Investigating the causes and consequences for soil properties of gorse encroachment at Troopers Hill

Group 3 – in association with Friends of Troopers Hill

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Contents:

Abstract

Woody shrub encroachment is a key driver of ecological change in heathlands, yet its effects on soil processes remain uncertain, particularly in heterogeneous urban systems. At Troopers Hill, rapid expansion of *Ulex europaeus* (gorse) raises the question of whether its distribution is driven by soil conditions or is actively modifying the soil profile, with implications for the wider ecology of the site. A stratified sampling design was used to compare soils under established gorse, early-stage gorse and control vegetation. Thirty samples were analysed regarding 5 different soil characteristics. Soils were consistently acidic (pH 4.04 - 5.11), with gorse-dominated areas showing lower pH and significantly higher sand content (27-37% vs. 10-22% in controls). In contrast, no clear relationships emerged between gorse cover and soil moisture, organic matter or nutrient concentrations. Instead, variability within the strata exceeded differences between them, suggesting that soil conditions, particularly acidity, may influence gorse distribution, while gorse does not exert a consistent effect on soil properties. Soil characteristics at Troopers Hill are primarily shaped by spatial heterogeneity and historical disturbance.

Introduction

Woody shrub encroachment into semi-natural grasslands and heathlands is widely recognised as a driver of ecological change, particularly through influences on soil properties and nutrient cycling (van Auken, 2009; Eldridge et al., 2011*).* On nutrient-poor acidic sites, such changes have disproportionate effects as vegetation is adapted to low fertility and specific pH conditions (Critcheley et al., 2002*).* One shrub frequently found in these types of habitats is *Ulex europaeus*, commonly known as 'gorse'. Native to western Europe but widely introduced to temperate landscapes worldwide, gorse is a long-lived, evergreen legume characterised by rapid growth and a prolific seedbank capable of remaining viable in the soil for decades (Udo, Tarayre and Atlan, 2016; Broadfield and McHenry, 2019).

Through nitrogen fixation, gorse can increase nitrogen availability in soils via symbiotic associations with rhizobia (a group of nitrogen-fixing bacteria), introducing biologically available nitrogen into otherwise nutrient-poor systems (Magesan et al., 2012; Vitousek et al., 2002). Furthermore, high litter production from gorse contributes additional organic inputs to the soil, increasing soil organic matter content and decomposing into key nutrients (Galappaththi et al., 2022; Magesan et al., 2012). In addition, gorse influences soil moisture dynamics through canopy interception and evapotranspiration, with studies showing it reduces the proportion of rainfall reaching the soil surface by up to 50% (Soto and Diaz-Fierros, 1997), potentially influencing microbial decomposition processes that are sensitive to moisture conditions (Schimel and Schaeffer, 2012). However, these effects are not likely to operate uniformly across all sites and research. While nitrogen is often emphasised as being strongly shaped by biological inputs from gorse, phosphorus is largely controlled by geochemical processes, particularly under acidic conditions or sites with higher heavy metals where sorption to minerals and metals can restrict availability (Penn and Camberato, 2019). This means that any nutrient enrichment associated with gorse may be constrained by underlying soil chemistry.
These interacting processes highlight the existence of plant-soil feedback mechanisms, whereby gorse both modifies and responds to soil conditions. However, other studies highlight more variable or

negligible effects, dependent on soil texture, disturbance history, climatic conditions and management (Eldridge et al., 2011; Edmonson et al., 2012). These feedback mechanisms can have serious impacts on ecosystems; enhanced nitrogen cycling, associated with nitrogen-fixing shrubs, can shift ecosystems away from nutrient limitation, increasing fertility but also leading to the outcompeting of specialised and often declining heathland flora (Galappaththi et al., 2022). Alternatively, Galappaththi et al. (2022) highlight potential beneficial ecosystem services by gorse, such as carbon sequestration and soil stabilisation, reiterating Eldridge et al. (2011) in concluding that links between gorse encroachment and subsequent environmental degradation is not universal, with soil response to gorse being contextually dependent. In heterogeneous, post-industrial landscapes such as Troopers Hill, these mechanisms are complicated by its industrial legacy, potentially limiting the extent to which vegetation alone influences soil properties.

Much of the existing research on gorse has been conducted within its introduced range, particularly in regions such as New Zealand and the Americas, where it is studied primarily as an invasive species (Leary et al., 2005; Magesan et al., 2012). This has resulted in a strong focus on large-scale invasion dynamics and the adoption of simplified invaded-uninvaded comparisons, which is important to question given the widely acknowledged highly dynamic spatial expansion exhibited by gorse and influenced by multiple factors (Altamirano et al., 2016; Da Re et al., 2024). Furthermore, much of this research has been conducted in semi-natural or agricultural systems, whereas urban soils are often highly disturbed, heterogeneous and influenced by legacy contamination, limiting the transferability of existing findings to urban heathland environments (Burghart, 1994; Edmondson et al., 2012). This study addresses this gap by investigating soil characteristics at Troopers Hill, an urban heathland in East Bristol (Figure 1).

Figure 1: A map of Trooper's Hill conservation site with its location within the wider Bristol area (top left) and a representation of the gorse distribution at the site (top right)

Specifically, it examines how soil properties vary across the different stages of gorse encroachment on the site and whether soil conditions may both influence and respond to the gorse expansion present. This study aims to provide answers to the Friends of Troopers Hill organisation and aid them in understanding the causes and impact of gorse expansion on the site.

Physical and chemical properties, including pH, soil moisture, nitrogen, phosphate, particle size distribution and soil organic matter, were analysed to provide a multi-metric assessment of soil conditions. By integrating these variables, this study aims to investigate the interactions between gorse and soil characteristics at Troopers Hill, an urban post-industrial heathland. Specifically, it addresses two research questions:

1) How are the characteristics of the soil at Troopers Hill influencing the growth and distribution of gorse?

2) How is gorse inundation influencing the soil characteristics of Troopers Hill?

It is hypothesised that established gorse will be associated with increased organic matter and nitrogen availability due to litter inputs and nitrogen fixation, while soil moisture may vary due to canopy interception and soil structure. However, given Troopers Hill's complex history, it is also expected that the results may be highly variable, with other factors overriding vegetation effects and soil-driven mechanisms beyond what is investigated within this study.

Methodology

Site overview

Troopers Hill is an ecologically significant urban site located in East Bristol, designated a 'Site of Conservation Interest' due to its high conservation value. The site consists of a south-facing hillside overlooking the River Avon and is characterised by varied topography and different vegetation communities. The underlying geology of the area is primarily Pennant sandstone with smaller mudstone deposits (Wessex Ecological Consultancy et al., 2019), seen in Figure 2.

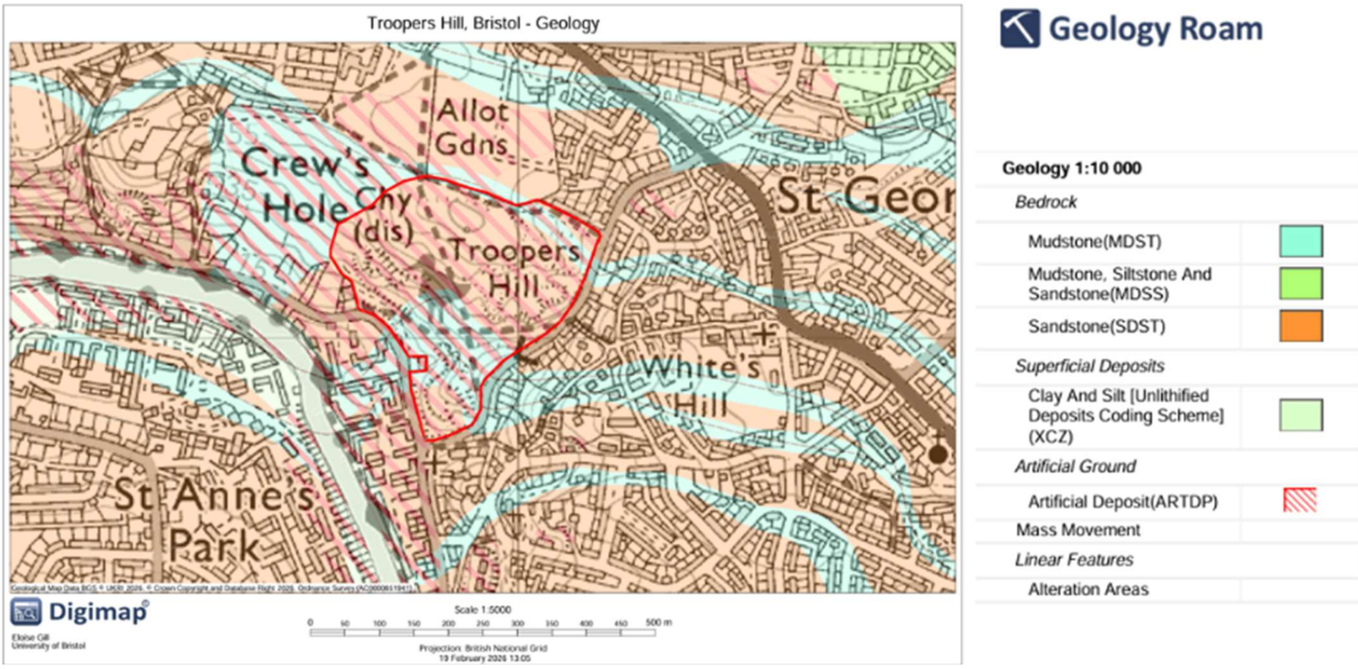

Figure 2: Map of Trooper's Hill showing its underlying geology – Troopers Hill mainly consists of Pennant Sandstone, with evidence of artificial deposits from previous land uses (Ordnance Survey and Digimap, 2025)

This geology contributes to the development of the soil profile of the area, which supports a range of heathland vegetation, specifically ling heather (*Calluna vulgaris*) and bell heather (*Erica cinerea*) (Tibbett et al., 2019). The site has a complex and varied history, being previously used for quarrying, mining, chemical refining, and metal smelting, with the byproducts and waste from these industries often deposited on other areas of the site (Acton-Campbell, 2006; Beighton, 2013). The uneven topography and various artificial deposits have led to areas of erosion around the site, adding to the factors important to consider at Troopers Hill.

