The impact of Alder on Soil Carbon Storage in Agricultural Hedgerows.

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MSc Island Biodiversity and Conversation – Thesis

Abstract

Hedgerows are prominent features of Jersey's arable landscape and important elements for climate-smart farming. Whilst recognised for their role in biodiversity conservation and climate change mitigation through soil carbon storage, little is known about how hedge composition influences soil carbon dynamics. Soil carbon stocks were quantified beneath 15 hedgerows of contrasting make up (Alder, Alder with Others, Other Species & No Vegetation) and compared with adjacent arable controls. Samples were analysed for carbon concentration, bulk density and, for a subset, elemental carbon & nitrogen. Generalised linear mixed models were used to assess the datasets.

Carbon concentrations were consistently higher in surface soils and declined with depth while bulk density was consistently lower under hedgerows. Other Species hedgerows showed the highest carbon stocks outperforming Alder and Alder with Others.

These finding confirm that hedgerows in Jersey enhance soil carbon stocks relative to open cropland with reduced bulk density indicating improved soil structure. While Alder was the central focus of the study the greatest carbon gains were found beneath Other Species hedges, especially near the surface. Hedgerow management therefore offers a substantial opportunity to support soil health and increase carbon storage in agricultural systems.

Acknowledgments

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Keywords: Soil organic carbon, Alder, Hedgerow, Carbon stock, Bulk density, Jersey,

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1. Introduction

Hedgerows are a key component of agricultural landscapes, providing ecological, environmental and cultural benefits. (Kiepe, 1995; Alignier *et* al., 2020) In addition to their role in supporting biodiversity, acting as wildlife corridors and preventing soil erosion, hedgerows can also contribute to climate change mitigation through soil carbon storage. (Chabbi *et al*., 2022). Soils represent the largest terrestrial carbon pool, containing more than the atmosphere and vegetation combined (Scharlemann *et al*., 2014). Small changes in soil carbon stocks can have significant implications for the global carbon cycle as around 40% of the world's land area is taken up by agriculture. (Lal, 2004; Alston & Pardey, 2014) Hedgerows can enhance soil carbon through increased organic matter inputs from leaf litter and root turnover, reduced soil disturbance at their bases and the modification of soil microclimate conditions. (Holden *et al*., 2019) This potential has gained attention over the past decades leading many countries to introduce protections for hedgerows and to support planting and restoration projects that form part of wider strategies to increase ecosystem services and meet emissions targets. (Holder, 2019)

Soil organic carbon (SOC) is particularly central to hedgerow functionality. Agricultural soils are often depleted in carbon due to repeated cultivation, removal of crop residues and reduced organic inputs. Hedgerows can counteract these losses through the supply of organic matter, microbial interactions and the creation of areas of reduced disturbance. Studies in the UK and Europe have demonstrated that SOC is enriched beneath hedgerows in comparison to cropland although this varies with the hedge structure, age, soil type and the management.

Within the context of hedgerow planting schemes Alder (*Alnus spp*) is of particular interest due to the nitrogen-fixing capabilities it has thanks to the symbiotic relationship with the actinorhizal bacteria *Frankia alni*. (Põlme *et al*., 2014; Tobita *et al*., 2016) This process can increase soil fertility and stimulate plant growth as nitrogen availability is often a limiting growth factor. (McIntyre, 2001) Research into the value of Alder and other nitrogen-fixing trees in agroforestry systems has been undertaken but the contribution of Alder to hedgerows in temperate climates is not well understood. (Parmar *et al*., 2022)

In Jersey hedgerows are a valued feature of the landscape operating as traditional field boundaries and offering habitats to a range of fauna and flora. There have been several studies in Jersey that look at the biodiversity benefits of hedgerows but no studies that investigate the soil carbon benefits. (Government of Jersey, 2011, 2022) This lack of data represents a knowledge gap at a time when a number of organisations are actively engaged in hedgerow planting schemes. Due to the island's small size, high proportion of agricultural land and intensive land use, better understanding how hedgerow composition impacts soil carbon is essential for guiding land management decisions and ensuring that planting schemes deliver the greatest environmental benefit.

The main aim of this project is to determine whether the inclusion of Alder in hedgerows leads to an increase in soil carbon compared with other hedgerow types and non-vegetated boundaries. To assess this aim four categories of boundaries have been examined a) hedgerows solely containing Alder, b) hedgerows containing Alder and other species, c) hedgerows without Alder and d) non-vegetated boundaries (earthen banks). Combining transects taken at the base of the hedgerows with control transects taken parallel further within the field this project provides a direct comparison of each boundary type.

The specific objectives of this project are:

1. Quantify soil organic carbon (SOC) and carbon stocks across different hedgerow types and soil depths.
2. Assess whether hedgerows containing Alder show greater soil carbon storage than hedgerows without Alder.
3. Evaluate the importance of hedge species composition compared to the absence of vegetation and its impact on soil carbon storage.
4. Provide baseline data to inform local planting schemes.

The hypothesis is that the nitrogen-fixing capabilities of Alder will enhance both tree and shrub growth, leading to greater soil organic carbon beneath Alder-containing hedges. It is therefore expected that carbon stocks will also be higher beneath Alder-containing hedges. The findings of this study will add to the limited evidence currently available on hedgerows and soil carbon in Jersey and provide useful guidance for future hedgerow planting schemes on the island and further afield.

2. Methodology

2.1 Study sites

The study area consisted of 15 fields from 3 farms located within the parish of St Ouen in the northwest of Jersey on the interior agricultural plateau (Fig. 1).

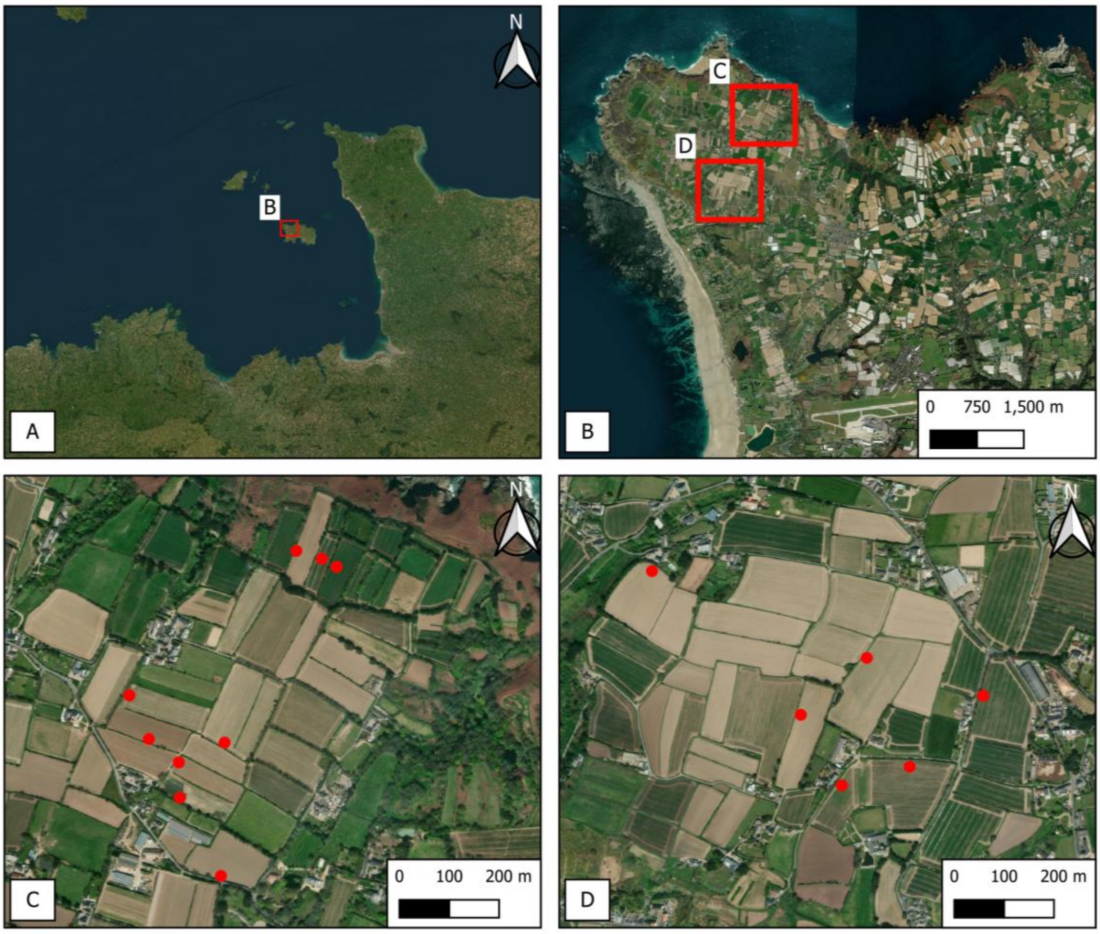

Figure 1A, Jersey's position within the Bay of St Malo. 1B, Parish of St Ouen in the Northwest corner of Jersey. 1C Northern Field area, 1D, Southern Field area. Maps created using QGIS (qgis.org, 2025)

The bedrock in this area of the island is granite (Nichols, 2023) and the fertile soils of sandy loam were formed of loess drift deposits during the Devensian glacial period. (Fiona Fyfe Associates. (2020). (Fig. 2a & 2b) The nature of the soils in this area makes them attractive for agriculture but liable to erosion unless protected by hedgerows.

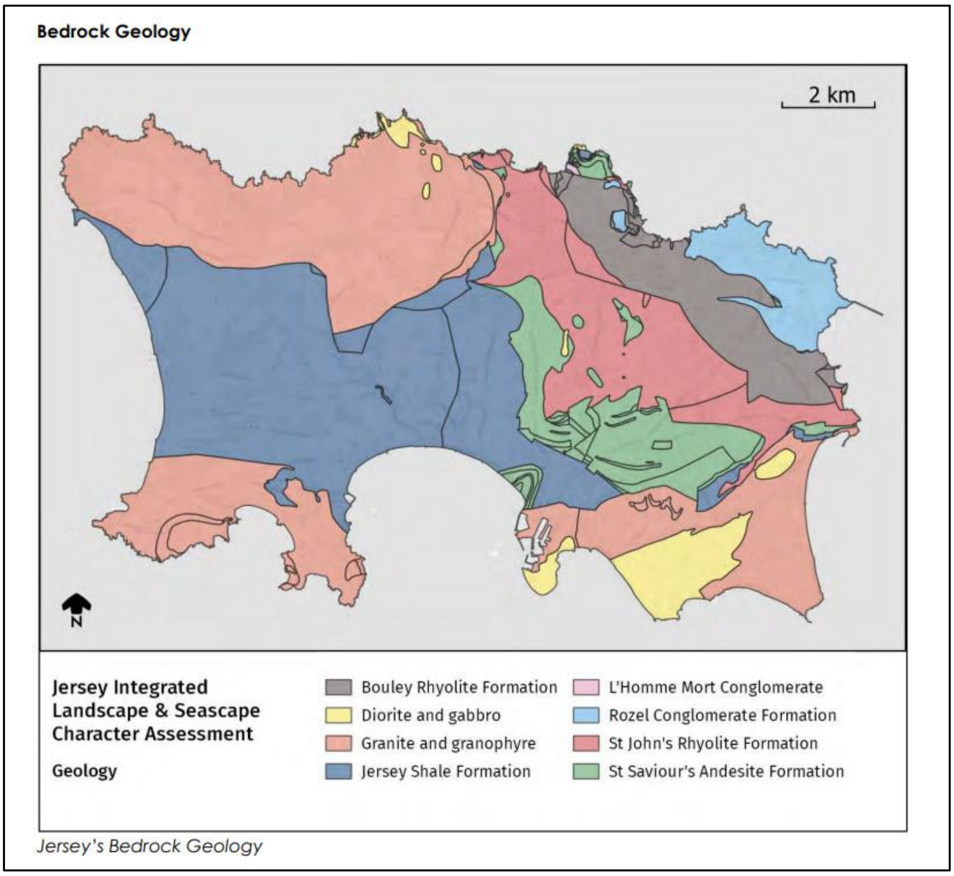

Figure 2a. Jersey Bedrock Geology (Nichols, 2023)

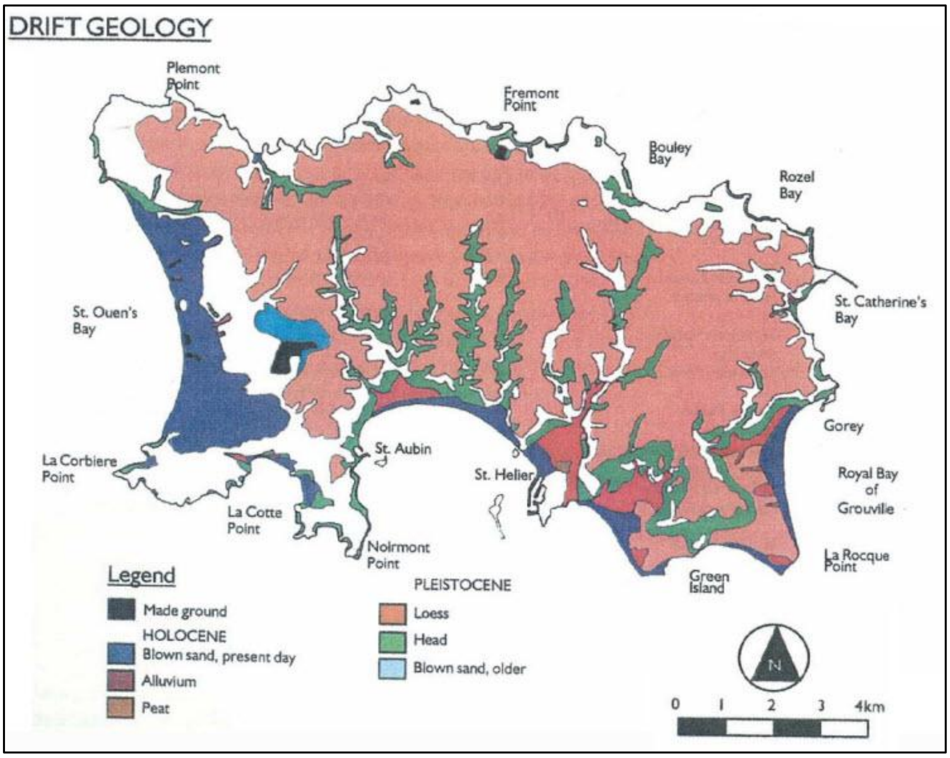

Figure 2b. Jersey Drift Geology indicating areas of loess on the island including the sample sites.

2.2 Hedgerow characteristics

Sites were selected according to species make up with 4 categories: Hedgerows with (A) Alder only, (AO) Alder plus other species, (OS) Other species only, and (NV) no vegetation. All hedgerows bordering public roads and footpaths in Jersey are subject to the branchage, a traditional and legal requirement, whereby twice a year the vegetation must be trimmed back to maintain a clear height of 12 feet over roads and 8 feet over footpaths. Hedgerows between fields are managed by tractor mounted mechanical flail to ensure maximum optimisation of arable field space. There is a large mix of species found in the selected sites including Sycamore (*Acer pseudoplatanus*), Leylandii (*Cupressus* × *leylandii*), Hawthorn (*Crataegus monogyna*), Elder (*Sambucas negra*), Privet (*Ligustrum ovalifolium*) and Alder *(Alnus glutinosa*).

2.3 Soil sampling

All hedgerows selected were a minimum of 30m long and bordered arable fields planted for Jersey Royal potatoes. (Fig. 3)

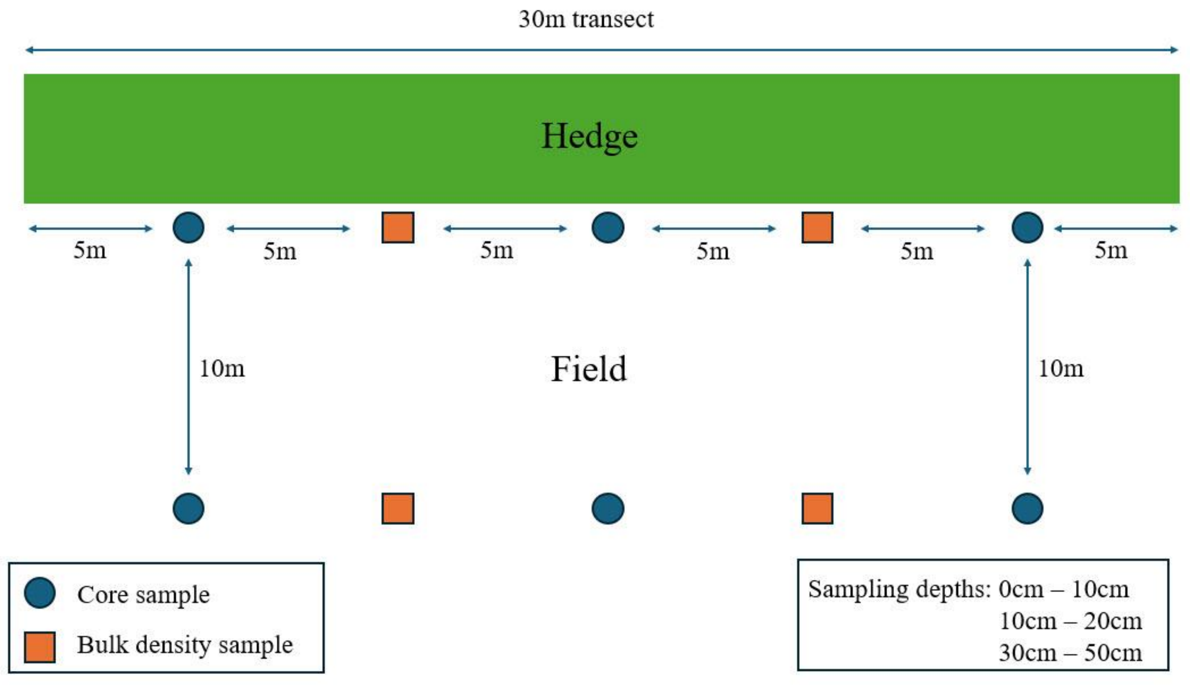

Figure 3. Soil sampling design

Soil samples were taken with a Soil Core Sampler (60cm x 13mm c/w hammer head) (Fig. 4a) at the edge of the foliage at 5m, 15m and 25m along the length of the hedgerow. Control samples were taken parallel to the hedgerow samples 10m further into the centre of the field. Each soil sample was split into depths at 0-10cm deep, 10-20cm deep and 30-50cm deep and placed in sealed polythene bags for storage. Sample depths were chosen to allow the identification of discrete layers: The A Horizon at 0-20cm was split into 2 samples. 0-10cm is rich in organic matter and biologically active, 10-20cm is used to track changes due to root activity. The B Horizon was sampled at 30-50cm where less organic matter is expected but it is important for longer term storage of carbon. This lower layer is also below the usual ploughing depth and so exhibits a more intact soil structure. Samples were weighed and then dried at 65°C for 24hrs or until no further weight loss was recorded. Each sample was hand ground in a pestle and mortar before being sieved through a 2mm mesh.

