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An Approach for Assessing Soil Organic Carbon Uplift Across Different Land Types

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Abstract

The aim of this study was to assess potential uplift in soil organic carbon (SOC) levels within different types of agricultural land. A total of 1,032 soil samples were collected from 43 fields across six farms during the same year. Fields were used for arable, temporary grass and permanent grass production. The study compared SOC levels (in g/kg, ratio to clay and ratio to nitrogen) between the field boundary and within field areas. The field boundary was classed as either open (boundary with fence and/or wall) or covered (with hedgerow and/or trees). From the fields sampled, 69% of within field samples and 88% of boundary samples were categorized as having 'very good' levels of SOC. On average, the SOC in g/kg and ratio to clay were higher for permanent grass and boundary field areas compared to temporary and within field areas, with no difference between open or covered boundary areas. Benchmarking fields against the field boundary area or based on SOC to clay ratio can be used by land managers to identify fields for potential SOC uplift.

Keywords: soil organic carbon; land type; field areas; benchmarking; management

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1. Introduction

The nutrient content of soil plays a central role in maintaining the soil's functionality and resilience, acting as a key driver of biological, chemical, and physical processes in the soil. The measurement of SOC, and identification of the need for uplift in farmland, is a key area of research that is increasingly gaining significance for sustainable soil management and farmland resilience. Soil disturbance by cultivation and nutrient applications determines the balance between carbon inputs and losses in the field [1]. For example, intensive arable farming with ploughing can reduce SOC and often accelerate organic matter decomposition, while in permanent grass fields the continuous presence of vegetation cover tends to promote SOC accumulation [2,3]. Permanent grasslands typically accumulate higher SOC due to minimal soil disturbance and consistent organic inputs from root biomass and litter [4]. In contrast, arable systems frequently exhibit reduced or fluctuating SOC levels due to repeated soil disturbance and lower organic inputs [5]. However, the amount of SOC gained in temporary grasslands depends on how long they are kept as grass and how they are managed [6]. Management practices, such as adding crop residues to temporary fields or converting them to permanent fields with no or reduced soil disturbance, can help increase SOC in agricultural farming systems [7].

It is important to identify field areas below their potential for SOC storage, as SOC helps soils aggregation, maintain adequate water holding capacity, store nutrients, enhance nutrients availability, support proper plant growth, and reduce climate change by storing carbon in the ground instead of the atmosphere [8,9]. Clay helps protect and store SOC, so soils with more clay can usually store more carbon, therefore SOC to clay ratio is often used as an indicator of soil quality [10,11]. However, SOC levels are also influenced by climate, land use, and management, not just clay content [12–14]. In addition, field boundaries represent unique microenvironments within agricultural landscapes. Features such as hedgerows and trees contribute organic inputs through leaf litter and root turnover, while also reducing soil disturbance preventing loss of SOC and clay contents [15,16]. The field boundary areas therefore often contain higher SOC levels than adjacent cultivated areas [16]. The field boundary offers a potentially useful reference point for evaluating the potential of within field areas. Covered field boundaries, such as hedgerows, often have higher SOC because they are less disturbed and receive more organic material (reference). For example, hedgerows have been shown to increase soil carbon storage compared to nearby arable land [17].

The aim of this study was to assess differences in SOC between different areas within a field and amongst different land types, to propose an approach for benchmarking fields based on SOC levels.

2. Materials and Methods

2.1. Study Farms and Fields

This study was carried out on six farms within the Cotswolds National Landscape (51° 48′ 18″ N, 1° 55′ 11″ W) in the South West of the UK in September 2025. The soil in the area was predominantly calcareous loams. A total of 43 fields were studied across the six farms, with 24 fields classed as 'temporary' with grass or arable crops in rotation and 19 'permanent' fields with grassland of five or more years using the agricultural land type class of England and Wales [18]. Of the fields studied, 23.3% were arable, 32.6% were temporary grass and 44.2% were permanent grass. The arable fields were either harvested during the summer or recently sown with a new crop, while both temporary and permanent grass fields were used for conservation and livestock grazing.

2.2. Field Areas Studied

Soil samples were collected around the field boundary and within the field, as illustrated in Figure 1.

