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An estimation of Network Rail soil carbon stocks based on data from disused rail lines

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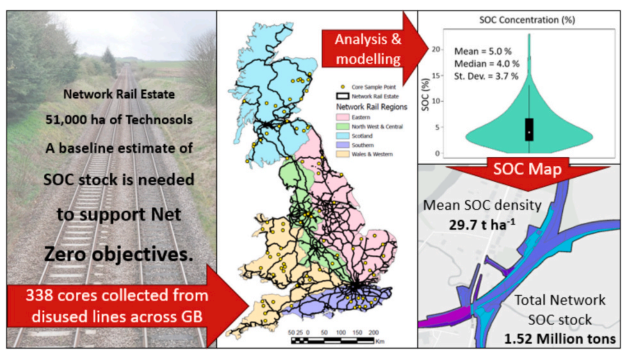
HIGHLIGHTS

- C19th railway construction created 30,000 km of Technosols in Great Britain.
- Analysis of disused railway line soils revealed an average SOC concentration of 5 %.
- Parent material, BD, moisture and soil texture were significant factors impacting SOC.
- A first SOC map of the Network Rail estate yielded a total stock of 1.52 million tons.
- The low mean SOC density of 29.7 t ha^{-1} suggests opportunities for sequestration.

GRAPHICAL ABSTRACT



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ABSTRACT

The rapid expansion of the rail network in the 19th century created nearly 30,000 km of Technosol corridors across Great Britain (GB). Today, the GB railway estate covers over 51,000 ha and is managed by Network Rail Infrastructure Limited. A base line estimate of the soil organic carbon (SOC) stock is required to support Net Zero objectives. For this study 338 cores from 87 sites were collected from disused railway lines as an accessible proxy to the active network. Technosols are often excluded from soil carbon accounting and there are no estimates of railway soil carbon stocks.

Our analysis of soil cores revealed a mean (±SD) SOC concentration (SOCc) of 5.0 % (±3.7), corresponding to an average SOC density of 49.7 t ha^{-1} (±27.8) to a depth of 30 cm. Significant factors affecting SOCc included parent material, bulk density, moisture and soil texture while habitat and climate had less influence. Railway-specific factors such as structure, construction and abandonment dates had minimal impact. Mixed effects linear modelling explained 55 % of the SOCc variation ($R^2 = 0.55$). With no soil data available for the working railways, a reduced-factor general linear model, incorporating underlying bedrock, adjacent soil type and habitat ($R^2 = 0.19$), was used to produce an initial SOC density map for the active rail network This gave an average carbon density for the Network Rail estate of 29.7 t ha^{-1} and a total soil carbon stock of 1.52 million tonnes

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(±6430). This is significantly lower than natural soils and many other technosols and suggests that these immature soils have the potential to sequester more carbon, assisted by appropriate land and vegetation management.

1. Introduction

Soil Organic Carbon (SOC) is a significant carbon stock in terrestrial environments amounting to over 2300 Gt globally (Stockmann et al., 2013). Consequently, soils have the potential to contribute substantially to carbon sequestration efforts to mitigate climate change with relatively small percentage gains in SOC (Minasny et al., 2017). Most research in this area has focussed on natural and agricultural soils with fewer studies on Technosols (Cornu et al., 2021; Allory et al., 2022). Technosols (IUSS Working Group WRB, 2015) are defined as being strongly impacted by human activity with ≥20 % of artefacts, materials that have been created, modified or brought to the surface, in the upper 100 cm. They make up a small but growing proportion of the world's surface estimated, by using urbanisation as a proxy, at 3 % globally (Liu et al., 2014) yet are often overlooked or excluded from soil carbon accounting. As they are very young soils, akin to natural Regosols that have not fully developed their biological processes, they have the potential to increase their organic carbon content (Allory et al., 2022).

The pedogenesis of Technosols including the generation and retention of SOC, is subject to the same factors as natural soils – parent material, climate, organisms and biogenic activity, topography and time – with the additional factor of recent anthropogenic disruption to the fabric and material of the soils (Leguédois et al., 2016; Basile-Doelsch et al., 2020). For railway soils, subsequent land management (Lehmann and Klebber, 2015) including vegetation control, the input of coal ash, various oily residues and contaminants from locomotives and freight (Hiller, 2000; Network Rail, 2021) and, until relatively recently, the organic sewage from passenger train toilets, may also influence SOC.

Technosols are immature and often exhibit properties that inhibit healthy soil development and vegetation growth (Haigh, 2000). Thin or absent topsoil, a deficiency in nutrients, soil structure with low water retention and sometimes soil compaction exacerbated by low pH and potential contamination can reduce the fertility of the soil and hence SOC (Filcheva et al., 2021).

Railway infrastructure in Great Britain covers over 51,000 ha of land and is largely owned and managed by Network Rail Limited (ORR, 2024a). As a publicly owned landowner, Network Rail (NR) is expected to proactively manage the land to improve biodiversity (Varley, 2018) and to help achieve national goals of net zero greenhouse gas (GHGs) emissions by 2050, or 2045 in Scotland (Network Rail, 2020a; Scottish Government, 2020; UK Government, 2021). While planning for reduced railway related emissions is underway (Network Rail, 2020b; Network Rail, 2020c), little is known about the role that its land holdings could play in capturing and storing carbon. A key part of that is understanding current carbon stocks in the soil and vegetation within the NR estate. Access to the live network is restricted to minimise the risk of trackside injuries with moving trains and rolling stock. Any work to gather soil samples would require exhaustive planning well in advance of site visits which strictly limits the potential to gather a representative selection from active railway lines across GB. Therefore, this study has focused on disused rail lines as a proxy to establish a base line of soil carbon stock estimates and investigate the factors that influence soil organic carbon (SOC) distribution and density. The disused lines have suffered a variety of fates since abandonment. Some have been maintained as heritage railways or repurposed as paths and cycle lanes, other sections have been left untouched and exist as relic structures across the landscape while some have been lost completely through development or incorporation back into farmland.

The opening of the Stockton and Darlington Railway in 1825 provided the world's first public steam locomotive service. The first intercity service followed soon after between Liverpool and Manchester in 1830 which set the template for modern railway infrastructure and heralded a boom in railway construction funded by the 'Railway Mania' stock market bubble of the 1840s (Odlyzko, 2010). By 1850 the network had grown without any overarching plan to nearly 10,000 route km (Bradley, 2015). Infrastructure expansion and consolidation of companies continued into the 20th century but with increasing competition from roads, low use lines became increasingly unprofitable. The 1963 Beeching Report (Beeching, 1963) led to the closure of about 30 % of routes and the network shrank from 29,140 km to 19,350 km by 1970 (Bradley, 2015). As of March 2024, the route length open for traffic in Great Britain was 15,849 km (ORR, 2024b).

The construction of track beds, embankments, cuttings and tunnels impacted the land within and often adjacent to the land owned by the rail companies. The foundation materials used were driven by cost and availability, promoting the use of line excavated rock and soil from cuttings, material from local quarries or 'borrow pits' alongside the track and local waste products such as clinker and ash (Skempton, 1996).

Once the earthwork and railroad foundation were completed, coarse rock chipping ballast could be added, latterly onto a sand blanket (Network Rail, 2020d). These were commonly coarse igneous or limestone rocks though sandstones, gravels and even burnt clay have been used (Williams, 1883). Spent ballast and coal ash was often added to embankments and flat ground on top of whatever vegetation was established particularly where soil creep and slips had occurred (Mair, 2021).

Management of drainage and minimising erosion are critical for maintaining slope stability and were often achieved through dressing slopes with turf or topsoil soil sown with grass seed (Sheail, 1979).

The potential for deeper rooting trees and shrubs to enhance slope stability was also occasionally trialled (Williams, 1883) but for the most part vegetation was cut back to maintain sight lines and to reduce the risk of fires from passing steam locomotives. Track ballast was also cleared of weeds, initially by hand and later with sprayed herbicides, to help maintain free drainage (Sheail, 1979). With the phasing out of steam power in favour of diesel and electric engines in the 1960's, the management of vegetation was considerably reduced, allowing shrubs and trees to establish and grow with intervention by exception only. The number of trees has consequently expanded to over 6 million, most of which are <55 years old (Varley, 2018).

Today, woodland habitat makes up over 20 % of the Network Rail estate while grasslands account for just 13 %; bramble scrub and ruderal habitats, indicative of disturbed ground (Sargent, 1984), make up about 43 % (Network Rail, 2023). There has also been little, or no vegetation management along the lines closed in the 1960's and these therefore, despite their change of use, provide an accessible proxy for the active network.

In a meta-analysis of global technosol studies, Allory et al. (2022) showed the wide range of SOC concentration (SOCc) and SOC stocks (SOCs) reported from different climate zones and land usage. Across all studies analysed, mean SOCc and SOCs to 30 cm depth were 4.3 % and 73.2 t ha^{-1} respectively. Temperate climate technosols had a mean SOCc of 4.5 % and all mining related technosols had a mean of 4.2 %. This compares to typical SOCc values of 3.5 % for arable soils and 4.7–6.5 % for grassland soils (Ward et al., 2016; Lilly and Baggaley, 2021). To our knowledge, this is the first study to look at the SOC of railway lines and attempt to answer the following questions:

1. What is the magnitude and variability of SOCc and SOCs of abandoned railway line soils?

2. What are the factors that influence railway SOCc and SOCs?

2. Materials and methods

2.1. Site selection

From August 2022 to October 2023, soil samples were collected from 87 sites on disused railway lines across England, Scotland and Wales (Fig. 1). These sites were selected to reflect the variety of structures and settings of the active network across Great Britain. Different geographic areas were targeted for core collection trips lasting no more than 4 days to minimise the time from sampling to laboratory processing and analysis. An online rail map (https://railmaponline.com/) was used to locate disused rail lines and identify potential sampling sites. Online geological (BGS, 2024a) and soil maps (UKSO, 2024) were then used to ensure a spread of underlying bedrock and soil types adjacent to the railway lines were covered. These websites, along with Google Maps, were also used to identify sites based on a mix of habitat and structural settings (cuttings, embankments, etc.) and to exclude sites that have been radically altered since abandonment. Parts of the disused rail network have been redeveloped as industrial sites or for housing, incorporated back into fields or repurposed in some way that renders them unsuitable as an analogue for the active network (e.g. gardens, livestock pens, caravan parks). Not least in the site selection process were pragmatic considerations of access and logistics in developing a practical daily sample collection plan. A list of sampled sites is available in Supplementary Table S1.

2.2. Soil sampling

At each site, typically 4 cores were taken to a depth of up to 30 cm, 2 on either side of, and at varying distances from the edge of the old track bed but within the fence lines of the old rail line. The distances thus varied depending on the width of railway land at each site. The 40 cm stainless steel, split tube corer used (Eijkelkamp Fraste UK), has an internal diameter of 5.3 cm and contains a plastic insert to retain the material collected (Fig. 1). Each core was subsequently split into 3 sections covering 0–10 cm, 10–20 cm and 20–30 cm depth intervals and placed in labelled, sealable plastic bags. In total, 338 cores were taken yielding 930 core sections.

Sampling of the central track bed itself was avoided as this sometimes consisted of large ballast stones or may have been altered to provide a suitable footpath or cycle path by resurfacing with tarmac or compacted grit. It was assumed that the track bed of an active railway line, consisting of coarse stone ballast underlain by sand, would have negligible SOC. The sample bags were stored in a refrigerated dark room for no more than 3 days prior to commencing laboratory analysis.

2.3. Data collection

A mix of field observations, laboratory analysis and spatial data which could represent factors influencing SOCc were collated for each sample. These are summarised in Table 1.

2.3.1. Field observations and railway line data

At each site, the location (Northing & Easting), elevation, structure type (embankment, cutting, flat), structure size (height/depth m), position of the sample core taken on the structure (top, base, mid-slope) and distance from the track was recorded. The habitat was also noted and, based on those mapped on the active rail network (Network Rail, 2023), placed into one of 6 categories (Fig. 2) – woodlands, bramble scrub, ruderal, grassland, urban and 'other', covering a variety of habitats including conifer forests, heathland, fens, bogs and marshes, coastal environments and inland rock and scree.

Railway woodland habitats are dominated by deciduous trees. Bramble scrub habitat, naturally populated by Brambles (*Rubus* sp.), can also include species such as Blackthorn (*Prunus spinosa*), Rosebay willowherb (*Chamaenerion angustifolium*) and nettles (*Urtica dioica*).

