture on microbial community structure and N_2O emissions. *Soil Biology and Biochemistry*, *95*, 40–50. https://doi.org/10.1016/j.soilbio.2015.12.004

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, *47*(2), 151–163. https://doi.org/10.1111/j.1365-2389.1996.tb01386.x

Climate-data.org. (2022). Climate Bideford (United Kingdom). Available online at: https://en.climate-data.org/europe/united-kingdom/england/bideford-10705/

Collins, A. L., Zhang, Y. S., Winter, M., Inman, A., Jones, J. I., Johnes, P. J., Cleasby, W., Vrain, E., Lovett, A., & Noble, L. (2016). Tackling agricultural diffuse pollution: What might uptake of farmer-preferred measures deliver for emissions to water and air? *Science of The Total Environment*, *547*, 269–281. https://doi.org/10.1016/j.scitotenv.2015.12.130

Conant, R. T., Cerri, C. E. P., Osborne, B. B., & Paustian, K. (2016). Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, *27*, 662–668. https://doi.org/10.1002/eap.1473

Crabtree, J. R., Thorburn, A., Chalmers, N., Roberts, D., Wynn, G., Barron, N., Barraclough, F., & Macmillan, D. (1999). Socio-economic and agricultural impacts of the environmentally sensitive areas scheme in Scotland, economics and policy series 6. In *Economics and policy series 6*. Macaulay Institute.

Cranfield University. (2023). *The soils guide*. Cranfield University. Available: www.landis.org.uk. Last Accessed Feb 21, 2023

Davidson, E. A., & Ackerman, I. L. (1993). Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry*, *20*, 161–164. https://doi.org/10.1007/BF00000786

Devon County Council (2022). *Environment*. Devon County Council. Available online at: https://www.devon.gov.uk/environment/wildlife/habitats-and-species/farms

Dexter, A. R., Richard, G., Arrouays, D., Czyz, E. A., Jolivet, C., & Duval, O. (2008). Complexed organic matter controls soil physical properties. *Geoderma*, *144*, 620–627. https://doi.org/10.1016/j.geoderma.2008.01.022

Farm Net Zero. (2021). *Monitoring Soil Carbon:a Practical Field, Farm and Lab Guide*. www.farmcarbontoolkit.org.uk/farm-net-zero, Accessed Nov 21, 2022.

Fish, R., Seymour, S., & Watkins, C. (2003). Conserving English landscapes: Land managers and Agri-environmental policy. *Environment and Planning A*, *35*(1), 19–41. https://doi.org/10.1068/a3531

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., … Zheng, B. (2022). Global carbon budget 2022. *Earth System Science Data*, *14*, 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

Gashu, D., Nalivata, P. C., Amede, T., Ander, E. L., Bailey, E. H., Botoman, L., Chagumaira, C., Gameda, S., Haefele, S. M., Hailu, K., Joy, E. J. M., Kalimbira, A. A., Kumssa, D. B., Lark, R. M., Ligowe, I. S., McGrath, S. P., Milne, A. E., Mossa, A. W., Munthali, M., … Broadley, M. R. (2021). The nutritional quality of cereals varies geospatially in Ethiopia and Malawi. *Nature*, *594*, 71–76. https://doi.org/10.1038/s41586-021-03559-3

Gee, G. W., & Bauder, J. W. (1986). Particle-size analysis. In A. Klute (Ed.), *Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9* (pp. 383–411). ASA and SSSA Particle-size Analysis.

Getahun, G. T., Munkholm, L. J., & Schjønning, P. (2016). The influence of clay-to-carbon ratio on soil physical properties in a humid sandy loam soil with contrasting tillage and residue management. *Geoderma*, *264*, 94–102. https://doi.org/10.1016/j.geoderma.2015.10.002

Guo, R., & Gifford, M. (2002). Soil carbon stocks and land use change: A meta analysis. *Global Change Biology*, *8*, 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x

Hopkins, D. W., Waite, I. S., McNicol, J. W., Poulton, P. R., Macdonald, A. J., & O'Donnell, A. G. (2009). Soil organic carbon contents in long-term experimental grassland plots in the UK (palace leas and park grass) have not changed consistently in recent decades. *Global Change Biology*, *15*, 1739–1754. https://doi.org/10.1111/j.1365-2486.2008.01809.x

Jeffrey, D. (1970). A note on use of ignition loss as a means for approximate estimation of soil bulk density. *Journal of Ecology*, *58*, 297. https://doi.org/10.2307/2258183

Jenkinson, D. S. (1971). The accumulation of organic matter in soil left uncultivated. In *Rothamsted experimental station. Report for 1970. Part 2* (pp. 113–137). Lawes Agricultural Trust.

Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P. C., & Boivin, P. (2017). Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? *Geoderma*, *302*, 111–121. https://doi.org/10.1016/j.geoderma.2017.04.021

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*, 1623–1627. https://doi.org/10.1126/science.1097396

Lal, R. (2016). Beyond COP21: Potential and challenges of the "4 per thousand" initiative. *Journal of Soil and Water Conservation*, *71*, 20A–25A. https://doi.org/10.2489/jswc.71.1.20A

Lal, R. (2018). Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology*, *24*, 3285–3301. https://doi.org/10.1111/gcb.14054

Leavitt, S. W. (2009). Carbon isotopes, stable. In V. Gornitz (Ed.), *Encyclopedia of paleoclimatology and ancient environments. Encyclopedia of earth sciences series*. Springer.

López-Santiago, J. G., Casanova-Lugo, F., Villanueva-López, G., Díaz-Echeverría, V. F., Solorio-Sánchez, F. J., Martínez-Zurimendi, P., Aryal, D. R., & Chay-Canul, A. J. (2019). Carbon storage in a silvopastoral system compared to that in a deciduous dry forest in Michoacán, Mexico. *Agroforestry Systems*, *93*, 199–211. https://doi.org/10.1007/s10457-018-0259-x

Mattila, T. J., Hagelberg, E., Söderlund, S., & Joona, J. (2022). How farmers approach soil carbon sequestration? Lessons learned from 105 carbon-farming plans. *Soil and Tillage Research*, *215*, 105204. https://doi.org/10.1016/j.still.2021.105204

Natural England. (2015). *Summary of evidence: soils. Access to evidence information note*. EIN012.

North Devon Biosphere. (2022). *About the North Devon UNESCO biosphere*. Available Online at: https://www.northdevonbiosphere.org.uk/about.html.

Pabst, H., Gerschlauer, F., Kiese, R., & Kuzyakov, Y. (2016). Land use and precipitation affect organic and microbial carbon stocks and the specific metabolic quotient in soils of eleven ecosystems of Mt. Kilimanjaro, Tanzania. *Land Degradation and Development*, *27*(3), 592–602. https://doi.org/10.1002/ldr.2406

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate*, *1*, 8. https://doi.org/10.3389/fclim.2019.00008

Poulton, P. R., Pye, E., Hargreaves, P. R., & Jenkinson, D. S. (2003). Accumulation of carbon and nitrogen by old arable land reverting to woodland. *Global Change Biology*, *9*, 942–955. https://doi.org/10.1046/j.1365-2486.2003.00633.x

Proctor, M. E., Siddons, P. A., Jones, R. J. A., Bellamy, P. H., & Keay, C. A. (1998). Land information systems for sustainable development in the UK. In H. J. Heineke, W. Ecklemann, A. J. Thomasson, R. J. A. Jones, L. Montanarella, & B. Buckley (Eds.), *EUR 17729 EN* (pp. 219–233). Office for Official Publications of the European Communities.

Prout, J. M., Shepherd, K. D., McGrath, S. P., Kirk, G. J. D., & Haefele, S. M. (2021). What is a good level of soil organic matter? An index based on organic carbon to clay ratio. *European Journal of Soil Science*, *72*, 2493–2503. https://doi.org/10.1111/ejss.13012

Prout, J. M., Shepherd, K. D., McGrath, S. P., Kirk, G. J. D., Hassall, K. L., & Haefele, S. M. (2022). Changes in organic carbon to clay ratios in different soils and land uses in England and Wales over time. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-09101-3

Rural Payments Agency. (2018). Crop Map of England (CROME) 2018. https://data.gov.uk/dataset/fb19d34f-59e6-48e7-820a-fe5fda3019e5/crop-map-of-england-crome-2018. Accessed April 15, 2021.

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences*, *114*, 9575–9580. https://doi.org/10.1073/pnas.1706103114

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, *79*, 7–31. https://doi.org/10.1016/j.still.2004.03.008

Stock, O., & Downes, N. K. (2008). Effects of additions of organic matter on the penetration resistance of glacial till for the entire water tension range. *Soil and Tillage Research*, *99*, 191–201. https://doi.org/10.1016/j.still.2008.02.002

van Eekeren, N., Bommelé, L., Bloem, J., Schouten, T., Rutgers, M., de Goede, R., Reheul, D., & Brussaard, L. (2008). Soil biological quality after 36 years of ley-arable cropping, permanent grassland and permanent arable cropping. *Applied Soil Ecology*, *40*, 432–446. https://doi.org/10.1016/j.apsoil.2008.06.010

von Unger, M. Emmer, I. (2018). *Carbon market incentives to conserve, restore and enhance soil carbon. Silvestrum and the nature conservancy*. Silvestrum and The Nature Conservancy.

Wright, C. K., & Wimberly, M. C. (2013). Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proceedings of the National Academy of Sciences*, *110*(10), 4134–4139. https://doi.org/10.1073/pnas.1215404110

Zhang, Z., Kaye, J. P., Bradley, B. A., Amsili, J. P., & Suseela, V. (2022). Cover crop functional types differentially alter the content and composition of soil organic carbon in particulate and mineral-associated fractions. *Global Change Biology*, *28*, 5831–5848. https://doi.org/10.1111/gcb.16296

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