Bulk density (BD) samples were also taken at 10m and 20m along the hedgerow canopy line along with controls at the 10m parallel. For these a 50cm deep pit was dug out at each position. A soil core ring was hammered into the soil on a side wall to avoid any additional compaction whilst digging the pit. (Fig 4b) The soil core ring had a diameter of 69mm and depth of 60mm giving a total volume of 224.36cm^3. Bulk samples were also dried at 65°C for 24hrs or until no further weight loss was recorded. These samples were ground and sieved at 2mm. The coarse fragments (>2mm) were removed and weighed, and the volume of the coarse fragments was calculated via volumetric dispersal using water-filled graduated cylinders.

Figure 4a. Soil core.

Figure 4b. Bulk density ring core.

Calculation to find the fine earth BD excluding the rocks was done with the following equation:

$$BD_{fine} = \frac{W_{fine}}{V_{core} - V_{rock}} \quad (\mathrm{g/cm^3})$$

Where W*fine* is the total dry weight of the sample, V*core* is the volume of the core and V*rock* is the volume of the rocks removed from the sample.

2.4 Loss on ignition

The soil core samples were taken to the geography lab at the University of Exeter for testing. Each sample was tested by loss on ignition (LOI). This required crucibles to be heated to 100°C overnight before being cooled and weighed. A soil sample was added to the crucible, and it was weighed again. (Fig 5a) Samples were heated at 100°C overnight to ensure they were totally dry. Samples were then placed in a Carbolite AAF 1100 muffle furnace at 550°C for 4 hours to burn off the organic matter (Fig. 5b). Once removed the samples were placed into desiccator jars to cool and when cool the crucible with the ash was weighed and the following equation was used to get the carbon content of each sample:

$$\text{LOI (\%)} = \left(\frac{W_{\text{dry}} - W_{\text{ash}}}{W_{\text{dry}}} \right) \times 100$$

Where W*dry* is the crucible plus oven-dried soil (g) before burning, W*ash* is the crucible plus ash after ignition. Converting LOI to Organic Carbon is regularly done using the Van Bemmelen factor of 1.724 or inversely 0.58% but there are concerns that this can overestimate organic matter due to the combustion of clays and other inorganic constituents. (Minasny *et al.,* 2020) As such a conservative value of 0.50% was used to avoid inflating C estimates. (Pribyl, 2010)

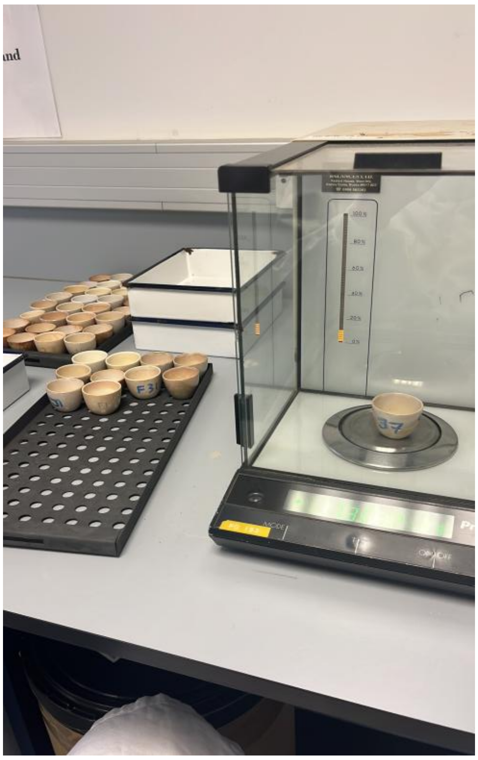

Figure 5a. Weighing soil samples.

Figure 5b. Loss on ignition testing in the furnace.

2.5 Carbon Stocks

Total C stocks were calculated and converted into metric tons per hectare using the following equation (adapted from Van Den Berge *et al*., 2021)

$$\textbf{Bulk Density (g/cm}^3\textbf{)} \times \left(\frac{\textbf{Carbon Content (\%)}}{100} \right) \times \textbf{Layer Thickness (cm)} \times 0.1$$

2.6 Elemental Analysis

LOI was chosen as an analysis technique due to time and cost considerations. However, an opportunity arose at the University of Exeter to perform a small Elemental Analysis run. As such it was decided that samples from the centre of the hedgerow (15m position) should be tested. Shallow samples from a depth of 0-10cm from the hedgerow transect were selected along with shallow and deep samples (0-10cm and 30-50cm) from the control transect at 10m parallel.

The rationale behind this was to look for maximum contrast with minimal laboratory costs. More detailed testing of the topsoil on the hedge transect and the control transect better reflects the impact of biological enrichment from leaf litter and root exudates. Testing both deep and shallow samples on the control transect shows the vertical nutrient distribution in the absence of the hedgerow.

Testing required soil samples between 15-20mg to be placed in individual tin capsules. These capsules are then sealed and compressed to ensure they are airtight. (Fig. 6)

Figure 6. Preparation of samples for elemental analysis.

Capsules are loaded into a ThermoFisher Scientific Flash 2000 Elemental Analyser (Fig. 7) where they are introduced into the reactor with a specific amount of oxygen to facilitate combustion. The combustion gases are analysed to give accurate readings of Carbon and Nitrogen content within the sample and a resultant C:N ratio.

Figure 7. Elemental Analyser

2.7 Biodiversity sampling

Earthworm counts were performed for all the fields selected. Sample pits were dug along each hedgerow transect at 5m, 10m, 15m, 20m, and 25m. (Fig. 8) Each pit measured 20cm x 20cm x 20cm and soil removed from the pit to a plastic container and then hand sorted to locate and

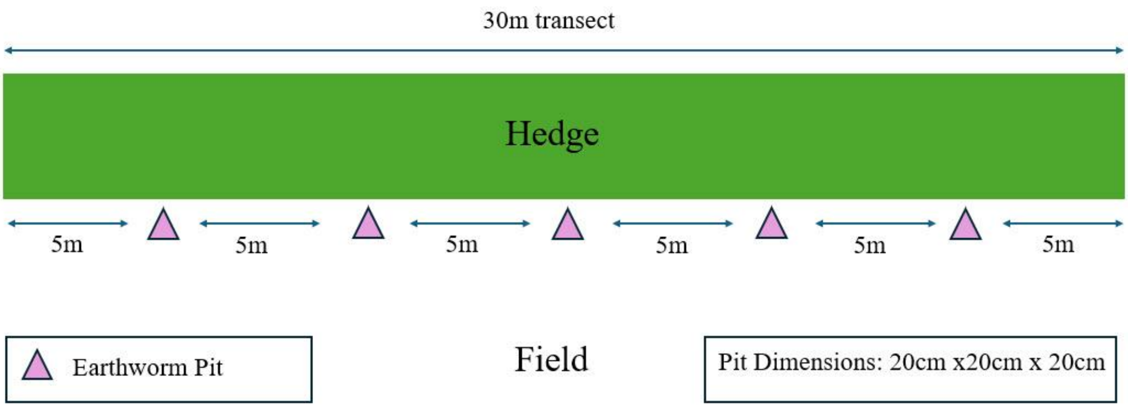

Figure 8. Earthworm sampling design.

identify earthworms before replacing the soil. Earthworms were to be sorted into adult and juvenile and by functional group, namely Epigeic (found in the soil surface or leaf litter), Endogeic (found within the upper soil layers) and Anecic (found in permanent vertical burrows extending deep within the soil profile).

2.8 Statistical Analysis

All of the statistical analyses were undertaken in R version 4.3.1 (R Core Team 2025) using R Studio version 2025.05. Build 513 (Posit Team, 2025). Additional packages used include:

- lme4 (Bates *et al*., 2015)
- lmerTest (Kuznetsova *et al*., 2017)
- DHARMa (Hartig, 2022)
- influence.ME (Nieuwenhuis *et al*., 2012)
- emmeans (Lenth, 2024)
- ggplot2 (Wickham, 2016)
- stringr (Wickham *et al*., 2023)
- dplyr (Wickham *et al*., 2023a)
- tidyr (Wickham *et al*., 2023b)
- multcompView (Graves *et al*., 2019)

A Generalised Linear Mixed Model (GLMM) was run on the LOI-derived SOC dataset as well as the BD dataset and then the merged result of these to calculate Carbon Stocks. The fixed effects were hedge type (A, AO, OS or NV), field location (Hedge or Control transects) and sample depth (0-10cm, 10-20cm & 30-50cm). Random effect used was field number. This model was used due to the hierarchical sampling design. Estimated Marginal Means (EMM) were run to identify the adjusted means over the other predictors.

On the Elemental Analysis dataset due to the smaller quantity of data a series of one-sample t-tests were used on within-field differences. A Linear Mixed Model (LMM) was used to look for hedge type and field location effects and an EMM was run.

3. Data Analysis

3.1 GLMM on LOI-derived SOC data.

The initial GLMM included field number as a random effect, with a variance estimate of 0.289 (Standard Deviation (SD) = 0.538), confirming that there was variance between fields. The residual variance was 0.413 (SD = 0.643)

For the fixed effects, field location showed a strong main effect ($t = 4.62$, $p < 0.001$), with hedge transects having significantly higher LOI-derived SOC compared to controls across hedge types. In contrast, hedge type ($t = 0.14 – 1.59$, p-value = 0.13 – 0.89) and sample depth ($t = -0.75$ - -0.07, p-value = 0.45 – 0.94) did not show significant main effects.

Within the interactions, hedge type x field location showed a significant effect for OS ($t = 2.73$, $p < 0.001$), indicating that OS hedges had greater SOC in hedge transects than in control transects. A marginal interaction was also seen for NV x field location ($t = -1.86$, p-value = 0.065). Also, field location x depth (30-50cm) was significant ($t = -2.72$, p-value = 0.007), showing that hedge transects had relatively lower SOC at depth compared to controls. All other two and three-way interactions were not significant ($p > 0.1$).

Model assumptions were checked by using DHARMa to simulate residuals and check for uniformity, dispersion and outliers. The diagnostics indicated several high-carbon outliers were influencing the model residuals. As such Cook's distance plot was run to identify them. The influential points came mainly from hedge transects including several from Field 1176AW (Alder) and Field 120W (Other Species) at depths of 0-10cm. (Diagnostic plots can be seen in Appendix 2 B1)

3.2 Refitted GLMM with outliers removed.

The model was run again with the outliers removed to check for robustness (Figure 9).

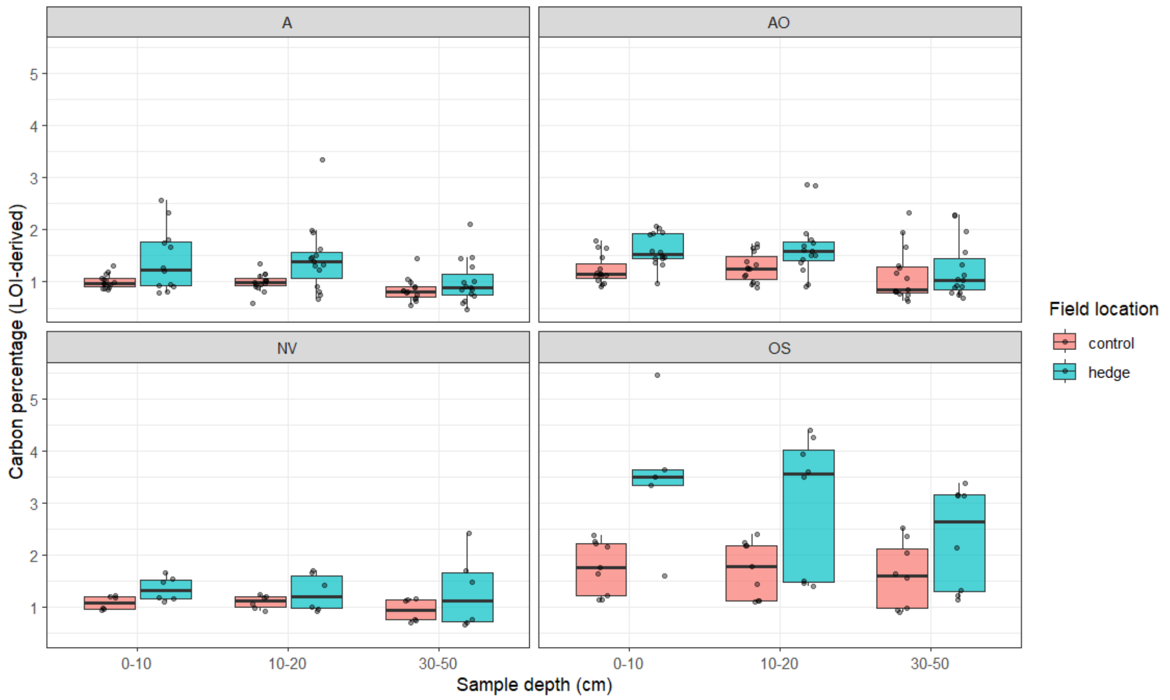

Figure 9. Boxplot of LOI-derived SOC by hedge type, depth and transect. Outliers were removed prior to plotting.

Variance dropped from 0.289 (SD = 0.538) to 0.208 (SD = 0.456) with residual variance dropping from 0.413 (SD = 0.643) to 0.126 (SD = 0.355)

The refitted model showed the effect of hedge type remained highly significant (t = 3.25, p-value = 0.0013) with higher SOC values in the hedge transects compared to the controls. The OS hedge now shows a near significant main effect (t = 2.08, p-value = 0.055), while other hedge type (AO & NV p-value > 0.45) and sample depth (p-value = 0.19-0.90) were not significant.

Significant interactions were found for hedge type OS x field location (t = 4.47, p-value < 0.001) showing a much higher SOC in OS hedge transects compared to the control transects. A borderline effect was also seen for hedge type OS x field location x depth at 30-50cm (t = -1.67, p-value = 0.096). All other interactions were not significant (p-value > 0.1)

EMMs from the refitted model are shown (Figure 10) illustrating the strong hedge-control contrast, particularly in OS hedges across all depths and for A and AO hedges in the surface layers. Further analysis of the differences identified in the refitted GLMM produced pairwise contrasts of EMMs

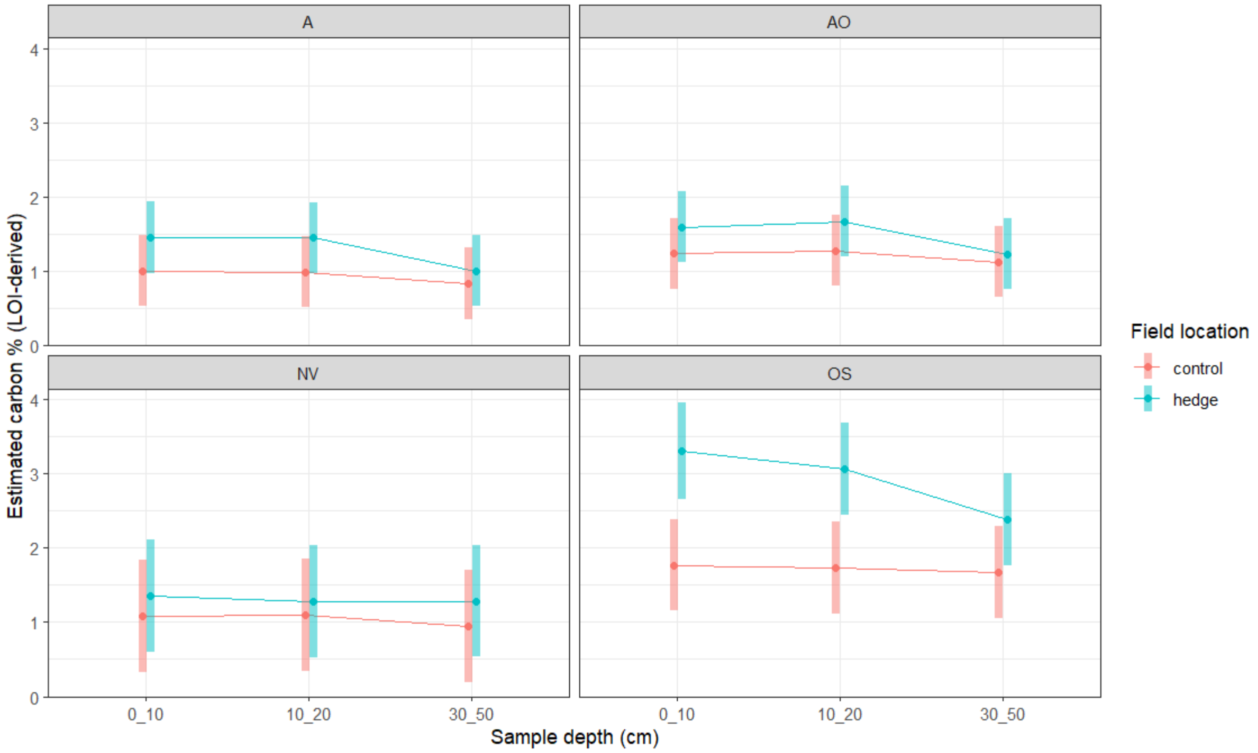

Figure 10. EMMs of (±95% confidence intervals) of LOI-derived SOC from refitted GLMM.