Within this environment, gorse has expanded substantially from 2 plants in 1994, (Friends of Troopers Hill, 2026b) to over 2000 m^2 today and is now a dominant component of the vegetation in some areas. The co-occurrence of heather and gorse in heathland systems is widely observed (Flint, 2018), potentially due to their broadly similar requirements in soil habitat. Gorse's ability to thrive in acidic, nutrient-poor soils and disturbed conditions aligns with the environmental characteristics of the site (Leary et al., 2005). However, its expansion poses a potential threat to the heathland present through competitive exclusion and successional change.

To manage this, the site is divided into 17 compartments in a targeted conservation management plan. An overview of these compartments and site locations can be seen in Figure 3. The gorse is almost entirely confined to compartments 12, 10 and 15, so this was our focus area within the site. Soil samples were taken from within two of these compartments of Troopers Hill on Thursday 5th February 2026, in weather conditions of light rain and overcast skies.

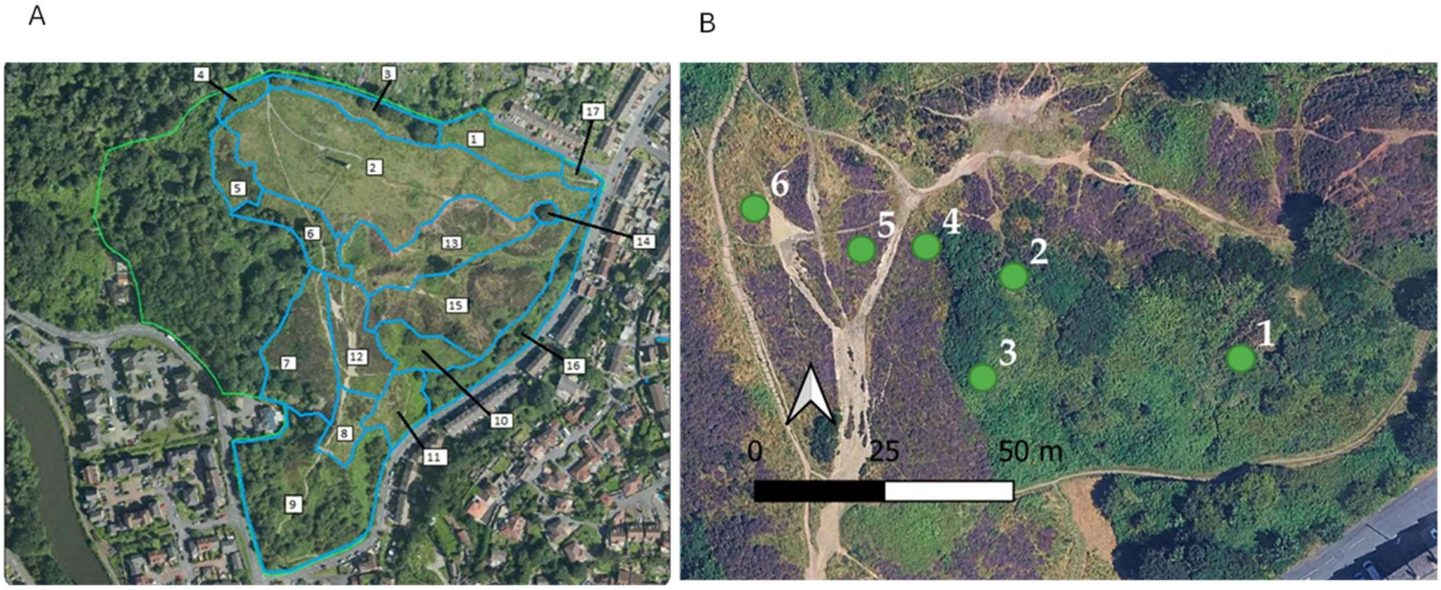

Figure 3A: A map showing the compartment divisions of Troopers Hill. This study takes place within 12 and 15 (Wessex Ecological Consultancy et al., 2019), Figure 3B: Map showing chosen site locations for sampling.

Field methodology

A stratified purposive sampling design was established to capture variation in soil properties across stages of gorse growth. Stratified sampling is widely used in soil studies to ensure representation of diverse vegetation types and improve estimates of mean soil properties (Potash et al., 2023). Three vegetation-based strata were defined: established (mature) gorse, early-stage (new) gorse and control areas (grassland and heather). Sites were initially identified using a combination of historical and current satellite imagery, utilising the different flowering times of early-stage and established gorse to distinguish between growth stages (Tarayre et al., 2007) and select sites. Given the frequent removal of gorse on the site, historical satellite imagery was useful to help ensure our sampling sites were temporally relevant. The site selection was then further refined through consultation with Susan and Rob Acton-Campbell (Friends of Troopers Hill) and a site visit.

Two sampling areas within each stratum were selected (six sites in total), all located with compartments 12 and 15 (Figure 3A). Due to Troopers Hill's varied topography, a constant elevation between sampling sites was not possible. The sites selected range in elevation from 43.6m to 49.6m above sea level. Although soil properties such as soil drainage and nutrient content are known to vary over large elevation gradients (Nie et al., 2023; Rotich et al., 2025), the relatively small elevation range (~6m) suggests that elevation is unlikely to be a primary driver of variation within this study.

At each site, a 2m x 2m quadrat was demarcated using a tape measure and marked with flags to standardise the sampling extent (Figure 4).

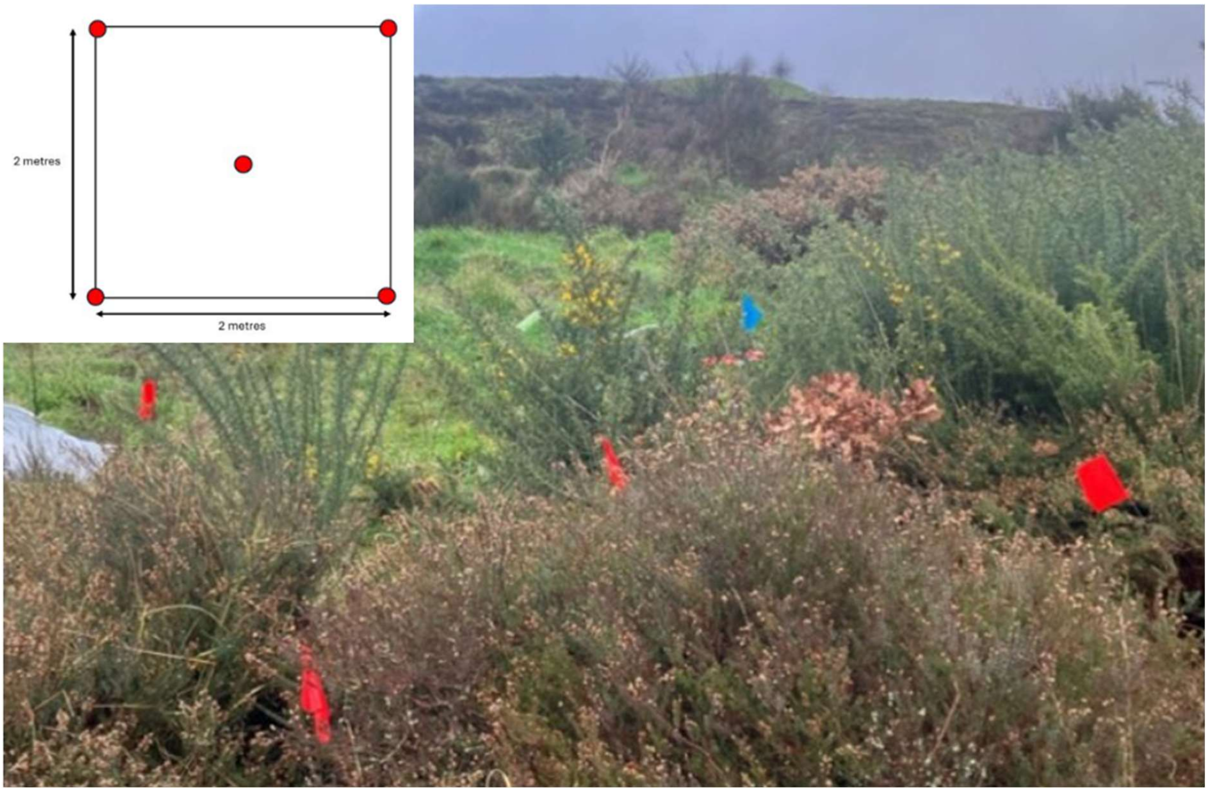

Figure 4: Field photograph showing sampling quadrats demarcated by red marker flags, with inset diagram illustrating quadrat dimensions.

Subsamples were collected from each corner and the centre of each of the 6 sites quadrats using hand trowels. This replicate-focused design aims to capture small-scale spatial variability and improve the representativeness of our study given the inherent heterogeneity of soil properties (Brouder et al., 2005). A total of 30 samples were collected across 6 sites, a limit imposed by time and laboratory constraints. Despite the relatively limited sample size, it is sufficient for statistical testing and allowing detection of variability within and between vegetation types, but the narrow scope of this study must be considered when interpreting the results.

Soils were collected from the upper ~20cm of the profile due to the shallow soils present across Troopers Hill, making the site unsuitable for soil coring techniques. Most biological activity in soils occurs in the topsoil layer due to the greater abundance of microbial biomass in surface soils, declining significantly with depth (He et al., 2023), further justifying the sampling technique used. Approximately 300g of soil was collected at each sampling point, tools cleaned between each site, and samples were stored in labelled bags before transportation to the laboratory and refrigerated prior to analysis.

Antecedent weather conditions are important to consider when interpreting soil moisture data. January 2025 record precipitation levels approximately 156% above the long-term average in South-West England (Met Office, 2026), see Figure 5, potentially resulted in elevated baseline soil moisture conditions. Furthermore, sampling was conducted under light rainfall, potentially influencing near-surface moisture measurements. To account for this, in situ soil moisture was measured at each sampling point using a ThetaProbe sensor, providing contextual field data to support laboratory-based gravimetric analysis; this data must be considered cautiously alongside other analyses given the impact of soil disturbance and integrity on probe-based measurement (Drescher et al., 2024).

