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RESEARCH ARTICLE

Woodland creation scheme in the Yorkshire Dales successfully focuses tree planting on soils with lower soil organic carbon stocks

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Abstract

1. Tree planting is a key climate mitigation strategy, but afforestation on organo-mineral soils may cause soil organic carbon (SOC) losses, limiting long-term ecosystem carbon gains over decadal timescales. New woodland creation guidance aims to avoid tree planting on high-carbon soils to protect existing SOC stocks.
2. We measured topsoil SOC stocks (0–15 cm) at a new native woodland in the Yorkshire Dales, UK, with highly variable organo-mineral soils typical of many UK uplands. The woodland design was based on peat depth, vegetation classification, archaeological features and breeding bird surveys.
3. Our study had two aims. First, to test whether the woodland design resulted in tree planting in areas with lowest SOC stocks at a site scale. Second, to assess whether low-disturbance, hand-planting techniques avoided high SOC stocks at plot scale. Five replicate 10 × 10 m plots were established for each of three treatments: unplanted, low-density and high-density tree planting. Each planted plot was paired with a topographically similar unplanted control. Soil cores were sampled randomly across each plot as well as close to planted trees. Fieldwork occurred 9–13 months after planting began.
4. We found SOC stocks were significantly lower in high-density plots (median = 75.60 t C ha^{-1}; IQR = 66.44–87.95) than in unplanted (97.70 t C ha^{-1}; 80.74–115.59) and low-density plots (91.47 t C ha^{-1}; 78.67–99.98; $p < 0.05$), indicating that areas selected for tree planting preferentially targeted lower carbon soils as planned. No evidence was found to suggest avoidance of higher carbon soils at the 10-m plot scale.
5. *Practical implications*. Our results show that careful woodland design can avoid tree-planting on high-carbon organo-mineral soils. Our work shows that new woodland creation guidelines in England are likely to reduce the potential for SOC losses by targeting high-density tree planting on soils with lower SOC stocks.

KEYWORDS
carbon stocks, native woodland creation, nature-based solutions, restoration, soil organic carbon, tree-planting, upland grasslands

1 | INTRODUCTION

Reforestation and expansion of native woodlands are widely recognised as a globally important nature-based solution capable of restoring vital ecosystem functions (Bradfer-Lawrence et al., 2021; Seddon et al., 2020). Globally, reforestation is one of the few reliable methods available to expand terrestrial carbon sinks (Bastin et al., 2019; Gregg et al., 2021; Griscom et al., 2017). Across the United Kingdom, 30,000–50,000 ha of new woodland needs to be created each year to achieve atmospheric carbon sequestration and storage targets by 2050 (CCC, 2022). In England, plans include expanding current woodland cover from 14.5% to 16.5% over the next 25 years (Defra, 2021).

Mature broadleaf woodlands (30–100 years) hold the second largest carbon stock by habitat type in the United Kingdom, second only to peatlands (Gregg et al., 2021). Carbon is sequestered by photosynthesis and stored in above-ground biomass (AGB: leaves, branches, trunk) and below-ground biomass (BGB: roots) (Calders et al., 2022). Over time, trees can also lead to an increase of soil organic carbon (SOC) via root exudates, leaf litter and deadwood inputs (Rees et al., 2005). In mature woodlands in the United Kingdom, 75% of total organic carbon is stored in the soil (Ngatia et al., 2021; Vanguelova et al., 2013).

The change in SOC stocks during the first few decades of temperate woodland creation is strongly influenced by the previous land use (Guo & Gifford, 2002; Matthews et al., 2020; Thom et al., 2018). Woodland creation on cropland persistently increases SOC stocks, as arable soils are often depleted of organic matter due to tillage, residue removal and limited organic inputs (Guo & Gifford, 2002). In contrast, woodland creation on peat and highly organic soils consistently reduces SOC stocks, since these soils already hold large SOC stocks that are destabilised when hydrology is altered (Mayer et al., 2020; Sloan, 2019; Sloan et al., 2024; West, 2011). An exception is areas of wet woodlands, which can be peat forming—creation of wet woodlands could store large amounts of carbon below-ground in peat in addition to the carbon in the tree biomass (Milner et al., 2024). Woodland creation on grasslands shows mixed outcomes (Guo & Gifford, 2002; Ostle et al., 2009; Poeplau & Don, 2013). Meta-analysis suggests neutral or slightly negative SOC changes over decadal timescales, reflecting the relatively high initial SOC of many grassland soils and potential disturbance at planting (Guo & Gifford, 2002; Laganière et al., 2010; Post & Kwon, 2000; Shi et al., 2014).

Carbon loss in organic soils is mainly accredited to soil disturbance during tree establishment, which exposes mineral-free particulate organic matter to drying and increased rates of decomposition (Antony et al., 2022; Vanguelova et al., 2018, 2019). Furthermore, tree water uptake via roots and canopy interception of precipitation causes soil drying (Chandler & Chappell, 2008), which may stimulate microbial activity, increase soil respiration and lead to a decline in SOC stocks during the early decades of new woodland establishment (Friggens et al., 2020; Rees et al., 2005). The transition in vegetation from heather or grass dominated to woodland is also thought to cause a shift in dominant mycorrhizal communities, which have poorly understood consequences for soil organic matter and carbon (Guy et al., 2022).

There are limited data on native broadleaf woodland creation in the English uplands on grasslands and permanent pasture underlain by organo-mineral soils, particularly from low disturbance tree planting. Few studies have examined the outcomes of low-disturbance, variable-density planting on changes in SOC stock in these settings. While the UK evidence base is growing, most research has focussed on conifer plantations (Bavin, 2021; Matthews et al., 2020; Vanguelova et al., 2013, 2018, 2019), lowland agroforestry (Ashwood et al., 2019; Upson et al., 2016) and reforestation of the Scottish uplands (Friggens et al., 2020; Valette et al., 2024; Warner et al., 2022). Previous studies also differ by planting technique (Laganière et al., 2010), species growth traits (Vanguelova et al., 2013) and environmental conditions (Bailey et al., 2019; Thom et al., 2018). Crucially, most studies reflect past woodland creation policies rather than current guidelines (Fuentes-Montemayor et al., 2022).

Woodland creation guidelines have been developed to reflect a shift from woodland creation for timber production to a broader approach that balances outcomes for timber, carbon, biodiversity, water, soils and people. New woodland creation guidelines aim to avoid tree planting on carbon rich soils. Current UK Forestry Standard (UKFS) guidelines advise against planting on soils with organic layers deeper than 50 cm (UKFS, 2024). In England, recent guidance prohibits woodland creation on soils with an organic horizon (O horizon) deeper than 30 cm (Natural England and Forestry Commission, 2023). Across the United Kingdom, woodland creation is allowed on organic and organo-mineral soils if the organic layer is between 5 and 30 cm depth. Upland areas contain a mosaic of organic and organo-mineral soils that store approximately 30% and 22% of the UK's SOC, respectively (Bradley et al., 2005; Reynolds, 2007; West, 2011). In upland England, 29% of all rough grassland, 35% of bracken and 33% of acid grasslands are underlain by organo-mineral soils (Bol et al., 2011).

Tree planting on these soils could lead to SOC losses (Matthews et al., 2020; West, 2011) that may not be offset by increased tree biomass even after several decades (Friggens et al., 2020; Warner et al., 2022; Woodland Trust, 2023). For instance, low-disturbance planting of *Betula pendula* (Silver birch: initial densities of 10,000–40,000 trees/ha) in moorland habitats of northern Scotland resulted in no net gain of total ecosystem carbon, and losses of up to 58%

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SOC stocks from the O horizon after 39 years (Friggens et al., 2020). Similarly, a study of woodland restoration in the Scottish Highlands found newly reforested areas (initial densities of 119–1549 trees/ha) had lower topsoil (0–10 cm) SOC stocks than both the mature woodland and heather moorland control sites 6–28 years after planting (Warner et al., 2022).

Assessing how effective current planting guidelines are for avoiding higher carbon soils will be crucial for understanding the contribution of woodland expansion to regional and national net zero targets. For example, the Yorkshire Dales National Park Authority aims to plant 6000 ha of woodland by 2030 as part of its net zero strategy (YDNPA, 2020). However, net carbon sequestration may be less than expected if tree planting results in a decline of SOC stocks.

In this study, we investigate a new planned native broadleaf woodland in the English uplands. The woodland has been designed based on current UKFS guidelines (Forestry Commission, 2024) and principles outlined in the Woodland Trust woodland creation guidelines (Woodland Trust, 2022). Areas selected for tree planting were constrained by data obtained from ground surveys including peat depth, national vegetation classification, archaeological features and breeding bird surveys. We hypothesised that the woodland design would avoid tree planting on the highest carbon soils at site scale. We also hypothesised that the low-density hand-planting technique would avoid tree planting in the highest carbon soils at plot scale. We measured topsoil SOC stocks 9–13 months after tree planting and compared areas selected for two different densities of tree planting with areas that were left unplanted.