From the refitted GLMM, model-predicted SOC percentages at 0-10cm were significantly higher in the hedge transects than the control transects across hedge types (Table 1).

Hedge type	Sample Depth	Contrast	Estimate	SE	df	t	p-value
A	0_10	hedge - control	0.4510	0.1390	223.376	3.25	0.001
AO	0_10	hedge - control	0.3610	0.1320	223.026	2.74	0.007
OS	0_10	hedge - control	1.5420	0.2000	223.355	7.7	<0.001
A	10_20	hedge - control	0.4610	0.1300	223.000	3.55	<0.001
AO	10_20	hedge - control	0.3910	0.1300	223.000	3.01	0.003
OS	10_20	hedge - control	1.3290	0.1730	223.054	7.69	<0.001
NV	30_50	hedge - control	0.3440	0.2050	223.000	1.68	0.095
OS	30_50	hedge - control	0.7090	0.1780	223.145	3.97	<0.001

Table 1. Pairwise contrasts (Hedge vs Control) from EMMs of the refitted GLMM for LOI-derived SOC where differences were significant or marginal. Estimates are on the response scale (% carbon)

Under A hedges SOC increased from 0.76% in controls to 1.79% in hedge transects, a 135% increase (p-value = 0.001). For AO hedges, SOC rose from 1.04% to 1.90%, an 83% increase (p-value = 0.007). The strongest effect was seen under OS hedges where SOC increase from 1.26% in control transects to 3.01% in the hedge transects, a 140% increase (p-value < 0.001). In contrast

NV hedges showed very little difference (0.92% vs 1.01%, a roughly 10% increase and not significant).

3.3 GLMM on Bulk Density data.

The GLMM model again included field number as a random intercept with a variance estimate of 0.0126 (SD = 0.112) and residual variance = 0.0169 (SD = 0.130) indicating more within-field variability, but with a substantial field element.

Raw data boxplot of BD data shows distributions of BD across hedge types, depths and field locations. showing generally lower bulk density in hedge transects with the strongest differences seen under OS hedges. (Figure 11). Model-EMMs backed up these patterns with predicted values and 95% confidence intervals.

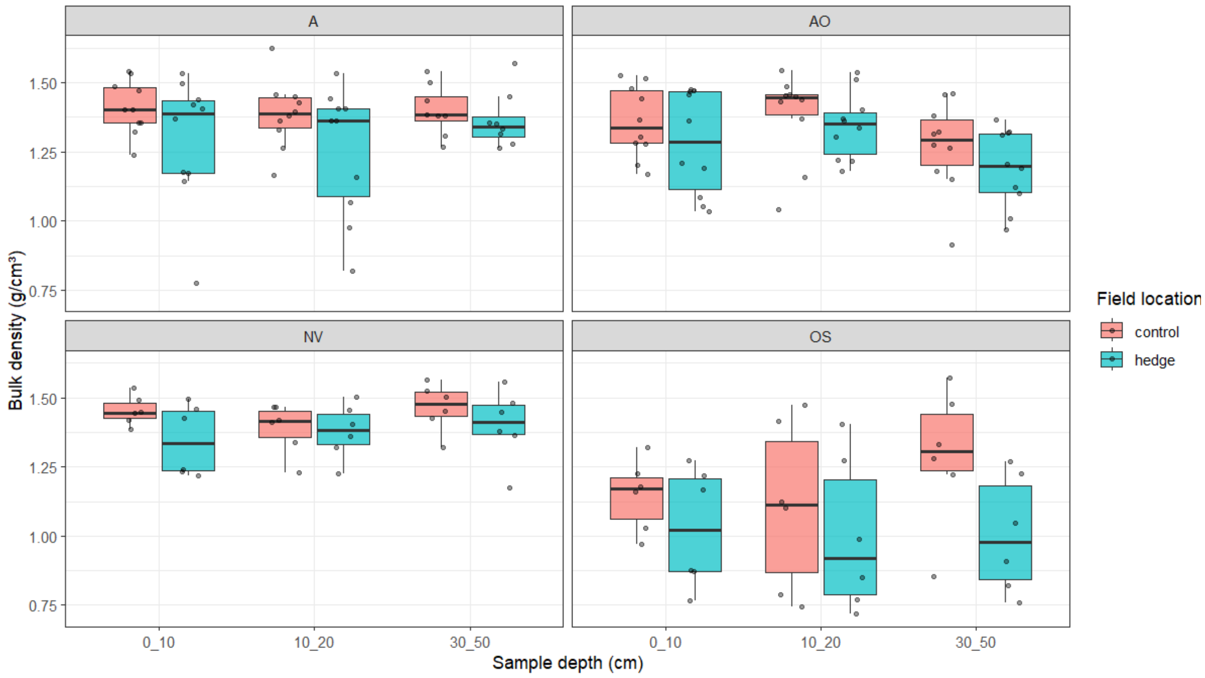

Figure 11. Raw boxplot of bulk density (g/cm^3) across sample depths, field location and split by hedge type.

Looking at fixed effects the main effect of hedge type was significant at OS only (t = -2.49, p-value = 0.019) showing lower BD compared to A hedges. The main effect of field location was also significant (t = -2.02, p-value = 0.045) showing lower BD values in hedge transects compared to controls. The other hedge types (p-value = 0.56 - 0.68) and sample depth (p-value = 0.61 - 0.67) were not significant.

Among the interaction terms, none were found to be significant at p-value < 0.05 although two terms were near significant: hedge type OS x depth (30-50cm: t = 1.79, p-value = 0.076) and hedge type OS x field location x depth (30-50cm: t = -1.81, p-value = 0.072). No other interactions were found to be significant.

EMMs of BD were calculated from the mixed model to show predicted values across sample depths, field locations and hedge types. (Figure 12). This plot shows mean predictions with 95%

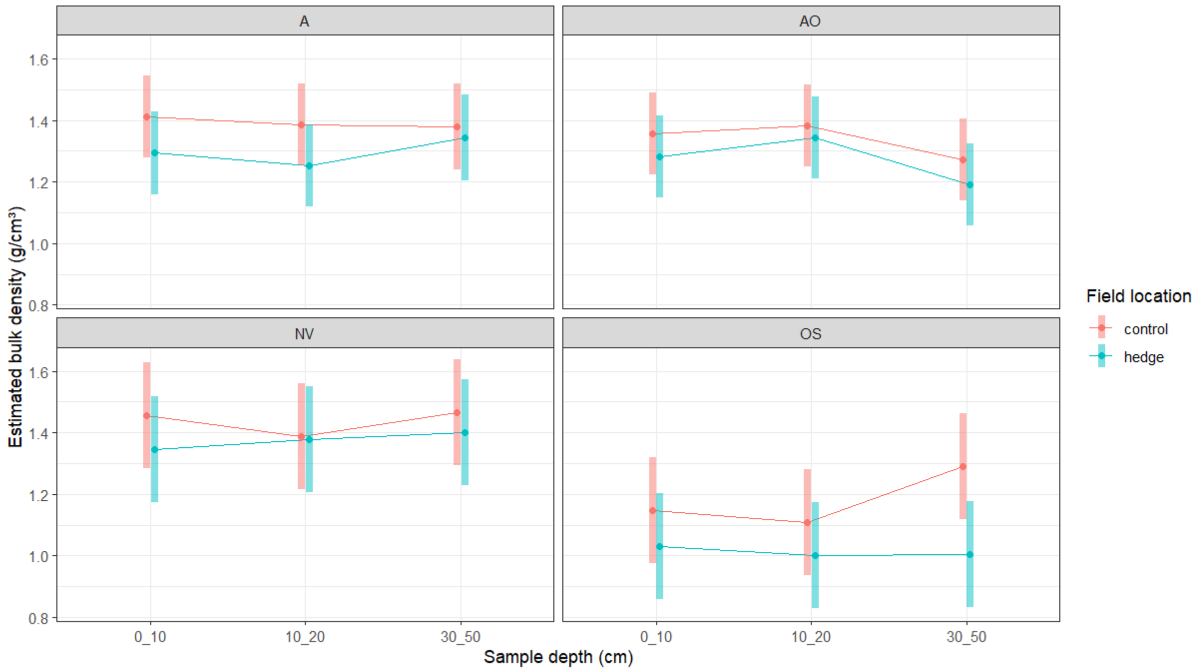

Figure 12. EMMs of bulk density (g/cm^3). Points represent model-predicted means with 95% confidence intervals.

confidence intervals for each hedge type in both hedge and control transects and at each of the sample depths. This highlights significantly lower bulk densities in hedge transects for A hedges in the surface depths and for OS hedges at 30-50cm. (Table 2)

Hedge type	Depth	Contrast	Estimate	SE	df	t	p-value
A	0-10	hedge - control	-0.117	0.058	152	-2.02	0.045
A	10-20	hedge - control	-0.133	0.058	152	-2.28	0.024
OS	30-50	hedge - control	-0.284	0.075	152	-3.78	<0.001

Table 2. Significant pairwise contrasts (hedge vs control) of EMMs from bulk density GLMM. Negative estimates indicate lower bulk density in hedge transects compared to control transects.

Under Alder hedges the BD decreased at 0-10cm from 1.41g cm^{-3} in the controls to 1.29g cm^{-3} in the hedges giving an 8.5% reduction (p-value = 0.045) and at 10-20cm from 1.39g cm^{-3} to 1.25g cm^{-3}, a 10.1% reduction (p-value = 0.024). The strongest effect was observed under OS hedges at

30-50cm depth, where the BD declined from 1.29g cm^{-3} in the controls to 1.01g cm^{-3} in the hedges, a 21.7% reduction (p-value = <0.001)

Diagnostic testing was carried out to verify the model assumptions for the BD GLMM. Residuals were normally distributed. There were no major outliers, no significant skewing and no dispersion issues. Mild nonlinearity was observed in the residual spread. (Diagnostic plots are provided in Appendix 2, B4)

3.4 Carbon Stocks (3 depth layers)

A GLMM was fitted to investigate the carbon stocks. The model again had fixed effect for hedge type and field location and sample depth and used field number for a random effect. The variance estimate of 41.8 (SD = 6.47) and residual variance of 66.6 (SD = 8.16), confirming that there is considerable variability both between and within fields.

For fixed effects field location showed a strong main effect (t = 4.12, p-value < 0.001) with hedge transects having significantly higher carbon stocks compared to control transects across hedge types. Sample depth also showed a significant effect at 30-50cm (t = 3.30, p-value = 0.0011), with carbon stocks being substantially higher than in the 0-10cm layer. This is likely due to the greater thickness of this layer (20cm thick as opposed to 10cm thick for the other layers sampled). In contrast, hedge types did not show significant main effects (AO, OS, N p-value = 0.34 – 0.81).

Within the interactions, no terms achieved significance (p-value < 0.05) although a number were marginal. Interactions between NV hedges and field location (t = -1.94, p-value = 0.054 indicated that NV provided little extra carbon compared to the control transects. OS x depth (30-50cm) was also marginal (t = 1.93, p-value = 0.055) suggesting OS may store more carbon at deeper layers. Hedge x depth (10-20cm) was marginally negative (t = -1.93, p-value = 0.055) meaning hedge transects did not accumulate as much carbon in the mid layers as they did at the surface and deeper layers. No other two and three-way interactions were significant (p-value = > 0.1).

Raw data visualisation (Figure 13) shows distribution of carbon stocks across all three variables with higher stocks seen in hedge transects especially for OS hedges. Model-EMMs

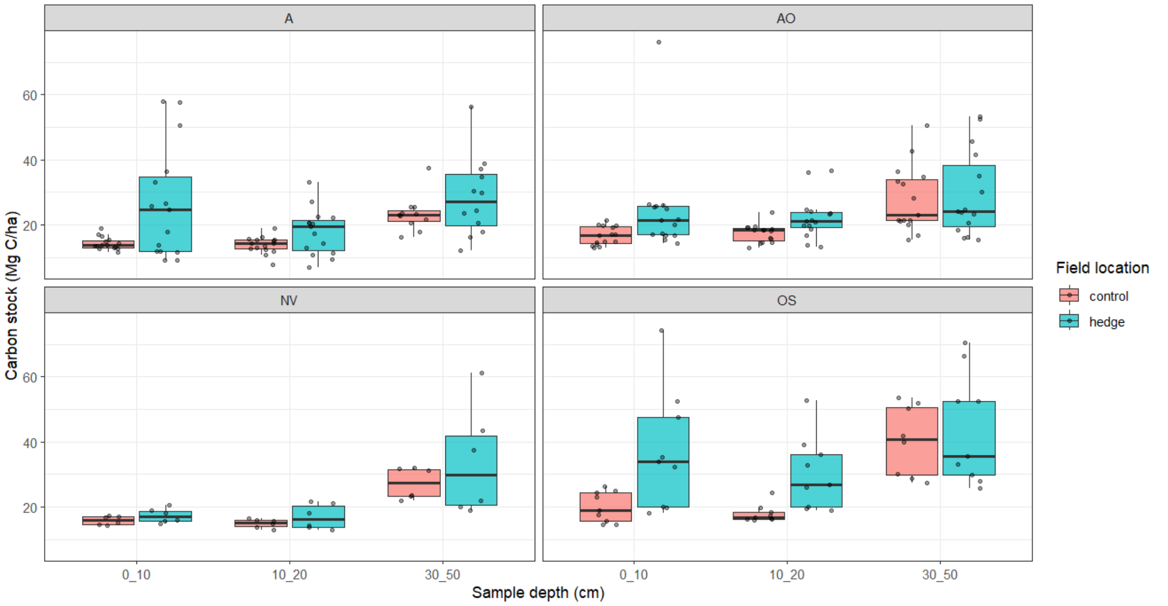

Figure 13. Raw boxplots of soil carbon stocks (Mg C ha^{-1}) across hedge types, field location and sample depths.

(Figure 14) confirmed the patterns showing hedge transects to have consistently higher predicted carbon stocks than controls. Pairwise contrasts of EMMs showed significant hedge-control

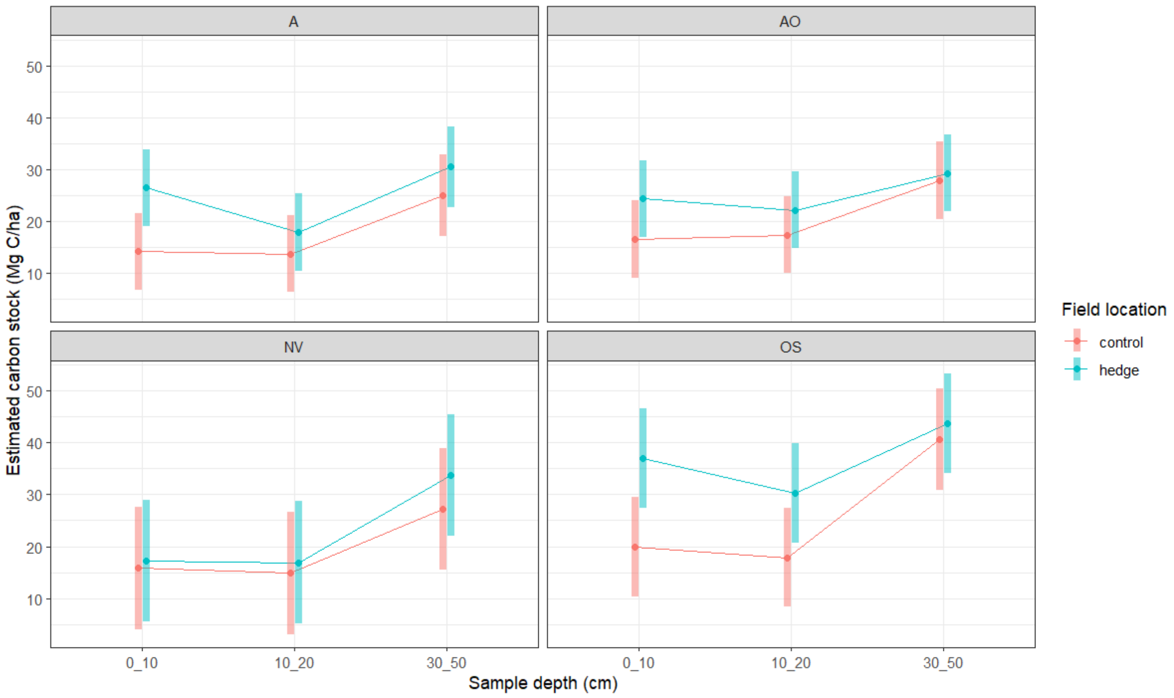

Figure 14. EMMs (±95% CI) of soil carbon stocks (Mg C ha^{-1}).

differences at specific depths (Table 3). Hedge transects had significantly higher carbon stocks than controls in A (0-10cm), AO (0-10cm), OS (0-10cm) and OS (10-20cm). All other contrasts were not significant.

hedge type	sample depth	contrast	estimate	SE	df	t.ratio	p.value
A	0_10	hedge - control	12.263237	2.980058	227.0014	4.1151	< 0.001
AO	0_10	hedge - control	7.789286	2.980058	227.0014	2.613804	0.010
OS	0_10	hedge - control	17.138869	3.847238	227.0014	4.45485	< 0.001
OS	10_20	hedge - control	12.324449	3.847238	227.0014	3.203454	0.002

Table 3. Significant pairwise contrasts (hedge vs control) of EMMs for soil carbon stocks (Mg C ha^{-1})

At 0-10cm carbon stocks increased by 12.3 Mg C ha^{-1} (86% increase) under A hedges (p-value <0.001), 7.8Mg C ha^{-1} (47% increase) under AO hedges (p-value = 0.010) and 17.1 Mg C ha^{-1} (86% increase) under OS hedges. (p-value < 0.001). At 10-20cm depths a significant increase of 12.3 Mg C ha^{-1} (69% increase) was seen under OS hedges (p-value = 0.002). No significant hedge-control differences were seen at 30-50cm

3.5 Total Carbon Stocks (0-50cm)

The GLMM used field number as random effect with a variance estimate of 288.8 (SD = 17.0) and residual variance of 249.1 (SD = 15.8), showing substantial variation in total carbon stocks between and within fields.