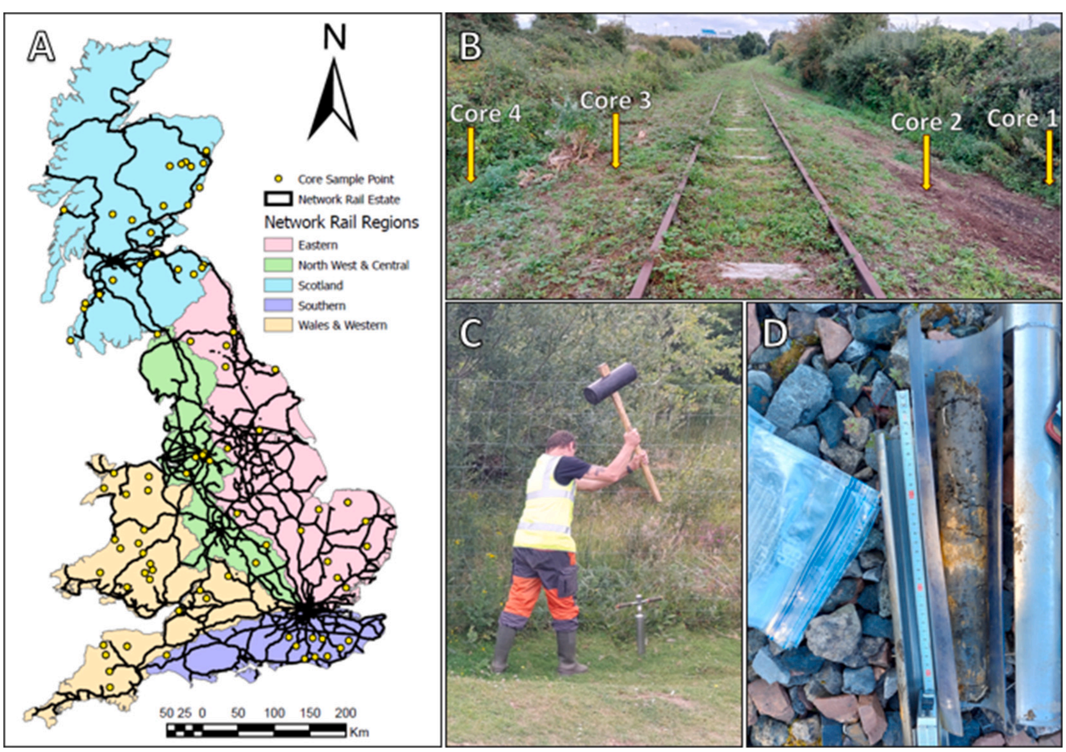

Fig. 1. A. Map of the UK rail network managed by Network Rail and the location of the 87 sites sampled on disused railway lines. B. Typical core sampling transect across the rail track, here at Portishead. C. Hammering in the split tube core sampler to a maximum depth of 30 cm (Dartmoor). D. Core from Slaggyford, Northumberland inside plastic insert to help contain material prior to splitting into 3 × 10 cm samples.

Table 1
Data collected for each soil sample.

Field observations & railway line data	
Site and core location	Easting & Northing
Elevation	m
Core depth and core section thickness	cm
Structure type	e.g. cutting, embankment
Structure size (height/depth)	m
Position of core on the structure	e.g. top, mid slope, base
Distance of core sample from track centre	m
Habitat type	e.g. bramble scrub, woodland
Line construction	date
Line abandonment	date
Laboratory analysis	
Soil moisture content	%
Gravel content (>2 mm)	%
Bulk density of sieved soil (<2 mm)	g cm^{-3}
Texture of sieved soil (<2 mm)	sand %, silt % & clay %
SOC concentration from loss-on-ignition (LOI)	%
SOC stock for each core	t ha^{-1}
Soil pH	
Spatial data	
Underlying bedrock type (simplified)	e.g. sandstone, granite
Underlying bedrock age	e.g. Cambrian, Jurassic
Adjacent soil type (WRB)	e.g. cambisol, arenosol
Annual average rainfall (1991–2020)	mm
Annual average temperature (1991–2020)	°C

Ruderal and ephemeral habitats are marked by patchy vegetation that may include Wintercress/Yellow rocket (*Barbarea* sp.) and the invasive Buddleia (*Buddleja davidii*) shrub on disturbed ground or marginal areas of thin or absent soils like derelict industrial sites and railway ballast (Network Rail, 2022a).

The urban habitat mostly covers stations, office buildings, industrial sites and paved over areas. The category "Other" covers a variety of habitats including conifer forests, heathland, fens, bogs and marshes, coastal environments and inland rock and scree. Often sites exhibited more than one habitat type and the habitat type selected was that considered to be most representative.

The date of the line's construction and abandonment was taken from a variety of online sources principally linked from https://railmaponline.com/.

2.3.2. Laboratory analysis

2.3.2.1. Soil organic carbon. The SOC was determined using the loss on ignition (LOI) method (Ball, 1964; Hoogsteen et al., 2015).

a. Each sample was weighed in an aluminium tray and then dried in an oven at 105 °C to a constant weight. The tray was then reweighed and the gravimetric moisture content determined from the difference.

$$Moisture(\%) = \frac{(fresh\ soil\ mass - dry\ soil\ mass)\ x\ 100}{fresh\ soil\ mass} \tag{1}$$

b. The sample was sieved through a 2 mm mesh and the gravel, coarse roots and fine soil portions were separated and weighed. The coarse roots constituted an average of 0.25 % of the samples and were not included in the SOC calculations. Any fine roots that passed through the sieve were included in the SOC pool.

c. The bulk density (BD) (g cm^{-3}) of the fine (<2 mm) dry soil was calculated by dividing the soil mass by the sample volume.

$$BD\ (g\ cm^{-3}) = \frac{dry\ soil\ mass\ (g)}{sample\ volume\ (cm^3)} \tag{2}$$

d. Approximately 10 g of the fine dry soil was weighed in a crucible, placed in a kiln at 550 °C for 2 hours and then reweighed. A selection of repeat samples were also heated at 375 °C for 16 hours to confirm that inorganic carbon (e.g. coal dust) was not being lost at the higher temperature. The total organic matter (TOM) was then calculated as

$$TOM(\%) = \frac{(oven\ dry\ soil\ weight - weight\ of\ soil\ after\ ignition)\ x\ 100}{oven\ dry\ soil\ weight} \tag{3}$$

e. The SOCc (%) was estimated using a regression equation (Ball, 1964).

$$SOCc(\%) = 0.467x - 1.87 \tag{4}$$

where x = TOM(LOI).

f. The total SOCs for each core (g cm^{-2} of surface area) is calculated as the sum of SOCs in each individual core section (*i*) of the core profile, following Eq. (5).

$$SOCs\ (g\ cm^{-2}) = \sum_{1}^{n} \left(SOCc_i(\%) \times BD_i\ (g\ cm^{-3}) \times thickness_i(cm)\right) \tag{5}$$

where n = number of core sections. Values of g cm^{-2} are unit equivalent to Mg ha^{-1} or t ha^{-1}.

2.3.2.2. Soil texture. The gravel fraction for each core section was first determined by weight and then, assuming a mineral density of 2.65 g cm^{-3}, converted to a volume percentage of the whole sample. Sieved soil (<2 mm) texture was determined using a laser particle size analyser (LS13 320 Particle Size Analyser, Beckman Coulter Inc., California, USA) to give the percentages of sand, silt and clay for each core section by volume. The volumes were combined to give core section percentages for gravel, sand, silt and clay.

For example, for sand

$$V_{scs} = (1 - V_{gcs}) \times V_{sf} \tag{6}$$

where

V_{scs} = Volume of core section sand (%)
V_{gcs} = Volume of core section gravel (%)
V_{sf} = Volume of sub-sample fine material (<2 mm) sand (%)

The core sections were then combined to give a volume percentage of gravel, sand, silt and clay for each core.

For example, for sand

$$V_{sc} = \frac{\sum_{1}^{n} (V_{scsi}\ x\ t_{csi})}{t_c} \tag{7}$$

where

V_{sc} = Volume of core sand (%)V_{scsi} = Volume of core section *i* sand (%)
T_{csi} = thickness of core section *i* (cm)
t_c = thickness of whole core (cm)

Fig. 2. Examples of disused railway habitat. A. birch woodland at Aboyne, NE Scotland. B. Bramble scrub near Carlisle, Cumbria. C. Grassland at Cwm Prysor, North Wales. D. Ruderal habitat, East Anglia. E. Coastal marsh at Bideford, Devon. F. Urban environment at Heaton Railyard, Newcastle.

n = number of core sections

2.3.2.3. Soil pH. The soil pH was measured from the dried, sieved core sections. For each measurement, 10 g of soil was mixed with 25 ml of deionised water for 30 min in an end-over-end shaker (Stuart Scientific Rotator Drive STR4). Further shaking using a whirlpool mixer was conducted after 90 min and 120 min before measuring the pH with a pH meter (Hanna Instruments HI2210).

2.3.3. Spatial data

The bedrock type and age were taken from the British Geological Society Geology Viewer (BGS, 2024a) and the soil type (World Reference Base classifications) in land adjacent to collection sites was taken from the UK Soil Observatory (UKSO, 2024). The bedrock recorded is a simplification of the actual underlying geology which will frequently be interbedded layers of different rock types and our aim was to represent the dominant type. The 30-yr average annual rainfall and temperature (1991–2020) for each site was taken from the Esri UK dashboard 5 km grid maps (Esri UK, 2022) using data from the UK Meteorological Office.

Mapping and spatial analysis was conducted using ArcGIS® software (ArcGIS® Pro 3.2.2.). A polygon map at 1:625,000 scale of bedrock geology was obtained from the British Geological Survey (BGS, 2024b) and 1:250,000 scale WRB soil maps were sourced from the James Hutton Institute (JHI, 2024) for Scotland and from the Cranfield Environment Centre, LandIS® website (LandIS, 2024) for England and Wales.

The habitat map for Network Rail was generated by the UK Centre for

Ecology and Hydrology (UKCEH) using remote sensing to identify twenty-one UKCEH land cover types broadly aligned to the UK-Habitats classification system (Morton et al., 2020). These were grouped to the six main habitat types found on the Network Rail estate (Fig. 5, Table S2).

To estimate the proportion of the rail estate that has no soil and thus no soil organic carbon, 100 random points were generated in ArcGIS® Pro and the percentage of land covered by station platforms, buildings and the railway line ballast calculated for transects at those points orthogonal to the line covering the width of the Network Rail land holding.

2.4. Data analysis

From the 87 sites visited, 338 cores were taken yielding 930 core sections for analysis. For the 144 cores that failed to reach 30 cm, due to encountering bedrock, large stones or rubble, an assumption was made that the depth recovered in the core profile represented the total soil depth.

Three outlier cores with 8 core sections were removed from the data set prior to statistical analysis. Of these, two cores were taken outside the old railway boundary and one had an anomalously high carbon content for a 20 cm – 30 cm depth core section: 66 % above the 3rd quartile +1.5 * the interquartile range and 117 % higher than the shallower core sections from the same core. This resulted in 335 cores available for the analyses. Ball's equation (Eq. (4)) can give negative SOCc results for soils with very low organic matter content. In these 52 core section cases, the small negative values were set to zero.

Data plotting and ANOVA linear regression modelling of individual factors was undertaken in Minitab (version 20.3.0.0) (Minitab, LLC, 2020) and using R (version 4.1.1) (R Core Team, 2021). For the development of the SOCc and SOCs explanatory models, we used General Linear Mixed Effects Modelling (GLMM) to account for spatially correlated observations at sites with multiple core data points. This separates fixed effects, which explain variation in the dataset expected to hold across the entire population of data, from random effects, which explain variation unique to specific groupings (i.e. site) of the data. The most parsimonious model was achieved by backward elimination of non-significant covariates using chi-squared testing at the 5 % significance level ($p = 0.05$). Due to data limitations and model stability the models were developed using a training data set from 74 randomly selected sites (85 %) rather than the more usual 25 % and validated against data from the remaining 13 sites (15 %) (Bukoski et al., 2017). Since the retained factors varied depending on which sites were selected for training and validation, the process was repeated 50 times to build up a frequency of retained significant factors and a distribution of validation parameters including R^2, RSME, slope and intercept values. This enabled a representative model to be selected that matches the mean R^2 value across the iterations. All modelling was performed with the 'lmer' function of the 'lme4' package of R.

2.5. SOC spatial mapping

The same process was followed with a limited subset of factors available from maps of the unsampled Network Rail estate (bedrock type and age, soil type, habitat, rainfall, temperature and geographical location) to identify which were most significant (McBratney et al., 2003). A final model was then selected to match the mean R^2 value of 100 iterations using different splits of testing and training data. This enabled an estimation of the total soil carbon stock (t C) of the estate using a mapping package (ArcGIS® PRO 3.1). The bedrock, adjacent soil type and habitat mapped polygons were clipped to the Network Rail estate and combined using the 'Union' geoprocessing function in ArcGis® Pro. The combined attribute table was used to calculate the SOCs (t ha^{-1}) for each polygon (Bodlák et al., 2012) using an equation generated from ANOVA general linear modelling of the mapped input factors. In this case, mixed-effects models are unsuitable as there are no measurement sites on the active network and therefore the site cannot be used as a random variable to predict polygon SOCs values. This was uploaded back into ArcGIS® Pro to create a single mosaic SOC density (t ha^{-1}) map for the rail network (Fig. 11). The SOCs for each polygon were summed and a blanket 39 % discount applied to account for the area of the network without soil (rail line ballast, buildings and paved areas), yielding an estimation of the SOC stock (t C) for the entire NR estate. Bootstrapping, repeatedly resampling the data set 1000 times, was used to produce a distribution of SOCs and estimate uncertainty around the mean value.

3. Results

3.1. SOCc and SOCs data summary

The SOCc of the cores taken to a maximum depth of 30 cm gave a mean (±SD) of 5.0 % (±3.7) and a SOCs mean (± SD) of 49.7 t ha^{-1} (± 27.8) (Fig. 3). The shape of the distribution is different for the two plots as the SOCs values account for the soil depth, gravel fraction and bulk density.

There is a clear and significant ($p < 0.001$) drop off in SOCc with depth over the 30 cm interval sampled. 144 cores failed to reach 30 cm depth, with 89 and 20 cores not getting beyond 20 cm and 10 cm respectively. Other soil parameters also changed significantly ($p < 0.001$) with depth including BD and pH (increased), moisture content (decreased) and soil texture which became less sandy although the gravel (>2 mm) fraction increased (Table 2).

3.2. Regional variations

There was no significant difference in mean SOCc (%) ($p > 0.05$) across the Network Rail regions, indicated by a Tukey test and the overlap of 95 % confidence interval bars in Fig. 4. Scotland and Southern regions have the lowest mean SOCc at 4.36 % and Wales & Western the highest at 5.88 % (Table 3).