2 | MATERIALS AND METHODS

2.1 | Site description

The study site was the 529 ha Woodland Trust (WT) estate, Snaizeholme Valley, located 5 km southwest of Hawes, North Yorkshire, England (54°15′40″ N, 002°16′06″ W) (Figure 1). The valley is a north-facing, headwater catchment drained by several natural streams and man-made ditches draining into Snaizeholme Beck, a tributary of the River Ure. Elevation ranges between 297 m above ordnance datum (AOD) in the valley bottom and 668 m AOD (Figure 1). The site experiences mild winters and cool summers, with monthly mean temperatures ranging from 0.1°C (February) to 17.4°C (July) (Met Office, 2023). Mean annual precipitation is 1587 mm, with monthly total ranging from 91 mm (May) to 181 mm (December). Mean temperature and precipitation values for the period 1991–2020 were taken from Malham Tarn weather station at 391 m AOD, 22 km south of Snaizeholme (Met Office, 2023). The average annual rainfall at the valley top was 1950 mm at 571 m AOD (equivalent to 365 field capacity days) and 1681 mm at 297 m AOD (326 field capacity days) (Ryal Soil and Ecology, September 2022).

The site is underlain by the late Carboniferous Yoredale formation, which comprises bands of limestone, sandstone and argillaceous rock that run parallel along the hillslopes (British Geological Survey, 2022). The bottom of the valley is dominated by boulder clay and superficial alluvium deposits. Exposed limestone pavement is found at the top of the valley (British Geological Survey, 2022). The site-specific peat and soil survey estimated that the site comprises 110 ha (19.5%) deep peat (≥30 cm), 121 ha (21.5%) shallow peat (5–29 cm), 288 ha (50.9%) organo-mineral soil and 46 ha (8%) limestone pavement (Ryal Soil and Ecology, September 2022).

The site was previously sheep-grazed and largely treeless prior to recent planting interventions, reflecting the typical open-grazed grassland landscape that dominates the Yorkshire Dales (Gledhill, 1995).

The dominant habitats on the valley slopes are M23b *Juncus effusus/acutiflorus–Galium palustre* (Soft rush/Sharp-flowered rush–Marsh-bedstraw, rush-pasture) and U4a *Festuca ovina–Agrostis capillaris–Galium saxatile* (Sheep's-fescue–Common bent–Heath-bedstraw, grassland), within which there are small patches of higher priority vegetation communities. The site lies within the Yorkshire Dales Moorland Important Bird Area and the valley floor has been identified as a suitable breeding habitat for upland waders (Bird Survey Guidelines, 2022; Macaulay, 2022).

2.2 | Planting design and constraints

Woodland planting at Snaizeholme was guided by the principles of the Woodland Creation Guide (Woodland Trust, 2022). In the guide, the Woodland Trust follows the new requirements that prohibit the planting of new trees on soils with an O horizon thicker than 30 cm (Natural England & Forestry Commission, 2023; Woodland Trust, 2022). Site-based objectives and assessments are used to create woodland plans that are suited to the location and are guided by the following core conservation principles:

1. taking a whole-ecosystem, landscape or catchment approach to planning,
2. pursuing wider habitat connectivity in the surrounding landscape,
3. consideration of each new woodland site's unique geographic and historical context,
4. creating resilient woodland through incorporation of structural diversity and the use of locally sourced seeds,
5. prioritising planting with suitable native species,
6. using scientific evidence and inclusion of all appropriate site surveys to guide planning and
7. engaging local communities and put people at the heart of woodland creation.

An initial desk-based study found the resolution of existing soil and peat maps (1:250,000 scale by the Soil Survey of England and Wales) and vegetation was too coarse for guiding woodland design. Additional site-based surveys (Table 1) were conducted and provided information on peat depth and soil type, National Vegetation Classification (NVC), breeding birds and archaeological features. Data from all four surveys were combined into one site map and used to

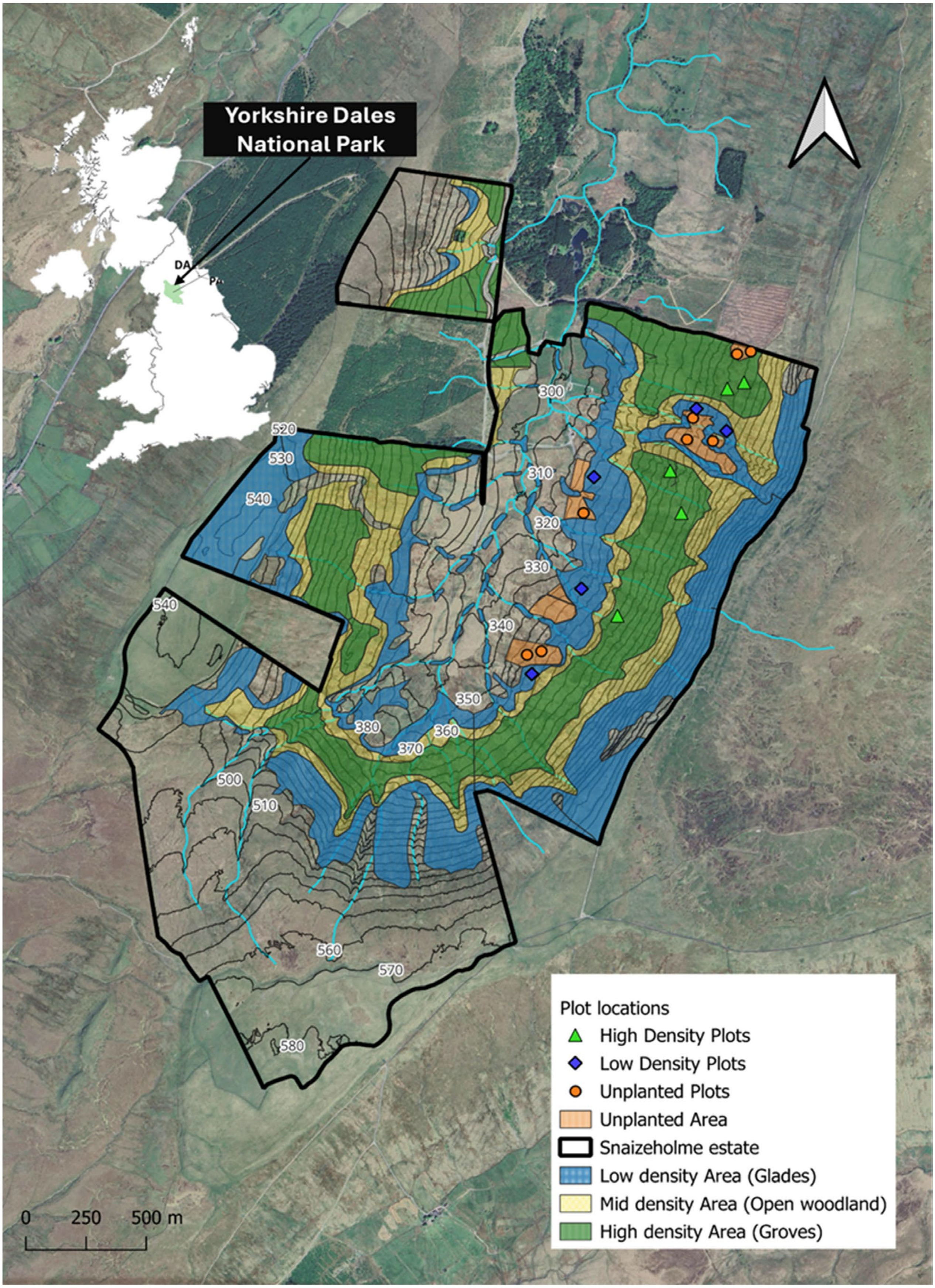

FIGURE 1 Site map of Snaizeholme with inset showing the location of the Yorkshire Dales National Park within the United Kingdom. Contour labels indicate elevation in metres above ordnance datum (AOD). The location of plots within the tree planting areas of different densities is indicated.

TABLE 1 Summary of key site assessment surveys carried out as part of woodland creation.