For the fixed effects, field location showed a strong main effect (t = 3.83, p-value < 0.001), with hedge transects storing on average 22.0 Mg C ha^{-1} more carbon than controls across all hedge types. Hedge type main effects were not significant, although OS hedges showed a borderline increase in total stocks relative to A (t = 2.04, p-value = 0.061). AO & NV did not differ significantly from A (p-value = 0.19 – 0.44). No significant interaction terms were observed. The OS x field location was near significant (t = 1.62, p-value = 0.11) indicating OS hedges may store more additional carbon in hedge transects compared to control transects but this was not statistically robust.

Raw distributions (Figure 15) and EMMs (Figure 16) both illustrate consistently higher total carbon stocks in hedge transects with OS showing the largest overall values. (Mean carbon stocks per hedge type are given in Appendix 3 C1).

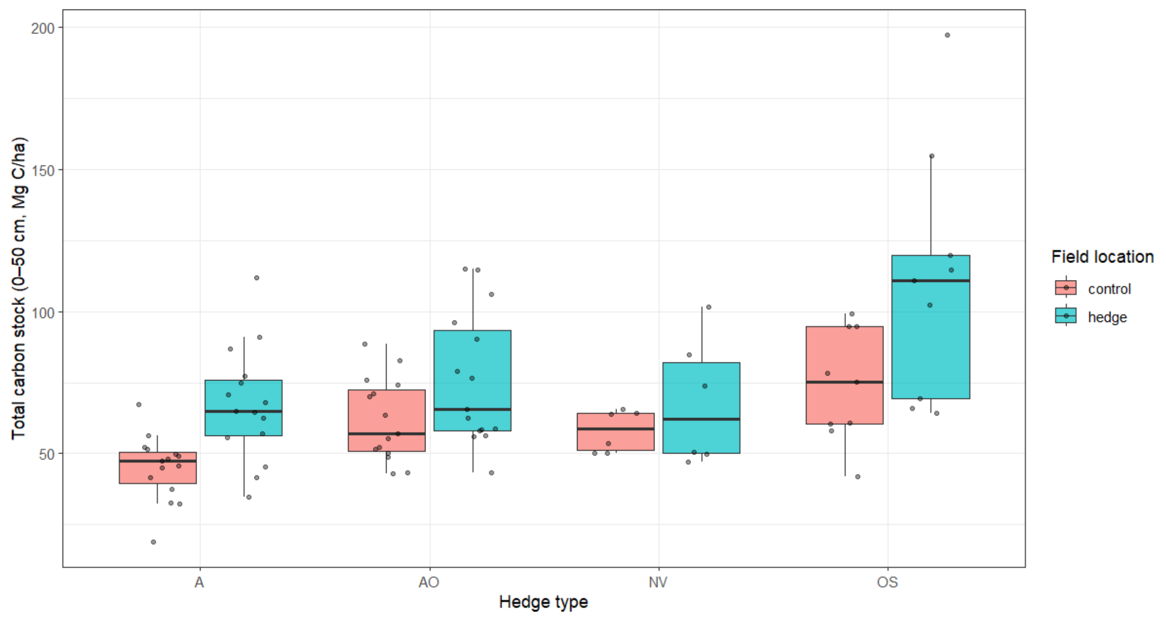

Figure 15. Raw boxplots of total (0-50cm) soil carbon stocks (Mg C ha^{-1}) across hedge type and transect.

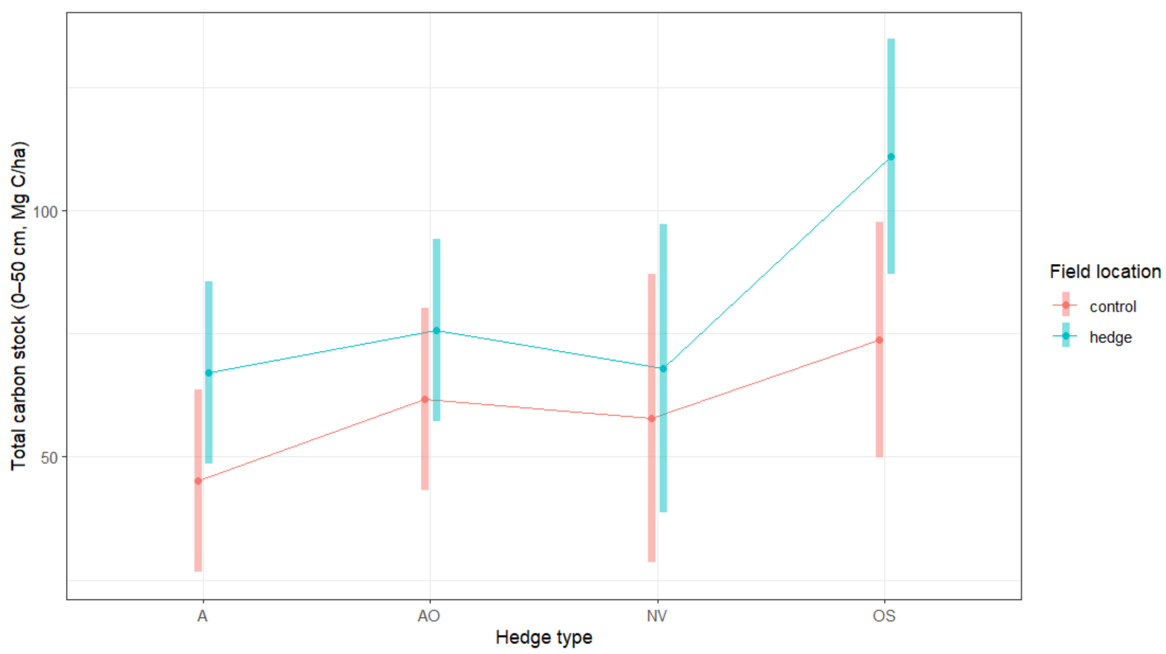

Figure 16. EMMs (±95% CI) of total carbon stocks (0-50cm) from the GLMM.

Pairwise contrasts of EMMs confirmed significant differences between hedge and control transects for several hedge types (Table 4). Hedge transects stored significantly more total carbon than controls in the A hedges (+22.0 Mg C ha^{-1}, 42% increase, p-value = 0.003), AO hedges (+14.0 Mg C ha^{-1}, 23% increase, p-value = 0.018), and OS hedges (+37.3 Mg C ha^{-1}, 51% increase, p-value < 0.0001).

In contrast NV hedges showed no significant difference between hedge and control transects (+10.0 Mg C ha^{-1}, 17% increase, p-value = 0.28). These results show that hedges are associated with higher total carbon stocks across the full 0-50cm soil profile, particularly for OS hedges whilst NV hedges contribute little additional carbon relative to controls.

Hedge type	Contrast	Estimate (Mg C ha)	SE	df	t	p-value
A	hedge - control	22.0	5.76	71	3.83	< 0.001
AO	hedge - control	14.0	5.76	71	2.43	0.018
OS	hedge - control	37.3	7.44	71	5.01	< 0.001

Table 4. Significant pairwise contrasts of EMMs for total (0-50cm) soil carbon stocks (Mg C ha^{-1})

3.6. LMM on Elemental Analysis

3.6.1 Carbon Data

A linear mixed model to look at C% in topsoils (0-10cm) used field number as a random effect with variance of 0.170 (SD = 0.412) and with residual variance of 0.948 (SD = 0.974). Mean C% in the control transects was 0.99 ± 0.29%. Hedge transects showed a significant enrichment, with SOC higher by 0.79% (t = 2.21, p-value = 0.040) (Figure 17)

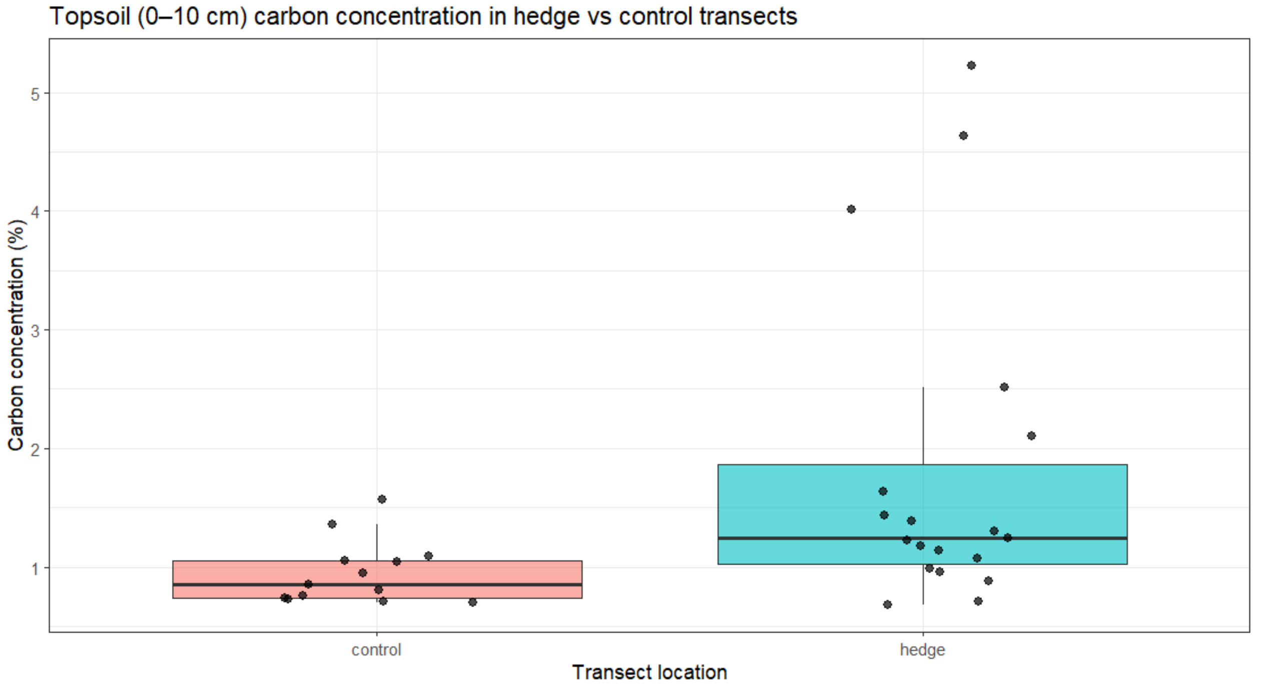

Figure 17. EA -derived SOC(%) in topsoils. Hedge transects generally showed higher SOC with greater variability than control transects

The model showed that whilst hedge soils tend to have higher C%, the differences were not statistically significant once hedge type was included. Field number variance was 0.056 (SD = 0.236) much lower than when just looking at field location. Residual variance also differed at 1.094 (SD = 1.046) indicating that the main variability is within the fields. The intercept (control and hedge type A) was ~0.76% C. Hedge effect for A was +1.03% C but not significant (p-value = 0.15). AO, OS & NV hedge types showed no significant difference from A (p-value > 0.60). Interaction (hedge x hedge type) were not significant (p-value > 0.40).

Despite the lack of statistical significance, the EMMs (Figure 18) show a general trend towards higher SOC in hedge transects in particular in the OS hedges where the mean concentration is almost three times higher under hedges compared to the controls. However, the wide confidence intervals for both OS and NV reflect a high variability.

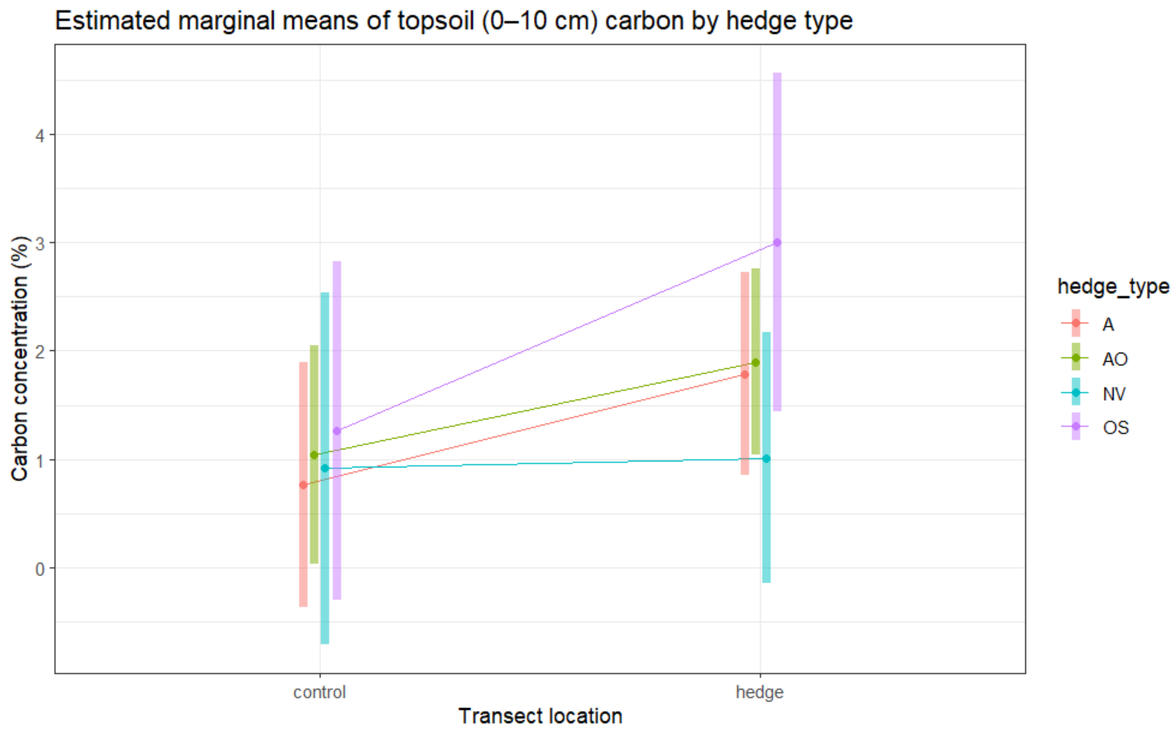

Figure 18. EMMs of SOC (%) in topsoil across hedge type and field location. Hedge transects generally show higher SOC especially in OS hedge type.

A LMM was undertaken for control transect samples at 0-10cm vs 30-50cm. The intercept for 0-10cm was 1.03% C and the 30-50cm effect was -0.14% C showing that deeper soils tended to have slightly lower C% but that it was not significant (t = 1.37, p-value = 0.20).

The LMM was run again to include hedge type, and it was found that SOC did not differ significantly by hedge type (p-value = 0.28 – 0.98). A non-significant trend was seen for slightly higher values in OS hedges but the effect was small. Depth (0-10cm vs 30-50cm) did not significantly influence C% (p-value = 0.52).

3.6.2 LMM on Elemental Analysis Nitrogen data

Running the LMM on Nitrogen data estimated a random variance of 0.00164 (SD = 0.040) which is small compared to the residual variance of 0.0044 (SD = 0.066) showing within-field variance of N% is roughly 0.07%. The results show that at 0-10cm N concentration (NC) averaged 0.092%. Hedge soils had significantly higher N with an estimated increase of 0.055% (t = 2.21, p-value = 0.040). Random effects indicated little variation between fields compared to within fields. (Figure 19).

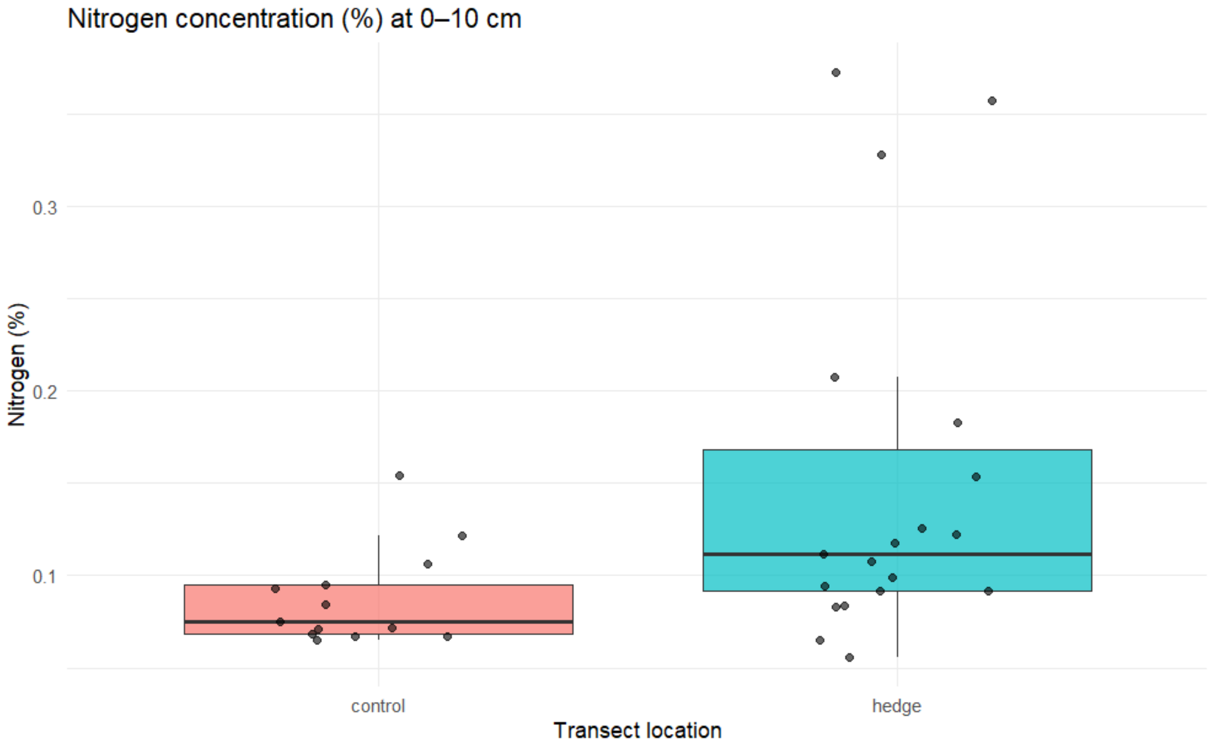

Figure 19. Boxplot of NC (%) showing higher NC in hedge transects.