3.3. Categoric factors

The bedrock type and age data represent the varied geology of the British Isles with cores taken from railway lines overlying Precambrian metamorphic rocks in Scotland to the Tertiary clays of East Anglia. One-way ANOVA significance tests for SOCc (%) show that bedrock type is a significant factor ($p = 0.001$) but the low correlation coefficient ($R^2 = 0.085$) indicates that it explains little of the variance (Table 4) and on its own is not a reliable predictor for SOCc. Similarly, the age of the bedrock is a significant factor for SOCc ($p < 0.001$) with a low correlation coefficient ($R^2 = 0.14$).

The World Reference Base (WRB) classification allows a comparison of soil types across Scotland, England and Wales through which the railway lines were constructed and which may have contributed parent material. This category is also a significant factor for SOCc ($p = 0.001$) with a low correlation coefficient ($R^2 = 0.09$).

Network Rail describes 5 key habitats that cover 92 % of their estate (Network Rail, 2023). The habitats noted at the disused railway sites used the same categories and are a reasonable corollary to the active network (Fig. 5). Few urban habitats were sampled as the stations, buildings and sidings make up a smaller proportion of the available disused railway infrastructure and often the paved and developed areas have little or no soil. Habitat was not a significant factor for SOCc ($p = 0.176$).

Embankments and cuttings of a variety of sizes and flat sections of line are well represented as is the position of the core on the structure. One-way ANOVA tests for structure and position on the structure show weak significance for SOCc ($p = 0.021$ and $p = 0.016$ respectively).

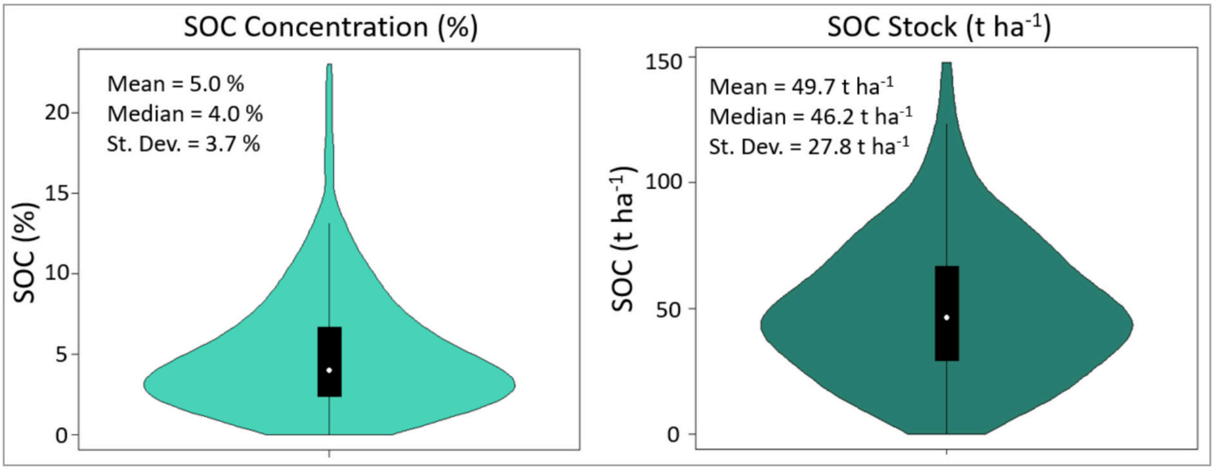

Fig. 3. Violin plots showing the distribution of SOCc (%) and SOCs (t ha^{-1}) for 335 cores collected from disused railway lines in Great Britain. The white dot shows the median value, the bar represents the interquartile range and the line is 1.5× interquartile range.

Table 2
Selection of soil parameters changing with depth through the 30 cm soil profile and their statistical significance.

Layer	BD of fine (<2 mm) soil (g cm^{-3})		Moisture (%)		pH		Gravel fraction of dry mass (%)		Fine soil fractions by volume			
									Sand (%)		Clay (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0–10 cm	0.44	0.19	24.66	10.81	6.02	1.12	34.95	20.95	66.04	18.72	3.65	3.06
10–20 cm	0.56	0.24	17.32	7.91	6.20	1.33	38.89	21.90	53.97	22.48	6.47	5.58
20–30 cm	0.67	0.30	15.66	6.52	6.47	1.38	37.82	22.45	46.94	23.30	8.68	6.53
R^2	0.136		0.170		0.020		0.006		0.119		0.135	
F-value	72.5		94.2		9.1		2.8		61.8		71.9	
P-value	<0.001		<0.001		<0.001		0.056		<0.001		<0.001	
Sig.	***		***		***				***		***	

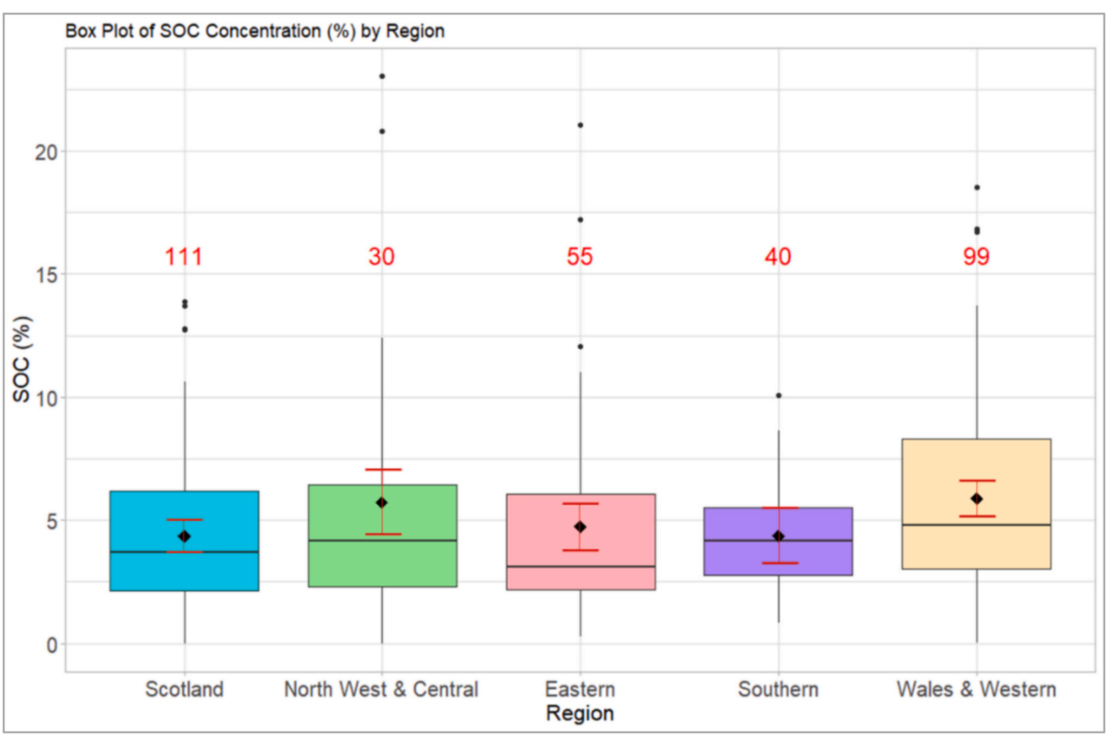

Fig. 4. Box plot of SOCc (%) for cores sampled to a maximum depth of 30 cm on disused railway lines within current Network Rail regional areas. The boxes indicate the 25 % and 75 % quartile, with a mean black diamond and 2 whiskers showing the 10 % and 90 % quantiles. Outliers are marked with a black dot. The red bars show the 95 % confidence intervals for the mean values. The red numbers indicate the number of cores taken in each region.

Table 3
Summary of SOCc (%) results for Network Rail regions.

Region	Count	Mean	StDev	Min.	Q1	Median	Q3	Max.
Scotland	111	4.36	3.03	0.00	2.12	3.70	6.27	13.87
Eastern	55	4.74	4.09	0.27	2.17	3.11	6.09	21.05
North-West & Central	30	5.72	5.54	0.00	2.14	4.15	7.12	23.02
Southern	40	4.36	2.16	0.83	2.74	4.17	5.58	10.07
Wales & Western	99	5.88	3.89	0.02	2.99	4.82	8.32	18.52

Table 4
Results of one-way ANOVA significance tests for SOCc for each categoric factor. Significance ratings – $p \leq 0.05$ = *, $p \leq 0.01$ = **, $p \leq 0.001$ = ***.

Factor	Levels	n(samples)	R^2	F-value	P-value	Sig.
Bedrock type	10	335	0.085	3.36	0.001	***
Bedrock age	10	335	0.139	5.83	<0.001	***
Adj. soil type	12	335	0.089	2.86	0.001	***
Habitat	6	335	0.023	1.54	0.176	
Structure	3	335	0.023	3.91	0.021	*
Core position	5	335	0.036	3.09	0.016	*

3.4. Continuous factors

Table 5 summarises the results for the continuous variables recorded for each core against SOCc in a single factor linear regression.

The highest correlation with SOCc was found with log transformed BD ($p < 0.001$, $R^2 = 0.59$). The BD of the sieved soil is affected by the gravel fraction. As the soil gravel fraction (>2 mm) increases the apparent BD of the soil fine fraction (<2 mm) decreases given the fixed volume of the core (Fig. 6).

Although the slope of the SOCc regression lines for several of the variables was significant ($p < 0.05$), R^2 was low and, except for BD, <0.13 (Table 5).

The gravel fraction (>2 mm) by volume for each core varied from 0.1 % to 38.0 % and is composed of local rock fragments, sometimes

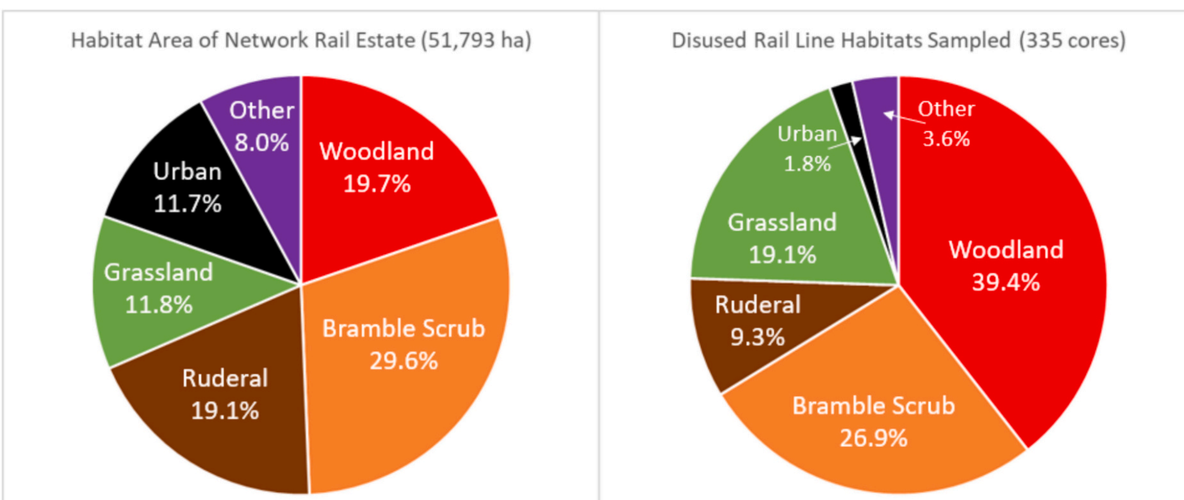

Fig. 5. Key habitat categories of the Network Rail estate (Network Rail, 2023) with the habitats noted at core sampling sites on disused railways.

Table 5
Summary of results for continuous factors and significance tests for SOCc from individual linear regression analysis. # Bulk density linear regression conducted on the natural log of BD. Significance ratings – $p \leq 0.05$ = *, $p \leq 0.01$ = **, $p \leq 0.001$ = ***.