Survey	Purpose	More information and citations
Bird Survey	To understand the potential impact the site reforestation may have on priority bird species, and how to tailor new habitat creation to protect existing important breeding bird species.	This bird survey comprised an initial desktop study of the site using the BTO Wader Zonal Map to inform surveyors what species are likely to be present on site, and field surveys of the site and a surrounding buffer area of 2 km were conducted following Bird Survey Guidelines (2022), Brown and Shepherd (1993), and O'Brien and Smith (1992).
Soil and Peat Depth	Estimate soil type and measure peat depth on site, so planting avoids breaking peat depth planting regulations.	In brief, peat depth and soil type were assessed across the site at each point in a 100 m grid which was reduced to 50 m whenever peat was found or suspected. A narrow-gauge Dutch Auger was used to determine the presence and nature of peat where present. The methodology used to carry out the survey is described in Forestry Commission guidance (Forestry Commission, 2021).
National Vegetation Classification	Determine broad habitat class and identify smaller pockets of different habitat.	The survey included two methodologies: the NVC methodology as described in the National Vegetation Classification (NVC) Users' Handbook, for identifying vegetation present, and the Biodiversity Metric 3.1 to identify condition of each habitat. During the surveys, a Garmin GPSmap62 device (with a ~3 m accuracy) was used to record quadrat locations. The method followed the approach for NVC survey as described by Rodwell and Joint Nature Conservation Committee (GB) (2006).
Archaeological features	Determine sites of cultural significance.	A desk-based assessment reviewed available heritage records held by the Yorkshire Dales National Park Authority within the Snaizeholme Valley and a 1 km buffer around the site's boundary. This informed a field archaeological survey which mapped the location of heritage to create a detailed photographic and GIS record.

Note: Survey results and woodland creation plans (see Appendix S1) were submitted to the Forestry Commission (FC) and assessed in consultation with statutory agencies and specialist consultees. Final woodland creation design at Snaizeholme was agreed based on consultee feedback, compliance with the UK Forestry Standard (UKFS) and sign off from FC. This ensures site features such as peat, archaeology, birds and priority NVC Communities are protected or enhanced by woodland creation designs.

inform the final woodland design (Appendix S1). This resulted in planting being proposed on 51% (291 ha) of the site to avoid deep peat (including hydrologically connected areas), high-priority habitat, bird breeding zones and significant archaeological features.

The trees were planted in three densities to achieve varied canopy cover outcomes once they reach maturity: high density (HD) planting (canopy cover exceeding 70% with 800 to 1600 stems/ha), medium density planting (canopy cover from 20% to 70% with 400 to 800 stems/ha) and low density (LD) planting (canopy cover <20%, 25 to 200 stems/ha) (Figure 1; Table 2). All trees were UK sourced, mostly native broadleaf species including Alder (*Alnus glutinosa*), Aspen (*Populus tremula*), Blackthorn (*Prunus spinosa*), Downy Birch (*Betula pubescens*), Hawthorn (*Crataegus monogyna*), Pedunculate Oak (*Quercus robur*), Rowan (*Sorbus aucuparia*), Silver Birch (*Betula pendula*), Grey Willow (*Salix cinerea*) and Goat Willow (*Salix caprea*) as well as Scots Pine (*Pinus sylvestris*). Different species mixes were planted within each of the three planting treatments (Table 2).

The trees were planted across three planting seasons 2021/2022–2024/2025. All trees were planted by hand to reduce soil disturbance using the 'screef' method, where a spade-sized top layer of turf was scraped and folded back on itself, helping to reduce vegetation competition (Forestry Research, 2025). A tree-plug or bare-root whip was then slot-planted in the bare soil. The project has not used tree guards, mechanical ground preparation treatments or herbicide during tree establishment. The only protective measure taken has been the construction of a livestock fence at the borders of the estate and between planting compartments. 50% more trees were planted than the target final stocking density to account for initial losses. However, the WT currently intends to leave 'failed' areas unstocked, enabling natural processes to create a more heterogeneous woodland–valley mosaic and allow colonisation over time.

2.3 | Experimental design

We focussed sampling efforts on the west-facing aspect of the native woodland scheme where tree planting had taken place in the spring of 2022/2023 and winter of 2023/2024. Our aim was:

TABLE 2 Summary of planting treatments.

Treatment and no. of plots	Elevation range (AOD, m)	Slope angle range (°)	Tree species	Stems/ha—Initial expected planting density	Average no. stems/haplanted as calculated from 100 m² study plots	Stems/ha—Expected tree survival
High density (HD) *n* = 5	411–442	10–17	Alder (*Alnus glutinosa*) Aspen (*Populus tremula*) Birch (*Betula* spp.)[a] Hawthorn (*Crataegus monogyna*) Rowan (*Sorbus aucuparia*) Scots Pine (*Pinus sylvestris*) Willow (*Salix* spp.)[a]	1600–3200	2940	800–1600
Low density (LD) *n* = 5	345–435	10–17	Hawthorn (*Crataegus monogyna*) Rowan (*Sorbus aucuparia*) Scots Pine (*Pinus sylvestris*) Willow (*Salix* spp.)[a]	50–800	860	25–400
Unplanted (UP) *n* = 8	348–443	10–18	N/A	0	0	0

Note: Description of elevation range (AOD), slope angle, number of trees planted, tree species, stems per hectare (stems/ha) planted and final stems per hectare (stems/ha) expected across the plots selected for topsoil sampling.

[a]Note that the distinction between the different Birch (*Betula* spp.) and Willow (Salix spp.) species was not specified due to age of tree.

1. to determine the differences in the soil carbon stock and vegetation structure between three treatments within the woodland design: high-density planted (HD), low-density planted (LD) and unplanted (UP) control sites;
2. to investigate whether tree planting had preferentially targeted lower-carbon soils at the plot scale.

The mid-density area was not included in this study. Pairwise plots were selected based on geographical parameters including topography, elevation and aspect, adapted from the method described by Warner et al. (2022).

Locations for pairs of unplanted (UP) control × high-density (HD) planted plots (10 × 10 m), and pairs of unplanted control (UP) × low-density (LD) planted plots were randomly selected. A Digital Elevation Model (DEM) within QGIS was used to ensure each HD and LD plot was paired with a UP plot of identical elevation, aspect and slope (Figure 1). To further ensure that comparable conditions were represented between each of the treatment categories, each plot was then ground-truthed and discarded if:

1. containing topographical features such as wet-flushes or gullies;
2. if the average slope angle of the plot area was not between 10 and 20° and varied by more than 5° across the plot.

In total, five HD plots and five LD plots were selected, along with paired unplanted controls. Our paired-plot approach was designed to limit variation in confounding site factors across treatments while accurately representing treatment conditions present because of the woodland design (Figure 1; Table 2).

In each 10 × 10 m plot, all trees were counted, and species were determined on the day of soil collection (Table 2). Four 1 × 1 m quadrats were placed in the centre of each quarter of the plot, and the maximum height of the ground vegetation and depth of the moss layer were then measured at five points evenly distributed across the diagonal of the quadrat as described by Warner et al. (2022). Vegetation surveys were all completed between the 9th and 11th of July 2024.

2.4 | Soil sampling

Soil samples were collected from March to July 2024. Samples from paired plots were extracted simultaneously within this time frame to minimise the effect of recent weather on paired samples. Samples were collected with a 5 cm diameter × 15 cm length PVC core, directly below any undecomposed litter. Soil was sampled to this depth as the surface layers were expected to be most sensitive to the change in land use (Emmett et al., 2010). Samples were transported and stored at 4°C prior to analysis at the School of Geography, University of Leeds, UK.

Five cores were extracted randomly from each treatment plot. A further five core samples were extracted in both the HD and LD site plots within a distance <20 cm from a randomly selected tree stem. Average distance from trees was recorded for each core sample. In total, 50 cores were collected across each of the five planting treatment plots (HD, $n = 50$ and LD, $n = 50$) and 40 were collected across the eight unplanted treatment plots (UP, $n = 40$). Permission to conduct fieldwork was obtained from the Woodland Trust Site Manager of the Snaizeholme Valley estate.

2.5 | Laboratory analysis

All soil core samples were analysed for bulk density, gravimetric soil moisture and soil organic carbon (SOC) content. The soil organic carbon (SOC) stock was subsequently estimated using the SOC and bulk density values.

The height of the soil within each PVC core was measured to determine the volume of soil sampled in each core to the nearest cm^3. Soil was then extracted from each PVC core, weighed and subsequently oven dried at 105°C for 16h before being weighed again for the determination of moisture content and bulk density. Gravimetric moisture content (%) was determined by dividing the water content by the weight of oven-dry soil and multiplying by 100. After drying at 105°C, the soil was sieved to 2mm and gravel and roots removed, and their masses recorded. Bulk density was then calculated as the difference between the total sample mass and the mass of gravel and roots, divided by the sample volume (Poeplau et al., 2017). This corresponds to the fine soil stock (FSS) where the SOC is contained. Given the heterogeneity of soil types across the site (Ryal Soil and Ecology, 2022), we prioritised direct estimation of fine-soil mass from the full mass of each sampled core to capture the variability by sample—used in subsequent SOC stock calculations—rather than relying on separate bulk density cores (Lee et al., 2009; Yimer et al., 2006).