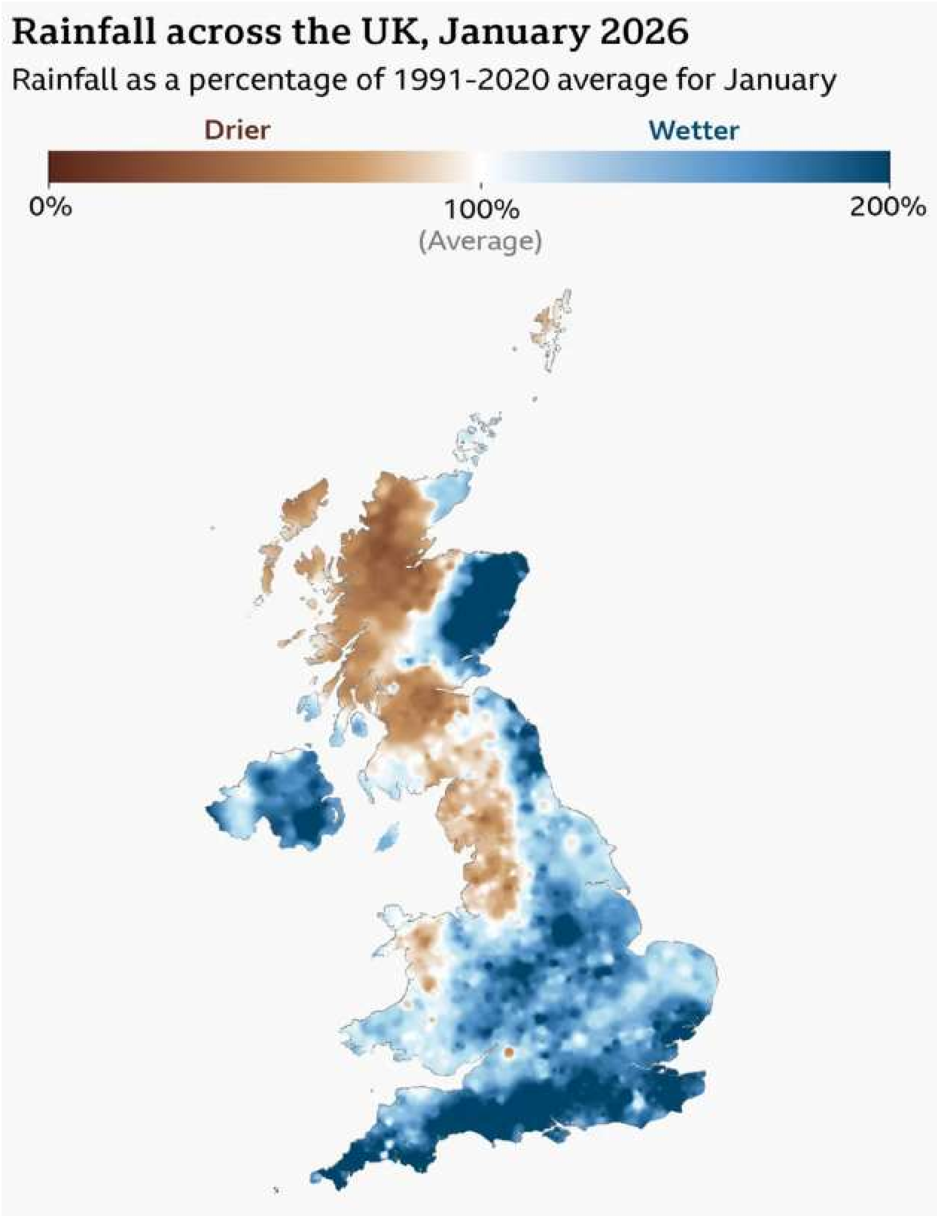

Figure 5: Map showing rainfall anomalies for January 2026 (Met Office, 2026)

Laboratory Analysis

Prior to analysis, visible roots and organic debris were removed and soils homogenised to improve sample consistency. All laboratory methods were followed in accordance with the laboratory handbook (Cobb, 2024).

Soil Moisture (Gravimetric):

Gravimetric soil moisture content was determined by weighing fresh soil (15g), drying at 50°C for 24 hours, and reweighing until a constant mass was achieved. Moisture content was calculated as percentage mass loss. This method provides a direct and reliable measure of water content, avoiding issues of calibration and variability associated with field sensors (Robinson et al., 2008)

Soil pH:

Soil pH was measured using a slurry method, mixing soil with deionised water at a 2:1 ratio. Samples were allowed to settle before measurement using a calibrated pH meter. These steps ensured consistency across samples and is appropriate for acidic heathland soils, where small variations in pH greatly influence nutrient availability and vegetation dynamics (Penn and Camberato, 2019).

Organic Matter (Loss on Ignition):

Soil organic matter was determined using loss on ignition (LOI). Dried and sieved (<2mm) samples were heated at 550°C for 5 hours, with organic matter calculated as percentage mass loss. This temperature was selected to remove organic material while minimising alteration of mineral components. Organic matter is a key indicator of soil composition.

Particle size distribution:

Soil texture was determined using laser diffraction (Mastersizer), measuring particle size based on light scattering. This method allows accurate quantification of fine particles difficult to assess using traditional sieving techniques. Soil texture influences both water retention and nutrient dynamics, providing important context for interpreting soil moisture and chemical properties. Due to time constraints, we only analysed 2 samples out of 5 from each site.

Nutrients:

Total oxidisable nitrogen formed of nitrates and nitrites (TON), as well as ammonium and phosphate were extracted using a 1M KCL solution. Samples were shaken, centrifuged and filtered prior to analysis using an auto-analyser. This targets plant-available nutrients rather than total concentrations, making it appropriate for assessing ecological differences between vegetation types and potential nitrogen inputs from gorse.

A summary of all laboratory analysis methods used is illustrated in Figure 6.

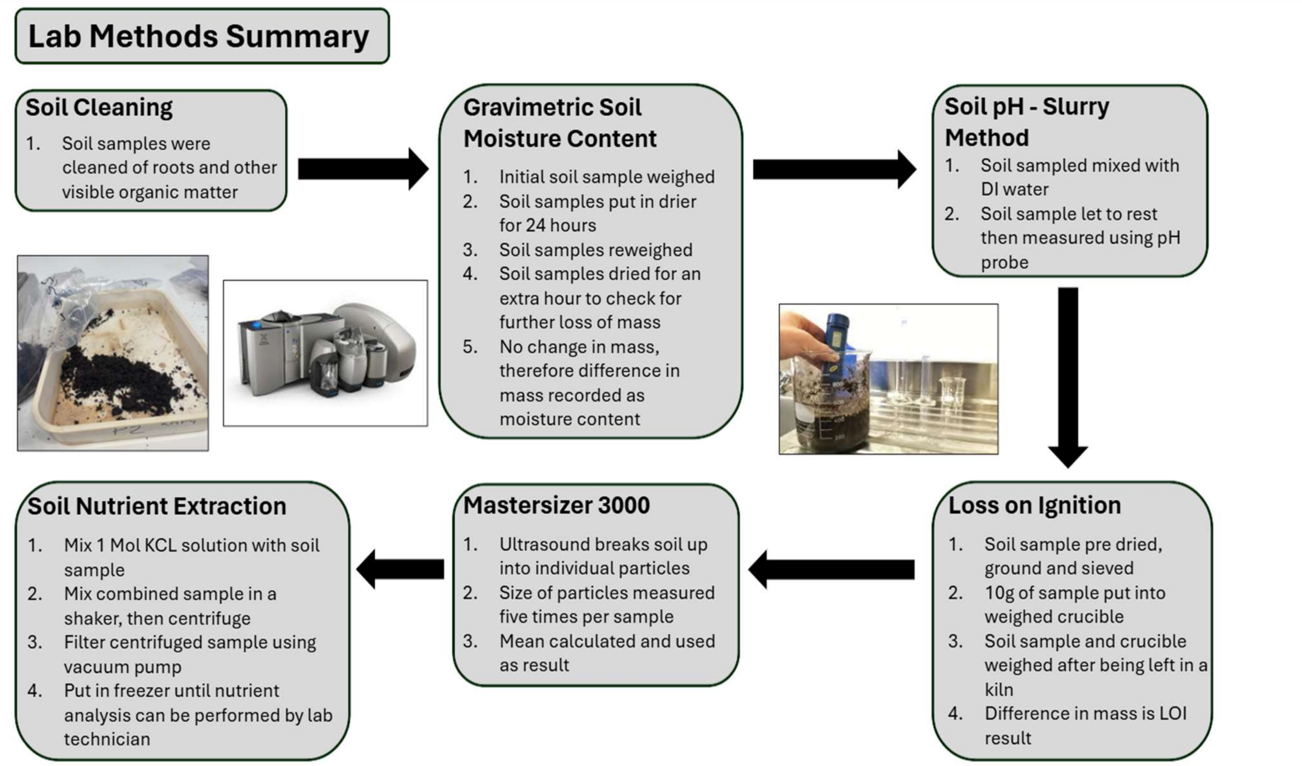

Figure 6: Flow chart showing lab methods summary

Statistical Analysis

Initial analysis explored possible outliers within the dataset. The data showed high variability across many of the variables, including between sites; given both the complex history of Troopers Hill and high variation identified in previous studies at this site, this was expected, with only 1 value removed from analysis. Sample 1.3 was removed from the TON analysis given that it was almost 9 times the interquartile range above Q3 and so was considered an outlier even within a heterogeneous site such as Troopers Hill.

Comparing sites/gorse cover:

Initially, the normality of the data was tested using the Shapiro Wilk test - whilst most of the variables at each site and under each gorse cover were normally distributed, some were very close to the p-value threshold (0.05). Histograms were done to further assess the normality of the data, and many appeared to not show a normal distribution, even when there was a high p-value from the Shapiro Wilk test due to the small number of observations per group (Figure 7). As a result of the small sample size and the non-normal appearance in the histograms, the non-parametric Kruskal-Wallis test was used to assess statistical difference between sites and gorse cover for each of the variables.