Refitting the LMM to include hedge type as a fixed effect contributed little random variation with variance = 0.0010 (SD = 0.032 and residual variance = 0.0050 (SD = 0.071). For the fixed effects neither field location nor hedge type main effects were significant predictors on NC (p-value = 0.52 – 0.91). Similarly, none of the interaction terms between hedge type and field location were significant (p-value > 0.48). Overall trends (Figure 20) show slightly higher NC in hedge transects but not significantly so.

The EMMs (Figure 20) show that in A hedges N% is higher at the hedge transect (0.137) than the control transect (0.075). AO shows a similar pattern: hedge (0.162) vs control (0.098). NV hedges show very little difference: hedge (0.089) vs control (0.083) whilst OS hedge soils have almost double the N% (0.241) compared to control soils (0.119)

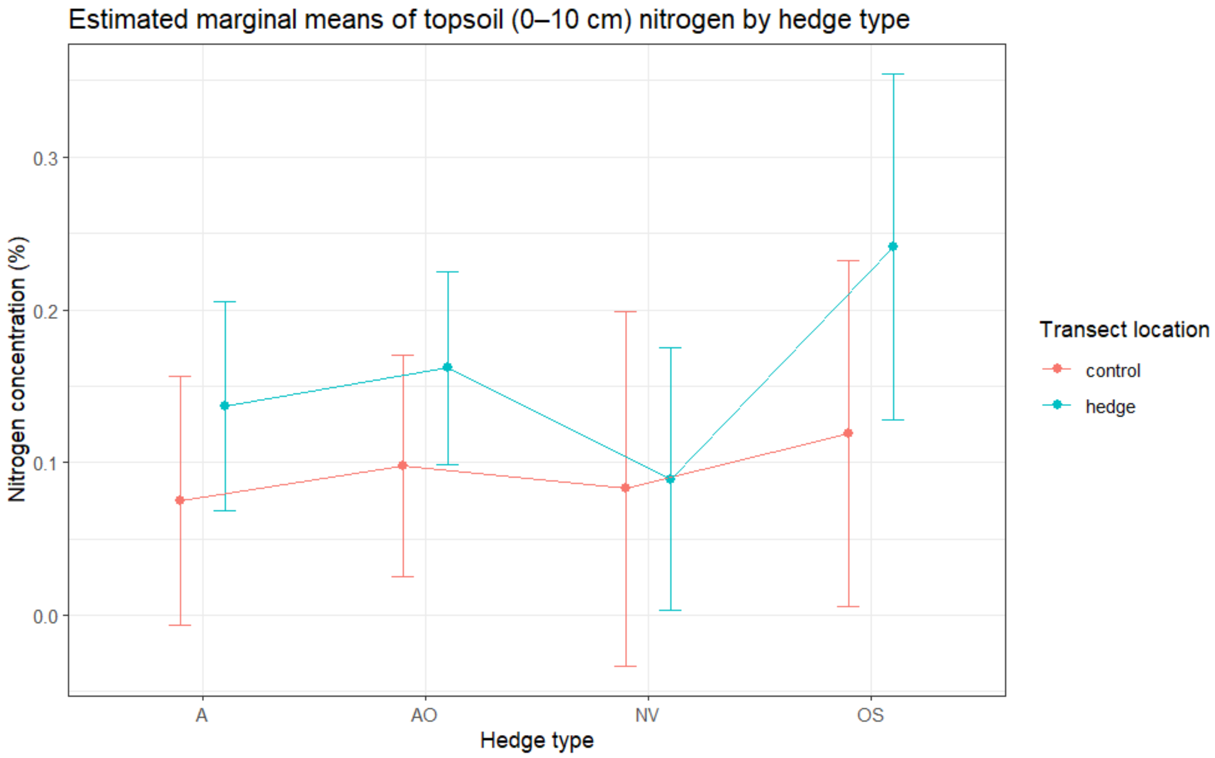

Figure 20. EMMs of NC (%) in topsoil across hedge type and field location. Error bars show 95% confidence intervals.

A LMM was run for NC at depth on the control transect. Random effects showed that variance was very small at 0.0012 (SD = 0.034) indicating little between-field variation. Residual variation was even smaller at 0.00041 (SD = 0.020) meaning within-field consistency was high. The fixed effect showed: Mean NC was 0.092% at 0-10cm depth (intercept). At 30-50cm NC was lower by 0.022% (Estimate = 0.022, SE = 0.0078). This depth effect was significant (t = -2.81, p-value = 0.017) suggesting that soil loses nitrogen with depth.

Rerunning the model after including hedge type dropped the variance between field to 0.0011 (SD 0.033) compared to the residual variance of 0.00045, (SD = 0.021) indicating most of the variability is within fields.

None of the hedge type main effects are significant against the intercept (A hedge at 0-10cm depth = 0.072) with all p-value > 0.18). Depth effect suggests a small decline at depth but not significantly. (Figure 21)

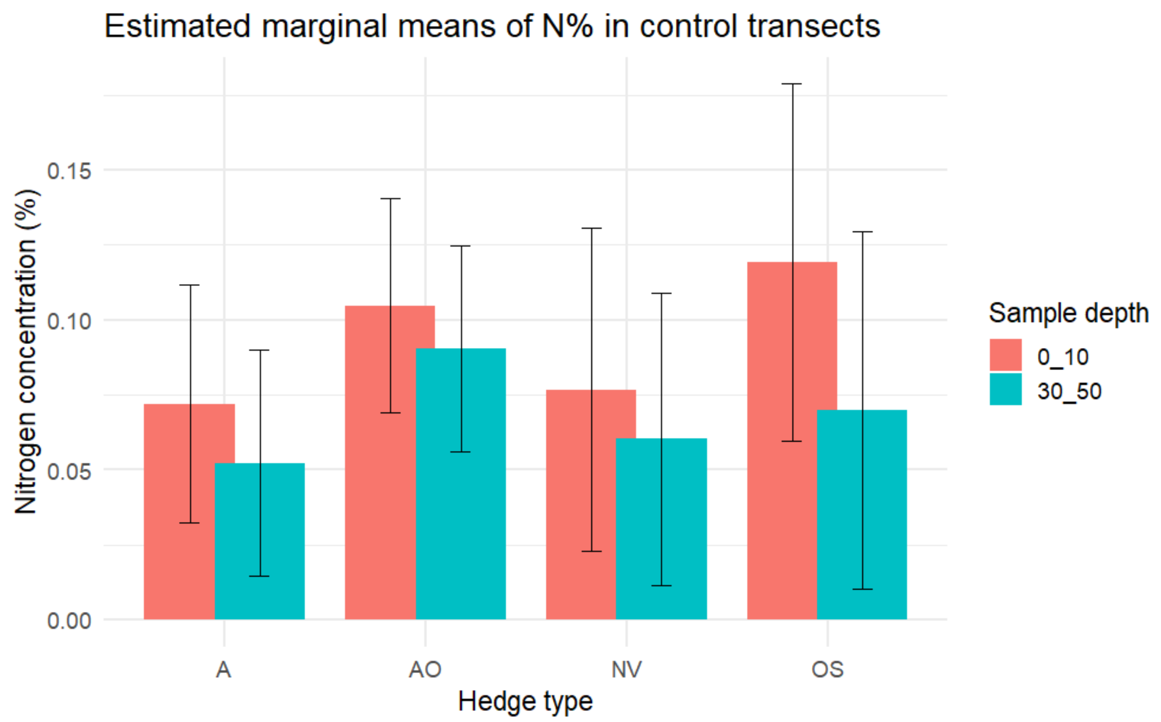

Figure 21. EMMs of NC (%) of 0-10cm vs 30-50cm at the control transect.

3.6.3 Carbon : Nitrogen Ratio

C:N ratios were relatively stable across hedge types, field location and depths typically ranging between 10-14 (Figure 22). As a figure derived from the C% & N% this shows that while hedges increase organic matter inputs the proportional balance of carbon to nitrogen remains stable in this study.

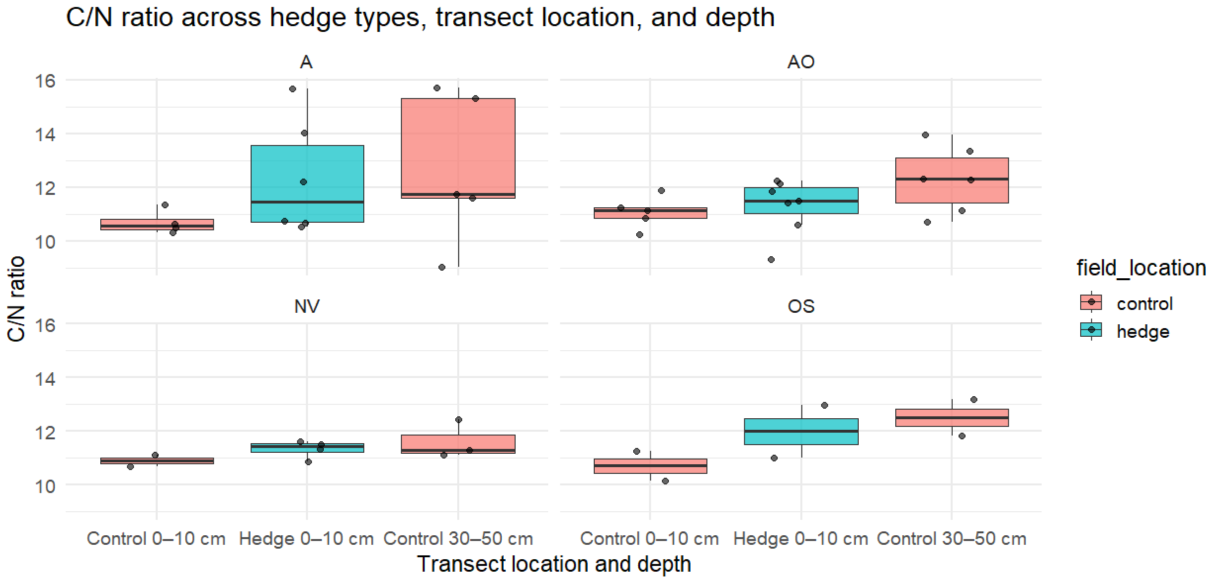

Figure 22. C:N Ratios across hedge type, field location and depth.

3.6.4 Hedge Only comparisons: NV vs Vegetated boundaries.

When restricted to hedge transects only NV, A & AO showed similar CC, with overlapping confidence intervals. OS hedges displayed higher mean CC significantly greater than A (p-value = 0.027) and with trends towards higher mean values than AO (p-value = 0.051) and NV (p-value = 0.083) (Figure 23).

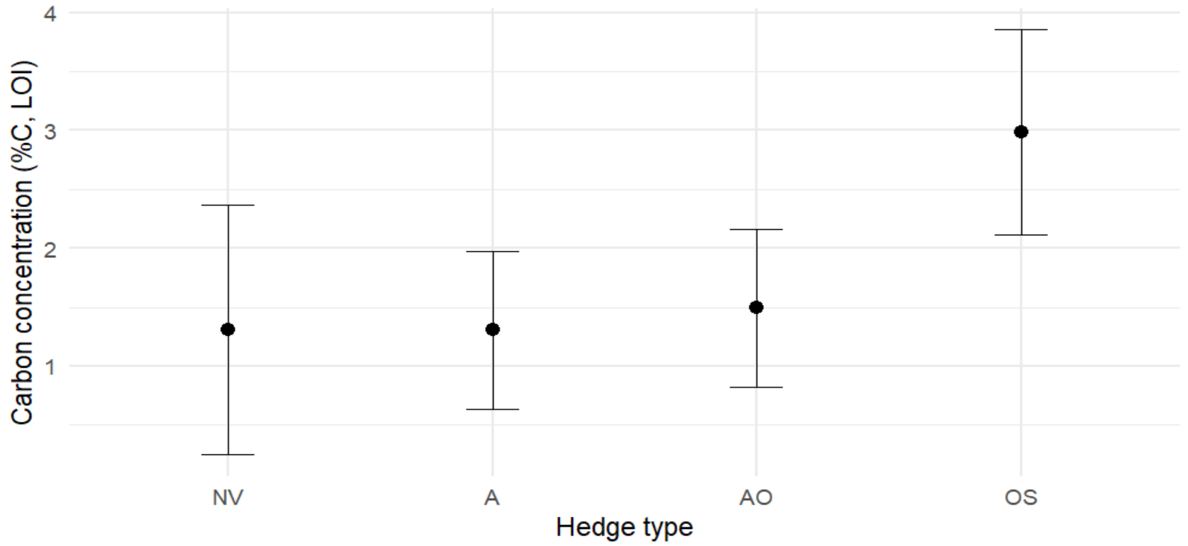

Figure 23. EMMs (±95% CI) of CC in hedge only transects.

BD estimates were highest in NV transects and comparable to those seen in A & AO. OS hedges showed the lowest mean BD and were significantly lower than NV (p-value = 0.044). Differences between A & AO were not significant. (Figure 24).

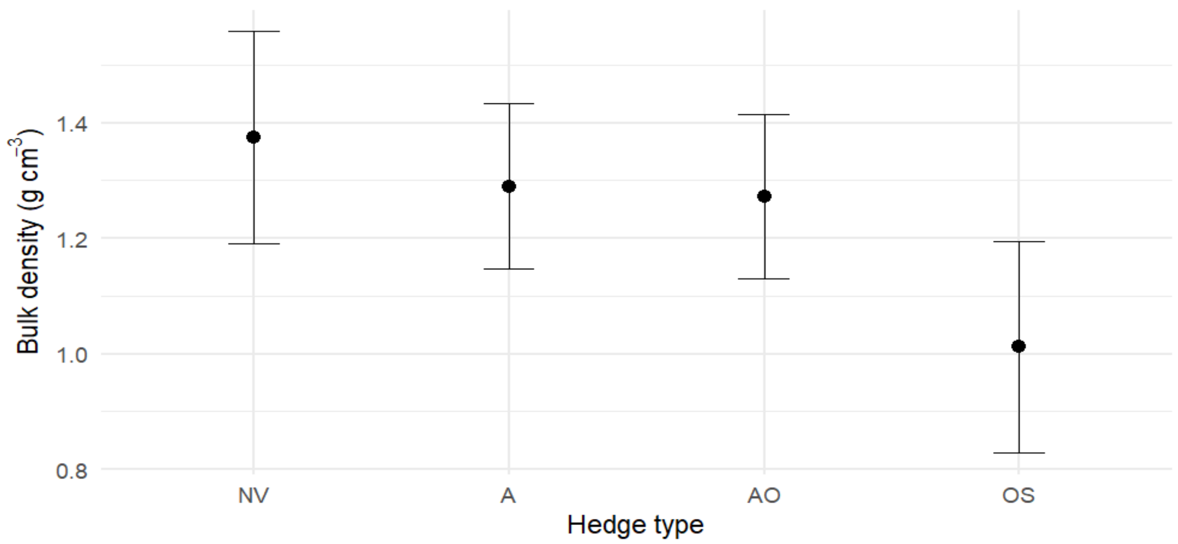

Figure 24. EMMs (±95% CI) of BD in hedge only transects

Total soil carbon stocks were similar in NV, A & AO hedges, OS hedges showed the highest mean stock values, although wide confidence intervals meant that no significant differences were detected in pairwise comparisons with NV, A or AO. (Figure 25)

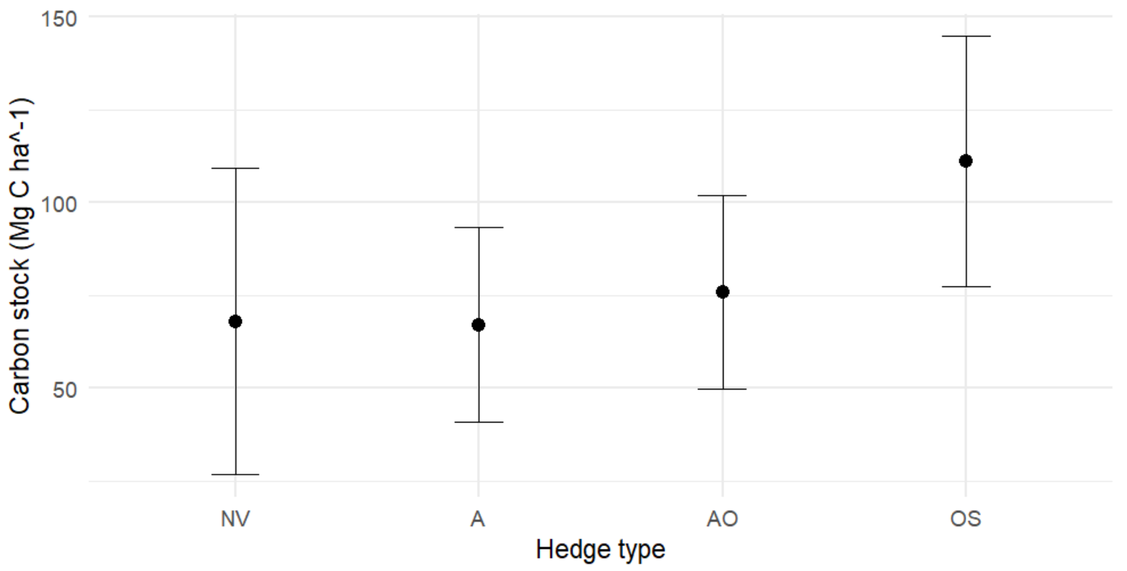

Figure 25. EMMS (±95% CI) of carbon stocks in hedge only transects.

Raw means reflected these patterns, with NV closely matching A & AO across all metrics, while OS hedge showed lower BD and higher CC and carbon stocks. (Table 5)

Hedge type	Carbon stock (Mg C ha^{-1})	Bulk density (g cm^{-3})	%C (LOI)
A	67.1 ± 5.2	1.30 ± 0.04	1.28 ± 0.09
AO	75.8 ± 6.0	1.27 ± 0.03	1.50 ± 0.08
NV	67.9 ± 9.2	1.37 ± 0.03	1.30 ± 0.11
OS	111.0 ± 14.7	1.01 ± 0.05	2.87 ± 0.27

Table 5. Raw means of CC, BD and carbon stocks taken at the field location Hedge only.