Well mixed sub-samples of oven dried, sieved to 2mm, topsoil were then placed in a furnace for 12h at 375°C for the determination of soil organic matter (SOM) content (%) via the loss-on-ignition (LOI) method. A replicate sample was included for every fifth sample for quality assurance. The method has a detection limit of 0.05%, and the balances used for weighing had an accuracy of 0.04g and were calibrated between weighing batches of samples. A lower ignition temperature was used in line with the countryside survey protocol to account for potential overestimation of organic matter that can occur in soils due to the presence of calcium carbonate that is likely when samples come from areas with limestone presence (Emmett et al., 2010). Soil organic carbon (SOC) was then estimated from the SOM content by assuming 58% of the SOM is made up of carbon (Pribyl, 2010). When applied without a site-specific calibration curve to derive conversion factors, LOI has known limitations (Sleutel et al., 2007), yet it offers an accessible and cost-effective means of estimating the relative SOC stocks over extended timeframes (Sollins et al., 1999).

The SOC stock ($Mg\,C\,ha^{-1}$) was estimated for each location by multiplying SOC content by FSS to a fixed soil depth as:

$$\text{SOC stock} = \text{SOC}_{\text{con}} \times \text{FSS} \times t \quad (1)$$

where SOC_{con} is the SOC content (%), FSS is the fine soil stock ($g\,cm^{-3}$), and t is the respective thickness (cm) of the soil layer sampled, which in this case was 15cm.

Soil type of samples was approximated using LOI categorisation as described in the Countryside Survey Soil Report 2007 (Emmett et al., 2010). Categories were based on soil organic matter content defined as mineral (0%–8% LOI; 0–44$\,g\,C\,kg^{-1}$), humus-mineral (8%–30% LOI; 44–65$\,g\,C\,kg^{-1}$), organo-mineral (30%–60% LOI; 165–330$\,g\,C\,kg^{-1}$) and organic (60%–100%; >330$\,g\,C\,kg^{-1}$) (Emmett et al., 2010).

2.6 | Statistical analysis

The dataset described as Darvill (2026), underpins all subsequent analyses, consisting of soil properties and vegetation data collected and processed as previously described. Shapiro–Wilk tests were used to assess the normality of soil properties (Table S1) and vegetation structure (Table S2) grouped by treatment (UP, HD, LD) and sampling types (random, <20cm to a tree). Despite log transformations, most grouped datasets continued to show significant deviations from normal distribution ($p < 0.05$). Given the small sample sizes and lack of normality in residuals, non-parametric methods were applied for further analysis of difference between treatments.

A Kruskall–Wallis test was used to compare medians of the soil properties (Table S3) and vegetation structure (Table S4) among the three treatments. Post hoc pairwise comparisons were performed using Dunn's post hoc test with Bonferroni adjustments applied to increase stringency and likelihood of false-positive findings (Tables S5 and S6) (Agbangba et al., 2024).

The Wilcoxon rank-sum test (Mann–Whitney *U*) was used to determine significant differences between the medians of the soil properties between the two sampling treatments (random and <20cm to tree) used within the two tree-planted treatments (HD and LD) (Tables S7 and S8). Associations between measured soil properties and potential environmental predictors including sward height, moss depth, elevation and slope angle were examined using linear regression models. However, due to lack of normality, the strength and direction of these relationships were assessed using Spearman's rank correlation coefficients, a nonparametric measure of monotonic association.

All analyses were carried out using R version 4.0.0; statistics were performed using the packages dplyr and R base (R Core Team, 2024; Wickham et al., 2023).

3 | RESULTS

3.1 | Tree species and tree-planting density estimates

The average stem density of newly planted trees was 2940 stems/ha and 860 stems/ha in the HD and LD treatments, respectively. Species presence in HD treatment plots included *Pinus sylvestris*, *Alnus glutinosa*, *Betula* spp., *Sorbus aucuparia*, *Salix* spp., *Crataegus monogyna* and *Populus tremula*, with mixes of three to seven species per plot. The LD treatment plots only contained *Sorbus aucuparia*, *Betula* spp., *Crataegus monogyna*, *Salix* spp. and *Pinus sylvestris*, with mixes of two to three species per plot (Table 2). The sampled plots contained the density and species expected based on the woodland creation plan.

3.2 | Soil properties and vegetation structure between planting densities

Bulk density, gravimetric soil moisture (GSM), SOC content and SOC stocks all differed significantly across the HD, LD and UP sites (Kruskall–Wallis test, $p<0.05$). Post hoc Dunn's test with Bonferroni correction showed SOC stocks were significantly higher in UP (median = 97.70 tC/ha; IQR: [80.74–115.59]) and LD (median = 91.47 tC/ha; IQR: [78.67–99.98]) compared to HD (median = 75.60 tC/ha; IQR: [66.44–87.95]; $p<0.05$; Figure 2D). Corresponding mean ± SE values were UP: 100.45 ± 4.56, LD: 90.78 ± 3.29 and HD = 80.42 ± 3.75 tC/ha. Bulk density was significantly higher in HD soils (median = 0.59 g/cm^3; IQR: [0.48–0.65]) than in UP (median = 0.22 g/cm^3; IQR: [0.14–0.67]; $p<0.05$; Figure 2A). Although LD (median = 0.57 g/cm^3; IQR: [0.26–0.65]) showed similar values to HD, the difference between LD and UP was not statistically significant. GSM was significantly greater in UP sites (median = 360.49%; IQR: [84.66–552.26]) than in HD (median = 110.90%; IQR: [98.55–127.37]; $p<0.05$; Figure 2B). LD sites (median = 107.34%; IQR: [92.98–264.60]) had lower GSM than UP but were not significantly different. SOC content was significantly lower in HD (median = 8.64%; IQR: [7.29–10.89]) than UP (median = 44.7%; IQR: [8.28–52.08]; $p<0.05$; Figure 2C), though no significant differences were found between LD (median = 9.77%; IQR: [7.99–20.52]) and either HD or UP.

Vegetation structure also varied significantly. Sward heights were greater in HD (median = 68.5 cm; IQR: [56.5–84.0]) than in UP (48.5 cm; IQR: [39–62], $p<0.05$) and LD (8.0 cm; IQR: [36.5–61.5]; $p<0.05$) (Figure 3A). Moss depths were significantly greater in UP (median = 12.0 cm; IQR: [5.0–18.0]) and LD (median = 13.0 cm; IQR: [8.75–17.0]) than HD (median = 7.0 cm; IQR: [0.0–11.0]; $p<0.05$) (Figure 3B).

3.3 | Relationships between soil properties and vegetation structures

Across the whole study site, vegetation height was positively related with bulk density ($R^2=0.33$, $\rho=0.57$, $p=0.013$) (Figure 4a), and negatively related with soil moisture ($R^2=0.35$, $\rho=-0.59$, $p=0.009$) (Figure 4b) and SOC content ($R^2=0.36$, $\rho=-0.6$, $p=0.009$) (Figure 4c). Conversely, moss depths were negatively associated with bulk density ($R^2=0.72$, $\rho=-0.85$, $p<0.001$), and positively related with gravimetric soil moisture ($R^2=072$, $\rho=0.85$, $p<0.001$) and SOC content ($R^2=0.6$, $\rho=0.77$, $p<0.001$) (Figure 4e–g). Vegetation structure showed minimal relationship with SOC stocks (Figure 4d,h).

Due to the wide variability of soil properties from the UP plots, we investigated our control factors. SOC stock was negatively related to elevation, with an estimated decrease in SOC stock of 0.33 tC/ha per metre of elevation gain ($y=-0.33\times x+225.66$; $R^2=0.27$, $\rho=-0.58$, $p=0.011$) (Figure 5d). We found no significant effect of elevation on other soil properties, and no significant relationships were found between SOC stock and average slope angles (Figure 5a–c,e–h).

Higher SOC % was strongly correlated with lower bulk density ($y=-0.01\times x+0.73$; $R^2=0.91$, $\rho=-0.85$, $p<0.001$) (Figure 5k). There was a strong positive trend between soil moisture and SOC % ($y=0.08\times x+1.69$; $R^2=0.92$, $\rho=0.88$, $p<0.001$) (Figure 5l).

3.4 | Soil properties between sampling treatments

The random soil samples were extracted an average of 98 cm from trees in HD and 168 cm in LD plots, compared to 15 cm in the samples taken close to trees. The difference in proximity of random samples to the closest tree within the two woodland densities reflects the differences in density of the newly planted stems per plot (Table 2). Within our small subset of samples collected from the 10 × 10 m plots, we found there was no significant difference between any of the measured soil properties in either HD or LD plots (Figure S1; Tables S9 and S10).