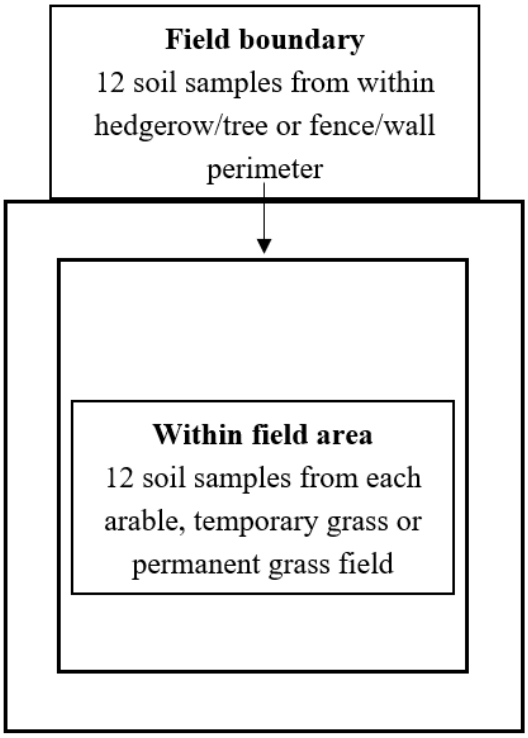

Figure 1. Illustration of field areas sampled.

Samples from the field boundary were collected within 1 metre of the field perimeter. Field boundaries generally include a grass margin with native grass species next to hedgerow/ trees (referred to as 'covered'; Figure 2) or stone wall /fence (referred to as 'open'; Figure 3). Trees and hedgerows were considered to provide organic material to field boundaries unlike wall or fenced boundaries.

Figure 2. Example of covered field boundary with trees and/or hedgerow.

Figure 3. Example of open field boundary with a fence and/or stone wall.

2.3. Soil Measurements and Analysis

Within each field studied, a total of 24 soil samples were collected, with 12 samples collected within the field and 12 from around the field boundary (Figure 1). The soil samples taken within a field along a W-pattern [19], whereas three soil samples were randomly collected for four boundary lengths per field. Due to the dry soil conditions when sampling, a foot operated steel soil sampler (Kingshay Farming & Conservation Ltd., Glastonbury, UK) was used to collect ~80 grams of soil into a funnel from 10cm depth for further analysis. Soil samples were collected into bags for immediate nutrient analysis by near infrared spectroscopy (NIRS) soil scanner (E Series; Agrocares, Wageningen, Netherlands) on the fresh material. The soil scanner has been reported to effectively analyse soil nutrients to inform farmland management in previous studies [19–22].

A total of 1,032 soil samples were collected. The soil NIRS scanner measures the spectrum of infrared energy reflected from a sample during scanning before analysing each sample, the device is calibrated using a standard white plate. Fresh soil samples are placed in a small dish to minimise interference from external light, and the soil surface is levelled prior to scanning. The scanner head is then positioned over the sample, and the four replicate scans are carried. Once scanning is complete, the nutrient analysis results are automatically uploaded to cloud storage via a tablet. The scanner itself has been calibrated using over 18,000 samples that were previously analysed in the laboratory [23,24].

The resulting nutrient analysis output is the average of the multiple scans. The following soil nutrients were measured: Organic matter (%), organic carbon (SOC; g/kg, ratio to nitrogen, and ratio to clay), total nitrogen (g/kg), clay (%), moisture (%), pH and cation exchange capacity (mmol/kg). The level of SOC was assessed based on the decimal ratio of SOC to clay, with categorises of ‘poor’ (ratio <0.06), ‘good’ (≥0.06 to <0.12), and ‘very good’ (≥0.12) developed based on the levels of SOC to clay of permanent grass fields found in previous research where the minimum SOC to clay for permanent grass fields was 0.06 and the lower quartile was 0.12 [22]. This modified the approach proposed by other researchers to categorise SOC levels based on SOC to clay ratio [18,25,26]. The percentage of soil samples within each SOC/clay ratio category from ‘poor’ to ‘very good’ were determined.

2.4. Statistical Analysis

A linear mixed model (Equation 1) in IBM SPSS Statistics (Version 29.0. Armonk, NY) was used to assess effects of land type, field area and boundary type on SOC.

$$Y_{ijk} = \mu + T_i \times B_j + F_k + e_{ijk} \qquad (1)$$

where Y_{ijk} is the dependent variable of SOC (g/kg, ratio to nitrogen, and ratio to clay); μ = overall mean; T_i = fixed effect of land type (i = temporary or permanent fields); B_j = fixed effect of field area and boundary type (j = within field, open or covered boundary); F_k = random effect of farm (k = 1 to 6); e_{ijk} = random error term. Significance was attributed at $P<0.05$.