Factor	Mean	S.Dev.	Min.	Max.	R^2	F-value	P-value	Sig.
Ln BD (g cm^{-3}) #	0.53	0.21	0.10	1.06	0.594	488.18	<0.001	***
Moisture (%)	19.75	7.80	3.00	55.21	0.107	39.83	<0.001	***
Depth (cm)	26.30	5.83	4.00	30.00	0.058	20.32	<0.001	***
Distance (m)	5.95	3.64	0.00	24.00	0.035	12.01	0.007	**
Structure Size (m)	3.04	2.62	0.00	10.00	0.007	2.32	0.129	
Rainfall (mm y^{-1})	1044.6	402.1	547.0	2312.0	0.018	6.04	0.014	*
Temperature (°C)	9.45	1.06	6.40	11.40	0.012	4.11	0.043	*
Easting (m)	378278	107582	190859	613746	0.011	3.53	0.061	
Northing (m)	419342	244116	69165	818546	0.005	1.75	0.187	
Elevation (m)	93.2	74.7	0.0	370.0	0.001	0.03	0.871	
Construction Age (y)	153.0	16.0	113	185	0.004	1.23	0.268	
Abandonment Age (y)	56.9	9.7	35	90	0.062	22.17	<0.001	***
Gravel (% by volume)	12.54	6.89	0.09	37.98	0.035	12.2	0.001	**
Sand (% by volume)	50.64	17.88	9.41	93.48	0.096	35.25	<0.001	***
Silt (% by volume)	31.81	14.89	5.87	75.21	0.140	54.07	<0.001	***
Clay (% by volume)	5.02	3.98	0.40	22.47	0.099	36.80	<0.001	***
pH (Units)	5.71	0.83	3.87	7.15	0.034	2.12	0.150	

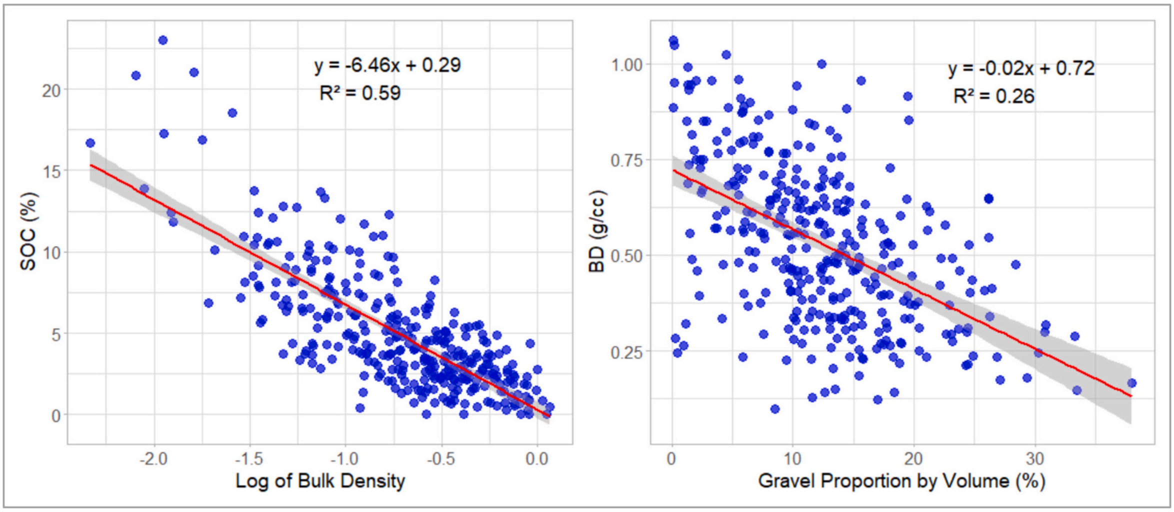

Fig. 6. Plots showing high correlation of SOCc (%) for each core with the natural log of bulk density (BD) and between the BD of the sieved soil fraction (g/cc) and gravel fraction by volume (%).

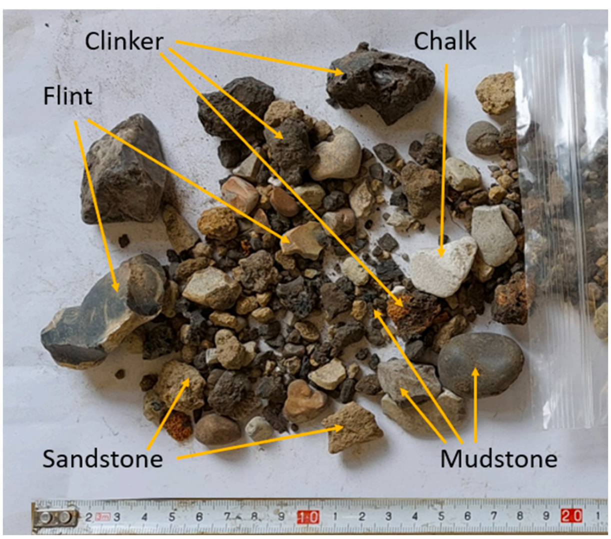

Fig. 7. Example gravel from a core near Cranleigh, SE England. The local Cretaceous geology is represented with clasts of sandstone, mudstone, chalk and flint along with clinker.

with ballast and/or spent ballast which may have been brought in from further afield to form the track bed. Samples often contained ash, slag and clinker waste from coal burning from steam locomotives or industry (Fig. 7).

The soil fine fractions (<2 mm) were dominantly coarse to fine sands with the clay fraction rarely getting above 25 %. Higher SOCc values are found in the coarser sand samples although not all coarse sand samples have high SOCc values (Fig. 8).

The annual average rainfall and temperature showed a statistically significant correlation with SOCc ($p < 0.05$) but again, these climate factors on their own only account for a small proportion of the variation ($R^2 < 0.02$). The same is true for the apparent drop off in SOCc with distance from track and with time since abandonment. There is no significant relationship ($p > 0.05$) between SOCc and location, elevation, structure size, time since construction or soil pH.

3.5. Linear models

Following our mixed-effects modelling methodology with 50 Monte Carlo iterations, the SOCc prediction models yielded a mean R^2 of 0.55 (range: 0.22–0.78), with a corresponding RMSE averaging 2.63 % and slope values clustering around 0.69, indicating moderate model performance with some variability (Table 6). The most frequently retained predictors were soil moisture, log BD and soil texture (sand %). Temperature, habitat and parent material factors (soil type, bedrock type & age) were less frequent. A representative model was selected that matches the mean R^2 of 0.552, with an RMSE of 2.66, and a slope of 0.78 (Fig. 9A & B). The marginal R^2 (fixed effects only) was 0.733, while the conditional R^2 (including site-level random effects) was 0.815 (Table 7). In this case soil moisture, log BD, soil texture, temperature, time since railway construction, parent material (soil type) and habitat were retained factors. Several soil types (e.g., Gleysol, Podzol, Leptosol) showed strong negative effects relative to the reference level (Arenosol), suggesting lower SOC stocks in these soils. Among habitats, only Urban had a significant negative effect, while others were not statistically distinguishable from the reference.

Similarly, for SOCs, model performance across 50 iterations revealed moderate predictive ability, with mean $R^2 = 0.31$ (range: 0.02–0.57), mean RMSE = 24.08 t ha^{-1}, and slope values averaging 0.43, indicating some underfitting in test predictions (Table 6). The representative model selected had an R^2 of 0.305, RMSE of 21.16 t ha^{-1}, and a slope of 0.527, closely aligning with average model performance (Fig. 9C & D). Fixed effects alone explained 45.8 % of the variance (marginal R^2), while inclusion of the random site effect increased the explained variance to 71.9 % (conditional R^2), highlighting variability between sites.

Significant predictors included moisture, bulk density, and depth, all of which are intuitive given their direct influence on carbon stock accumulation in the soil profile. Of the categorical variables, only Urban habitat showed a significant negative effect, implying lower SOC stocks in urban areas relative to the reference habitat type (bramble scrub). While bedrock age was retained in the model, none of the epochs (e.g., Carboniferous, Jurassic) were statistically significant at the 5 % level, suggesting weak or inconsistent influence of underlying bedrock age on SOC stocks.

Together, these results indicate that soil physical characteristics and sampling depth are primary drivers of SOC stock variation, while categorical predictors like habitat and geology may exert secondary, context-specific influence. The relatively modest R^2 values also suggest that additional unmeasured site-specific factors or temporal dynamics may be important in predicting SOC stock at finer scales.

A final general linear model based only on factors available for GIS mapping on the active rail network was developed for SOCs (t ha^{-1}).

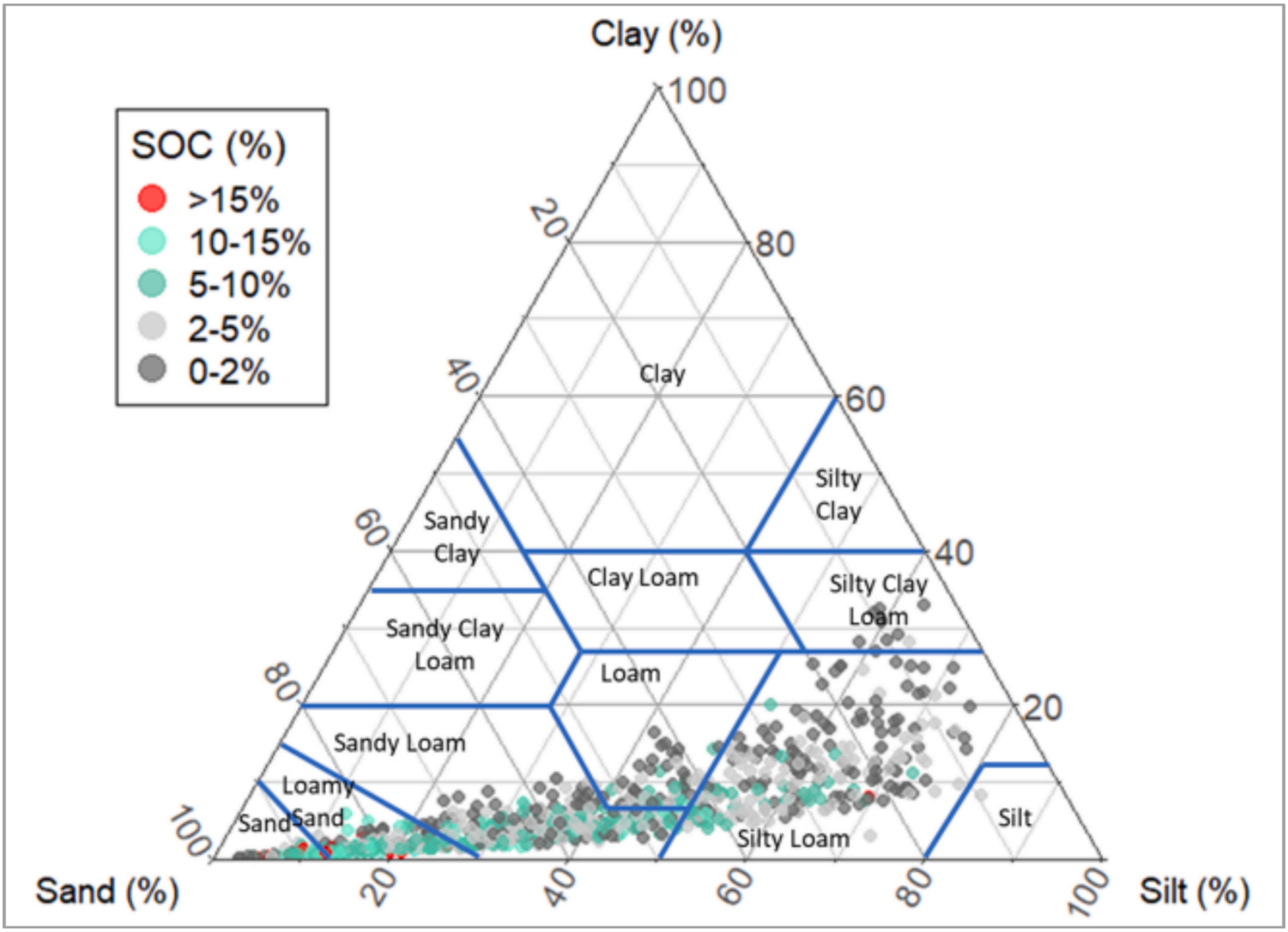

Fig. 8. Ternary plot of sieved (<2 mm) soil textures from 922 core sections as determined by a laser particle analyser. The points are coloured by SOC concentration (%). Note that the higher concentrations are generally associated with the sandier samples.

Table 6
Summary of results from multiple iterations of general linear mixed-effects models for SOCc and SOCs.

Model	Metric	Min	Mean	Median	Max	SD
SOCc (%)	R^2	0.219	0.549	0.562	0.783	0.128
	RMSE	1.78	2.63	2.59	5.22	0.61
	Slope	0.362	0.690	0.694	1.021	0.148
	Intercept	3.78	1.64	1.52	−0.50	0.80
SOCs (t ha^{-1})	R^2	0.023	0.308	0.301	0.575	0.120
	RMSE	16.96	24.08	23.72	31.42	3.38
	Slope	0.105	0.434	0.425	0.955	0.171
	Intercept	45.21	29.71	31.24	4.01	9.87

With multiple site level iterations with backward elimination these factors were reduced to underlying bedrock, adjacent soil type and habitat types after location, average annual rainfall and temperature were dropped (Fig. 10).

With fewer terms, the fit with the test data was poorer than the previous model, with the mean $R^2 = 0.185$ (SD = 0.060). A representative model used for calculating the carbon density generated the following predictive equation.

$$\text{Predicted SOCs}\left(\text{t ha}^{-1}\right) = 48.57 + x(\text{Bedrock Type}) + y(\text{Soil Type}) + z(\text{Habitat Type}) \quad (8)$$

where x, y and z are coefficients for the different types of bedrock, soil and habitat as listed in the supplementary information (Table S4).

Applying our spatial SOC mapping methodology to produce a carbon density map (Fig. 11) and estimate the total NR estate soil carbon stock resulted in a mean figure of 1.52 million metric tons (SD = 6430 t) at an average of 29.73 t ha^{-1} (Table 8). The Scotland Region has the lowest SOC density (27.17 t ha^{-1}) and the Southern Region the highest (30.97 t ha^{-1}).

From the bootstrapping iterations the total carbon stock 5th decile to 95th decile varied from 1.514 to 1.535 million tons. For comparison, applying the mean core SOCs value of 49.74 t ha^{-1} and applying the non-soil area discount would give a total NR estate SOC stock of 1.55 million tons of carbon.