3.5 | Classification of soil type

Based on the LOI categorisation described within the CEH Soil Survey 2007 (Emmett et al., 2010), 1.3% of soils sampled in this investigation were found to be mineral soils, 66.7% humus-mineral soils (HD = 28%; LD = 24%; UP = 14.7%), 7.3% organo-mineral soils (HD = 4%, LD = 2.7%; UP = 0. 7%), and 24.7% (LD = 6.7%; UP = 18%) organic (Figure 6). Both HD and LD planting were focussed on humus-mineral soils. HD planting completely avoided organic soils. In contrast, UP sites were dominated by organo-mineral and organic soils.

4 | DISCUSSION

4.1 | Soil in upland grasslands

Soil properties at our study site exhibited low bulk density, high soil moisture and high SOC content typical of upland organo-mineral systems (Bond et al., 2021; Emmett et al., 2010; West, 2011). Our estimated SOC stocks correspond with those reported in other studies for grasslands in upland Britain (Emmett et al., 2010; Eze et al., 2018; Gregg et al., 2021). SOC stocks at a nearby site (Nidderdale, Yorkshire Dales), also dominated by shallow, poorly draining, stagnohumic gley soils, were found to range from 58.9 ± 3.5 to 100.7 ± 8.6 tC ha^{-1} (Eze et al., 2018). The Countryside Soil Survey (Emmett et al., 2010) reported an average SOC stock of 67.2 tC/ha and 90.6 tC/ha in the top

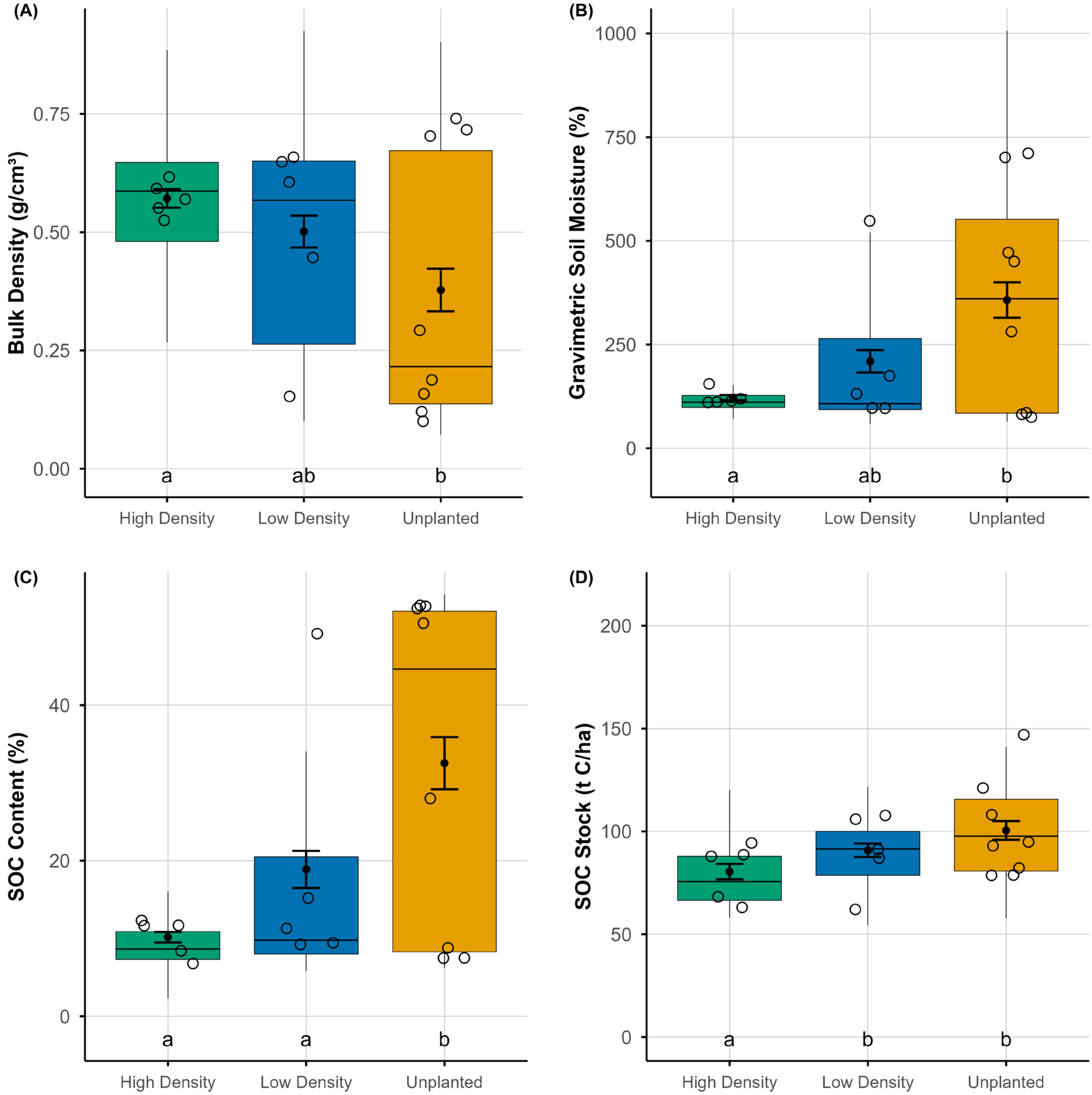

FIGURE 2 Soil properties (A) bulk density (g/cm^3), (B) gravimetric soil moisture (%), (C) soil organic carbon content (SOC_{con}; %) and (D) SOC stock (tC/ha) by tree planting treatment (high density (green), low density (blue) and unplanted (orange)). All samples are represented per treatment (HD, $n=50$; LD, $n=50$; and UP, $n=40$). Horizontal bars of the box plots represent the median and interquartile range. The overall treatment mean is shown as a solid black circle, with error bars showing the standard error of the mean (SEM). The mean of each plot within each treatment is shown as an open circle. Whiskers extend from first quartile (25th percentile) to third quartile (75th percentile). Different letters indicate statistically significant difference between treatment medians ($p<0.05$).

15cm of soil for UK improved grasslands and acid grasslands, respectively. The recent review by Natural England reported mean SOC stocks (0–15cm) of 87tC/ha in acid grasslands, 60tC/ha in neutral grasslands and 69tC/ha in calcareous grasslands (Gregg et al., 2021). Our results align with previous findings and confirm that a substantial carbon store already exists in our upland grassland site, like other upland grasslands in the United Kingdom.

4.2 | Strategic spatial planning for woodland creation

Our results indicate that HD tree planting was effectively targeted to lower SOC areas. SOC stocks were significantly lower in HD plots compared to LD and UP areas (Figure 2), and HD plots contained no organic soils; they were predominantly humus-mineral