The average SOC and SOC clay ratio for each field was calculated for the boundary and within field areas, and the percentage differences between the areas was compared.

3. Results

The average soil properties for samples collected during the study period and the coefficient of variation are presented in Table 1. Across the land types and locations of the fields studied, there were large variations in organic matter, SOC, SOC/clay, total nitrogen, cation exchange and moisture with coefficients of variation ranging from 23.3% to 35.4%. The SOC/clay ratio and soil moisture were the most variable, having 31.3% and 35.4% coefficient of variation, respectively.

Table 1. Average soil properties for samples collected during the study period.

Variable	Units	Mean (S.D)	Range	Coefficient of variation (%)
Organic matter	g/kg	7.6 (2.0)	2.8–17.0	26.8
SOC	g/kg	44.3 (11.9)	6.0–101.0	26.9
SOC/clay		0.2 (0.05)	0.1–0.4	31.3
Total nitrogen	g/kg	3.9 (1.0)	1.4–9.1	26.3
SOC to nitrogen ratio		11.3 (0.8)	9.4–16.7	6.9
Clay	%	28.0 (3.4)	14.0–42.0	12.3
pH (water)		7.4 (0.3)	5.5–8.0	4.4
Cation exchange		305.0 (71.3)	92.0–528.0	23.3
Moisture	%	33.4 (11.9)	3.4–66.0	35.4

SOC = Soil organic carbon. S.D = Standard deviation.

Differences in Soil Organic Carbon Amongst Field Types and Areas of the Field

On average, the SOC in g/kg and ratio to clay were higher for permanent grass and boundary field areas compared to temporary and within field areas. The analysis shows no difference in SOC to nitrogen ratio across land types and areas of the field. There was no interaction between land type and field area.

Table 2. Predicted mean (s.e)[1] soil organic carbon (SOC) for different land types and field areas.

Effect	SOC g/kg	SOC/clay ratio	SOC to Nitrogen ratio
Land type			
Permanent	51.5 (2.4)^a	0.20 (0.01)^a	11.4 (0.1)
Temporary	42.5 (2.3)^b	0.15 (0.01)^b	11.3 (0.1)
P value	<0.001	<0.001	0.081
Area			
Open boundary	47.9 (2.4)^a	0.18 (0.01)^a	11.4 (0.1)
Covered boundary	48.9 (2.4)^a	0.19 (0.01)^a	11.4 (0.1)
Within field	44.1 (2.3)^b	0.16 (0.01)^b	11.3 (0.1)
P value	<0.001	<0.001	0.112
Land type x area			
Temporary x open	43.9 (2.5)	0.16 (0.01)	11.3 (0.1)
Temporary x covered	44.5 (2.4)	0.16 (0.01)	11.3 (0.1)
Temporary x within field	39.0 (2.4)	0.14 (0.01)	11.1 (0.1)
Permanent x open	51.9 (2.5)	0.21 (0.01)	11.4 (0.1)
Permanent x covered	53.3 (2.6)	0.22 (0.01)	11.4 (0.1)
Permanent x within field	49.1 (2.4)	0.18 (0.01)	11.4 (0.1)
P value	0.416	0.489	0.1

[1] Means for field type and boundary type within a column and with different superscript letters (i.e., a, b, c) differ significantly. s.e = standard error.

Table 3. Percentage of samples collected that were categorised as poor to very good soil organic carbon (SOC) to clay ratio[1] for different land types and field areas.

Land type	Within field				Boundary			
	n	Poor	Good	Very good	N	Poor	Good	Very good
Temporary	324	0	44	56	324	0	18	82
Permanent	192	0	9	91	192	0	3	97
All samples	516	0	31	69	516	0	12	88

[1] Decimal ratio of SOC to clay, with categorises of ‘poor’ (ratio <0.06), ‘good’ (≥0.06 to <0.12) and ‘very good’ (≥0.12). n = number of samples.

Permanent fields had higher percentage of samples with very good levels of SOC both within the field (91%) and at field boundary (97%) while recording lower percentage of samples with good levels of SOC, 9% within the field and 3% at the boundary (Table 3). Temporary field had lesser percentage of samples with very good SOC in both field areas, 55% at within the field and 82% at the boundary area compared to permanent fields. The percentage of samples with good SOC was higher at the within field area in both fields, 9% in permanent and 44% in temporary fields compared to the boundary areas with 3% in permanent and 18% in temporary fields (Table 3).