4. Discussion

4.1. Disused railway lines as a proxy for the active rail network

The disused railway lines in GB share a common history with the active network through construction and use during the age of steam when trackside vegetation was managed by annual burning, scrub clearance and grass cutting (Sargent, 1984). Even after abandonment, mostly after the 1960s when steam locomotion was phased out, both disused and active lines were subject to a generally reactive approach to vegetation management for several decades. With the resultant growth of trees and scrub vegetation, Network Rail now proactively manage

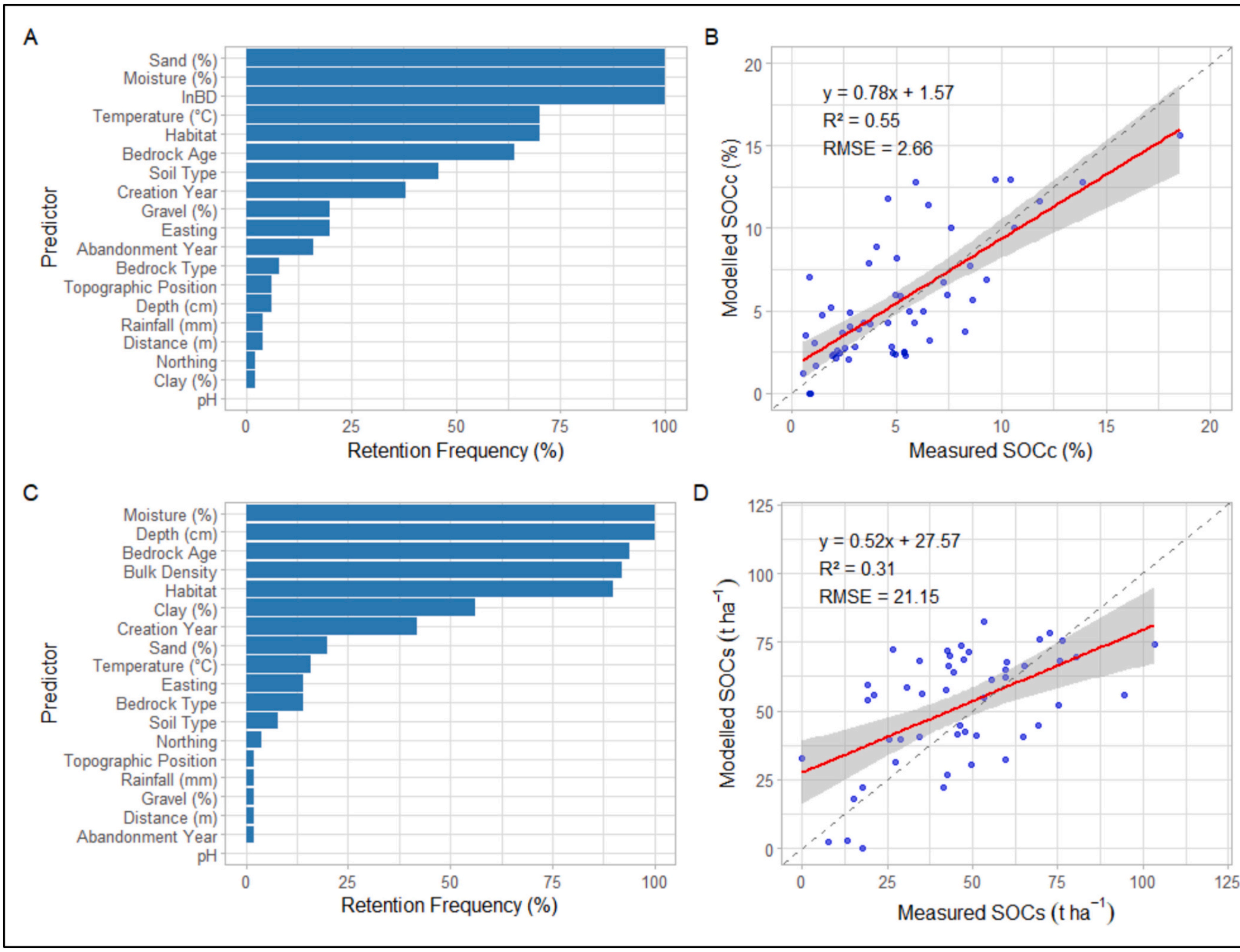

Fig. 9. Plots of the most frequently retained predictive factors for SOC and a representative models validated against test data showing lines of best fit with equations, R^2 correlations and RMSE. Plots A & B are for SOCc (%) and C & D are for SOCs (t ha^{-1}).

Table 7
Analysis of variation of fixed effects for SOCc (%) representative explanatory model. Random effects (Site and Residuals) account for a further 8.2 %.

Factor	Sum-Sq	% variance explained	F-value	P-value
Log BD (g cm^{-3})	785.6	50.82	287.4	0.000
Sand (%)	71.2	4.61	26.1	0.000
Moisture (%)	60.2	3.89	22.0	0.000
Annual Av. temperature (°C)	54.8	3.55	20.1	0.000
Line age (Y)	14.0	0.91	5.1	0.027
Clay (%)	11.5	0.74	4.2	0.042
Soil type	85.4	5.52	2.8	0.005
Habitat	50.5	3.26	3.7	0.005
Total	1133.1	73.3		

problematic tree growth, routinely cut back vegetation close to the track and continue to treat the track with herbicides. However, much of the land has received little or no intervention (Varley, 2018; Network Rail, 2024). Similarly, the disused lines that are in use as footpaths or cycle ways generally receive minimal vegetation management (e.g. Sustrans, 2024). The cores collected from disused railway lines across the UK may be considered a good proxy for the active rail network, but validation is required with measurements from active rail lines.

4.2. Potential measurement errors

4.2.1. Railway soil depth & BD

144 cores taken did not reach 30 cm depth. Sometimes this was because bedrock was encountered in cuttings, for example, but more often because large or densely packed stones, or occasionally tree roots brought penetration to a halt. A depth recorded as <30 cm then does not always mean that that is the limit to the soil depth. This will result in an underestimation of SOC stocks; however, since any lost material is from the base of the core where the SOCc is lowest, we consider the error to be relatively small.

Accurate measurement of the bulk density relies on knowing the volume of sample collected which in turn depends on accurately dividing the core sample into known increments. For many cores this was not an issue but for some dry and stoney cores it was more difficult to achieve a clean division and this will contribute to some of the variability in the data.

4.2.2. Inorganic and inert carbon

The loss-on-ignition method assumes the soil sample weight loss from combustion in the furnace is entirely organic matter (Hoogsteen et al., 2018). Inert carbon or carbonized matter such as coal or clinker, found in some of the cores, has a wide range of possible combustion temperatures dependent on the type of coal, particle size and ignition source (Fuertes et al., 1993). Combustion of unspent coal dust may be

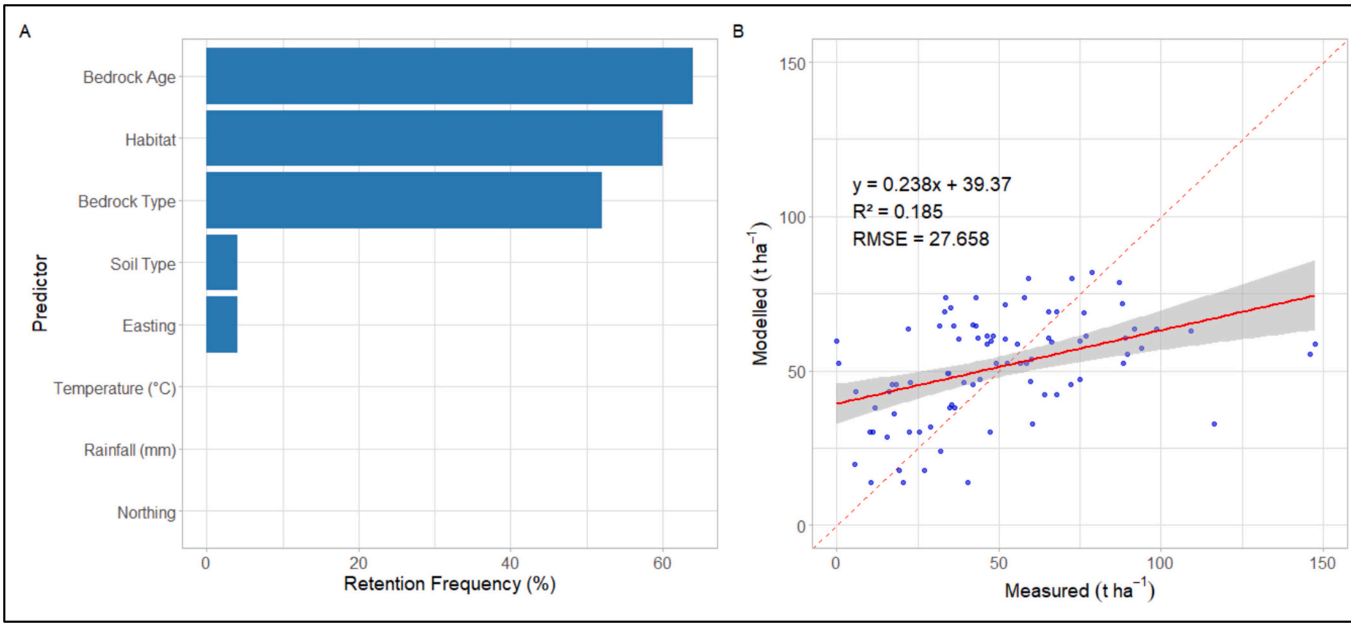

Fig. 10. A. Frequency plot of retained factors available for the unsampled active railway estate. B. The predicted SOCs for the validation core data set for the selected representative model.

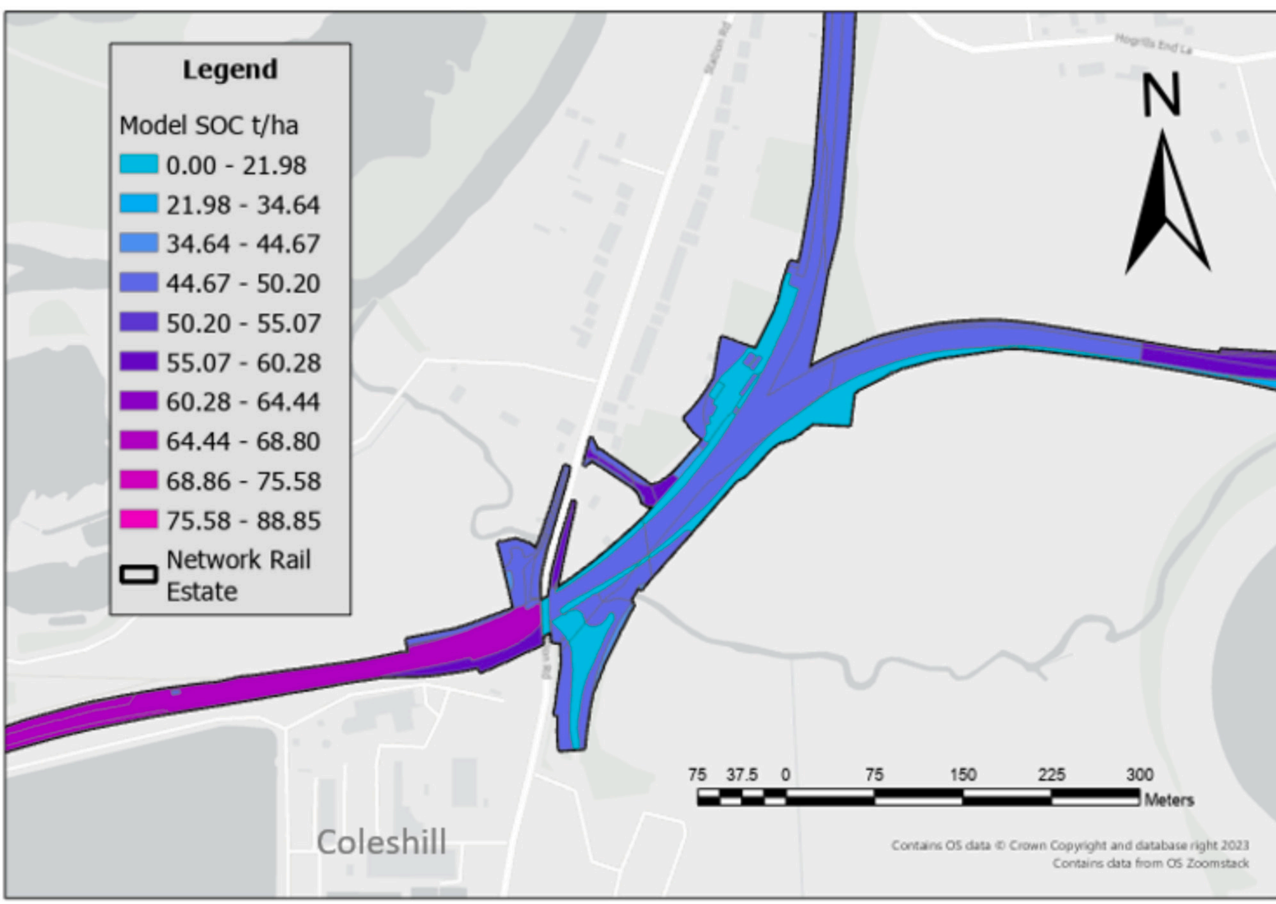

Fig. 11. Map of SOC density (t ha^{-1}) for part of the Network Rail estate at Coleshill near Birmingham.

possible even at lower temperatures of 375 °C (Essenhigh et al., 1989) which would overestimate SOC in those samples.

To test this potential error, 30 samples from 7 sites were repeated at 375 °C for 16 h. Only one site showed consistently lower SOCc results at the reduced temperature suggesting that some inert carbon, probably coal dust, was being lost at 550 °C. This was from Ystradgynlais in South Wales on a line that carried coal from local mines. On the other hand, the line that for many years carried coal to the Drax power station in

Table 8
Estimated mean Network Rail SOC density (t ha^{-1}) and stock (t C) by NR region.

Network Rail region	Estate area (ha)	Av. SOC (t ha^{-1})	Total SOC (t C)
Scotland	7,392	27.17	200,830
Eastern	15,836	29.86	472,896
Southern	7,704	30.97	238,601
NW & Central	11,280	30.78	347,156
Wales & Western	9,058	29.26	265,020
Totals	51,270	29.73	1,524,503

Yorkshire showed no significant difference (Supplementary Fig. S2). We concluded that the shorter duration, higher temperature combustion was sufficient to determine a reasonable SOCc value.