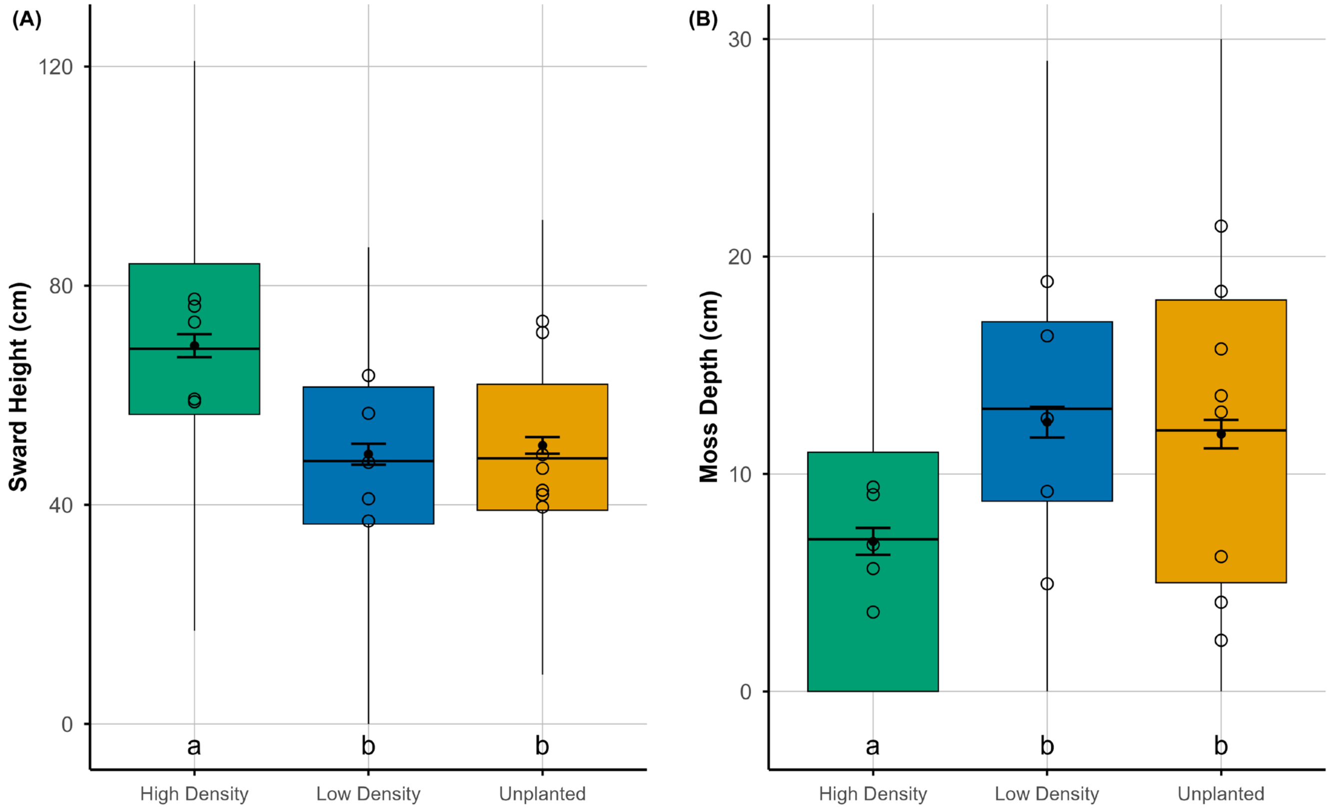

FIGURE 3 Sward height (cm) and moss depth (cm) by woodland density planting treatment. Horizontal bars in box plot shows median and interquartile range. The solid black dot represents treatment mean average and error bars show SEM (±). Open circles represent plot mean average. Treatments are high density in green, low density in blue, and unplanted in orange. Figure includes all data points from across all treatments. Different letters indicate statistically significant differences between treatment medians ($p < 0.05$) between treatments.

(Figure 6). This provides evidence that the combination of metrics used within the woodland design on this site created spatially explicit planting maps that constrained the highest density tree planting to the soils with the lowest SOC stocks. Targeting tree planting is important, as SOC losses in grasslands are more likely in peaty, waterlogged soils (Bateman et al., 2023). Planting in areas with lower SOC offers the greatest potential for additional carbon sequestration or, at a minimum, could help avoid emissions of carbon from soil disturbance (Antony et al., 2022; Guo & Gifford, 2002).

However, we found no significant SOC stock difference between LD and UP areas, and organic soils made up 24.7% of samples; 6.7% were within the LD treatment. This suggests that whilst broad-scale tree planting targeting was successful, finer-scale planting decisions could be improved to avoid a small percentage of high-carbon soils. We had hypothesised that planters might use visual cues such as vegetation or waterlogging to avoid high SOC patches at the plot (10 m × 10 m) scale, but found no significant difference in any soil properties between samples taken <20 cm and >20 cm from the planted tree (Figure S1).

Our findings suggest that existing spatial planning tools are effective, but plot scale refinements could improve outcomes further. Introducing simple field-based indicators could offer practical improvements. For example:

- Peat probes could be used at finer scales to assess O horizon depth and identify high-carbon patches, as demonstrated in larger-scale surveys (Miller & Olewski, 2025).
- Visual hydrological indicators such as standing water or high moss coverage could signal areas with suppressed decomposition and higher SOC (Doetterl et al., 2016; Jobbágy & Jackson, 2000).

We also explored vegetation structure as a potential low-cost, accessible tool for avoiding soil with high-carbon stocks. Vegetation influences organic inputs and decomposition rates (Kuznetsova et al., 2021), and distinct communities are associated with different SOC contents. Moss-dominated systems typically have deep, carbon-rich soils (Bradley et al., 2005; Emmett et al., 2010), while Juncus-dominated areas produce more labile litter with lower SOC (Agethen & Knorr, 2018). Our findings support this: we observed strong inverse relationships between vegetation structure and both SOC % and bulk density. However, the correlation with total SOC stocks was weak—likely due to our shallow sampling depth (15 cm). Deeper sampling (e.g. to 30 cm) may reveal stronger associations between vegetation and SOC stock (Harrison et al., 2011; Maillard et al., 2017).

Still, moss depth >10 cm was associated with higher SOC % and soil moisture, and lower bulk density (Figure 4g), suggesting moss cover could serve as a practical visual indicator for planters.

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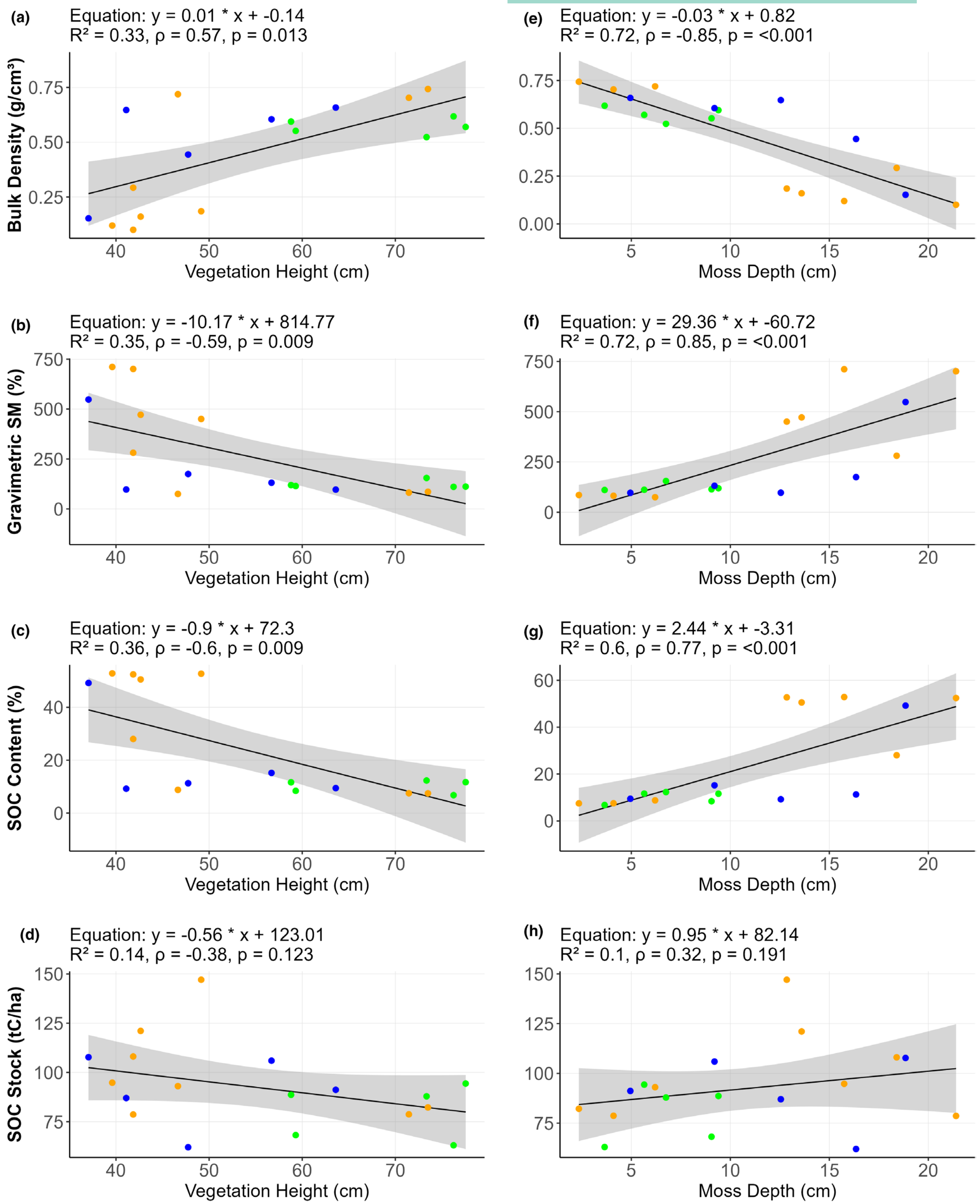

FIGURE 4 Linear regression relationships between vegetation height (cm) and soil properties (a–d), and moss depth (cm) and soil properties (e–h). Soil properties on the *y*-axis (in bold), from top to bottom, are bulk density (g/cm^3) (a and e), gravimetric soil moisture (%) (b and f), SOC content (%) (c and g), and SOC stock (tC/ha) (d and h). Each point represents the mean value per plot for the respective soil property, plotted against the mean vegetation height or moss depth for that plot. Colours indicate treatment type: Green = high density (HD), blue = low density (LD), and orange = unplanted (UP). Solid black lines represent linear regression fits, with grey shading indicating 95% confidence intervals. *y* = regression equation; R^2 = coefficient of determination from linear regression; ρ (rho) = Spearman's rank correlation coefficient; *p* = significance level for the Spearman correlation.