4. Discussion

Understanding the capabilities of hedgerows to sequester and store atmospheric carbon within agricultural soils is a vital component in the process of meeting obligations under both the Paris Agreement and the Carbon Neutral strategy the Government of Jersey agreed in 2020. (States of Jersey, 2022)

This study addresses the current knowledge gap concerning the soil carbon impacts of hedgerow planting on Jersey. By sampling a range of hedgerows and linear boundaries to understand the concentration of carbon in the soil under different boundary types along with testing the soil BD we have produced robust and transferable estimates of soil carbon stocks that can be disseminated to all interested parties.

Soil is known to store massive quantities of atmospheric carbon (Chabbi *et al*., 2022) and as previously noted is the largest terrestrial carbon pool on the planet. (Scharlemann *et* al., 2014) Agriculture takes up around 40% of the earth's land surface (Lal, 2004) so even small improvements to soil management could have outsize impacts on the balance of carbon held in the atmosphere.

Improvements in soil carbon stocks can not only help mitigate anthropogenic carbon emissions to the atmosphere but can influence a range of areas from food security (Lal, 2004), soil erosion (Barthès & Roose, 2002), drought resilience (Rawls *et al*., 2003) and support for above and belowground biodiversity. (Sheil *et al*., 2016)

The study first examines carbon concentrations in the soil beneath the hedgerows as well as using sampling sites within the fields as a control to allow for better visibility of the particular influence of hedgerows on the soil. Coupling this with studying the BD of the soils allows for the calculation of carbon stocks which represent the most important outcome of this study.

Alder was a central focus of this study due to its nitrogen fixing capacity. The results confirm that Alder hedges do contribute to enhanced SOC with surface soils showing substantial increases relative to hedges composed of other species. Alder did not generate the highest quantities of SOC though which suggests that its role in SOC storage may be more complex.

Looking in more detail at the impact of the particular hedge types in isolation showed that the species mix was less important than expected with results showing that NV, A & AO exhibited similar CC levels, BD and carbon stocks.

4.1 Soil Organic Carbon

This study confirmed that hedge transects consistently contain higher SOC than control transects, regardless of hedge type or depth. Whilst hedge type and depth were not significant on their own they both became important in interaction with field location suggesting that the hedges' composition influences the SOC distribution. At 0-10cm depth hedge transects contain 83-140% more SOC than the adjacent control transects, with the strongest effect under OS hedges. The high-carbon outliers, many from a site with a grassy field margin and subsequently reduced tillage, likely reflect genuine management effects rather than errors, highlighting the role of ground cover in boosting SOC. The overall pattern remained robust after removing the high-carbon outliers with the hedge transects continuing to show significantly elevated SOC. These findings align with previous studies (Pardon *et al*., 2017; Viaud & Kunnemann, 2021; Lesaint *et al*., 2023) which demonstrated that SOC stocks are greatest at the base of hedgerows and decline to background levels within 10m into the adjacent field. A meta-analysis of 83 sampled hedgerows by Drexler *et al*., 2021 found that hedgerows exhibited SOC levels 32% higher than adjacent agricultural cropland while Drexler *et al*., 2022 reported a 36% greater SOC level between hedgerows and cropland.

The large percentage increases observed in this study (83-140%) are likely to be a function of the low baseline SOC levels in Jersey's intensively cultivated fields. With control transects containing only 0.8 – 1.3% SOC at 0-10cm even moderate gains translate into larger percentage increases. This clearly shows the vulnerability of Jersey's soils to carbon depletion and the impact that hedgerows can have in a low-carbon system.

The increased organic inputs that arise from reduced tillage at the field margin, increased leaf litter (Walter *et al.,* 2003), enhanced soil microclimates and root exudates (Cardinael *et al*., 2018) are all drivers of elevated SOC levels found under hedgerows.

Leaf litter from Alder species was found to be N-rich and fast decomposing to form stable C compounds within soil (Innangi *et* al., 2017). OS hedges by nature of their diverse species composition however will have complementary root systems and extended periods of leaf litter fall which may account for some of the increased soil carbon beneath them.

Alder has been shown to increase SOC stocks in agroforestry systems in the Indian sub-Himalayas with levels 59% higher than control plots (Parmar *et al*., 2022). The effect of age on carbon sequestration by Alder is also relevant. Alazmani *et al*., 2021 produced a study looking at the effect of Alder age on soil carbon sequestration. They found that the oldest Alder stands at 35yrs showed the highest carbon sequestration rates. This is relevant for tree planting schemes as it may be that Alder have the capacity to sequester carbon over several decades and the younger trees sampled in this study are yet to reach peak sequestration. Several of the Alder hedges sampled are approximately 15yrs old (D. Hellio, pers. comm, 2025) and increase their rate of carbon sequestration over the coming decades.

In this study whilst we found strong evidence of the influence of hedgerows on SOC levels we did not find the expected strong Alder effect. The relatively young age of the trees may well account for this. Management of the hedgerows in the study sites could also have bearing on the quantity and quality of leaf litter inputs. Annual flailing of hedgerows reduces biomass carbon sequestration and irregular shaped hedges with less frequent trimming show an elevated above-ground biomass carbon stock (Black *et al*., 2023) which would lead to increased leaf litter inputs.

4.2 Bulk Density

Two clear fixed-effects patterns emerged from the BD analysis. First, hedge transects had lower BD than control transects by ~0.117 g cm^{-3} (SE = 0.058, p-value = 0.045). This is an 8.5% reduction in density relative to the dataset mean. Secondly, relative to the reference hedge type (A), OS hedges showed roughly 21.7% lower BD (~0.264g cm^{-3} (SE = 0.106, p-value = 0.019). AO and NV did not vary from A and depth on its own showed no main effect.

Interactions were not significant, but a post-hoc contrast indicated that under OS hedges at 30-50cm BD was significantly lower in the hedge than the control. The average depth effect remains small but deeper reductions in density can occur under certain hedge types. Lower BD beneath hedges is likely to reflect root distribution and soil biological activity.

Reduction in compaction and the resultant increased porosity from the root systems and faunal bioturbation along with greater organic matter inputs will reduce the mass of soil per unit volume. Canopy cover protection from the extremes of weather may also reduce soil consolidation.

These findings echo those of other studies who found that BD was lower under hedgerows (1.127 g cm^{-3} ± 0.22 under hedgerows and 1.297 g cm^{-3} ± 0.17 under grassland) and also found that BD differences declined to background levels within 20m of the hedgerow (Van Den Berge *et al*., 2021). BD was higher in fields than hedgerows, although densities were also high beneath 2-4yr old trees. (Biffi *et al*., 2022). Holden *et al*., 2019 also found that density was significantly lower in hedgerow soils and lower at all sampled depths. The overall BD results show that hedgerows and especially OS hedge types are associated with less compact soils.

4.3 EA Data

The elemental analysis data broadly supports the trends seen in the larger LOI dataset. The small sample size of the EA dataset however limits the statistical power. At 0-10cm SOC concentrations tended to be higher in hedge transects compared to controls which is consistent with the LOI findings of richer SOC underneath the hedgerow. Once hedge type was included in the EA analysis it showed no statistically significant differences amongst hedge types with wide confidence intervals in OS and NV hedge indicating high variability. The EA data did not resolve hedge type effects to the same extent as the LOI data where differences were more visible. This is likely due to the size of the EA dataset rather than a genuine difference. Depth effects were also aligned with both datasets showing a modest and non-significant reduction in SOC from 0-10cm to 30-50cm. Overall the EA analysis reinforces the LOI analysis confirming the trend of carbon enrichment under the hedgerow whilst they both show that a lot of the variation occurs within fields.

4.4 Nitrogen

The EA Nitrogen data also supports the LOI pattern whereby there are higher NC in the hedge transects than the controls. Once hedge type was introduced to the analysis the statistical significance was removed and large confidence intervals showed high variability amongst the hedge types. The EMMs suggest a consistent trend towards higher NC under hedges in particular OS where concentrations were almost double those in the control.

Unlike the SOC data NC showed a clear depth pattern with significantly lower concentrations at depths suggesting a vertical reduction of N stocks. Hedgerows add N to the soil through leaf litter, root exudates. N is more labile and mobile than the C stocks which become stabilised within soil organic matter and aggregates (Blanco-Canqui & Lal, 2004). Microbial processing drives N through the nitrogen cycle. (Chen *et al*., 2003) meaning while C may stabilise and persist in the soil profile, N accumulates but declines rapidly with depth.

4.5 C:N Ratio

Ratios were consistent across hedge type, field location and depth ranging from 10-14 which is within the typical range for a mineral topsoil (Cleveland & Liptzin, 2007; Cools *et al*., 2014). This stability suggests that whilst hedges appear to increase organic matter, and Alder is expected to introduce nitrogen-rich leaf litter and root exudates the balance of carbon and nitrogen remains unchanged. The stability of this ratio can be put down to the homeostatic nature of soil microbial community (Rocci *et al*., 2024). The quantity of inputs will be balanced out by soil microbes. Our findings are therefore in agreement with the view that hedgerow effects on SOC and N are additive, increasing the stock of both elements without shifting their relationship

4.6 Carbon Stocks

This study found that hedgerows significantly enhance the soil carbon stocks relative to the adjacent field transects both in individual depth layers and across the full 0-50cm profile. At 0-10cm, hedge transects contained 47-86% more carbon that in the controls, with significant increases under A, AO and OS hedge types. Additional gains were also seen at 10-20cm under OS hedges (69%) increase while no significant gains were seen at the lowest depth layer sampled. When combined across the entire soil profile total carbon stocks were 23-51% higher under hedges depending on the hedge and with the strongest effect seen under OS hedges. These are considerably higher than those seen under NV hedges. Baseline stocks are low in the sites sampled and this is reflective of the intensively managed arable soils in Jersey.

Several mechanisms seem likely to contribute to these increases. The elevated SOC concentrations under hedges combined with the reduced BD still give rise to higher carbon stocks. Increased organic inputs from leaf litter, ground cover, root turnover and reduced tillage at field margins directly contribute to the SOC accumulation. (Walter *et al*., 2003; Cardinael *et al*., 2018) Hedgerow canopies also buffer the soils against erosion and moisture extremes, stabilising organic matter inputs. The species composition of the hedges may further influence these effects: whilst Alder leaf litter in N-rich and rapidly decomposes to form stable C compounds (Innangi *et al*., 2017) the more diverse OS hedges showed the largest overall carbon stock increase in this study.

These results demonstrate that hedgerows and particularly those dominated by diverse species mix make a substantial contribution to the soil carbon storage. In intensively managed, low-carbon agricultural soils, their impact may be even greater, offering a valuable strategy to enhance soil carbon stocks alongside above-ground biodiversity and meet our climate mitigation goals. The results have a clear implication for land managers with the reduction in BD beneath hedges representing an improvement in soil structure, with greater porosity supporting better water infiltration, drainage and root growth. These improvements can translate into crop resilience particularly in light of record-breaking warm temperatures and lack of rainfall in Jersey in recent months. Alder while not showing the largest immediate carbon gains should not be discounted given its nitrogen-fixing role and the likelihood of increased sequestration as the trees mature. Integrating hedgerows into carbon accounting frameworks could provide a measurable, local contribution to climate mitigation.

4.7 Hedge Only Comparisons.

When analyses were restricted to hedge transects only, NV (non-vegetated grassy banks) showed very similar carbon stocks, BD and CC levels to A & AO hedges. This suggests that the strong hedgerow effects observed across the full dataset, when hedges were compared to adjacent control transects may not be driven by woody species composition after all but rather by the presence of the boundary itself. OS hedges were the only group to stand out, with higher CC, lower BD and a trend towards greater carbon stocks. This suggests that the hedgerow composition may just amplify the boundary effects whereby the existence of the boundary leads to reduced soil disturbance, compaction and still provides some element of erosion protection from wind etc. Other studies have shown that grassland and forests share similar CC levels (Dass *et* al., 2018) and so potentially the undisturbed grassy banks are storing similar amounts of carbon without the presence of an actual hedgerow.

5. Conclusion

This study set out to investigate the role of Alder in supporting soil carbon storage within agricultural hedgerows and comparing its performance to other hedge types in the intensively cultivated fields in Jersey. Hedgerows are widely valued for the biodiversity and landscape function, and their role in storing carbon in soil is well understood. The influence of Alder on this is less well understood. By integrating SOC, BD and carbon stock calculation across 3 soil depths this research is one of the first quantitative assessment of Alder's contribution to soil carbon storage on the island's depleted arable soils and looks to fill in this knowledge gap.

The results show a clear and consistent effect of increased SOC and carbon stocks across the hedge types. BD was significantly lower in the hedge soils and together these factors translate into substantially greater carbon stocks. These effects were strongest under hedges dominated by more diverse species and while the Alder containing hedges showed clear benefits they were less impactful. Non-vegetated boundaries contributed little additional carbon relative to controls.

In terms of Alder's role, the results highlight both its potential and current limitations. Alder hedges increased SOC by ~135% at 0-10cm and raised total carbon stocks by 22 Mg C ha^{-1} relative to the controls confirming that Alder contributes significantly to below-ground carbon storage. Alder did not however outperform hedges dominated by other species and was found to be similar in characteristics to NV boundaries.

Overall, this study demonstrates that pure Alder hedges and Alder containing hedges do enhance soil carbon storage, but they do so as part of a broader boundary effect. The impact of Alder should be understood not in isolation but as part of the hedgerow system where age, management and species diversity determine long-term carbon storage outcomes.

When looking purely at the results of sampling at the hedge transect the similarity of the A & AO hedge types to the NV type poses the question of just how important the hedge is when looking at carbon stocks. NV's grassy banks would preclude tillage from taking place and the heights of the banks (1.1m and 1.4m) would provide some element of protection from the prevailing South Westerly winds. Undisturbed grassland has been shown to store comparable levels of soil carbon to hedgerows (Drexler *et al*., 2021) although this doesn't take into consideration the above-ground biomass that hedgerows provide.

A limitation of this study is the number of samples sites and the balance between the different hedge types. Another limitation of this study is the small number of elemental analysis samples compared to the LOI data which constrained the statistical power to identify differences between hedge types. Similarly, the sampling design of at the edge of the hedge and 10m away for the control could have missed an important element of just how far the hedgerow carbon benefits stretch into the field. Longitudinal studies of the sample sites would potentially pick up on the increasing sequestration ability of the species as they age as well as lessening the potential impacts of current weather patterns.

In conclusion, Alder hedges clearly increase soil carbon storage relative to controls, but they do not outperform more diverse hedgerows. Planting Alder alone is therefore unlikely to maximise carbon sequestration, yet it can make a meaningful contribution when included as part of a species rich hedgerow system.

6. Recommendations

6.1 Sample Size

This research project could have been improved with more samples per hedge type improving the statistical power and reducing the chance of Type II errors. This would also give more accurate estimates of within-group variation.

6.2 Sample depths

It was decided to sample 0-10cm, 10-20cm and 30-50cm to get a better picture of the soil horizons as many sampling projects only sample to ploughing depth c. 23cm. The missing 10cm layer at 20-30cm could be useful to show a complete dataset for the soil profile and if this project was rerun, sampling of each 10cm layer down to 50cm would be undertaken.

6.3 Sample Pattern

Two transects were taken in each field, at the edge of the canopy of the hedgerow and 10m further into the field and parallel. To improve the visibility of the impact of hedgerows future sampling should include a transect 1m from the hedge line as well. This would allow insights to be gained on how far from the hedgerow the carbon benefits still accrue.

6.4 LOI Vs Elemental Analysis

Elemental Analysis provides a high-resolution direct measurement of both total C and N but is more expensive and more time consuming than LOI which allows for a faster workflow via batch processing. LOI may be better used when looking at large scale C patterns but the requirement for a conversion factor to get from Organic Matter to C introduces a level of uncertainty to the results. The elemental analysis of a subset of samples was provided as an opportunity late in the booked laboratory time and so a decision had to be made as to which samples to test. Jersey does not have the facilities to offer either testing and so samples had to be flown to the UK to utilise Exeter University facilities. Sourcing additional funding and booking more time in the laboratory would have allowed the entire dataset to undergo elemental analysis leading to more robust results.

6.5 Bulk Density

The process of collecting BD samples required a cylinder hammered into the soil horizon to collect the sample, which is then bagged up, dried, ground then sieved introduces several areas where soil loss can occur. Any soil lost during these steps increases the uncertainty in the BD estimates which is then propagated through to the carbon stock calculations. BD sampling kits range in cost up to

$600 which was outside the budget for this project, but which would increase accuracy of sampling efforts. Access to a lab with large scale milling and drying facilities would have also improved accuracy. In this project BD samples were taken at 10m & 20m. Taking samples at 5m, 15m & 25m would have aligned with the core samples giving densities for each core site and depth. This would have provided greater accuracy when calculating carbon stocks.

6.6 Timing

Cores samples were all collected within 1 month of each other but due to adverse weather condition the BD samples were collected over the course of 3 months. As samples were collected from 3 different working farms it was not feasible to plan the schedule perfectly and so samples were taken from field before and after planting, fertiliser application and harvesting. All these external factors could impact the results. Scheduling the sampling in any future extension or replication of this project would remove as many of these differences as possible to ensure sampling was as consistent as possible.

6.7 Biodiversity sampling

The lack of worms found during the earthworm pit sampling is likely due to several factors: Jersey experienced the driest and warmest spring 30 years (Met Office, 2025) which would have encouraged earthworms to burrow deeper into the soil and thus below the standard 20cm x 20cm x 20cm pit dimensions. For further research earthworm biodiversity sampling would take place earlier in the spring or at the end of the winter period to stand a better chance of finding earthworms and having usable data to discuss.

6.8 Number of sample sites

The limited and uneven replication across hedge types (5 x Alder, 5 x Alder and Others, 3 x Other Species and 2 x Non-Vegetated) reduced the statistical power and increased uncertainty around mean estimates especially for OS and NV. A larger and more balanced sample size would have reduced the chance of Type II errors and allowed for true differences to be detected statistically.