4.3. Effect of construction on SOC

The creation of the UK railway infrastructure significantly disrupted the corridors of land along which the tracks were laid. The redistribution of soil and rock from cuttings and borrow pits to form embankments and track foundations would have destroyed or significantly reduced the SOC content of that material through increased microbial decomposition, loss of plant material and breakdown of soil structure (Grandy and Robertson, 2006). The rapid loss of SOC with soil disruption is well documented from studies on the effects of land use change and tillage on agricultural soils (e.g. Degryze et al., 2004; Bailey et al., 2019; Ye et al., 2020; Zhang et al., 2024) and the same dynamic principles hold for the creation of technosols. Shrestha and Lal (2011), for example, report the loss of up to 86 % of SOCc in reclaimed mine soils compared to undisturbed ground.

While much of the land adjacent to the track may be undisturbed since construction, the track ballast requires regular replacement - every 20 years on a busy line. Therefore, modern track bed design needs to be considered when assessing its SOC potential. The track bed is engineered to provide a stable base for the rails, minimise vibrations and facilitate the rapid lateral drainage of water (Network Rail, 2020d) and given the periodic renewal of the track bed, we consider it reasonable to assume negligible or zero SOC for the top 30 cm.

4.4. Comparison with other Technosols and UK soils

While the average SOCc of the sieved soils at 5 % is higher than many arable soils, the high gravel content results almost universally low SOCs values, averaging 49.7 t ha^{-1}, lower than typical natural soils (e.g., Vanguelova et al., 2013; Ward et al., 2016; Gregg et al., 2021; Lilly and Baggaley, 2021) and many other Technosols (Allory et al., 2022; Chien and Krumins, 2022) (Table 9). A meta-analysis of 130 articles covering the carbon content of Technosols from around the globe found that the mean SOCc and SOCs reported for the 0–30 cm layer is 4.3 % and 73.2 t ha^{-1} respectively (Allory et al., 2022). The SOCs average for the Network Rail estate is reduced further to 29.7 t ha^{-1} when taking into consideration that 39 % of the land has no soil.

4.5. Soil parameter changes with depth

The dressing of railway margins and slopes with a thin layer of topsoil may explain the higher SOCc in the top 10 cm and clear drop off with depth (Table 2). This is also the layer which typically has the most abundant microbial communities to transform accumulated plant litter to SOC (Spohn et al., 2016). This decrease in SOCc with depth is also seen in studies of vegetated spoil heaps (Shrestha and Lal, 2011; Yao et al., 2023) and revegetated coal mining sites (Baier et al., 2022) but not commonly demonstrated in a broad range of other Technosols (Allory et al., 2022).

In the top 30 cm of the fine (<2 mm) soil fraction of disused railway soils, compaction is evident although the fraction of gravel does not change with depth (Table 2). Severe compaction can impede root growth; however, only eight core section samples, all within the 20–30 cm depth range, had total bulk densities exceeding 1.65 g cm^{-3} — a threshold often used as a guideline for root growth restriction (USDA, 2008). Therefore, compaction within the top 30 cm of railway soils is not considered a significant factor limiting vegetation growth or carbon input into these soils.

Table 9
Comparison of mean SOCc and SOCs values from disused railway soils with other global technosols and UK soils from various sources. Studies vary in the soil depths and SOC units quoted and may not include SD analysis.

Source	Soil & habitat sampled	SOCc (%)		SOCs (t ha^{-1})	
		Mean	SD	Mean	SD
This study (0–30 cm)	Disused railway soils	5.0	3.7	49.7	27.8
Allory et al., 2022	Global Technosols	4.3	7.5	73.2	
Meta-analysis of global Technosols (0–30 cm)	Temperate climate technosols	4.5	5.4		
	Urban Technosols	3.4	4.5		
	Mining Technosols	4.2	8.5		
	Industrial Technosols	6.9	9.1		
Chien and Krumins, 2022	Urban - green spaces			54.61	22.0
Urban soils (0–30 cm)	Urban – intensive habitats			65.88	35.3
	Arable	3.5	2.0	111.5	15.6
	Permanent grass	4.7	2.2		
Lilly and Baggaley, 2021	Improved grassland	6.5		138.1	21.4
Scottish Soil Survey (0–100 cm)	Semi-natural grassland			185.2	27.1
	Woodland			267.5	40.5
	Moorland			290.8	26.3
	Bog			528.3	23.0
Ward et al., 2016	Grassland (20–40 cm)	6.3	0.4		
English grasslands	Grassland (0–40 cm)			136.0	15.8
	Native woodland (0–100 cm)			151.0	
Gregg et al., 2021 Review of carbon storage in English habitats	Heathland (0–15 cm)			94.0	
	Neutral grassland (0–15 cm)			60.0	
	Arable (0–100 cm)			120.0	
	Blanket Bog (0–50 cm)			259.0	
Biffi et al., 2022	Permanent pasture	2.6	0.1	97.3	4.1
NW England (0–30 cm)	Hedgerows - mixed ages	3.8	0.2	112.7	6.6
	Rankers (Leptosols)			108.0	24.0
Vanguelova et al., 2013	Brown earths (Cambisols)			135.0	6.0
UK Forest Soils (0–80 cm)	Podzols			136.0	16.0
	Surface-water gleys (Stagnosols)			147.0	10.0
	Groundwater gleys (Gleysols)			155.0	18.0
	Deep peats (Histosols)			448.0	36.0

4.6. SOC and parent material

Parent materials play a crucial role in shaping soil properties through the mechanical and biogeochemical breakdown of rock, influencing soil texture, clay mineralogy and nutrient availability (Stahr, 2016). These properties, in turn, affect vegetation establishment, root development and root exudation (Angst et al., 2018), all of which contribute to the formation and preservation of soil organic matter (SOM). Consequently, it is unsurprising that local bedrock type, bedrock age and soil type are significant factors influencing SOCc (Table 4). Soils derived primarily from coarse sandstones typically contain fewer nutrients, less clay and therefore lower SOC compared to those formed from siltstones, mudstones, or nutrient-rich substrates (Anderson, 1988).

However, the inherently heterogeneous nature of railway soils complicates this relationship. The low correlation coefficients (R^2 values) for these factors indicate that, independently, they account for only a small portion of the observed variance in SOCc. Other factors, such as climate, may also contribute to this variability. For instance, Precambrian and Palaeozoic igneous and metamorphic rocks form the cooler, wetter uplands of northern and western Great Britain, whereas younger Tertiary sedimentary deposits occur in the warmer, drier southeast of England, potentially influencing SOC dynamics.

In addition, the lithologies found in the railway soils will not exactly match the underlying bedrock for two reasons. Firstly, the bedrock type recorded is a simplified estimation based on the BGS geological map (BGS, 2024a) of the most common type from what could be a complex interbedded range of lithologies. Secondly, the material in an embankment may have come from a cutting some distance away and will not match the bedrock underlying that section of line. The same is true for the adjacent soil types.

4.7. SOC and habitat type

Our results show no significant difference in SOCc or SOCs between the main habitat types found along railway margins. Other studies of reclaimed land have shown significant differences in SOCc, often rapidly, between vegetation types (Liu et al., 2015; Zhang et al., 2020; Yao et al., 2023; Li et al., 2024). Yao et al., 2023 for example, reported a clear increase in mean SOCc on spoil heaps from bare land (1.42 %) to grassland (2.97 %), shrub land (3.79 %) and woodland (4.40 %) after just 9 years.

This may be due to changes in railway habitats since construction and particularly since the 1960s when vegetation management changed with the switch away from steam locomotives and the loss of grassland for scrub and woodland (Network Rail, 2020e).

4.8. SOC and soil texture & moisture

Our results show an inverse relationship between SOCc and clay and silt fractions (Fig. 8). This is contrary to expectations as other studies show clay and silt can adsorb SOC and aid its retention (Six et al., 2002; Matus, 2021).

The railway engineers avoided using clay rich material where possible and the clay fraction of the railway soils in the top 30 cm is low (mean = 5.0 %) which may itself contribute to the modest SOCc. The relationship between SOCc and soil texture is not straightforward and can be dependent on the clay type, nature of the organic matter and how it is protected from normal decay and dispersal processes and may not necessarily be a good predictor of SOC (Plante et al., 2006).

Soil moisture is a significant factor for SOCc ($p < 0.001$). However, the soil moisture can be affected by the soil texture, recent rainfall and very local topography so that two cores taken close together on different days may have quite different moisture outcomes. The railway embankments and cuttings are designed to be free draining, but ditches, hollows and boggy trackside areas retain moisture, are more likely to be anoxic, reducing decomposition rates and hence show a positive correlation with SOCc (Guo et al., 2024).

4.9. SOC and climate

The main climate factors of mean annual rainfall and temperature show significance ($p < 0.05$) but very low correlation with SOCc (Table 5). This is surprising given the correlation between SOC and soil moisture and that other studies find a stronger link to climate (Allory et al., 2022) albeit in conjunction with other factors (Manning et al., 2015). It may be that the climate range is insufficient to show up as a stronger factor given the short time that the soils have had to develop since construction.

4.10. SOC and time

The results from our survey show no significant differences in SOCc or SOCs between lines constructed between 1838 and 1910. However, the retention and positive effect of time since railway line creation ($p \approx 0.05$) in our linear modelling suggests older construction may be associated with increased carbon accumulation over time. This would be more in accord with some literature suggestions that the heterogeneous nature and mix of transported and artificial parent material in technosols results in more rapid soil evolution (Séré et al., 2010; Leguédois et al., 2016). In the early stages of soil genesis, soil properties can change over annual to decadal time scales (Richter Jr., 2007; Egli et al., 2014; Moreno-Barriga et al., 2017) including reclaimed and vegetated industrial sites (e.g. Rees et al., 2019; Downey et al., 2021; Honscha et al., 2021; Baier et al., 2022) though often with management intervention (Filcheva et al., 2021). While the dressing of railway line slopes with thin seeded soil or turf helped develop organic matter in the near surface fine soil fraction (5 % average SOCc) there does not appear to have been sufficient time since the UK railways were constructed for the biogeochemical processes to have resulted in SOC stocks comparable with natural soils.

4.11. SOC and pH & macrofauna

The disused railway soils exhibited a wide range of pH values (3.5 to 8.7, with a mean of 6.0) and we found no significant correlation with SOCc. Dry, coarse soils with a pH < 6 are conditions that are unfavourable for earthworm activity. Although the macrofauna of the soils was not specifically recorded in this study, only a few cores contained earthworms, ants, or other invertebrates, which are known to play a crucial role in developing organic matter in soils (Liao et al., 2016). Earthworms prefer fine texture soils that are neutral to alkaline and moist (Butt and Briones, 2017; Edwards and Arancon, 2022). Some land reclamation projects have demonstrated significant increases in macrofauna populations and SOC through the addition of topsoil and the planting of mixed grasses and trees (Haigh et al., 2020; Filcheva et al., 2021). However, a study of urban soils found that it took decades for earthworm and ant numbers to recover to those in natural environments even with the addition of topsoil which encourages the establishment of soil macrofauna (Vergnes et al., 2017). Although railway embankment and cutting slopes were often dressed with thin seeded soil or turf, this has been insufficient to facilitate rich macrofauna communities in railway soils.

4.12. Modelling

A key finding in this study is that SOCc (%) and SOCs (t ha^{-1}) vary little across the country regardless of location, parent material, climate or soil texture. No single factor had a major influence on either SOCc or SOCs and the best explanatory models included inputs from the interplay of several factors, each with relatively low correlation to SOCc or SOCs.

This study shows that the interaction of multiple factors drives railway SOC density and distribution and need to be considered in explanatory and predictive modelling. For example, the underlying bedrock type and soil type adjacent to the railway as potential parent materials are significant factors ($p = 0.001$) for SOCc but with a low correlation ($R^2 < 14$ %) (Table 4). The rock and soil types used in construction, including industrial waste components, will impact the texture and pH of the resultant technosol and its capacity to retain and accumulate organic carbon (Leguédois et al., 2016). Thus, a site with soil derived from local granitic bedrock and podzol soil will result in an acidic technosol that inhibits earthworm and invertebrate activity (Butt and Briones, 2017; Edwards and Arancon, 2022) and influence the vegetation and habitat present. For improved SOCc correlation other factors need to be included. Combining parent material with climate data, soil texture and gravel content, which impacts bulk density and water retention capacity, all in turn affect biogenic activity and SOC development (Fig. 9).

Significant predictors for SOCs included moisture, bulk density, and depth, all of which are intuitive given their direct influence on carbon stock accumulation in the soil profile. Of the categorical variables, only Urban habitat showed a significant negative effect, implying lower SOC stocks in urban areas relative to the reference habitat type (bramble scrub). While bedrock age was retained in the model, none of the epochs (e.g., Carboniferous, Jurassic) were statistically significant at the 5 % level, suggesting weak or inconsistent influence of underlying bedrock age on SOC stocks.

Together, these results indicate that soil physical characteristics and sampling depth are primary drivers of SOC stock variation, while categorical predictors like habitat and geology may exert secondary, context-specific influence. The relatively modest R^2 values also suggest that additional unmeasured site-specific factors or temporal dynamics may be important in predicting SOC stock at finer scales.