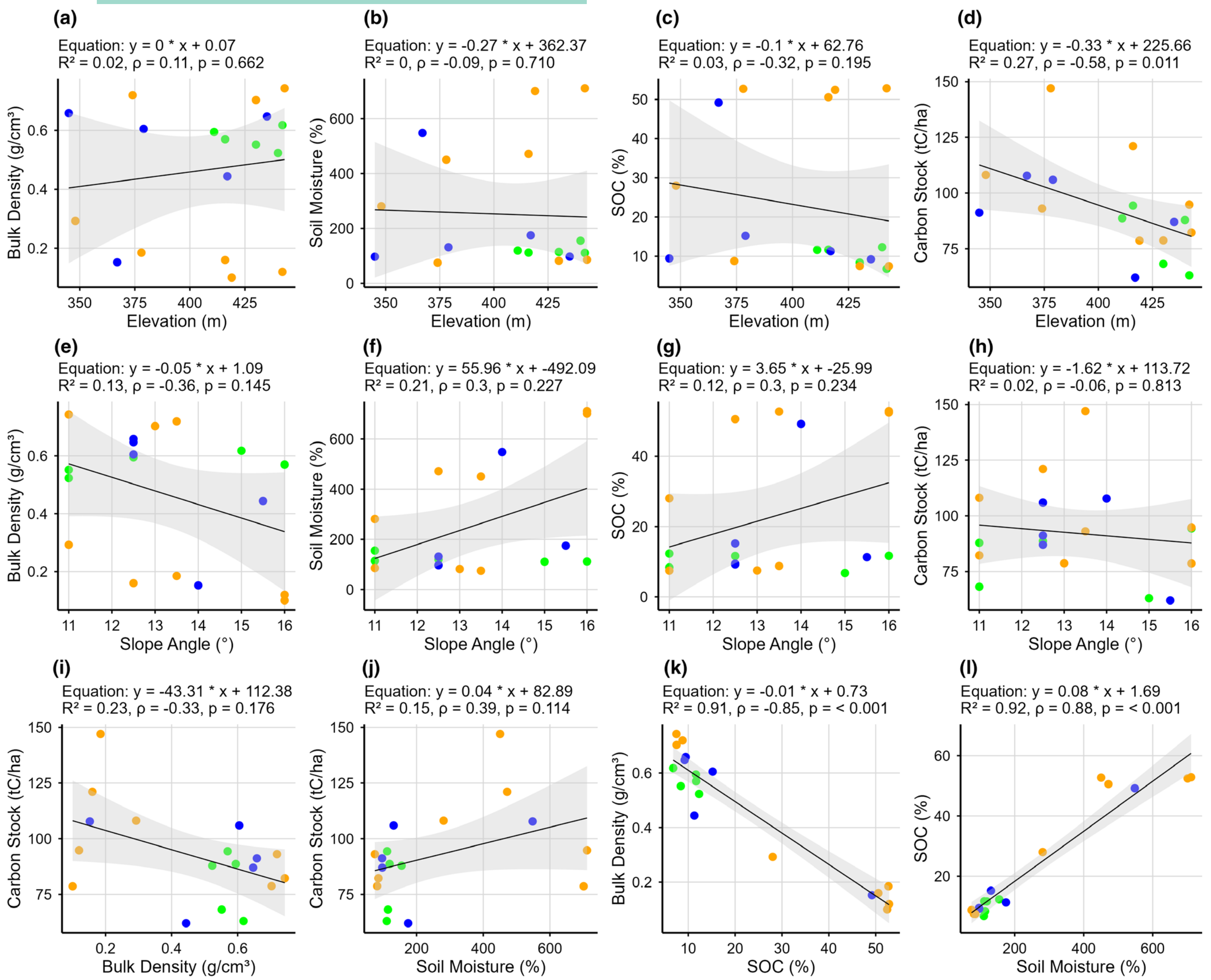

FIGURE 5 Linear regression relationships between elevation and soil properties (a–d), slope angle and soil properties (e–h) and between soil properties (i–l). Closed circles indicate the calculated mean average of each soil property by plot (bulk density, gravimetric soil moisture, SOC content and SOC stock) against the elevation of each plot. Colour coding displays which treatment type each plot belongs too (green = HD, blue = LD and orange = UP). Solid black lines represent linear regression fits, with grey shading indicating 95% confidence intervals. y = regression equation; R^2 = coefficient of determination from linear regression; ρ (rho) = Spearman's rank correlation coefficient; p = significance level for the Spearman correlation.

While vegetation structure may not directly predict SOC stock, it may help flag higher-carbon areas that should be avoided during planting.

Earlier broadleaf woodland schemes often resembled plantation forestry with high-density planting in straight lines, with little attempt to avoid areas of high-carbon soil (Fuentes-Montemayor et al., 2022). Previous studies often represent outcomes of change in SOC stocks of woodlands created under these older guidelines (Friggens et al., 2020; Matthews et al., 2020) or provide evidence of upland woodland creation with limited spatial planning (Warner et al., 2022). In contrast, our study provides SOC stock baseline data from an upland woodland creation site, designed using England's new woodland creation guidelines. This is important as soils with higher organic carbon per unit area are more vulnerable to carbon losses (Cagnarini et al., 2019; Sloan, 2019). Mineral soils tend to be more resilient to changes in decomposition, and thus SOC change, associated with the first few decades of woodland establishment (Kaiser et al., 2012). Successfully targeting planting where SOC stocks are lowest could reduce relative carbon losses associated with tree planting and growth, which has recently been reported by other studies (Friggens et al., 2020; Warner et al., 2022).

Overall, our results show that following new recommended woodland creation guidelines and enforced forestry standards effectively prevented the planting of new trees on higher carbon soils at Snaizeholme (Natural England & Forestry Commission, 2023). Specifically, incorporating variable density tree planting into the woodland design has avoided high-density planting on carbon-rich soils (Woodland Trust, 2022). The outcome at Snaizeholme is a demonstration of how the use of detailed site surveys by woodland

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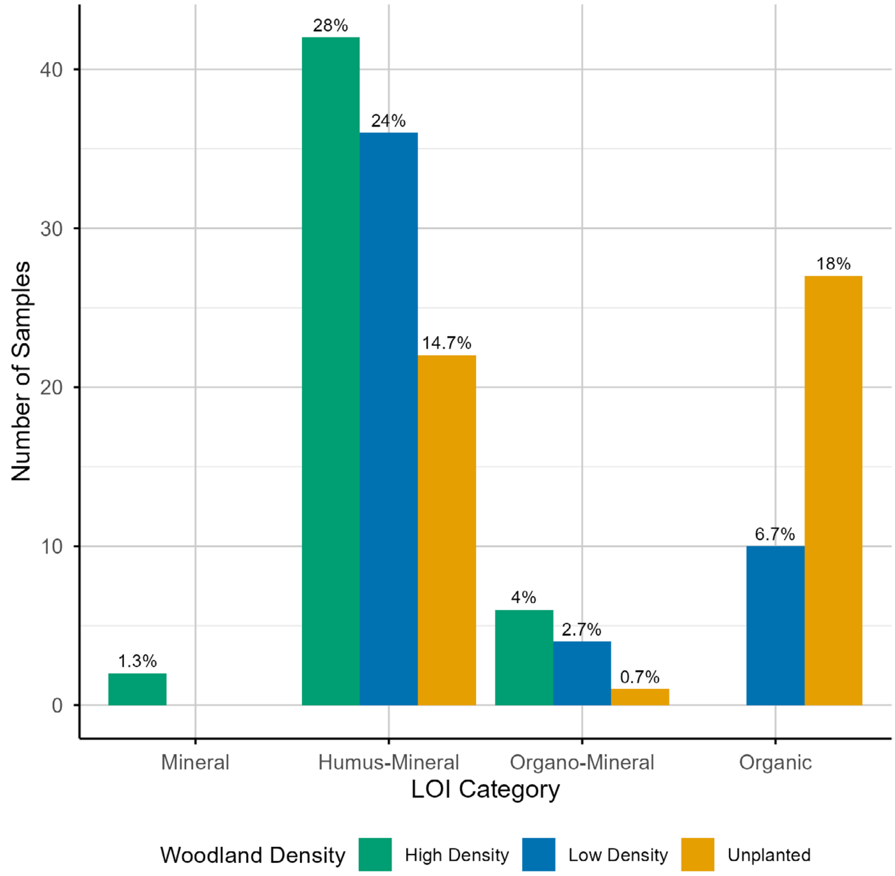

FIGURE 6 Soil type distribution determined by the loss-on-ignition categorisation method. Bars show the number of samples in each LOI category (Mineral, Humus-Mineral, Organo-Mineral, and Organic) for high-density (HD, green), low-density (LD, blue), and unplanted (UP, orange) treatments. Percentages above each bar indicate the proportion of the total dataset represented by each treatment–LOI category combination.

planners can target tree planting to specific areas and protect important existing soil carbon stores, as well as avoid high priority vegetation, areas of archaeological importance, and bird habitats. However, future data collection over the next few decades will be required to assess long-term outcomes.