Assessment of the average SOC for field boundaries and within field areas per field showed that boundary areas had very good SOC clay ratio (≥0.12) on average. Approximately 78% of all the fields studied had SOC clay ratio ≥0.12 and were classified as having 'very good' SOC content while 22% of the field studied had SOC clay ratio range of ≥0.06 to <0.12 and were classified as having 'good' SOC content. It appears the SOC content of both the boundary and within field areas of all fields studied were at least 'good', but the boundary areas were 'very good' and several within field areas were below boundary area level (Table 4). It was also observed that 22% of fields having 'good' SOC/clay ratio were arable fields, while the remaining 78% of fields with 'very good' SOC/clay ratio were all grass fields. Up to 46.7% of the 30 fields with 'very good' SOC (14 out of 30) were temporary grass fields, while 53.3% of fields (16 out of 30) were permanent grass fields. Average percentage differences in SOC for different measures between field boundary and within field areas across land types are presented in Table 4.

Table 4. Percentage difference in average soil organic carbon (SOC) between boundary and within field areas for fields of temporary and permanent land type.

Land type	SOC (g/kg)	SOC/clay ratio[1]	SOC to Nitrogen ratio
Temporary	16.6	21.9	**2.0**
Permanent	7.5	15.2	**0.0**

[1] Decimal ratio of SOC to clay, with categorises of 'poor' (ratio <0.06), 'good' (≥0.06 to <0.12) and 'very good' (≥0.12).

The percentage difference of SOC between boundaries and within field areas for temporary land type of 11.9 was higher compared to permanent field percentage difference of 7.5 (Table 4). The same pattern was observed for soil SOC clay ratio and SOC to nitrogen ratio, where the percentage difference of SOC clay ratio between boundary and within field areas of 15.7 for temporary land type was higher than the SOC clay ratio percentage difference of 7.5 for permanent land type, and that of SOC to nitrogen ratio were 2.0 for temporary and 0.0 for permanent land type types (Table 4).

4. Discussion

Assessment of SOC levels within field and at field boundaries across permanent and temporary field types showed variations in SOC in the different field areas across the different field types. A consistent pattern of higher SOC levels at field boundaries compared to within-field areas was observed across the study. Boundary areas had significantly higher SOC g/kg and ratio with clay. On average, field boundary areas were mainly categorized as having "very good" SOC/clay ratios (≥0.12), whereas within-field areas had a higher proportion of "good" SOC levels. This study finding agrees with previous studies showing that field margins and hedgerows tend to accumulate more carbon due to lower disturbance and greater organic inputs [27,28]. However, no clear difference was found between open and covered boundaries, indicating that the presence of a boundary itself may be more important than the type of vegetation. This further suggests that reduced disturbance may be the factor that plays the strongest role in the differences observed across the temporary and permanent field boundaries and within field areas. The observed higher SOC at field boundaries suggest that field margins, hedgerows, and buffer strips act as carbon "hotspots" in agricultural landscapes as these areas normally experience reduced disturbance from tillage or traffic, which allows organic matter to accumulate and stabilize [27]. Other researchers have reported that

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undisturbed zones enhance soil aggregation and carbon protection, resulting in higher SOC compared to cultivated areas [29]. Studies of hedgerows and agroforestry boundaries show similar patterns, with continuous litter inputs and root turnover contributing to greater SOC storage [16]. These results align with this study finding that shows that boundary areas often have “very good” SOC/clay ratios compared to the within field area and can be used as a potential benchmark for other areas of the field.

Greater percentages of samples that had very good SOC were from permanent fields and boundary areas of the fields. Temporary fields and the within field area had higher percentages of samples with good SOC levels, which were not as good as those of the samples that recorded very good SOC levels. Good SOC level is a fair level, but it would benefit the soil and sustainable productivity more if it could be maintained at very good classification of the SOC ratings [22,26]. This therefore indicates the need for uplifting in the level of SOC in temporary fields and within field areas of farmland. Permanent fields and the boundary area of a field tend to have more vegetation or shade cover, increased litter fall from hedgerows and less soil disturbances [7,30]. This may explain why the permanent field and boundary area recorded higher sample percentages with very good SOC compared to temporary fields and the within field areas. Another research had reported that vegetation type can influence soil nutrients [21,31]. Increase in the level of SOC through root biomass and litter inputs has been specifically reported in other research findings [31]. These current study findings emphasis the importance of the role of vegetation cover and less soil disturbances in soil nutrients maintenance. But disturbance gradients may be more influential than vegetation type, and this is supported by research showing that tillage and soil management often drive SOC losses more strongly than differences in plant cover [32,33]. However, it is emphasized in other studies that even minimally vegetated or unmanaged boundaries can accumulate SOC over time when disturbance is low [34]. These findings are consistent with this study findings showing that transitions between managed and unmanaged areas of land create distinct biogeochemical conditions that enhance carbon storage relative to intensively managed farmlands [20,35]. Revealing boundaries as the field area with higher carbon levels in this study compared to the within field area provides a practical basis for benchmarking and targeted SOC improvement.