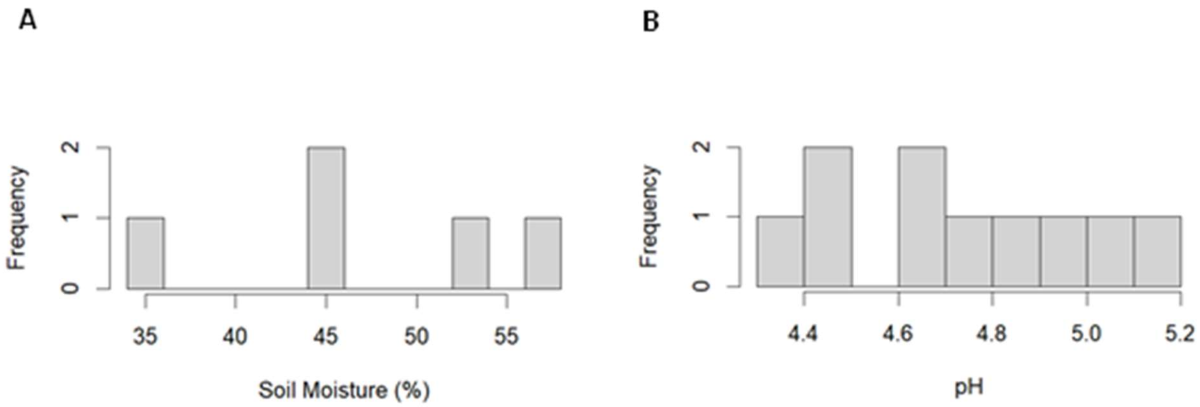

Figure 7: Histograms showing the distribution of (A) gravimetric soil moisture at site 6 (Shapiro Wilk, p = 0.7999) and (B) pH in the early-stage gorse cover (Shapiro Wilk, p = 0.6208)

To assess the variability in soil properties under different gorse cover, scatter plots were used alongside the Kruskal-Wallis test and Dunn post hoc test to see if the differences were statistically significant. Given the high variability within the same gorse cover shown in these plots and the heterogenous nature shown in previous studies at Troopers Hill, these statistical tests were also done between sites to assess the variability between different areas with the same gorse cover and see if the gorse cover was the factor causing the trends seen.

To understand these patterns between different sites and gorse cover, we assessed the relationship between variables through the Spearman's rank correlation test (due to the non-normal nature of the data) and linear regression models to find if the relationships were statistically significant.

Other Studies:

Our results were compared with several other secondary sources to situate our results within wider literature of soil properties in gorse sites and to assess how our results varied from other parts of Troopers Hill without gorse. Two previous Avon projects had taken place at Troopers Hill in 2024 and 2025 in different areas of the site, measuring many of the same variables as our study. Comparing GPS points for the 2024 and 2025 projects, only 5 samples out of 60 were taken from within compartments 12 and 15, where our study took place. These overlapping samples, as well as our control (non-gorse) samples, were removed, and the dataset was used to compare our area of gorse-covered hill to the rest of the site.

Due to the limited past research in this area, peer-reviewed studies with available data were limited. However, means, ranges and some submitted data were extracted for comparative use to situate our data within other gorse-covered heathland areas in the UK.

Results

Many variables showed significant differences between sites with the same gorse cover (Table 1), showing large variation in soil properties. For example, there was a significant difference in gravimetric soil moisture between Sites 1 and 2 (both established gorse sites) and Sites 5 and 6 (both control sites), but despite this, there was also a significant difference between established gorse and control sites (Table 2). When this was the case, caution was taken in making conclusions about differences in soil properties between gorse covers, and, as a result, variation between sites was often considered alongside/instead.

Table 1: Table showing all statistically significant differences between sites for all variables with p-values in brackets. The Kruskal-Wallis test and Dunn post hoc test were used for all variables due to the non-normal nature of the data. The boxes highlighted in red show significant differences between sites within the same gorse cover.

Site	1	2	3	4	5
2	GSM (0.0080) OM (0.0225) Ammonium (0.0064)				
3	OM (0.0028) GSM (0.0005) Ammonium (0.0003) pH (0.0335) Sand (0.0357) Silt (0.0357) TON (0.0321)				
4	OM (0.0021) GSM (0.0013) Ammonium (0.0009) TON (0.0003)	pH (0.0170) TON (0.0171)	pH (0.0023) Clay (0.0480) TON (0.0434)		
5	OM (0.0012) GSM (0.0001) Ammonium (0.0004) Sand (0.0261) Silt (0.0261)		pH (0.0423) Clay (0.0480)	TON (0.0020)	
6	pH (0.0013) Sand (0.0063) Silt (0.0092) TON (0.0083)	OM (0.0267) pH (0.0285) Clay (0.0357) Phosphate (0.0291)	OM (0.0034) GSM (0.0130) Ammonium (0.0096) Phosphate (0.0344)	OM (0.0027) pH (0.0000) Clay (0.0092) Ammonium (0.0205) GSM (0.0262)	OM (0.0015) pH (0.0018) GSM (0.0049) Clay (0.0092) Ammonium (0.0104) Phosphate (0.0031) TON (0.0355)

Table 2: Table showing all statistically significant differences between different gorse cover for all variables with p-values in brackets. The Kruskal-Wallis test and Dunn post hoc test were used for all variables.

Gorse Cover	Established	Early-Stage
Early-Stage	OM (0.0046) GSM (0.0028) Ammonium (0.0021) TON (0.0036)	
Control	Sand (0.0071) Silt (0.0071) GSM (0.0494)	OM (0.0329) Silt (0.0478)

pH:

Soils across Troopers Hill were consistently acidic, with pH values ranging from 4.04 to 5.11 (See Appendix B Table 1). Whilst variation occurred between sites, no clear pattern emerged in terms of gorse cover (Table 2). Significant differences were observed between Sites 3 and 4 (early-stage gorse) and between Sites 5 and 6 (controls), indicating that within-group variability exceeded differences between vegetation types (Table 1). This suggests that, whilst all the sites were acidic, there is limited evidence for an interactive relationship between gorse cover and soil pH.

Grain Size Distribution:

Across samples, the silt fraction dominated, followed by sand, with very low clay content (maximum mean of 3.4% at control sites) (Figure 8A). A general increase in sand content, accompanied by a decrease in silt, was observed with increasing gorse cover (Figure 8B). Established gorse sites exhibited significantly higher sand content (21-33%) compared to control sites (5-19%) (Kruskal-Wallis, $p < 0.01$).

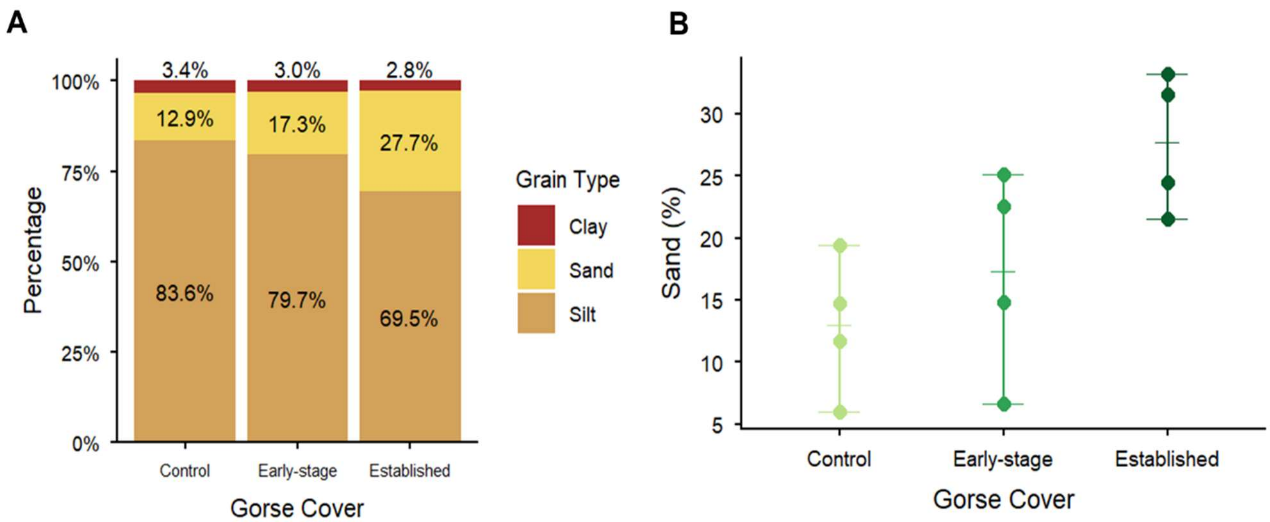

Figure 8: Graphs displaying variation in grain size distribution by gorse cover with (A) a stacked bar chart showing variation in clay, sand and silt percentage and (B) a grouped dot plot showing only variation in sand distribution where the error bars show the range within each gorse cover and the middle line shows the mean.

Gravimetric Soil Moisture:

Gravimetric soil moisture showed substantial variability across Troopers Hill, ranging between 15.31% and 142.10%, with high variability shown both between and within sites, often exceeding 100% between replicates (Figure 9A). Site 1 had a mean soil moisture of 20.3%, significantly lower than most other sites, although no consistent pattern was observed across stages of gorse growth given the high variability between replicates (Table 1).

A strong positive relationship was observed between gravimetric soil moisture and organic matter (Figure 9B).

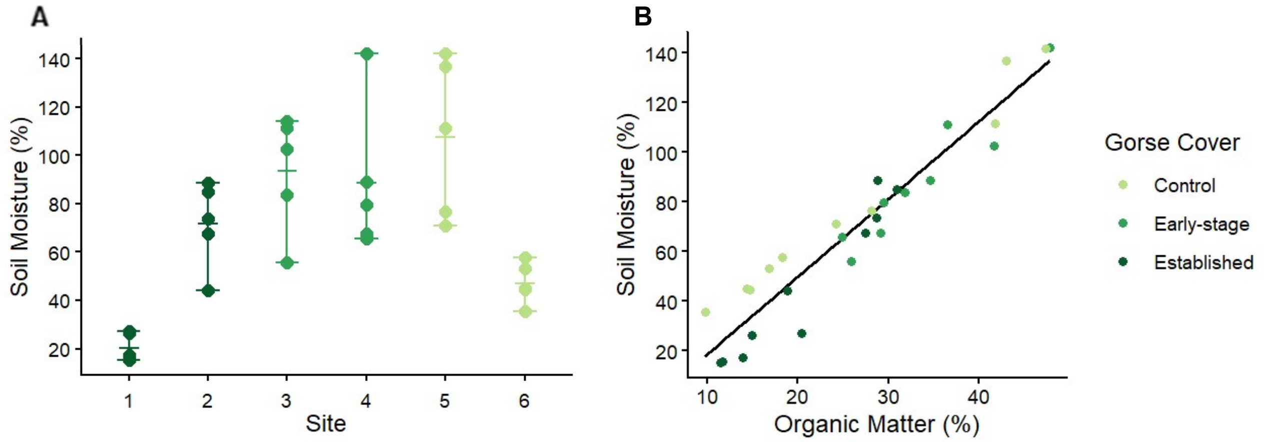

Figure 9: (A) Grouped dot plot showing variation in gravimetric soil moisture in different sites, the error bars show the range within each site, and the middle line shows the mean and (B) scatterplot showing relationship between gravimetric soil moisture and organic matter ($R^2 = 0.9122$, $p < 0.001$).