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Appendix 1

A1 Hedge Dataset – LOI Carbon Content

hedge_data.csv

A2 Bulk Density Dataset – Adjusted Bulk Density

bulk_density_data.csv

A3 Elemental Analysis Dataset – C% & N% with C:N Ratio

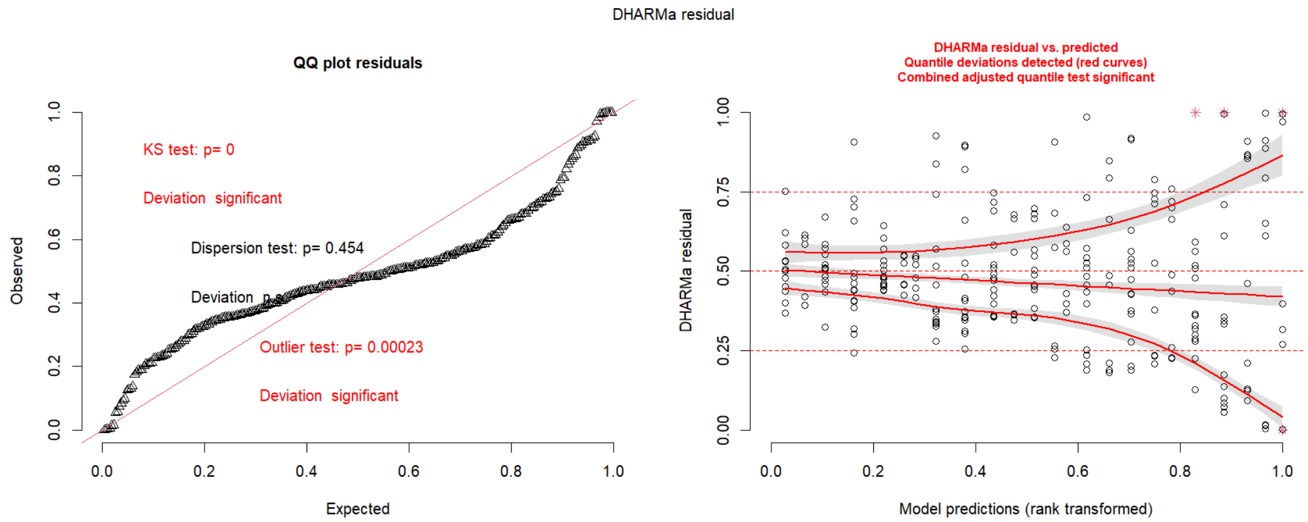
cn_data.csv

A4 Hedge sample site coordinates and dimensions

Hedge Coords and
Dimensions.xlsx

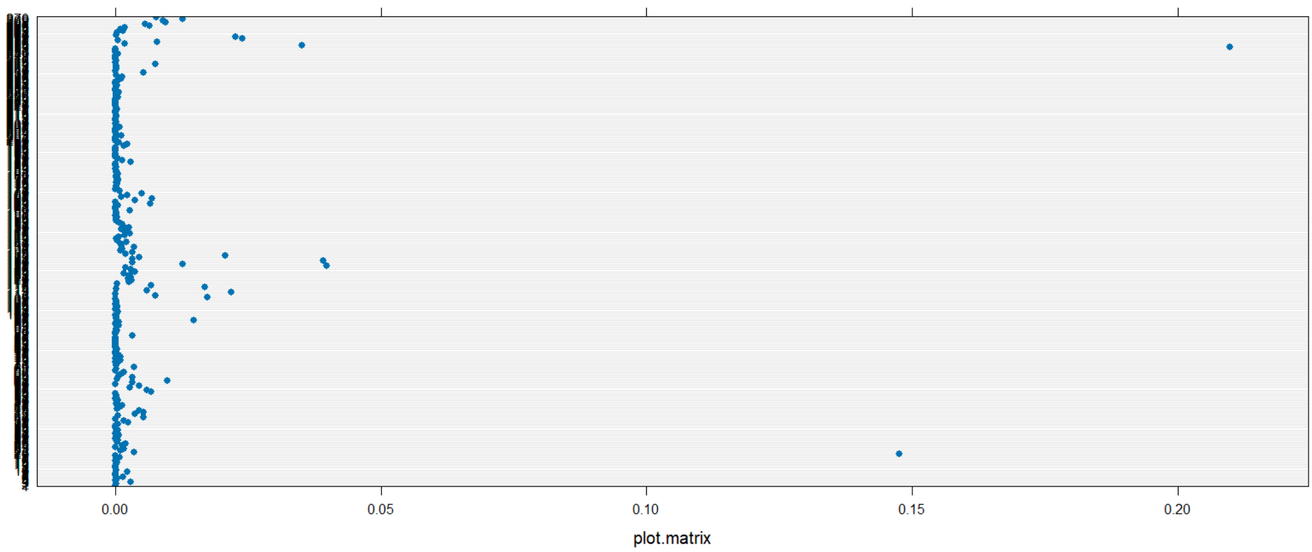
Appendix 2

B1 - Diagnostic tests for hedge data GLMM



DHARMa simulation-based residual diagnostics. KS Test and outlier test indicated significant deviation due to high-carbon outliers. Dispersion test showed no evidence of overdispersion.

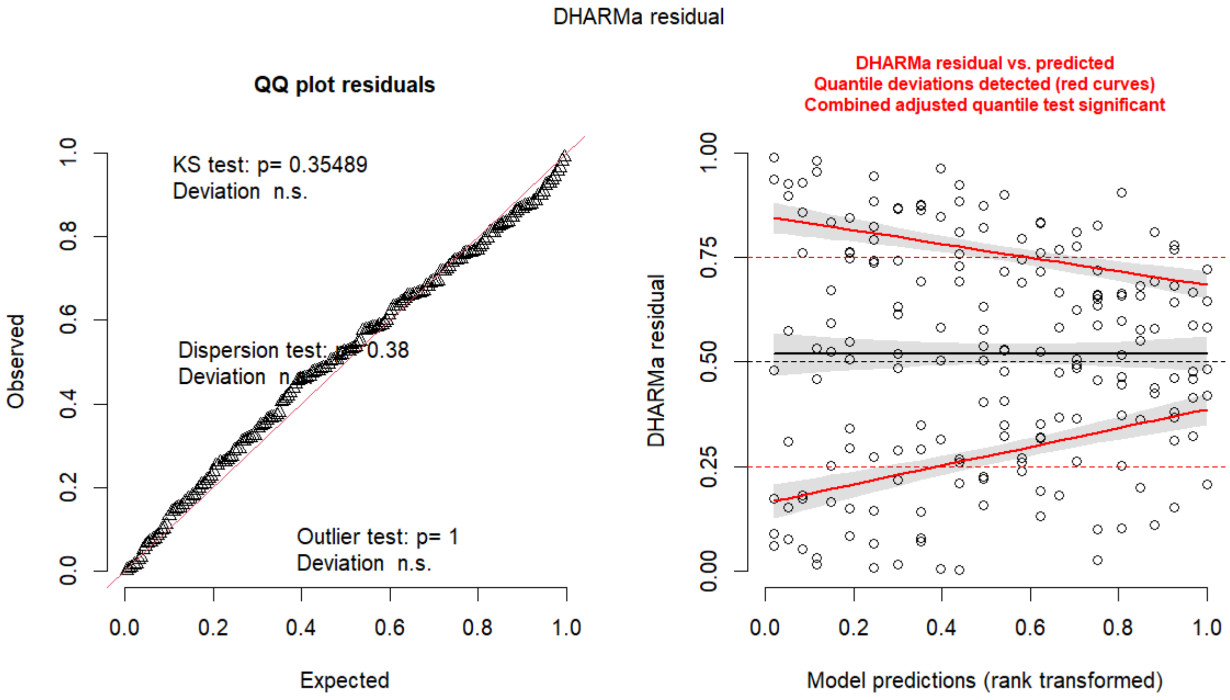
B2 LOI GLMM - Cook's Distance Plot



B3 - High-Carbon Outliers identified in Cook's Distance Plot

	Field Number	Hedge Type	Field Location	Sample Depth	Carbon Percentage
19	1156W	AO	hedge	0_10	6.0465
109	228W	OS	hedge	0_10	1.5877
112	228W	OS	hedge	0_10	1.4395
115	228W	OS	hedge	0_10	1.6032
127	1176AW	A	hedge	0_10	4.9916
130	1176AW	A	hedge	0_10	4.9747
133	1176AW	A	hedge	0_10	4.3626
253	120W	OS	hedge	0_10	8.4851
254	120W	OS	hedge	10_20	5.7512
258	120W	OS	hedge	30_50	1.5761
259	120W	OS	hedge	0_10	6.0075

B4 - Diagnostic tests for bulk density data GLMM



DHARMa diagnostic plots for GLMM of bulk density. Q-Q Plot of simulated residuals and residuals vs predicted values. Model assumptions were met with normal distribution, dispersion and outlier tests were non-significant and only mild quantile deviations were seen.

Appendix 3

C1 Total soil carbon stock (0-50cm) by hedge type and transect

Hedge Type	Transect	Mean stock (Mg C/ha)	SE (Mg C/ha)	n_fields
A	control	46.3	3.98	5
A	hedge	67.1	7.54	5
AO	control	61.8	6.08	5
AO	hedge	75.8	9.42	5
NV	control	57.9	6.64	2
NV	hedge	67.9	18.8	2
OS	control	79.5	10.3	3
OS	hedge	111	26.2	3