The high percentage differences of 11.9 for SOC and 15.7 for SOC clay ratio recorded in temporary land types and the lower value of 7.5 recorded in permanent land types indicates significant variations in the level of SOC and SOC clay ratios between field boundary and within field areas and suggest an increased need for a lift in SOC in temporary land type compared to permanent land type. The percentage difference in SOC to nitrogen ratio between field boundaries and the within field areas was also higher in temporary field compared to permanent land type. The variations in these SOC properties measurements show higher SOC in permanent land types than in temporary land types as already mentioned, and recording the same trend in the SOC properties variations across the different fields indicates that the screening of each of these properties can be used to gain rough knowledge of the others. Permanent land type is characterized by increased vegetation cover, height and density due to fallowing with increased litter fall and organic matter addition to the soil capable of increasing the soil nitrogen level [36,37]. The boundaries of fields are mostly not subjected to disturbances thus preserving nutrient supply in the boundary areas compared to the within field areas which are mostly disturbed by farming practices and activities [4,7]. The observed higher SOC in grasslands compared to arable fields aligns with well-established evidence that land use strongly influences soil carbon. Grasslands, both temporary and permanent, maintain continuous carbon inputs through dense root systems, litter deposition, and minimal disturbance. This promotes higher SOC storage compared to croplands. Land use influenced SOC distribution, with grassland systems (both temporary and permanent) accounting for most fields classified as having “very good” SOC, while arable fields were mainly in the “good” category. This is consistent with existing evidence that grasslands support higher SOC levels due to continuous root inputs and reduced soil disturbance, whereas arable systems are more prone to carbon loss due to cultivation [2,4]. Grasslands retain more SOC due to continuous root turnover and reduced erosion [38,39]. In contrast, arable land often has lower SOC because of repeated tillage, residue removal, and increased decomposition to disruptt soil aggregates and accelerate carbon loss [5,40]. Practices such as fertilization, grazing, residue management, and tillage can strongly affect SOC, sometimes as much as the land uses itself [6,41,42]. In this study's findings, it could be viewed that while land use is a key driver of SOC patterns, the type of management practice carried out on fields such as fertilization can reduce obvious differences. This highlights the importance of combining land use and information on management practice history in farmland assessments to more accurately capture SOC dynamics.

The use of the SOC/clay ratio as a classification metric provides a useful way to assess soil carbon status, as it accounts for the role of soil texture in carbon stabilization [26]. However, its wider applicability remains debated. Recent studies suggest that SOC concentration or combined indicators may offer more reliable assessments, particularly across different soil types and regions [8,11,13]. Therefore, while the SOC/clay ratio is suitable for comparisons within this study, caution is needed when applying it more broadly. The SOC/clay ratio is widely used to assess soil carbon stabilization because clay helps protect organic carbon from decomposition. It provides a texture-normalized measure of SOC, allowing comparisons between soils with different clay contents [26]. This makes it more standardized than using absolute SOC values, as clay-rich soils naturally store more carbon. However, the SOC/clay ratio may not always be reliable across all soil types or large spatial scales. This is because previous studies have shown that it may fail to capture carbon stabilization in soils with variable mineralogy, organic matter composition, or land-use history [43]. Factors such as soil aggregates, minerals beyond clay, moisture, and temperature can also influence SOC independently of clay content. For this reason, multi-indicator approaches such as the one used in this study are recommended. Other research presented that a multi-indicator approach combining SOC/clay with other measures such as SOC concentration, particulate organic carbon, or aggregate-associated carbon can improve accuracy and allows more robust comparisons across different soils [44]. Overall, SOC/clay is a useful tool for within-study comparisons but should be applied cautiously when comparing soils across regions or soil types. A multi-faceted approach is therefore essential for reliable and generalizable SOC assessments.