None of the models developed were able to accurately predict the relatively small number of samples with high SOC concentrations or stocks. As might be expected, models incorporating a greater number of factors produced more accurate predictions for both SOCc and SOCs. In contrast, models with fewer factors—particularly those lacking key soil parameters such as bulk density (BD), moisture and texture—exhibited flatter predictive slopes, converging towards mean values, and showed reduced R^2 values. The model used to generate a map of SOC density and estimate the total SOC stock across the Network Rail estate relied on only three parameters (Eq. (8)), resulting in limited explanatory power ($R^2 = 0.19$) and underestimating the true variability. Despite this, the model provides a preliminary map of SOC density (t ha^{-1}) and a baseline estimate of SOC stock for the Network Rail estate, which is valuable given the lack of direct measurements from the active network. Given the limited data set used, caution should be used in reading too much into the relatively small regional variations (Table 8). Scotland has a higher proportion of older metamorphic and granite rocks and podzol soils correlated with lower SOCs while the Southern region has a higher proportion of rock and soil types (e.g. Luvisols) associated with higher SOCs.

4.13. *Further work & SOC sequestration implications*

The quantification of carbon stocks on the UK rail network could be improved primarily by extensive sampling across the active rail network and it is hoped that this study will act as a catalyst for Network Rail to include soil sampling and SOC analysis into their routine trackside work activities. The measuring, monitoring and reporting of SOC is fundamental to meet the stated aim of increasing sequestration and carbon stocks on the estate (Network Rail, 2022b). Over time this would build up a much more accurate picture of SOC density and distribution and inform action plans to increase soil carbon stocks. An improved habitat map that better characterised the trackside environments and recognised the nature of the central track ballast could be derived from higher resolution satellite data or from Network Rail's existing LIDAR data. However, this would come at increased cost and NR would need to assess the benefit value.

In terms of enhancing current SOC sequestration going forward, further work might quantify the rock types and clay mineralogy assemblages present in railway soils to better understand how these impact SOCc. Analysis of nutrient availability and presence of heavy metals and other contaminants would give insight into factors that may be limiting vegetation development and microbial activity. Similarly, analysis of the soil macro-biota, critical to the development of SOC, could highlight areas that would benefit from remediation.

The relatively low SOC density in the railway margin soils (49.7 t ha^{-1}) suggests that there is an opportunity for accelerated sequestration. The Varley Report (Varley, 2018) recommended that Network Rail value and manage its lineside estate for nature, the environment and biodiversity. The active and disused lines can provide additional ecosystem benefits connecting habitats along transport corridors and with neighbouring land. Extending this to include enhancing carbon sequestration will be difficult given the constraints of running a safe and reliable railway on a limited budget but these are not necessarily mutually exclusive. Studies have shown that improving biodiversity can be beneficial to the creation and retention of SOC (e.g. Canedoli et al., 2020; Schittko et al., 2022) which Network Rail are actively pursuing. The creation of hedgerows as an estate barrier may also enhance SOC (Biffi et al., 2022) as well as biodiversity. More active soil intervention strategies such as the addition of compost or biochar or the establishment of specific plant species will be logistically and financially challenging and require detailed study to assess viability.

5. Conclusion

The 19th century excavation of soil and rock from cuttings and creation of railway foundations and embankments severely disrupted the material with likely resultant loss of SOC. At around 5 %, the mean SOC concentration in the soil fine fractions across disused railway soils, which we consider to be a reasonable proxy for the active Network Rail estate, is higher than many arable soils and comparable with other technosols. However, the high coarse gravel fraction results in low SOC stocks overall (mean = 49.7 t ha^{-1}) reducing still further for the active estate when accounting for the areas without soil, particularly the central track bed. While several factors were significant in estimating SOC concentration, the data were highly variable and correlation coefficients were low except for BD. A first map and assessment of the Network Rail estate generated a SOC stock estimate of 1.52 million tons at a mean density of 29.7 t ha^{-1}. This suggests that SOC on the estate is very low compared to more natural soils. The time elapsed since construction, up to 185 years in this study, has not been sufficient for biogeochemical processes to develop mature soils. An improved SOC density map and carbon stock estimate will come from direct sampling of soil from the active railways which Network Rail can then use to inform how they might enhance carbon sequestration into the future.

CRediT authorship contribution statement

Justin Thomas: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jon McCalmont:** Writing – review & editing, Validation, Methodology, Investigation. **Neil Strong:** Writing – review & editing, Conceptualization. **Zoe Wright:** Writing – review & editing, Investigation. **Astley Hastings:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Justin Thomas reports financial support was provided by Biotechnology and Biological Sciences Research Council. Neil Strong reports a relationship with Network Rail Infrastructure Ltd. that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179763.

Data availability

Data will be made available on request.

References

Allory, V., Sere, G., Ouvrard, S., 2022. A meta-analysis of carbon content and stocks in Technosols and identification of the main governing factors. Eur. J. Soil Sci. 73 (1). https://doi.org/10.1111/ejss.13141.

Anderson, D.W., 1988. The effect of parent material and soil development on nutrient cycling in temperate ecosystems. Biogeochemistry 5, 71–97.

Angst, G., Messinger, J., Greiner, M., Häusler, W., Hertel, D., Kirfel, K., Kögel-Knabner, I., Leuschner, C., Rethemeyer, J., Mueller, C.W., 2018. Soil organic carbon stocks in topsoil and subsoil controlled by parent material, carbon input in the rhizosphere, and microbial-derived compounds. Soil Biol. Biochem. 122, 19–30. https://doi.org/10.1016/j.soilbio.2018.03.026.

Baier, C., Modersohn, A., Jalowy, F., Glaser, B., Gross, A., 2022. Effects of recultivation on soil organic carbon sequestration in abandoned coal mining sites: a meta-analysis. Sci. Rep. 12, 20090. https://doi.org/10.1038/s41598-022-22937-z.

Bailey, V., Hicks Pries, C., Lajtha, K., 2019. What do we know about soil carbon destabilization? Environ. Res. Lett. 14 (083004). https://doi.org/10.1088/1748-9326/ab2c11.

Ball, D., 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. J. Soil Sci. 15, 84–92.

Basile-Doelsch I. Balesdent J. Pellerin S. 2020 Reviews and syntheses: The mechanisms underlying carbon storage in soil Biogeosciences Discuss. Copernicus Publications 17 5223 5242 https://doi.org/10.5194/bg-17-5223-2020.

Beeching, R. 1963. The reshaping of British Railways - Part 1: report. London: HMSO. Accessed April 12, 2024. https://www.railwaysarchive.co.uk/docsummary.php?docID=13.

BGS, 2024a. BGS Geology Viewer. Accessed April 12, 2024. https://www.bgs.ac.uk/map-viewers/bgs-geology-viewer/.

BGS, 2024b. BGS Geology: onshore digital geological map of Great Britain data. Accessed February 15, 2024. https://www.bgs.ac.uk/datasets/bgs-geology/.

Biffi, S., Chapman, P., Grayson, R., Ziv, G., 2022. Soil carbon sequestration potential of planting hedgerows in agricultural landscapes. J. Environ. Manage. 307, 114484. https://doi.org/10.1016/j.jenvman.2022.114484.

Bodlák, L., Křováková, K., Kobesová, M., Brom, J., Šťastný, J., Pecharová, E., 2012. SOC content - an appropriate tool for evaluating the soil quality in a reclaimed post-mining landscape. Ecol. Eng. 43, 53–59. ISSN 0925-8574,. https://doi.org/10.1016/j.ecoleng.2011.07.013. https://www.sciencedirect.com/science/article/pii/S0925857411002758.

Bradley, S. 2015. The Railways: Nation, Network and People. Profile Books. ISBN-10 1846682096.

Bukoski, J., Broadhead, J., Donato, D., Murdiyarso, D., Gregoire, T., 2017. The Use of Mixed Effects Models for Obtaining Low-Cost Ecosystem Carbon Stock Estimates in Mangroves of the Asia-Pacific. PloS ONE 12 (1), e0169096. https://doi.org/10.1371/journal.pone.0169096.

Butt, K.R., Briones, M.J., 2017. Earthworms and mesofauna from an isolated, alkaline chemical waste site in Northwest England. Eur. J. Soil Biol. 78, 43–49. https://doi.org/10.1016/j.ejsobi.2016.11.005.

Canedoli, C., Ferrè, C., Abu El Khair, D., Comolli, R., Liga, C., Mazzucchelli, F., Proietto, A., Rota, N., Colombo, G., Bassano, B., Viterbi, R., Padoa-Schioppa, E., 2020. Evaluation of ecosystem services in a protected mountain area: Soil organic carbon stock and biodiversity in alpine forests and grasslands. Ecosyst. Serv. 44, 101135. https://doi.org/10.1016/j.ecoser.2020.101135.

Chien, S.C., Krumins, J.A., 2022. Natural versus urban global soil organic carbon stocks: a meta-analysis. Sci. Total Environ. 807, 150999. https://doi.org/10.1016/j.scitotenv.2021.150999.

Cornu, S., Keller, C., Béchet, B., Delolme, C., Schwartz, C., Vidal-Beaudet, L., 2021. Pedological characteristics of artificialized soils: A snapshot. Geoderma 40, 115321. https://doi.org/10.1016/j.geoderma.2021.115321.

Degryze, S., Six, J., Paustian, K., Morris, S.J., Paul, E.A., Merckx, R., 2004. Soil organic carbon pool changes following land-use conversions. Glob. Chang. Biol. 10, 1120–1132. https://doi.org/10.1111/j.1529-8817.2003.00786.x.

Downey, A.E., Groffman, P.M., Mejía, G.A., Cook, E.M., Sritrairat, S., Karty, R., Palmer, M.I., McPhearson, T., 2021. Soil carbon sequestration in urban afforestation sites in New York City. Urban For. Urban Green. 65, 127342. https://doi.org/10.1016/j.ufug.2021.127342.

Edwards, C.A., Arancon, N.Q. 2022. Biology and ecology of earthworms - fourth edition. New York: Springer. 978–0–387-74942-6 978–0–387-74943-3 (eBook) https://doi.org/10.1007/978-0-387-74943-3.

Egli, M., Dahms, D., Norton, K., 2014. Soil formation rates on silicate parent material in alpine environments: Different approaches-different results. Geoderma 213, 320–333. https://doi.org/10.1016/j.geoderma.2013.08.016.

Esri UK, 2022. 50 Years of UK Weather. Accessed May 14, 2024. https://www.arcgis.com/apps/dashboards/d29ad7056f3548eb8affeb1c0ad50106.

Essenhigh, R.H., Misra, M.K., Shaw, D.W., 1989. Ignition of coal particles: A review. Combust. Flame 77, 3–30. https://doi.org/10.1016/0010-2180(89)90101-6.

Filcheva, E., Hristova, M., Haigh, M., Malcheva, B., Noustorova, M., 2021. Soil organic matter and microbiological development of technosols in the South Wales Coalfield. Catena 201, 105203. https://doi.org/10.1016/j.catena.2021.105203.

Fuertes, A.B., Hampartsoumian, E., Williams, A., 1993. Direct measurement of ignition temperatures of pulverised coal particles. Fuel 72 (9), 1287–1291. https://doi.org/10.1016/0016-2361(93)90127-N.

Grandy, A.S., Robertson, G.P., 2006. Aggregation and Organic Matter Protection Following Tillage of a Previously Uncultivated Soil. Soil Sci. Soc. Am. J. 70, 1398–1406. https://doi.org/10.2136/sssaj2005.0313.

Gregg, R., Elias, J.L., Alonso, I., Crosher, I.E., Muto, P., Morecroft, M.D., 2021. Carbon storage and sequestration by habitat: a review of the evidence. Second edition. Natural England research report NERR094. York.. https://publications.naturalengland.org.uk/publication/5419124441481216.

Guo, Y., Han, J., Bao, H., Wu, Y., Shen, L., Xu, X., Chen, Z., Smith, P., Abdalla, M., 2024. A systematic analysis and review of soil organic carbon stocks in urban greenspaces. Sci. Total Environ. 948, 174788. https://doi.org/10.1016/j.scitotenv.2024.174788.

Haigh, M. (Ed.), 2000. Reclaimed Land: Erosion Control, Soils and Ecology. CRC Press, Rotterdam, NL. Balkema (ISBN-10: 9054107936; ISBN-13: 978-9054107934).

Haigh, M., Woodruffe, P., D'Aucourt, M., Alun, E., Wilding, G., Fitzpatrick, S., Filcheva, E., Noustorova, M., 2020. Successful ecological regeneration of opencast coal mine spoils through forestation: from cradle to grove. Minerals 10 (5), 461–488. https://doi.org/10.3390/min10050461.

Hiller, D.A., 2000. Properties of Urbic Anthrosols from an abandoned shunting yard in the Ruhr area, Germany. Catena 39, 245–266. https://doi.org/10.1016/S0341-8162(00)00081-3.

Honscha, L.C., Campos, A.S., Tavella, R.A., Ramires, P.F., Volcão, L.M., Halicki, P.C.B., Pech, T.M., Bernardi, E., Ramos, D.F., Niemeyer, J.C., Baisch, P.R.M., 2021. Bioassays for the evaluation of reclaimed opencast coal mining areas. Environ. Sci. Pollut. Res. 28, 26664–26676. https://doi.org/10.1007/s11356-021-12424-9.

Hoogsteen, M.J., Lantinga, E.A., Bakker, E.J., Groot, J.C., Tittonell, P.A., 2015. Estimating soil organic carbon through loss on ignition: effects of ignition conditions and structural water loss. Eur. J. Soil Sci. 66 (2), 320–328. https://doi.org/10.1111/ejss.12224.

Hoogsteen, M.J.J., Lantinga, E.A., Bakker, E.J., Tittonell, P.A., 2018. An evaluation of the loss-on-ignition method for determining the soil organic matter content of calcareous soils. Commun. Soil Sci. Plant Anal. 49 (13), 1541–1552. https://doi.org/10.1080/00103624.2018.1474475.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome. https://openknowledge.fao.org/handle/20.500.14283/i3794en.

JHI, 2024. The James Hutton Institute. Soil Maps. Accessed June 16, 2024 https://www.hutton.ac.uk/soil-maps/.