Volumetric probe measurements showed no statistically significant relationships with gravimetric soil moisture ($R^2 = 0.321$, $p < 0.001$), likely reflecting limitations of probe-based methods in shallow, disturbed sites, where soil moisture probe sensors are known to be sensitive to soil structure, stone content and contact quality (Robinson et al., 2008; Drescher et al., 2024). As a result, gravimetric soil moisture measurements were considered more reliable, as they provide a direct measure of water content independent of field conditions, strengthening confidence in subsequent interpretations.

Organic Matter:

Organic matter content showed a general increase from established gorse (11-31%) to early-stage gorse (25-48%) to control sites (10-47%), although this pattern was inconsistent (Figure 10). Significant differences were observed within vegetation groups, particularly between Sites 1 and 2 (both established gorse) and Sites 5 and 6 (controls), indicating that variability within groups exceeded any differences between sites (Table 1).

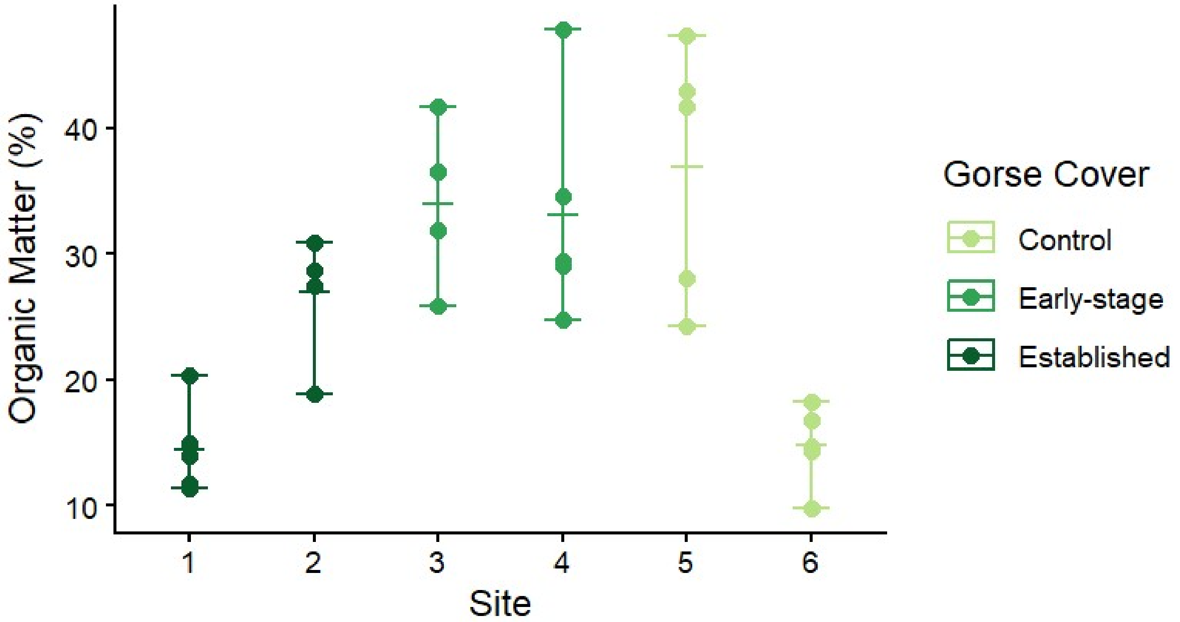

Figure 10: Grouped dot plot showing variation in organic matter in different sites. The error bars show the range within each site, and the middle line shows the mean.

Nutrients:

Established gorse sites exhibited significantly higher Total Oxidisable Nitrogen (TON) than early -stage sites, with a mean of 2.70µg/g compared to 0.67µg/g (Kruskal-Wallis, $p < 0.01$) (Figure 11A). However, no significant difference was observed between gorse-covered sites and control sites. Considerable variability was present within gorse stage groups.

No significant correlation was found between TON and ammonium (Spearman's test, $\rho = -0.1310$, $p = 0.5064$, see Appendix A Figure 1), indicating a lack of coupling between these nitrogen forms.

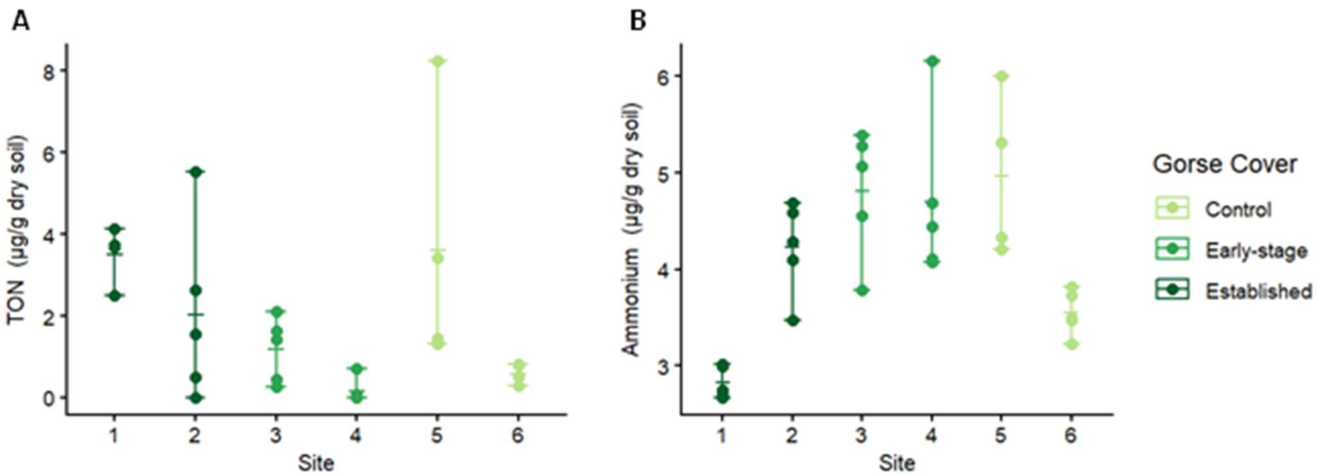

Figure 11: Grouped dot plot showing variation in (A) TON and (B) ammonium in different sites. The error bars show the range within each site, and the middle line shows the mean.

Ammonium concentrations were significantly higher in the early-stage gorse compared to established gorse (Kruskal-Wallis, $p < 0.005$), although this pattern was strongly influenced by a single low-value site (Site 1 with a mean of 2.8µg/g compared to 4.2µg/g at Site 2), and no consistent differences were observed between gorse and control sites (Figure 11B).

A strong positive correlation was observed between ammonium and organic matter (Spearman's $\rho = 0.953$, $p < 0.001$) (Figure 12), suggesting a close relationship between ammonium availability and organic matter content.

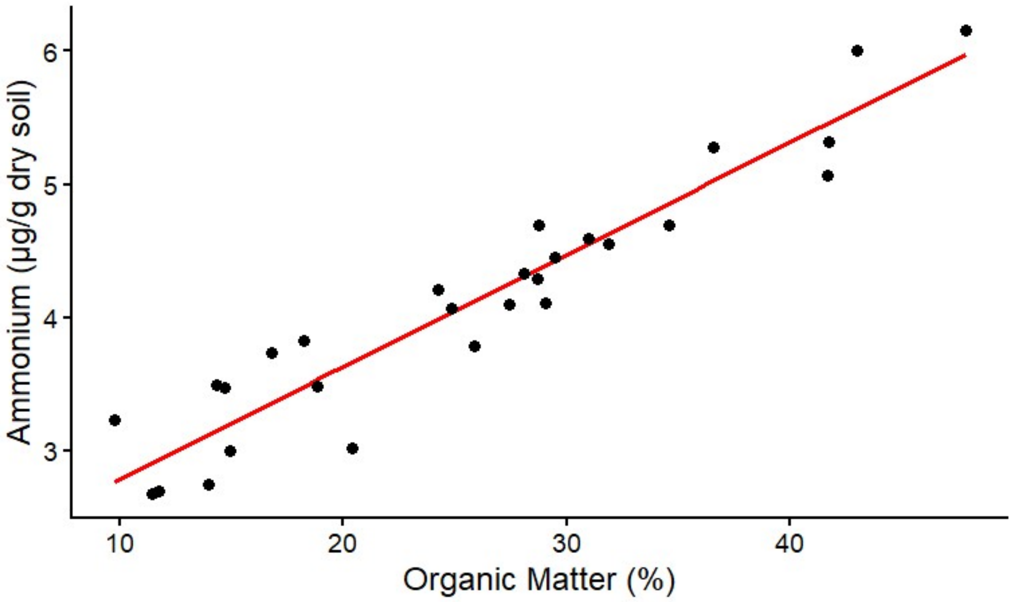

Figure 12: Scatterplot showing the relationship between ammonium and organic matter ($R^2 = 0.9003$, $p < 0.001$).

Phosphate concentrations showed no consistent pattern across sites or vegetation types (Table 3). While mean values differed between sites, statistically significant differences were limited. Variability within sites was high, as reflected in large ranges relative to mean values.

Table 3: Table showing phosphate mean and range by site and gorse cover.

Gorse Cover	Site	Phosphate Mean (µg/g of dry soil)	Phosphate Range (µg/g of dry soil)
Established	1	2.86	5.52
Established	2	2.75	2.70
Early-stage	3	2.78	3.50
Early-stage	4	2.75	2.55
Control	5	4.43	7.22
Control	6	1.51	1.86

Discussion

This discussion addresses two key research questions: (1) How soil properties influence the distribution of gorse at Troopers Hill, and (2) how gorse encroachment influences soil properties at this site. It is first important to highlight an important but indirectly important event, revealed during background research. In 1995, a major fire is understood to have affected large areas of the site (Friends of Troopers Hill, 2026a), potentially creating favourable conditions for the establishment of gorse. Fire is known to promote the regeneration and spread of gorse by stimulating germination from long-lived seed banks and reducing competition from existing vegetation (Soto and Diaz-Fierros, 1997; Reyes and Casal, 2004). However, while such disturbance may explain early distribution patterns, it is unlikely to account for the continued and spatially variable expansion observed today, and a lack of information about the specific location and characteristics of the fire makes its impact highly uncertain. This discussion therefore primarily focuses on the initial aim of the study to evaluate soil characteristics on this site in relation to the expansion of gorse.

pH (RQ1: Soil controls on gorse distribution):

Soil pH across the study sites indicates a consistently acidic soil profile (pH 4.04-5.11), shown in Figure 13. This aligns with the wider understanding that acid grassland and heathland typically develop on acidic, nutrient-poor soils (Maddock, 2008). These findings are also consistent with Beighton (2013), who reported similarly acidic soils over a decade earlier, suggesting temporal stability in soil acidity despite ongoing vegetation change.