4.3 | Implications for monitoring change in soil carbon stock

Monitoring SOC stock change is challenging. Soil carbon changes slowly, and the signal may be small relative to background variability—making it difficult to detect significant trends, especially in the short term (Flack et al., 2022; Webster, 2000). Even statistically significant differences can take decades to emerge (Kravchenko et al., 2006), and baseline SOC datasets pre-woodland creation are rare (Warner et al., 2022). Furthermore, changes to sampling protocols over time complicate comparisons (Friggens et al., 2020). In the absence of long-term data, space-for-time substitution (SFTS) is often used to assess land-use impacts on soil properties (Damgaard, 2019). This approach assumes that intervention and control plots had the same land-use history and soil conditions prior to land cover change (Lovell et al., 2023). While chronosequences and paired designs aim to minimise baseline differences, they cannot eliminate them entirely (Poeplau & Don, 2013). To explore differences between intervention and control plots, we compared soil properties across our different treatments. Our selection of UP control sites matched approaches used in previous SFTS, so it provides an indication of potential baseline differences. We found that areas selected for high-density tree planting had significantly lower ($p < 0.05$) SOC stocks than the unplanted (UP) matched control sites. The difference in median SOC stocks between the HD and UP plots (22.1 tC/ha) was as large as the difference in SOC stocks observed between grassland (60–100 tC/ha) and woodland soils (84.7 tC/ha) to a depth of 15 cm in the UK Countryside Survey (Emmett et al., 2010). In our study, we also matched plots by aspect, elevation and topography, which is a common approach in SFTS (Levy et al., 2024). Our results demonstrate that the UP sites in this woodland have lower baseline SOC stocks and do not reflect pre-planting conditions of HD tree planted areas. This suggests SFTS monitoring approaches would overestimate the change (i.e. loss) in SOC stock associated with woodland creation at this site.

They also highlight the challenges of SFTS for assessing changes in SOC stock associated with land-use change within heterogeneous soil landscapes. Other studies corroborate that SFTS approaches for assessing the effect of land management treatments can be difficult to interpret, often critiquing their reliability (Cardinael et al., 2015; Levy et al., 2024). SFTS remains crucial when long-term data are lacking (Levy et al., 2024), but care will be needed in interpreting previous results. Using older woodland datasets to predict how new woodlands with stricter planning may not provide accurate outcomes, potentially overestimating carbon losses caused by new tree planting (Fuentes-Montemayor et al., 2022). However, we recognise the need for SFTS approaches where baseline data sets are unavailable, or time constraints make waiting for the results of long-term monitoring untenable.

4.4 | Other ecosystem service benefits

Native woodlands enhance ecosystem resilience and help mitigate climate change impacts on people and nature (Seddon et al., 2021). Increased woodland cover can also reduce downstream flooding (Monger et al., 2021), lower surface temperatures, improve water quality and supply, and support biodiversity recovery (Defra, 2021). Collectively, these benefits contribute to nature recovery, climate action, and net-zero targets. However, the net carbon impact of new woodlands varies locally, depending on previous land use, initial habitat condition, woodland and soil types, and weather (Griscom et al., 2017; Matthews et al., 2020; Thom et al., 2018). Our findings indicate that robust baseline data and long-term monitoring are critical to assess the impacts of woodland expansion in heterogeneous upland landscapes.

5 | CONCLUSIONS

Woodland creation and tree planting are a major component of climate mitigation efforts. However, tree planting on carbon-rich organic and organo-mineral soils may lead to the loss of carbon. We measured soil properties at a woodland creation site in upland Northern England to assess whether careful woodland design following new Woodland Creation guidelines can avoid tree planting on carbon-rich soils. We found significantly lower soil carbon in areas selected for high-density tree planting compared to unplanted areas. Our study shows that well-planned woodland creation that incorporates information on soil type, peat depth, vegetation, archaeology and bird breeding can successfully target tree planting onto lower carbon soils.

Within 10 m × 10 m plots, we found no evidence that tree planting avoided higher carbon soils. Simple tools such as finer-resolution peat depth probing could help further minimise planting on higher carbon stock soils. We examined the relationships between vegetation and soil properties as a potential method to avoid tree planting on higher carbon soils at smaller spatial scales. We found relationships between soil properties and vegetation structure measurements such as moss depth and sward height. Vegetation structure has potential to be an accessible, easily interpretable, low-cost indicator of lower carbon soils in upland grassland sites that could complement site-wide surveys.

Overall, we show that woodland creation following new Woodland Creation Guidance with detailed site surveys can successfully target tree planting to humus-mineral soils, avoiding organic soils with higher SOC stocks. Finding effective ways to target tree planting to lower carbon soils in upland landscapes helps to protect existing carbon stocks and increases the potential for net carbon sequestration from woodland creation.

AUTHOR CONTRIBUTIONS

Francesca Darvill conceived the study's conceptual framework; developed the methodology; collected soil samples; carried out laboratory analyses; curated the dataset; and led the writing of the manuscript, including drafting, revising and data visualisation. Dominick V. Spracklen supervised the project, contributed to the development of the methodology, and assisted with revising and editing the manuscript. Catherine E. Scott and Pippa J. Chapman provided additional supervision, supported the design of the methodology, and contributed to editing the manuscript. John Crawford and Robert Mills contributed to validating the study's findings, offered further supervisory support, and reviewed the manuscript. Tamba Komba assisted with laboratory analyses of soil samples, and Robyn Wrigley contributed to vegetation structure surveys. All authors approved the final version for publication.

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CONFLICT OF INTEREST STATEMENT

The authors affirm that there are no conflicts of interest pertaining to this manuscript. This encompasses any financial or other affiliations that might be perceived as potential conflict sources, in alignment with the *Journal of Ecological Solutions and Evidence*'s Conflict of Interest guidelines.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data associated with this paper are openly available from the University of Leeds Data Repository: https://doi.org/10.5518/1804 (Darvill, 2026).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1: Final Woodland Design Plan for the Woodland Trust's Snaizeholme site, with annotations highlighting key planning decisions and spatial design considerations.

Table S1: Shapiro–Wilk test of normality of residuals of soil properties (bulk density, gravimetric soil moisture, soil organic carbon content, carbon stock) grouped by woodland density.

Table S2: Shapiro–Wilk test of normality of residuals of vegetation structure (moss depth, sward height) grouped by woodland density.

Table S3: Kruskal–Wallis test comparing soil properties (bulk density, soil moisture, soil organic carbon, carbon stock) across woodland density treatments.

Table S4: Kruskal–Wallis test comparing vegetation structure (sward height, moss depth) across woodland density treatments.

Table S5: Dunn's post hoc test for soil properties (bulk density, soil moisture, soil organic carbon content, carbon stock) across woodland density categories.

Table S6: Dunn's post hoc test for vegetation structure (sward height, moss depth) across woodland density categories.

Table S7: Results of Wilcoxon's ranked sum test (Mann–Whitney *U*) for high woodland density treatment 10 × 10 m plots near to tree (<20 cm) versus >20 cm from tree.

Table S8: Results of Wilcoxon's ranked sum test (Mann–Whitney *U*) for low woodland density treatment 10 × 10 m plots near to tree (<20 cm) versus >20 cm from tree.

Table S9: Results of Wilcoxon's ranked sum test (Mann–Whitney *U*) for high woodland density treatment 10 × 10 m plots near to tree (<20 cm) versus >20 cm from tree.

Table S10: Results of Wilcoxon's ranked sum test (Mann–Whitney *U*) for low woodland density treatment 10 × 10 m plots near to tree (<20 cm) versus >20 cm from tree.

Figure S1: Soil properties (a) bulk density (g/cm^3), (b) gravimetric soil moisture (%), (c) soil organic carbon content (SOC_{con}; %) and (d) SOC stock (t C/ha) by woodland density (labelled in *x*-axis as High Density and Low Density).

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