LandIS, 2024. World Reference Base Soil Map for England and Wales - NATMAP wrb. 2006 version. Accessed May 12, 2024. https://www.landis.org.uk/data/nmwrb.cfm.

Leguédois, S., Séré, G., Auclerc, A., Cortet, J., Huot, H., Ouvrard, S., Watteau, F., Schwartz, C., Morel, J.L., 2016. Modelling pedogenesis of Technosols. Geoderma 262, 199–212. https://doi.org/10.1016/j.geoderma.2015.08.008.

Lehmann, J., Klebber, M., 2015. The contentious nature of soil organic matter. Nature 528, 60–68. https://doi.org/10.1038/nature16069.

Li, C., Ji, Y., Ma, N., Zhang, J., Zhang, H., Ji, C., Zhu, J., Shao, J., Li, Y., 2024. Positive effects of vegetation restoration on the soil properties of post-mining land. Plant and Soil 497 (1), 93–103. https://doi.org/10.1007/s11104-022-05864-w.

Liao, K., Wu, S., Zhu, Q., 2016. Can soil pH be used to help explain soil organic carbon stocks? CLEAN Soil Air Water 44 (12), 1685–1689. https://doi.org/10.1002/clen.201600229.

Lilly, A., Baggaley, N.J., 2021. Scoping study to identify current SOC stocks and the potential for increasing carbon sequestration in Scottish soils. Scottish Government. Accessed August 24, 2024. doi:ISBN 9781802017496 https://www.gov.scot/publications/scoping-study-identify-current-soil-organic-carbon-sequestration-scottish-soils/.

Liu, S., Zhang, W., Wang, K., Pan, F., Yang, S., Shu, S., 2015. Factors controlling accumulation of soil organic carbon along vegetation succession in a typical karst region in Southwest China. Sci. Total Environ. 521, 52–58. https://doi.org/10.1016/j.scitotenv.2015.03.074.

Liu, Z., He, C., Zhou, Y., Wu, J., 2014. How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. Landsc. Ecol. 29, 763–771. https://doi.org/10.1007/s10980-014-0034-y.

Mair, R., 2021. A Review of Earthworks Management. Task Force Report, Network Rail. Accessed July 17, 2022. https://www.networkrail.co.uk/who-we-are/our-approach-to-safety/stonehaven/.

Manning, P., de Vries, F.T., Tallowin, J.R., Smith, R., Mortimer, S.R., Pilgrim, E.S., Harrison, K.A., Wright, D.G., Quirk, H., Benson, J., Shipley, B., 2015. Simple measures of climate, soil properties and plant traits predict national-scale grassland soil carbon stocks. J. Appl. Ecol. 52 (5), 1188–1196. https://doi.org/10.1111/1365-2664.12478.

Matus, F.J., 2021. Fine silt and clay content is the main factor defining maximal C and N accumulations in soils: a meta-analysis. Sci. Rep. 11, 6438. https://doi.org/10.1038/s41598-021-84821-6.

McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3–52.
Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., Field, D.J., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.
Minitab, LLC, 2020. Minitab (20.3.0.0). https://www.minitab.com.
Moreno-Barriga, F., Díaz, V., Acosta, J.A., Muñoz, M.Á., Faz, Á., Zornoza, R., 2017. Organic matter dynamics, soil aggregation and microbial biomass and activity in Technosols created with metalliferous mine residues, biochar and marble waste. Geoderma 301, 19–29. https://doi.org/10.1016/j.geoderma.2017.04.017.
Morton, D., Ridding, L., O'Conner, R., Pyewell, R., 2020. Baseline habitat map. Habitat map for network rail. Report by the UK centre for ecology and hydrology. Project 07675. (confidential).
Network Rail, 2020a. Network Rail Environmental Sustainability Strategy 2020–2050. https://www.networkrail.co.uk/. Accessed May 23rd, 2024. https://www.networkrail.co.uk/who-we-are/publications-and-resources/environmental-sustainability-strategy/.
Network Rail, 2020b. Network Rail. Our ambition for a low-emission railway 2020–2050. https://www.networkrail.co.uk/. Accessed May 2024. https://www.networkrail.co.uk/sustainability/a-low-emission-railway/.
Network Rail, 2020c. Network Rail. Traction Decarbonisation Network Strategy, Interim Programme Business Case. https://www.networkrail.co.uk/ (web archive link, 23 May 2024). 31 July. Accessed May 23, 2024. https://www.networkrail.co.uk/sustainability/a-low-emission-railway/.
Network Rail, 2020d. NR/L2/TRK/4239. Track Bed Investigation, Design and Installation, Issue 2. Network Rail Infrastructure Ltd (Internal), London.
Network Rail, 2020e. Biodiversity Action Plan. Biodiversity on Britain's Railway. 12. Accessed November 26, 2024. https://www.networkrail.co.uk/wp-content/uploads/2020/12/Network-Rail-Biodiversity-Action-Plan.pdf.
Network Rail, 2021. NR/Tm/ESD001. Contaminated land technical manual. Network Rail. https://safety.networkrail.co.uk/home-2/environment-and-sustainable-development/environment/contaminated-land/.
Network Rail, 2022a. Network Rail State of Nature Summary Report 2020/21. https://www.networkrail.co.uk/sustainability/biodiversity-on-britains-railway/. February. Accessed November 15, 2024. https://www.networkrail.co.uk/wp-content/uploads/2022/10/Network-Rail-State-of-Nature-report-plus-six-appendices.pdf.
Network Rail, 2022b. A National Nature Network - sustainable land use strategic framework. Biodiversity on Britain's railway. 10. Accessed November 26, 2024. https://www.networkrail.co.uk/wp-content/uploads/2022/10/Sustainable-land-use-strategic-framework-national-nature-network.pdf.
Network Rail, 2023. Network Rail State of Nature Summary Report 2021/22. https://www.networkrail.co.uk/sustainability/biodiversity-on-britains-railway/ (August). https://www.networkrail.co.uk/wp-content/uploads/2024/04/Network-Rail-State-of-Nature-report-2021_22.pdf. (Accessed 15 November 2024).
Network Rail, 2024. Vegetation Management. Accessed November 28, 2024. https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/vegetation-management/.
Odlyzko, A. 2010. Collective hallucinations and inefficient markets: the British railway mania of the 1840. Social Science Research Network. 15 January. Accessed April 12, 2024. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1537338.
ORR, 2024a. Network Licence granted to Network Rail Infrastructure Limited (As at 1 April 2019). Licence, Office of Rail and Road. Accessed July 23, 2024 https://www.orr.gov.uk/about/who-we-work-with/railway-networks/mainline-network.
ORR, 2024b. Statistics - Rail statistics compendium. Office of Road and Rail. Data Portal. (5 December) https://dataportal.orr.gov.uk/statistics/compendia/rail-statistics-compendium/. (Accessed 15 December 2024).
Plante, A.F., Conant, R.T., Stewart, C.E., Paustian, K., Six, J., 2006. Impact of soil texture on the distribution of soil organic matter in physical and chemical fractions. Soil Sci. Soc. Am. J. 70 (1), 287–296. https://doi.org/10.2136/sssaj2004.0363.
R Core Team, 2021. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.
Rees, F., Dagois, R., Derrien, D., Fiorelli, J.L., Watteau, F., Morel, J.L., Schwartz, C., Simonnot, M.O., Séré, G., 2019. Storage of carbon in constructed technosols: in situ monitoring over a decade. Geoderma 337, 641–648. https://doi.org/10.1016/j.geoderma.2018.10.009.
Richter Jr., D.D., 2007. Humanity's transformation of earth's soil: pedology's new frontier. Soil Sci. 172 (12), 957–967. https://doi.org/10.1097/ss.0b013e3181586bb7.
Sargent, C., 1984. Britain's Railway Vegetation. Institute of Terrestrial Ecology, Book, NERC, Cambridge. https://nora.nerc.ac.uk/id/eprint/5041/.
Schittko, C., Onandia, G., Bernard-Verdier, M., Heger, T., Jeschke, J., Kowarik, I., Maaß, S., Joshi, J., 2022. Biodiversity maintains soil multifunctionality and soil organic carbon in novel urban ecosystems. J. Ecol. 110, 916–934. https://doi.org/10.1111/1365-2745.13852.
Scottish Government, 2020. Building a greener railway: lineside vegetation management for nature and people in Scotland. Accessed May 24, 2024. https://www.transport.gov.scot/publication/building-a-greener-railway/.
Séré, G., Schwartz, C., Ouvrard, S., Renat, J.C., Watteau, F., Villemin, G., Morel, J.L., 2010. Early pedogenic evolution of constructed Technosols. J. Soil. Sediment. 10, 1246–1254. https://doi.org/10.1007/s11368-010-0206-6.
Sheail, J., 1979. The History of the Railway Formations. Interim report to the Nature Conservancy Council on British Rail Land - Biological Survey. NERC/Institute of Terrestrial Ecology. (ITE Project Number: 0466, CST Report 276) (Unpublished). https://nora.nerc.ac.uk/id/eprint/20263/. (Accessed 12 April 2024).
Shrestha, R.K., Lal, R., 2011. Changes in physical and chemical properties of soil after surface mining and reclamation. Geoderma 161, 168–176. https://doi.org/10.1016/j.geoderma.2010.12.015.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant and Soil 241, 155–176. https://doi.org/10.1023/A:1016125726789.
Skempton, A., 1996. Embankments and cuttings on the early railways. Constr. Hist. 11, 33–49. https://www.jstor.org/stable/41615443.
Spohn, M., Klaus, K., Wanek, W., Richter, A., 2016. Microbial carbon use efficiency and biomass turnover times depending on soil depth - implications for carbon cycling. Soil Biol. Biochem. 96, 74–81. https://doi.org/10.1016/j.soilbio.2016.01.016.
Stahr, K. 2016. Inorganic soil components - minerals and rocks. Scheffer/Schachtschabel soil science, by Blume, H.P., Brümmer, G.W., Fleige, H., horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.M., Blume, H.P., Brümmer, G. W. Chapter 2: 7-53. Berlin Heidelberg:springer-Verlag. https://doi.org/10.1007/978-3-642-30942-7_2.
Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., De Courcelles, V.D.R., Singh, K., Wheeler, I., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agr. Ecosyst. Environ. 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001.
Sustrans, 2024. Sustrans FAQs - Managing the Network. Accessed November 28, 2024. https://www.sustrans.org.uk/about-us/frequently-asked-questions-faqs/faqs-managing-the-network/.
UK Government, 2021. Great British Railways: The Williams-Shapps Plan for Rail. Accessed May 10, 2024. https://www.gov.uk/government/publications/great-british-railways-williams-shapps-plan-for-rail.
UKSO, 2024. UK Soil Observatory Map Viewer. Accessed March 10, 2024. https://www.ukso.org/.
USDA, 2008. USDA Natural Resources Conservation Service - Soil Health Assessment - Bulk Density. USDA Natural Resources Conservation Service, June. https://www.nrcs.usda.gov/sites/default/files/2022-10/nrcs142p2_051591.pdf. (Accessed 26 November 2024).
Vanguelova, E.I., Nisbet, T.R., Moffat, A.J., Broadmeadow, S., Sanders, T.G.M., Morison, J.I.L., 2013. A new evaluation of carbon stocks in British forest soils. Soil Use Manage. 29, 169–181. https://doi.org/10.1111/sum.12025.
Varley, J., 2018. Valuing nature - a railway for people and wildlife... The Network Rail Vegetation Management Review. UK Government, Department for Transport, London. Accessed March 10, 2024. https://www.gov.uk/government/publications/network-rail-vegetation-management-review-valuing-nature-a-railway-for-people-and-wildlife.
Vergnes, A., Blouin, M., Muratet, A., Lerch, T., Mendez-Millan, M., Rouelle-Castrec, M., Dubs, F., 2017. Initial conditions during Technosol implementation shape earthworms and ants diversity. Landsc. Urban Plan. 159, 32–41. https://doi.org/10.1016/j.landurbplan.2016.10.002.
Ward, S.E., Smart, S.M., Quirk, H., Tallowin, J.R., Mortimer, S.R., Shiel, R.S., Wilby, A., Bardgett, R.D., 2016. Legacy effects of grassland management on soil carbon to depth. Glob. Chang. Biol. 22, 2929–2938. https://doi.org/10.1111/gcb.13246.
Williams, F. Our iron roads: railroad history, construction and administration. CGR publishing. 1883 2021.
Yao, Y., Dai, Q., Gao, R., Yi, X., Wang, Y., Hu, Z., 2023. Characteristics and factors influencing soil organic carbon composition by vegetation type in spoil heaps. Front. Plant Sci. 14, 1240217. https://doi.org/10.3389/fpls.2023.1240217.
Ye, Y., Xiao, S., Liu, S., Zhang, W., Zhao, J., Chen, H., Guggenburger, G., Wang, K., 2020. Tillage induces rapid loss of organic carbon in large macroaggregates of calcareous soils. Soil Tillage Res. 199, 104549. https://doi.org/10.1016/j.still.2019.104549.
Zhang, P.P., Zhang, Y.L., Jia, J.C., Cui, Y.X., Wang, X., Zhang, X.C., Wang, Y.Q., 2020. Revegetation pattern affecting accumulation of organic carbon and total nitrogen in reclaimed mine soils. PeerJ 8, e8563. https://doi.org/10.7717/peerj.8563.
Zhang, Z., Lu, C., Chen, J., Li, S., Zheng, X., Zhang, L., Zhang-Zheng, H., 2024. Perturbation of soil organic carbon induced by land use change from primary forest. Environ. Res. Lett. 19, 124014. https://doi.org/10.1088/1748-9326/ad8668.