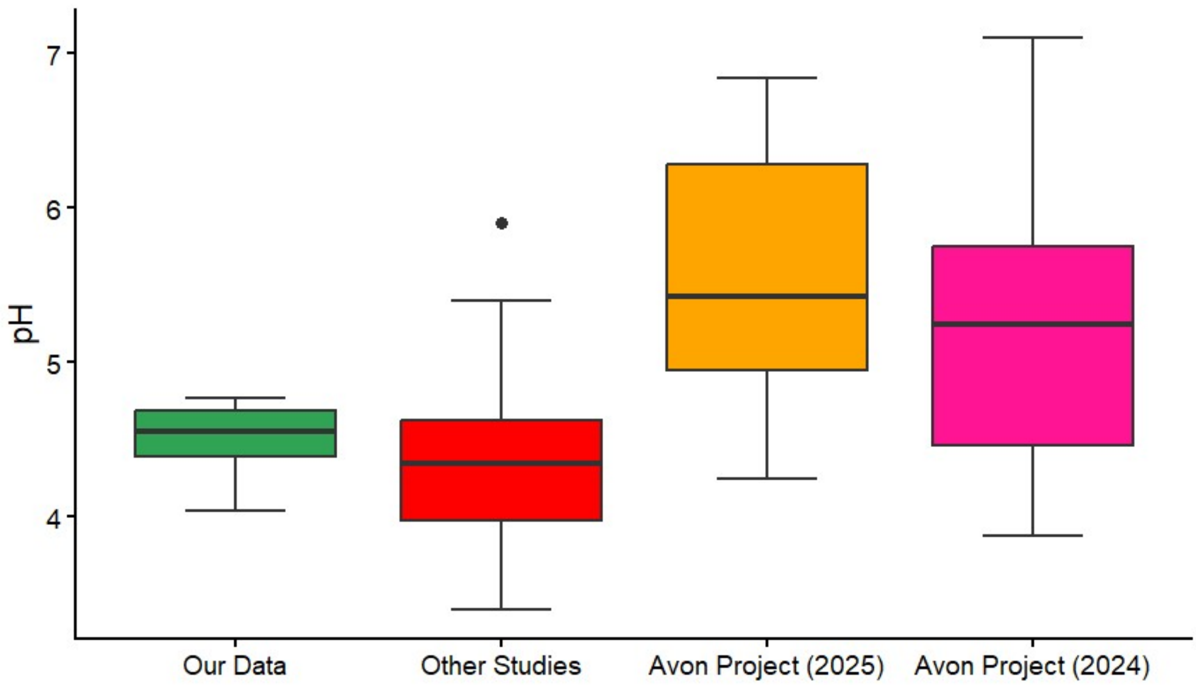

Figure 13: Boxplot comparing soil pH from our gorse covered sites, other studies on gorse covered Heathland, other Avon Project data from 2025 and 2024 collected from other, non-gorse covered, areas of Troopers Hill (5 samples removed from Avon Project 2024 that were taken from the gorse covered part of Troopers Hill).

No statistically significant difference was observed between this study's findings and average pH values reported in the studies grouped in Figure 13 of gorse heathlands elsewhere in the UK (Tibbet et al., 2019; Grubb et al., 1969; Mitchell et al., 1997), indicating that the soils of Troopers Hill fall within the typical pH range for gorse-dominated heathlands nationally. This study did, however, identify lower (more acidic) values in gorse-dominated areas compared to previous Avon project datasets (Avon Project, 2024; Avon project, 2025) from other areas of the site where gorse is entirely absent, with this difference being statistically significant (Kruskal-Wallis, $p < 0.01$). This represents one of the clearest links identified in this study between soil properties (lower pH) and vegetation patterns (presence of gorse).

In acidic systems, even relatively small changes in pH can influence nutrient concentrations; lower pH reduces nutrient availability while increasing the solubility of metals such as aluminium (Penn and Camberato, 2019), creating conditions which may limit less tolerant species. In addition, acidic conditions can suppress microbial activity, reducing rates of nitrification, slowing nutrient cycling and contributing to accumulation of organic matter (Zhang et al., 2022), though as Barrow and Hartemink (2023) emphasise, the relationship between pH and nutrient availability is highly soil-dependent and variable dependent on plant and mineral characteristics. While gorse is well adapted to such environments and able to tolerate acidic, nutrient-poor soils (Kato-Noguchi & Kato, 2025), many other plant species are less tolerant of these conditions. As such, these more acidic soils may indirectly favour gorse growth by reducing competition from less tolerant species, rather than directly enhancing its growth.

This interpretation may explain the observations of the Friends of Troopers Hill regarding the rapid and spatially uneven expansion of gorse at Troopers Hill which sparked their proposal of this research. However, the relatively narrow overall range of pH values indicates that pH alone is unlikely to fully explain the distribution of gorse at Troopers Hill. Instead, it is likely acting as a permissive control, interacting with other environmental factors, such as soil texture, moisture and the disturbance history of the site, to influence vegetation patterns. It is not possible to isolate pH from other co-varying factors and, as such, pH variation should be considered as one of several contributing controls rather than a dominant driver. Beighton (2013) highlights strong spatial variability in soil chemistry across the site, driven by localised contamination and topographic redistribution, reinforcing that pH must be considered within the wider context of a highly heterogenous system.

In relation to the first research question, these results show that soil pH may play a subtle but important role in influencing the growth and distribution of gorse at Troopers Hill. The acidic conditions recorded (pH 4.04-5.11) provide a broadly suitable environment for gorse, and slightly more acidic soils in gorse-dominated areas may have facilitated its initial establishment and contributed to its current distribution pattern from the reduction in competition. However, the expansion of gorse is likely governed by a combination of interacting factors at Troopers Hill, with pH appearing to act as a permissive rather than deterministic control.

Particle Size (RQ1: Supporting soil controls):

Soil texture is determined mostly by parent material, in this case Pennant sandstone, and long-term weathering processes (Buurman et al., 1997) and therefore particle size was analysed to assess whether soil texture may explain gorse distribution on Troopers Hill.

Across sites, samples were largely dominated by silt material. However, a consistent difference was observed between sand content in established gorse cover (21-33%), and control sites (5-19%) (Figure 8B). While this does not represent a fundamental shift in overall soil type, it indicates a difference in the proportion of large particles between strata.

This difference is relevant because sandier soils are typically more free-draining. Larger particles create wider pore spaces, increasing hydraulic conductivity and allowing water to move more rapidly through the soil profile (Flores-Ramirez et al., 2018). This can increase nutrient loss through leaching, as coarse-textured soils are less able to retain dissolved nutrients due to their free-draining nature (Meng et al., 2022; Joshi et al., 2026). These nutrient-poor sandy soils would normally constrain plant growth. However, gorse is less dependent on soil nitrogen due to its nitrogen-fixing ability, meaning that gorse may be better able to tolerate these conditions and outcompete less adapted species.

Despite this, relationships between sand content and other variables, such as soil moisture (see Appendix A, Figure 2) and nutrient concentrations (see Appendix A, Figure 3), were weak, suggesting that soil texture is not a dominant control on soil conditions at the site. Low clay content across all samples further limits the soil's ability to retain water and buffer against leaching losses of nutrients (Weil & Brady, 2017). This provides a partial explanation for the weak and highly variable relationships observed between soil moisture and nutrients elsewhere in this study, where drainage and retention processes appear to be influenced by multiple interacting controls.

In relation to the research question, it therefore seems more likely that gorse has established preferentially in sandier areas, and soil texture may contribute to the distribution of where gorse establishes and thrives by influencing drainage and nutrient retention. However, these relationships are limited, and soil texture can be described as a secondary control acting within wider soil mechanisms.

Soil moisture and Organic Matter:

Gravimetric soil moisture measurements exhibited substantial variability across Troopers Hill, with no clear separation between gorse strata (Figure 9A), indicating that within-site variation exceeds between-group differences.

The high variability, alongside the lack of clear trends between gorse inundation and soil moisture, suggests that local environmental controls, such as topography or historical industrial disturbance, exert a stronger influence on soil moisture than gorse cover alone. This interpretation is consistent with studies of post-industrial landscapes, where heterogeneous substrates and disturbance histories can result in highly patchy soil conditions (Burghardt, 1994; Edmonson et al., 2012), in addition to being consistent with high levels of variation in soil moisture and organic matter identified in past research at Troopers Hill (Avon Project, 2024; Avon Project, 2025); the interquartile range of soil moisture values within the 2025 dataset was 39.37 in comparison to 44.31 in this study.

Further analysis revealed a clear positive relationship between soil moisture and organic matter (Figure 9B), illustrating the role of organic matter in enhancing water retention through increased porosity (Weil and Brady, 2017*).* This relationship supports the dataset's internal consistency, suggesting that observed variability reflects environmental conditions rather than methodological error. However, organic matter itself showed no consistent relationship and displayed similarly high variability across sites (Figure 10). This contrasts with expectations that nitrogen-fixing shrubs increase soil organic matter through litter inputs (Vitousek et al., 2002).

This may be explained by site-specific factors such as the enduring influence of historical industrial activity, including soil disturbance, contamination, and uneven organic inputs, which can persist independently of current vegetation patterns (Edmonson et al., 2012). Active management, including periodic cutting and removal of gorse biomass, is likely to remove litter inputs, and this mechanism may also explain the observed reduction in ammonium concentration in established gorse areas, as decreased organic matter impacts available nitrogen. Alternatively, dense gorse cover may suppress understory vegetation, reducing the quantity of organic inputs, further limiting soil organic matter accumulation.

It is important to consider methodological limitations associated with loss-on-ignition (LOI) analysis, which can overestimate organic matter content in soils with high clay fractions due to structural water loss from clay minerals (Hoogsteen et al., 2015). However, clay content across all samples at Troopers Hill was consistently low (< 5%; Figure 8), meaning this effect is likely minimal, and values reported here can be considered a reliable representation.