Appendix 4

D1 R Studio Code

```
###################################################################
##
## Dissertation R Studio Code - FINAL CUT
##
###################################################################

## Starting with LOI Derived Carbon Concentration data



pkgs <- c("lme4","lmerTest","DHARMa","influence.ME","emmeans","multcompView",
    "ggplot2","dplyr","tidyr","stringr","forcats")
to_install <- setdiff(pkgs, rownames(installed.packages()))
if (length(to_install)) install.packages(to_install, quiet = TRUE)
invisible(lapply(pkgs, require, character.only = TRUE))

#set working directory
setwd("C:/Users/allyu/Dropbox/JBIM Overview/R Programming Video Course/Hedgerow")

#load hedge data file
hedge_data <- read.csv("hedge_data.csv")

# Inspect structure
str(hedge_data)

#confirm data is categorised correctly
hedge_data$hedge_type <- as.factor(hedge_data$hedge_type)
hedge_data$field_location <- as.factor(hedge_data$field_location)
hedge_data$sample_depth <- as.factor(hedge_data$sample_depth)
hedge_data$field_number <- as.factor(hedge_data$field_number)
```

```
# Convert carbon_percentage to numeric
if (is.factor(hedge_data$carbon_percentage)) {
  hedge_data$carbon_percentage <- as.numeric(as.character(hedge_data$carbon_percentage))
} else {
  hedge_data$carbon_percentage <- as.numeric(hedge_data$carbon_percentage)
}

# Quick check
str(hedge_data)

# remove surrounding/internal whitespace and tidy case in hedge_type
hedge_data$hedge_type <- stringr::str_squish(hedge_data$hedge_type)  # trims + collapses
spaces
hedge_data$hedge_type <- toupper(hedge_data$hedge_type)          # optional: consistent case
hedge_data$hedge_type <- factor(hedge_data$hedge_type)           # re-factor after cleaning

# check result:
levels(hedge_data$hedge_type)
table(hedge_data$hedge_type, useNA = "ifany")

#########################################################

#Fit a GLMM
library(lme4)

model_loi <- lmer(
  carbon_percentage ~ hedge_type * field_location * sample_depth + (1 | field_number),
  data = hedge_data
)

summary(model_loi)
```

```
############################################

# diagnostic check with DHARMa
library(DHARMa)

sim <- simulateResiduals(model_loi, n = 1000)
plot(sim)

# Cook's distance plot (per observation)
library(influence.ME)

infl_obs <- influence(model_loi, obs = TRUE)
plot(infl_obs, which = "cook")
# threshold line:
abline(h = 4/length(cooks.distance(infl_obs)), lty = 2)

# extract and inspect top Cook's distance values
cd <- cooks.distance(infl_obs)

# Order by Cook's D
head(sort(cd, decreasing = TRUE), 10)

# get sample details for top 10 Cook's distance outliers
top_ids <- order(cd, decreasing = TRUE)[1:10]

hedge_data[top_ids, c("field_number", "hedge_type", "field_location",
           "sample_depth", "sample_position", "carbon_percentage")]

# remove top Cook's D outliers
hedge_data_no_out <- hedge_data[-top_ids, , drop = FALSE]
```

```
#######################################################
# refit GLMM

model_loi_no_out <- lmer(
  carbon_percentage ~ hedge_type * field_location * sample_depth + (1 | field_number),
  data = hedge_data_no_out
)

summary(model_loi_no_out)

##########################################################

# make a clean plot frame and re-plot
library(dplyr); library(stringr); library(ggplot2)

pdat <- hedge_data_no_out %>%
  transmute(
    hedge_type = factor(hedge_type),
    field_location = factor(tolower(field_location), levels = c("control","hedge")),
    depth_cat = sample_depth %>%
      as.character() %>% str_trim() %>% toupper() %>%
      str_replace_all("_","-") %>% str_replace_all("\\s+",""),
    carbon_percentage = as.numeric(carbon_percentage)
  ) %>%
  mutate(
    depth_cat = ifelse(depth_cat %in% c("0-10","10-20","30-50"), depth_cat, NA_character_),
    depth_cat = factor(depth_cat, levels = c("0-10","10-20","30-50"), ordered = TRUE)
  ) %>%
  filter(!is.na(carbon_percentage), !is.na(depth_cat), !is.na(field_location), !is.na(hedge_type))

# raw boxplot of model
ggplot(pdat, aes(x = depth_cat, y = carbon_percentage, fill = field_location)) +
```

```
  geom_boxplot(alpha = 0.7, outlier.shape = NA) +
  geom_jitter(position = position_jitterdodge(jitter.width = 0.2), alpha = 0.4, size = 1) +
  facet_wrap(~ hedge_type) +
  labs(x = "Sample depth (cm)", y = "Carbon percentage (LOI-derived)", fill = "Field location") +
  theme_bw()

##################################################

# emmeans interaction plot
library(emmeans)

# Plot field_location across depths, faceted by hedge_type
emmip(model_loi_no_out, field_location ~ sample_depth | hedge_type,
      CIs = TRUE, type = "response") +
  labs(x = "Sample depth (cm)", y = "Estimated carbon % (LOI-derived)",
       color = "Field location") +
  theme_bw()

##################################################

# extract emmeans table

emm_table <- emmeans(model_loi_no_out,
                     ~ hedge_type * field_location * sample_depth)

emm_table

##################################################

# pairwise contrasts hedge vs control within each hedge_type × depth
emm_contrasts <- contrast(
  emmeans(model_loi_no_out, ~ hedge_type * field_location * sample_depth),
```

```
  method = "revpairwise",
  by = c("hedge_type", "sample_depth"),
  adjust = "tukey"
)

emm_contrasts

##################################################

# keep only significant / near-significant contrasts
sig_contrasts <- as.data.frame(emm_contrasts) %>%
  filter(p.value < 0.1) %>%
  select(hedge_type, sample_depth, contrast, estimate, SE, df, t.ratio, p.value)

sig_contrasts

##################################################

# format significant contrasts table better

sig_table <- sig_contrasts %>%
  mutate(
    Estimate = round(estimate, 3),
    SE = round(SE, 3),
    t = round(t.ratio, 2),
    p = ifelse(p.value < 0.001, "<0.001", round(p.value, 3))
  ) %>%
  select(Hedge_Type = hedge_type,
         Depth = sample_depth,
         Contrast = contrast,
         Estimate, SE, df, t, p)
```

```
sig_table

################################################

#

# Moving to the Bulk Density dataset

#

################################################


#load bulk data file

bulk_data <- read.csv("bulk_density_data.csv")

str(bulk_data)


# convert adj_bulk_density to numeric

bulk_data$adj_bulk_density <- as.numeric(bulk_data$adj_bulk_density)


# quick check

summary(bulk_data$adj_bulk_density)


################################################


#fit GLMM on bulk density


model_bd <- lmer(

  adj_bulk_density ~ hedge_type * field_location * sample_depth + (1 | field_number),

  data = bulk_data

)


summary(model_bd)


################################################


#  diagnostics for bulk density GLMM
```

```
sim_bd <- simulateResiduals(model_bd, n = 1000)
plot(sim_bd)

##################################################

#  raw boxplot of bulk density

ggplot(bulk_data,
      aes(x = sample_depth, y = adj_bulk_density,
        fill = field_location)) +
  geom_boxplot(alpha = 0.7, outlier.shape = NA) +
  geom_jitter(position = position_jitterdodge(jitter.width = 0.2),
          alpha = 0.4, size = 1) +
  facet_wrap(~ hedge_type) +
  labs(x = "Sample depth (cm)",
      y = "Bulk density (g/cm³)",
      fill = "Field location") +
  theme_bw()

###################################################

# emmeans plot for bulk density
emmip(model_bd, field_location ~ sample_depth | hedge_type,
     CIs = TRUE, type = "response") +
  labs(x = "Sample depth (cm)",
      y = "Estimated bulk density (g/cm³)",
      color = "Field location") +
  theme_bw()

###################################################
```

```
# calculate emmeans for bulk density

emm_bd <- emmeans(model_bd, ~ hedge_type * field_location * sample_depth)

emm_bd

##################################################

# pairwise contrasts for hedge vs control
emm_bd_contrasts <- contrast(
 emm_bd,
 method = "revpairwise",
 by = c("hedge_type", "sample_depth"),
 adjust = "tukey"
)

emm_bd_contrasts

##################################################

# significant contrasts table

sig_bd <- as.data.frame(emm_bd_contrasts) %>%
 filter(p.value < 0.05) %>%
 mutate(
  Estimate = round(estimate, 3),
  SE = round(SE, 3),
  df = round(df, 0),
  t = round(t.ratio, 2),
  p = ifelse(p.value < 0.001, "<0.001", round(p.value, 3)),
  Depth = gsub("_", "-", sample_depth)
 ) %>%
```

```
  select(Hedge_Type = hedge_type, Depth, Contrast = contrast,
         Estimate, SE, df, t, p)

sig_bd

##################################################
#
# Merging datasets to calculate carbon stocks
#
##################################################

# calculate mean bulk density per field × hedge × location × depth

mean_bd <- bulk_data %>%
  group_by(field_number, hedge_type, field_location, sample_depth) %>%
  summarise(mean_bd = mean(adj_bulk_density, na.rm = TRUE), .groups = "drop")

# merge with LOI data
carbon_stock_data <- hedge_data %>%
  left_join(mean_bd, by = c("field_number", "hedge_type", "field_location", "sample_depth"))

# quick check
str(carbon_stock_data)

###################################################

#inspect merged LOI + mean BD dataset

# Overall size + missing BD count
cat("\nRows & missing mean_bd:\n")
print(carbon_stock_data %>%
        summarise(n_rows = n(), n_missing_mean_bd = sum(is.na(mean_bd))))
```

```
# Where is BD missing? (distinct group keys)
cat("\nGroups with missing mean_bd:\n")
print(carbon_stock_data %>%
    filter(is.na(mean_bd)) %>%
    distinct(field_number, hedge_type, field_location, sample_depth) %>%
    arrange(field_number, hedge_type, field_location, sample_depth))

# LOI sample counts by group (should match your design)
cat("\nLOI counts by hedge_type × location × depth:\n")
print(carbon_stock_data %>%
    count(hedge_type, field_location, sample_depth, name = "n_LOI") %>%
    arrange(hedge_type, field_location, sample_depth))

# mean_bd snapshot
cat("\nmean_bd by group (first few):\n")
print(carbon_stock_data %>%
    distinct(field_number, hedge_type, field_location, sample_depth, mean_bd) %>%
    arrange(field_number, hedge_type, field_location, sample_depth) %>%
    head(20))

#  look at key columns
cat("\nFirst 10 rows (key columns):\n")
print(carbon_stock_data %>%
    select(field_number, hedge_type, field_location, sample_depth,
        sample_position, carbon_percentage, mean_bd) %>%
    head(10))

##########################################################

#Calculate Carbon Stocks
```

```
#  calculate carbon stock (Mg C/ha)

carbon_stock_data <- carbon_stock_data %>%
  mutate(
    # convert LOI % to fraction
    carbon_frac = carbon_percentage / 100,

    # assign layer thickness by depth
    layer_thickness = case_when(
      sample_depth == "0_10" ~ 10,
      sample_depth == "10_20" ~ 10,
      sample_depth == "30_50" ~ 20,
      TRUE ~ NA_real_
    ),

    # calculate carbon stock (Mg C/ha)
    carbon_stock = mean_bd * carbon_frac * layer_thickness * 100
  )

# quick check
summary(carbon_stock_data$carbon_stock)

#####################################################

# summarise carbon stocks by depth

carbon_stock_data %>%
  group_by(sample_depth) %>%
  summarise(
    mean_stock = mean(carbon_stock, na.rm = TRUE),
    sd_stock   = sd(carbon_stock, na.rm = TRUE),
    n          = n()
```

```
)

#####################################################

#Boxplot of raw data of carbon stocks

#  raw boxplot of carbon stocks

ggplot(carbon_stock_data,
      aes(x = sample_depth, y = carbon_stock,
        fill = field_location)) +
  geom_boxplot(alpha = 0.7, outlier.shape = NA) +
  geom_jitter(position = position_jitterdodge(jitter.width = 0.2),
          alpha = 0.4, size = 1) +
  facet_wrap(~ hedge_type) +
  labs(x = "Sample depth (cm)",
     y = "Carbon stock (Mg C/ha)",
     fill = "Field location") +
  theme_bw()

######################################################

# fit GLMM for carbon stock

model_cs <- lmer(
  carbon_stock ~ hedge_type * field_location * sample_depth + (1 | field_number),
  data = carbon_stock_data
)

# check summary
summary(model_cs)
```

```
########################################################

# calculate emmeans for carbon stock

emm_cs <- emmeans(model_cs, ~ hedge_type * field_location * sample_depth)

emm_cs

########################################################

#  emmeans plot for carbon stocks
emmip(model_cs, field_location ~ sample_depth | hedge_type,
     CIs = TRUE, type = "response") +
  labs(x = "Sample depth (cm)",
      y = "Estimated carbon stock (Mg C/ha)",
      color = "Field location") +
  theme_bw()

########################################################

# pairwise contrasts for hedge vs control

emm_cs_contrasts <- contrast(emm_cs, method = "revpairwise", by = c("hedge_type",
"sample_depth"))
emm_cs_contrasts



#########################################################

# Filter significant contrasts (p < 0.05)
emm_cs_sig <- as.data.frame(emm_cs_contrasts) %>%
```

```
  filter(p.value < 0.05) %>%
  select(hedge_type, sample_depth, contrast, estimate, SE, df, t.ratio, p.value)

emm_cs_sig

############################################################

# calculate total 0–50 cm carbon stock per sample
carbon_stock_totals <- carbon_stock_data %>%
  group_by(field_number, hedge_type, field_location, sample_position) %>%
  summarise(total_stock = sum(carbon_stock, na.rm = TRUE), .groups = "drop")

# quick check
summary(carbon_stock_totals$total_stock)
head(carbon_stock_totals)

############################################################

# boxplot of total 0–50 cm carbon stocks
ggplot(carbon_stock_totals,
       aes(x = hedge_type, y = total_stock, fill = field_location)) +
  geom_boxplot(alpha = 0.7, outlier.shape = NA) +
  geom_jitter(position = position_jitterdodge(jitter.width = 0.2),
              alpha = 0.4, size = 1) +
  labs(x = "Hedge type",
       y = "Total carbon stock (0–50 cm, Mg C/ha)",
       fill = "Field location") +
  theme_bw()

############################################################

# GLMM for total 0–50 cm carbon stock
```

```
model_cs_total <- lmer(
  total_stock ~ hedge_type * field_location + (1 | field_number),
  data = carbon_stock_totals
)

# check summary
summary(model_cs_total)

############################################################

# emmeans for total 0–50 cm carbon stocks
emm_cs_total <- emmeans(model_cs_total, ~ hedge_type * field_location)

emm_cs_total

############################################################

# emmeans plot for total 0–50 cm carbon stocks
emmip(model_cs_total, field_location ~ hedge_type,
      CIs = TRUE, type = "response") +
  labs(x = "Hedge type",
       y = "Total carbon stock (0–50 cm, Mg C/ha)",
       color = "Field location") +
  theme_bw()

############################################################

# pairwise contrasts for hedge vs control (by hedge type)
emm_cs_total_contrasts <- contrast(
  emm_cs_total,
  method = "revpairwise",
  by = "hedge_type"
```

```
)

emm_cs_total_contrasts

#########################################################
#
# Moving to EA Carbon / Nitrogen Data
#
#########################################################

# load and inspect CN dataset
cn_data <- read.csv("cn_data.csv")

str(cn_data)
head(cn_data)

#########################################################

# subset 0-10 cm samples and fit mixed model
cn_topsoil <- cn_data %>%
  filter(sample_depth == "0_10")

model_c_top <- lmer(
  c_percentage ~ field_location + (1 | field_number),
  data = cn_topsoil
)

summary(model_c_top)


########################################################
```

```
# raw boxplot of C% in hedge vs control (0–10 cm only)
ggplot(cn_topsoil, aes(x = field_location, y = c_percentage, fill = field_location)) +
 geom_boxplot(outlier.shape = NA, alpha = 0.6) +
 geom_jitter(width = 0.2, alpha = 0.7, size = 2) +
 labs(
  x = "Transect location",
  y = "Carbon concentration (%)",
  title = "Topsoil (0–10 cm) carbon concentration in hedge vs control transects"
 ) +
 theme_bw() +
 theme(legend.position = "none")

############################################################

# emmeans for C% at 0–10 cm
emm_c_top <- emmeans(model_c_top, ~ field_location)

emmip(model_c_top, ~ field_location, CIs = TRUE) +
 labs(
  x = "Transect location",
  y = "Carbon concentration (%)",
  title = "Estimated marginal means of topsoil (0–10 cm) carbon concentration"
 ) +
 theme_bw()

############################################################

# model with hedge_type included
model_c_top_ht <- lmer(
 c_percentage ~ field_location * hedge_type + (1 | field_number),
 data = cn_topsoil
)
```

```
summary(model_c_top_ht)

#########################################################

# emmeans for hedge_type × field_location C% at 0–10 cm
emm_c_top_ht <- emmeans(model_c_top_ht, ~ field_location | hedge_type)

# Plot with error bars
emmip(model_c_top_ht, hedge_type ~ field_location, CIs = TRUE) +
 labs(
  x = "Transect location",
  y = "Carbon concentration (%)",
  title = "Estimated marginal means of topsoil (0–10 cm) carbon by hedge type"
 ) +
 theme_bw()

#########################################################

#  depth effect on C% within controls (0–10 vs 30–50 cm)

cn_ctrl <- cn_data %>%
 filter(field_location == "control",
     sample_depth %in% c("0_10","30_50")) %>%
 mutate(sample_depth = factor(sample_depth, levels = c("0_10","30_50")))

model_c_depth_ctrl <- lmer(
 c_percentage ~ sample_depth + (1 | field_number),
 data = cn_ctrl
)

summary(model_c_depth_ctrl)
```

```
###########################################################

# add hedge type to the depth model (controls only)
model_c_depth_ctrl_ht <- lmer(
  c_percentage ~ hedge_type * sample_depth + (1 | field_number),
  data = cn_ctrl
)

summary(model_c_depth_ctrl_ht)

###########################################################

# Nitrogen data Subset topsoil (0–10 cm only)
cn_topsoil <- cn_data %>%
  filter(sample_depth == "0_10")

# LMM for nitrogen % (hedge vs control)
model_n_top <- lmer(
  n_percentage ~ field_location + (1 | field_number),
  data = cn_topsoil
)

summary(model_n_top)

###########################################################

#Boxplot of N% in topsoils

ggplot(cn_topsoil, aes(x = field_location, y = n_percentage, fill = field_location)) +
  geom_boxplot(alpha = 0.7, outlier.shape = NA) +
  geom_jitter(width = 0.2, alpha = 0.6) +
```

```
  labs(
    title = "Nitrogen concentration (%) at 0–10 cm",
    x = "Transect location",
    y = "Nitrogen (%)"
  ) +
  theme_minimal() +
  theme(legend.position = "none")

############################################################

model_n_top_ht <- lmer(
  n_percentage ~ field_location * hedge_type + (1 | field_number),
  data = cn_topsoil
)

summary(model_n_top_ht)

############################################################

# Get estimated marginal means for N% by hedge_type and field_location
emm_n <- emmeans(model_n_top_ht, ~ field_location * hedge_type)

# View the table
emm_n
# Get summary table of emmeans
emm_n <- emmeans(model_n_top_ht, ~ field_location * hedge_type)

# Convert to data frame
emm_n_df <- as.data.frame(emm_n)

# Plot with ggplot
```

```
ggplot(emm_n_df, aes(x = hedge_type, y = emmean,
           color = field_location, group = field_location)) +
 geom_point(position = position_dodge(width = 0.4), size = 2) +
 geom_errorbar(aes(ymin = lower.CL, ymax = upper.CL),
        position = position_dodge(width = 0.4), width = 0.2) +
 geom_line(position = position_dodge(width = 0.4)) +
 labs(
  x = "Hedge type",
  y = "Nitrogen concentration (%)",
  color = "Transect location",
  title = "Estimated marginal means of topsoil (0–10 cm) nitrogen by hedge type"
 ) +
 theme_bw()

##############################################################

# Subset control transects only
cn_ctrl <- cn_data %>%
 filter(field_location == "control")

# Fit mixed model with depth as fixed effect, field_number as random effect
model_n_ctrl <- lmer(n_percentage ~ sample_depth + (1 | field_number),
           data = cn_ctrl)

summary(model_n_ctrl)

##############################################################

# Linear mixed model: nitrogen in control transects by hedge type and depth
model_n_ctrl_ht <- lmer(
 n_percentage ~ hedge_type * sample_depth + (1 | field_number),
 data = cn_ctrl
```

```
)

# Model summary
summary(model_n_ctrl_ht)

##############################################################

#Emmeans of N% at control (0-10 vs 30-50cm)

emm_n_ctrl <- emmeans(model_n_ctrl_ht, ~ hedge_type * sample_depth)
emm_n_ctrl

##############################################################

#plotting emmeans

emm_df <- as.data.frame(emm_n_ctrl)

ggplot(emm_df, aes(x = hedge_type, y = emmean, fill = sample_depth)) +
 geom_col(position = position_dodge(width = 0.7)) +
 geom_errorbar(aes(ymin = lower.CL, ymax = upper.CL),
        position = position_dodge(width = 0.7),
        width = 0.2) +
 labs(
  title = "Estimated marginal means of N% in control transects",
  x = "Hedge type",
  y = "Nitrogen concentration (%)",
  fill = "Sample depth"
 ) +
 theme_minimal(base_size = 14)

##############################################################
```

```
#looking at C/N Ratio

ggplot(cn_data, aes(x = interaction(field_location, sample_depth),
           y = cn_ratio,
           fill = field_location)) +
  geom_boxplot(alpha = 0.7, outlier.shape = NA) +
  geom_jitter(width = 0.2, alpha = 0.6) +
  facet_wrap(~hedge_type) +
  labs(
    title = "C/N ratio across hedge types, transect location, and depth",
    x = "Transect location and depth",
    y = "C/N ratio"
  ) +
  scale_x_discrete(labels = c("hedge.0_10" = "Hedge 0–10 cm",
                "control.0_10" = "Control 0–10 cm",
                "control.30_50" = "Control 30–50 cm")) +
  theme_minimal(base_size = 14)

#################################################################

#Calculating total carbon stocks

library(dplyr)

# 1) Within-field layer means
field_depth_means <- carbon_stock_data %>%
  group_by(field_number, hedge_type, field_location, sample_depth) %>%
  summarise(mean_stock_layer = mean(carbon_stock, na.rm = TRUE), .groups = "drop")

# 2) Per-field totals
field_totals <- field_depth_means %>%
```

```
  group_by(field_number, hedge_type, field_location) %>%
  summarise(total_stock = sum(mean_stock_layer, na.rm = TRUE), .groups = "drop")

# 3) Summary table: mean ± SE across fields (Mg C/ha) + n
summary_totals <- field_totals %>%
  group_by(hedge_type, field_location) %>%
  summarise(
    mean_stock = mean(total_stock, na.rm = TRUE),
    se_stock   = sd(total_stock, na.rm = TRUE) / sqrt(n()),
    n_fields   = n(),
    .groups = "drop"
  ) %>%
  arrange(hedge_type, field_location)

summary_totals

#####################################################

library(knitr)

# format table with nicer column names and units
summary_totals %>%
  rename(
    `Hedge type` = hedge_type,
    Transect = field_location,
    `Mean stock (Mg C/ha)` = mean_stock,
    `SE (Mg C/ha)` = se_stock,
    `n (fields)` = n_fields
  ) %>%
  kable(digits = 1, caption = "Total soil carbon stocks (0–50 cm) by hedge type and transect.")
```

```
########################################################

#Checking SOC % change from control to hedge
summary(emm_c_top)

summary(emm_c_top_ht)

########################################################

#checking % change in BD

summary(emm_bd)

########################################################

#checking % change in Carbon stocks

summary(emm_cs)
summary(emm_cs_total)         # model-predicted means for total C stock
summary(emm_cs_total_contrasts)  # hedge - control differences + p-values

#########################################################

#Looking at hegde transects only to tease out NV vs vegetated differences

# Subset to hedge transects only (once)
hedge_loi   <- subset(hedge_data_no_out, field_location == "hedge")
hedge_bd    <- subset(bulk_data,        field_location == "hedge")
hedge_stock <- subset(carbon_stock_totals, field_location == "hedge")

# Fit one model per metric
glmm_loi_hedge    <- lmer(carbon_percentage ~ hedge_type * sample_depth + (1|field_number),
```

```
                data = hedge_loi)
glmm_bd_hedge    <- lmer(adj_bulk_density  ~ hedge_type * sample_depth + (1|field_number),
                data = hedge_bd)
glmm_carbon_hedge <- lmer(total_stock ~ hedge_type + (1|field_number),
                data = hedge_stock)

# Get emmeans averaged across depths (for CC & BD) and convert to data frames
emm_loi   <- emmeans(glmm_loi_hedge,    ~ hedge_type)
emm_bd    <- emmeans(glmm_bd_hedge,     ~ hedge_type)
emm_stock <- emmeans(glmm_carbon_hedge, ~ hedge_type)

df_loi   <- as.data.frame(summary(emm_loi,   infer = TRUE))
df_bd    <- as.data.frame(summary(emm_bd,    infer = TRUE))
df_stock <- as.data.frame(summary(emm_stock, infer = TRUE))

# Standardize order (NV → A → AO → OS)
ord <- c("NV","A","AO","OS")
df_loi$hedge_type   <- factor(df_loi$hedge_type,   levels = ord)
df_bd$hedge_type    <- factor(df_bd$hedge_type,    levels = ord)
df_stock$hedge_type <- factor(df_stock$hedge_type, levels = ord)

# Make plots (print() ensures they appear in the Plots pane)

# Carbon concentration
p_cc <- ggplot(df_loi, aes(x = hedge_type, y = emmean)) +
  geom_point(size = 3) +
  geom_errorbar(aes(ymin = lower.CL, ymax = upper.CL), width = 0.2) +
  labs(x = "Hedge type", y = "Carbon concentration (%C, LOI)") +
  theme_minimal(base_size = 14)
print(p_cc)

# Bulk density
```

```
p_bd <- ggplot(df_bd, aes(x = hedge_type, y = emmean)) +
  geom_point(size = 3) +
  geom_errorbar(aes(ymin = lower.CL, ymax = upper.CL), width = 0.2) +
  labs(x = "Hedge type", y = expression("Bulk density (g cm"^-3*")")) +
  theme_minimal(base_size = 14)
print(p_bd)

# Carbon stocks
p_cs <- ggplot(df_stock, aes(x = hedge_type, y = emmean)) +
  geom_point(size = 3) +
  geom_errorbar(aes(ymin = lower.CL, ymax = upper.CL), width = 0.2) +
  labs(x = "Hedge type", y = "Carbon stock (Mg C ha^-1)") +
  theme_minimal(base_size = 14)
print(p_cs)

#####################################################
```