The study benefits from a robust dataset comprising 1,032 samples across 43 fields and multiple land uses, providing a strong empirical basis for the analysis. The comparison of SOC metrics, land types, and field areas found differences between boundary and within-field areas. This study showed moderate to high variability in soil properties between field boundaries and the within field areas across temporary and permanent fields, with coefficients of variation ranging from 23.3% to 35.4%. This variability can be associated with the natural heterogenous state of agricultural lands following differences in management practices, vegetation cover, and environmental conditions. The relatively high variability observed in SOC/clay ratio and soil moisture highlights the combined influence of soil physical and chemical processes, and water dynamics on carbon behaviour [14,15,45]. The observed moderate to high variability in soil properties agrees with previous studies showing that SOC and related traits are highly heterogeneous between field boundaries and the within field areas across temporary and permanent fields [46,47]. Linear mix model analysis showed no significant difference in SOC to nitrogen ratio and its interactions across land types, field area, or boundaries. But there were differences in the SOC g/kg and SOC clay ratio for field areas and land types. High variability within groups can reduce the ability of statistical models to detect differences and has been reported as limitations in SOC study with high variability [1]. However, the absence of interaction effects confirms the non-significance difference in SOC to nitrogen ratio recorded in the study. High coefficients of variation 23.3% and above recorded in this study may further limit statistical power because it often produces non-significant results even when real ecological patterns exist causing linear mixed models to miss meaningful relationships [4,48,49]. Absence of significant interaction effects also aligns with evidence that soil-forming factors and management drivers rarely act independently; their effects are often interactive, nonlinear, and scale-dependent [50]. To address these challenges, combining inferential statistics with descriptive or exploratory analyses can reveal important spatial patterns. Stratified and descriptive approaches have been shown to identify SOC trends that are ecologically meaningful but statistically non-significant [51–53].

The consistently higher SOC levels observed at boundaries suggest that they represent realistic targets under similar soil and environmental conditions. This approach is valuable because it is based on site-specific data rather than general thresholds. However, achieving similar higher SOC levels in the within field areas of the land types may require changes in management practices, such as reduced tillage, increased organic inputs, or the use of cover crops, all of which have been shown to improve SOC [3,6,7]. Improving SOC within fields has broader benefits for soil function and agricultural sustainability. Higher SOC levels are associated with improved soil structure, water retention, and nutrient cycling, which can enhance crop productivity and resilience to environmental stress [5,9]. However, it has been reported that the potential for SOC increase in a field area can be limited by factors such as soil carbon saturation and past management history [14]. This highlights the importance of setting realistic targets and maintaining long-term monitoring. The analysis of 1,032 soil samples from 43 fields across six farms in the study provides a robust dataset for evaluating SOC variability. The inclusion of multiple land uses, arable, temporary grass, and permanent grass allows for meaningful comparisons and insights into how management influences SOC levels. Importantly, the comparison between within-field and boundary areas, alongside the classification of boundaries as open or covered, introduces a novel benchmarking method. The study finding that boundary areas consistently exhibit "very good" SOC to clay ratios, and these suggest that these zones can serve as realistic targets for within-field improvement. This approach offers practical value for land managers by identifying areas with the greatest potential for SOC uplift, ultimately contributing to improved soil health and resilience.

5. Conclusions

This study compared metrics for SOC across different land types and field areas. A consistent pattern of higher SOC levels at field boundaries compared to within-field areas was observed across the study. Boundary areas had significantly higher SOC g/kg and ratio with clay. On average, field boundary areas were mainly categorized as having "very good" SOC/clay ratios (≥0.12), whereas within-field areas had a higher proportion of "good" SOC levels. From the fields sampled, 69% of within field samples and 88% of boundary samples were categorized as having 'very good' levels of SOC. It could be proposed from the study findings that assessing the average SOC data records between field boundaries and within field areas and taking notes of the field types effects, permanent and temporary, are important for comparing and monitoring SOC levels in farmlands. An important contribution of this study is that field boundaries, and/or SOC to clay ratio, have been identified as the potential benchmarks for improving SOC within fields due to high SOC content found in the boundaries of the land types compared to the within field area of the field.

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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author. The study is part of a PhD thesis.

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Conflicts of Interest: The authors declare no competing interests.

Abbreviations

The following abbreviations are used in this manuscript:

SOC	Soil organic carbon
NIRS	Near infra-red spectroscopy

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