Despite the potential mechanism involved, the high variability within each vegetation category means these trends should be interpreted cautiously. Overall, the absence of consistent differences between vegetation types suggests that gorse is likely not a dominant control on soil moisture or organic matter at Troopers Hill. Instead, the results support the interpretation that the site functions as a highly heterogenous soil system, where small-scale variability overrides vegetation effects. This aligns with broader research highlighting the importance of historical land use and substrate variability in shaping soil properties in disturbed landscapes (Burghardt, 1994)

In relation to the research questions, these findings indicate that soil moisture and organic matter alone do not strongly determine gorse distribution and that gorse is likely tolerant of a wide range of conditions. Consequently, gorse expansion at Troopers Hill is more likely driven by competitive traits, including rapid growth, nitrogen fixation, and effective colonisation strategies, rather than specific soil constraints. Conversely, these findings provide no evidence that gorse is substantially modifying soil characteristics at Troopers Hill; instead, they reflect the influences of management and historical land use on the soil profile.

Nutrients (RQ2: Does gorse modify soil?):

Sites with established gorse cover (Sites 1 and 2) exhibited higher TON (Total Oxidisable Nitrogen) levels than early-stage gorse (Sites 3 and 4) (Figure 11A), with a statistically significant difference between stages of gorse growth (Table 2). This pattern aligns with previous work indicating that mature gorse stands are associated with greater nitrate accumulation due to increased litter inputs and longer-term nitrogen fixation (Egunjobi, 1971; Magesan et al., 2012). As a nitrogen-fixing species, gorse is expected to enhance soil nitrogen availability through symbiotic associations with rhizobia, increasing ammonium inputs through organic matter additions which are subsequently converted to nitrate via nitrification.

However, this expected pattern is not sustained when comparing gorse-covered sites to controls. No statistically significant differences in TON were observed between gorse-covered sites and control sites (Sites 5 and 6) and notably, the heathland control (Site 5) exhibited the highest TON values. This contradicts much of the literature, which typically reports elevated nitrogen availability under nitrogen-fixing shrubs (Magesan et al., 2012; Ortiz and Wolf, 2024) and so suggests that gorse is not exerting a dominant control on nitrogen dynamics at Troopers Hill. Instead, nitrogen availability appears to be influenced by a broader set of environmental controls that override vegetation-driven effects.

Comparison with previous Avon Project datasets further supports this interpretation, as TON values in gorse-dominated areas are not higher than those recorded in other non-gorse areas of Troopers Hill (Figure 14). This consistency across datasets strengthens the conclusion that gorse is not the primary determinant of nitrogen availability of Troopers Hill. However, the comparability between datasets is constrained given the dynamic nature of nutrient cycling and the exceptionally high rainfall preceding sampling. Nitrate is highly mobile in soils, and elevated precipitation can enhance nitrate leaching, potentially reducing measured concentrations (Sahrawat, 2008). As a result, absolute values should be interpreted cautiously, although relative comparisons between sites remain valid.

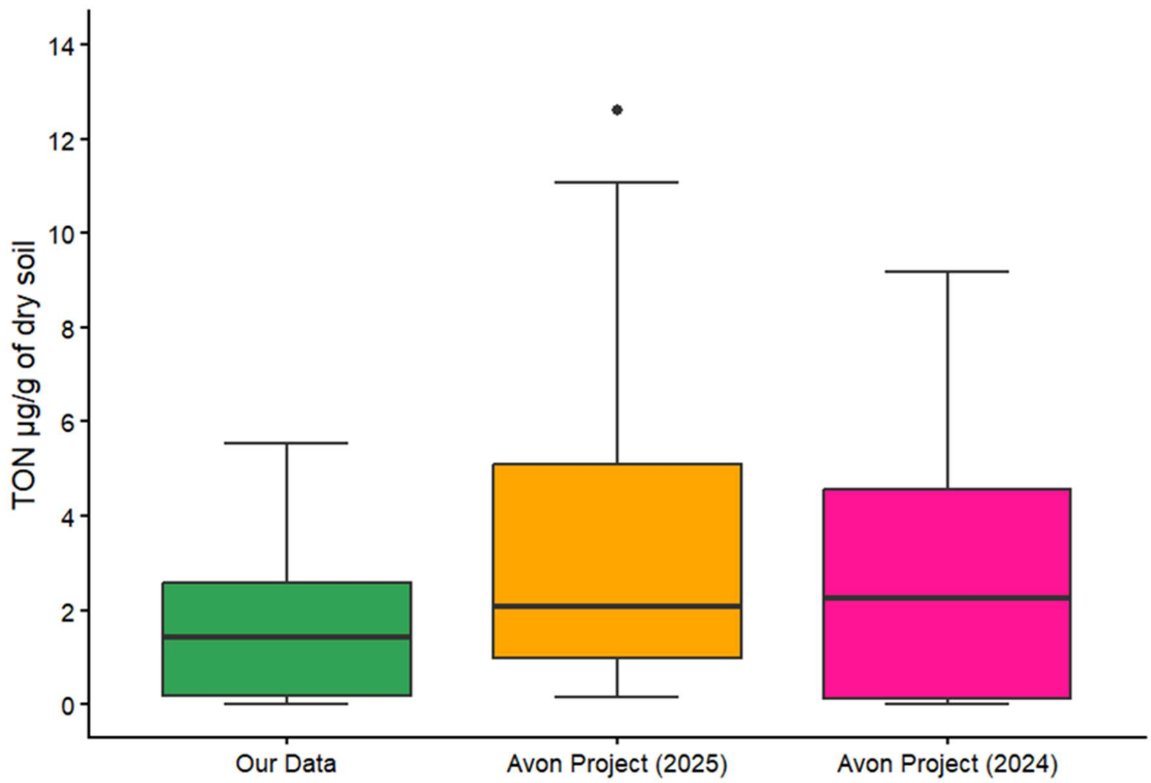

Figure 14: Boxplot comparing soil TON from our gorse sites and other Avon Project data from 2025 and 2024 collected from other, non-gorse-covered, areas of Troopers Hill (5 samples removed from Avon Project 2024 that were taken from the gorse covered part of Troopers Hill) (Avon Project, 2024; Avon Project, 2025).

Further insight into nitrogen cycling is provided by the lack of a significant relationship between TON and ammonium (Appendix A Figure 1), which contrasts expectations of a coupled system linked through nitrification. The highly acidic soils at Troopers Hill (pH 4.04-5.11) provide a plausible explanation for this, as low pH is known to suppress the activity of rhizobia (Yao et al., 2011; Sahrawat, 2008). This suggests that soil chemistry may constrain nitrogen cycling, limiting the conversion of ammonium to nitrate regardless of gorse presence.

In contrast to TON, ammonium concentrations were lower in established gorse sites compared to early-stage gorse sites (Figure 11B), although this pattern was influenced by high within-site variability. This again is inconsistent with research suggesting that mature gorse stands, through greater production of nitrogen-rich litter, would increase ammonium availability through ammonification (Egunjobi, 1971; Magesan et al., 2012). However, no clear trend in ammonium concentrations was observed between sites, reinforcing the conclusion that gorse does not exert a strong or consistent influence on soil nitrogen pools at this site. Instead, the high variability seen in both the ammonium and TON data, as well as the previous Avon Projects (Figures 14 & 15), supports the interpretation that soil properties at Troopers Hill are governed by multiple interacting controls rather than vegetation alone.

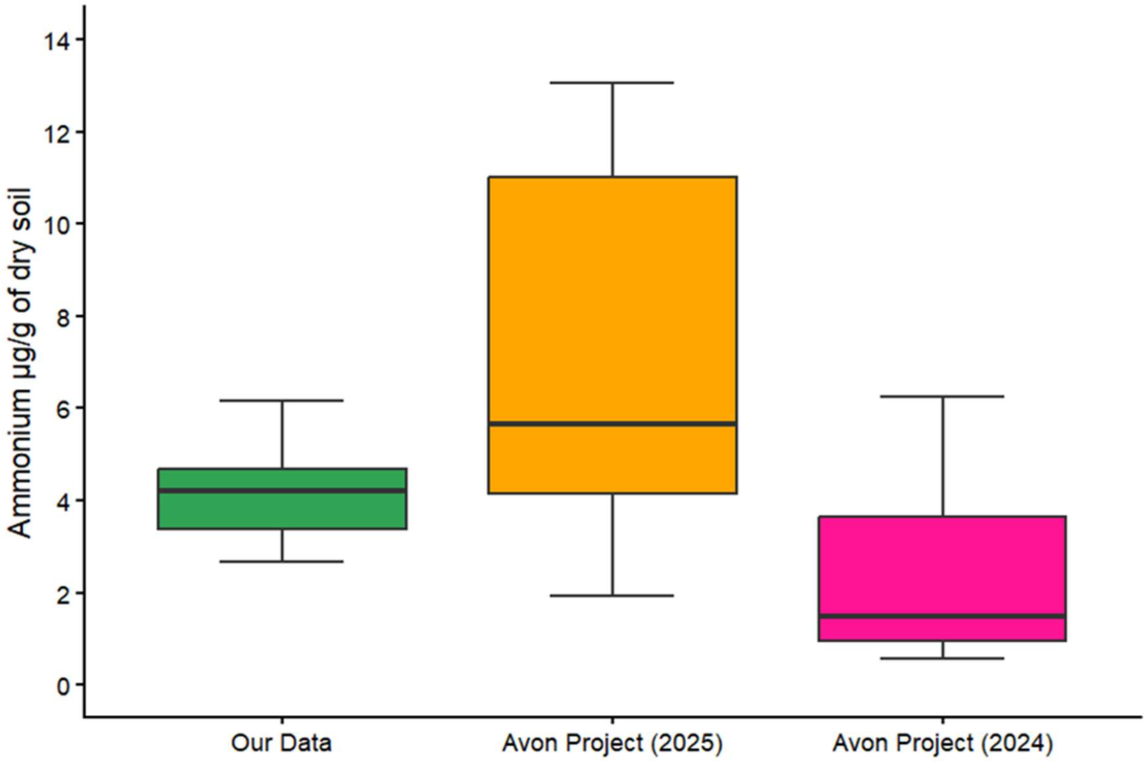

Figure 15: Boxplot comparing soil ammonium from our gorse sites and other Avon Project data from 2025 and 2024 collected from other, non-gorse-covered, areas of Troopers Hill (5 samples removed from Avon Project 2024 that were taken from the gorse covered part of Troopers Hill) (Avon Project, 2024; Avon Project, 2025).

A strong positive correlation, observed between ammonium and organic matter (Figure 12), supports established mechanisms of ammonification, whereby microbial decomposition of organic matter releases ammonium (Schimel and Schaeffer, 2012). This indicates that ammonium availability is more closely linked to organic matter content than gorse presence. Notably, neither ammonium nor organic matter displayed clear trends with gorse cover, suggesting that factors such as substrate composition, topography and historical disturbance are more influential controls. Beighton (2013) similarly identified strong spatial variability in soil chemistry at Troopers Hill, linked to localised contamination and redistribution processes associated with its industrial history, reinforcing the interpretation that nutrient dynamics are governed by site heterogeneity rather than vegetation alone.

The role of the current management scheme at Troopers Hill is potentially influential; periodic removal of gorse is likely to reduce litter inputs and disrupt nutrient accumulation, potentially constraining nutrient cycling (Wardle, 2004). The impacts of management are uncertain and difficult to quantify and, given the lack of research into post-industrial urban managed gorse landscapes, are poorly understood in wider research. But while these impacts of management may be somewhat intangible, they represent a potentially important mechanism through which vegetation-soil relations may be weakened or obscured in managed urban systems.

Phosphate concentrations showed no consistent relationship with gorse cover, with the highest values recorded at the heathland control site (Table 3). This reflects the fundamental differences between nitrogen and phosphorus cycling. While nitrogen is largely biologically regulated, phosphorus availability is primarily driven by geochemical processes, including sorption to mineral surfaces and interactions with soil pH (Vitousek et al., 2002; Penn and Camberato, 2019). In acidic soils such as those at Troopers Hill, phosphate is strongly absorbed into iron and aluminium oxides, limiting its availability to plants. As a result, phosphorus dynamics are less responsive to vegetation change and are unlikely to be significantly altered by gorse encroachment alone.

Phosphate concentrations in this study were higher than those reported in previous Avon Project datasets (mean = 2.79 µg/g compared to 1.09 in 2024 and 0.54 in 2025) (Figure 16), although values remain consistent with ranges reported for UK soils in large-scale surveys (Henrys et al., 2012). However, extremely high variability within sites, with large ranges (Site 1 range = 5.52 µg/g, almost twice the mean, 2.86 µg/g), indicates strong variability. This likely reflects the legacy of industrial activity at Troopers Hill, including mining and smelting, which may have introduced phosphorus and the metals it sorbs to, into the soil, contributing to its uneven distribution across the site. Unlike nitrogen, phosphate is less susceptible to leaching due to strong sorption, meaning that elevated concentrations may persist as a legacy of historical inputs rather than reflecting contemporary ecological processes.

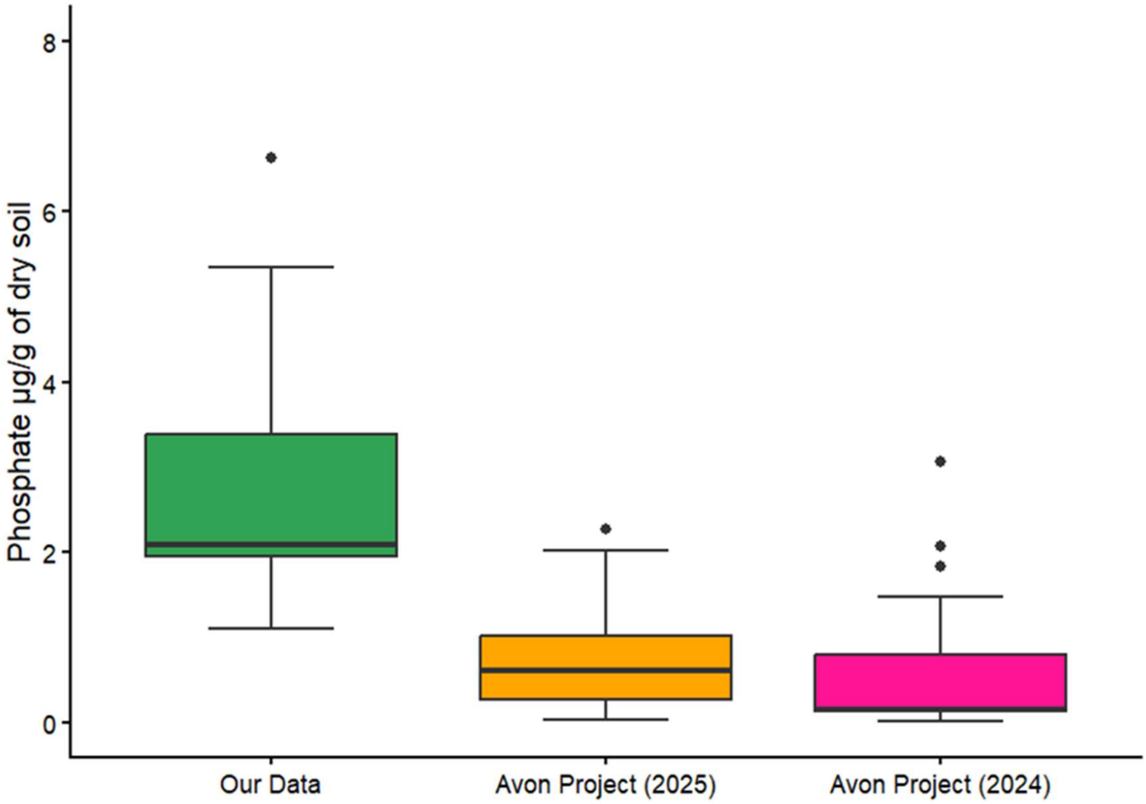

Figure 16: Boxplot comparing soil phosphate from our gorse sites and other Avon Project data from 2025 and 2024 collected from other, non-gorse covered, areas of Troopers Hill (5 samples removed from Avon Project 2024 that were taken from the gorse covered part of Troopers Hill) (Avon Project, 2024; Avon Project, 2025).

Across all nutrients analysed, there is limited evidence that gorse encroachment is exerting a dominant influence on the soil profile at Troopers Hill. While some differences are observed between stages of gorse development, these are inconsistent and frequently overshadowed by high within-site variability. Instead, the results highlight the importance of soil chemistry, environmental conditions, and the site's complex disturbance history in shaping nutrient dynamics.

Overall, these findings suggest that Troopers Hill functions as a highly heterogeneous soil system in which vegetation effects are secondary to other environmental factors. Gorse appears to be tolerant of a wide range of soil conditions rather than actively transforming them in a consistent manner, suggesting that its continued expansion likely reflects the broader adaptive strategies of Ilex europaeus such as its stress tolerance and seed production (Kato-Noguchi and Kato, 2025) rather than strong plant-soil feedback mechanisms.

The implications and limitations of this Study for Troopers Hill

Across all variables, there is limited evidence to suggest that gorse is a dominant driver of soil change at Troopers Hill. Instead, soil properties, particularly pH and texture, appear to influence where gorse establishes, while gorse itself has minimal and inconsistent effects on soil characteristics. This suggests that gorse is primarily responding to pre-existing environmental conditions rather than actively transforming them. This contrasts with much of the existing literature, which often reports strong vegetation-driven soil modification, and so highlights the importance of environmental context when applying research to urban and post-industrial heathlands. In a site such as Troopers Hill, legacy effects of disturbance, including at least one significant fire in 1995, geological and topographic variation appear to override the impacts of gorse and vegetation-soil feedback mechanisms, contributing to the high spatial variability observed across the dataset.

However, several limitations must be considered. The relatively small sample size and stratified sampling design may influence the strength of observed relationships; however, the number of samples (n = 30; 5 replicates across 6 sites) remains sufficient for non-parametric statistical analysis and detection of patterns between vegetation types, particularly given the strong effect sizes observed in some relationships (e.g. ammonium-organic matter, $\rho = 0.953$). However, the high within-site variability increases the likelihood of type 2 errors, i.e., failing to detect some weak relationships. The reliance on a single sampling period represents a more substantial limitation, particularly for nutrient data, which is known to respond to short-term weather changes as well as seasonal fluctuations. The exceptionally high rainfall preceding sampling may have enhanced nitrate leaching, potentially reducing observed TON concentrations. As a result, nutrient values should be interpreted cautiously, although, as all samples were collected under the same conditions, the lack of consistent relationships cannot be attributed solely to short-term weather effects.

Despite these constraints, several factors support the robustness of the dataset. Firstly, strong internal relationships between variables, particularly between organic matter and soil moisture, indicate that measurements reflect real environmental processes rather than errors in methodology. Second, consistency with previous Avon project datasets and Beighton (2013), particularly in terms of soil acidity and spatial variability, suggests that observed variability is characteristic of the site. These limitations do not undermine the central conclusion of this study, that gorse is not a dominant driver of soil change at Troopers Hill, as this interpretation is supported by consistently high within-group variability and a lack of statistical differences between vegetation types across multiple variables.

Troopers Hill is a difficult site to disentangle exactly because of its unique history and situation. Future research could incorporate repeated sampling across seasons and within the identified strata in order to better distinguish between the impacts of gorse and site heterogeneity. Additionally, greater spatial coverage and additional variables such as microbial activity, topography or metal concentrations could be explored to better understand the mechanisms driving soil variability and gorse expansion. Most importantly, repeated sampling at further dates would allow identification of changes possibly linked to gorse or other factors on the site, which cannot be captured within a single day of sampling. Adding a temporal dimension to the investigation would therefore increase the robustness of the findings on the consequences of gorse for soil properties at the site.

From a management perspective, as the soil profile at Troopers Hill is not homogenous, management efforts should not assume uniform spread of gorse across the site but, due to the competitive and prolific nature of gorse, should expect continued expansion. Sustained management is likely to be required to limit further expansion into vulnerable heathland areas.

Conclusion

This study demonstrates that, at Troopers Hill, soil characteristics, particularly acidity and drainage, play a greater role in influencing the distribution of *Ulex europaeus* than gorse itself does in modifying soil properties. This challenges assumptions within wider literature that nitrogen-fixing shrubs consistently act as dominant drivers of soil change and instead highlights the importance of spatial heterogeneity and historical disturbance in urban heathland systems. Based on these findings, gorse expansion is likely to continue across Troopers Hill, indicating that ongoing monitoring and targeted management may be necessary to limit further spread into vulnerable heathland areas. While this study identifies key soil-vegetation relationships, further research incorporating temporal sampling and additional variables is needed to better understand the mechanisms driving gorse expansion at Troopers Hill and inform long-term management strategies.