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# Pollution Legacy and Land Use Influence Peat Chemistry in Temperate Lowland Peatlands

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**Key Points:**

- Drained grassland sites had lower organic matter content compared to semi-natural sites
- Peatland cores near historic industrial centers had metal enrichment
- Agricultural land use was also linked to metal concentrations

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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## Abstract

Peatlands slowly accumulate carbon and other elements over time, making them excellent archives of historical environmental conditions. A large proportion of low-lying peat has been drained and converted to agricultural cropland or grassland use. Peatlands in some areas are also impacted by atmospheric deposition of metals from past industrial activities. We analyzed a suite of chemical elements in 13 peat cores from lowland peatlands across England with contrasting management histories, to assess the effects of these historic and recent human activities. The effects of peatland drainage were observed on organic matter content, which was significantly higher at semi-natural sites compared to drained, grassland sites. We found peaks in metal concentrations (copper, lead, mercury and zinc) at bog sites in north-east England, <50 km from a major hub of manufacturing during the industrial revolution. Arable and grassland sites had higher copper and phosphorous concentrations compared with semi-natural sites, likely attributed to agricultural amendments such as fertilizers. Away from historic industrial sources, metal concentrations were generally below safe limits for soils. We demonstrate the impacts that humans have on lowland peat, providing insights to help inform rewetting and other restoration strategies.

## Plain Language Summary

Peatlands store carbon and other elements, making them excellent archives of past environmental conditions. In England, many peatlands have been drained for agriculture and some have also been affected by pollution from industrial activities. To understand how these human activities impact peatlands, we analyzed chemical elements in 13 peat cores from peatlands across England with differing land uses. We found that drainage reduced organic matter content and peat cores near historic industrial centers had high metal concentrations. While peat cores further from these areas had metal concentrations generally below safe limits. Our study demonstrates the effects of humans on peatlands and can help inform rewetting strategies.

## 1. Introduction

Peatlands are major stores of carbon, containing at least 25% of the global soil carbon stock (Yu et al., 2010). This large accumulation of carbon in peatlands is due to water-saturated conditions, which constrain decomposition rates, allowing plant-derived organic matter to build up faster than it breaks down (Loisel et al., 2021). Beyond carbon, peatlands also accumulate a variety of other elements, including nutrients and metals. Certain elements cycle within the peat profile, while others remain relatively immobile (Novak et al., 2011). This accumulation creates distinct layered signatures over time (peat stratigraphy), producing an archive of past environmental conditions (De Vleeschouwer et al., 2010). This stratigraphy can be disturbed by human activities, including drainage and agriculture, altering these historic records.

Both peatland drainage and subsequent land use for agriculture can have impacts on peat chemistry. Peatlands are drained for agriculture as they have high organic matter content and high water-holding capacity relative to mineral soils. Drainage can accelerate decomposition rates, resulting in high carbon losses (Evans et al., 2017; IPCC, 2014). Although drained peat soils are often naturally rich in nitrogen (N), which is released as mineral N when the peat decomposes, they can be poorer in phosphorous (P) and potassium (K), resulting in the need for fertilizer additions or other amendments (Lockhart & Wiseman, 2023). Acid bog peats may also require application of lime to raise the soil pH to levels suitable for crop production (Indriyati, 2017). Excess nutrients and

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other solutes present in agricultural amendments can leach into adjacent surface waters, prompting eutrophication and other water quality concerns (Pham et al., 2023). With repeated use, agricultural inputs may lead to an accumulation of metals (Mantovi et al., 2003). Excessive use of amendments as well as irrigation can also lead to soil salinization (Corwin, 2021). Where elements contained in agricultural amendments are retained within the peat, they will be present in the peat profiles.

In addition to impacts from agricultural land use, regional industrial activity can leave lasting impacts on peat chemistry. Metal enrichment in surface peat may be due to atmospheric deposition from industrial activities such as coal combustion and metal smelting, as well as vehicle emissions (Cloy et al., 2011; C. Osborne et al., 2024). Due to the unique waterlogged and organic matter-rich conditions of peatlands, in their intact state, they are effective at retaining and immobilizing these heavy metals (Apori et al., 2024). Bogs in particular are excellent records of urban and industrial pollution due to their reliance on atmospheric inputs (Brännvall et al., 1997; Shotyk, 1996), whereas fens may also receive pollutant inputs via surface water or groundwater. At low levels, some metals serve as key enzyme cofactors, allowing for important microbial processes such as decomposition (Andreini et al., 2008). However, at high concentrations, metals can be toxic to plants and microbes, decreasing their abundance and productivity (Lenart-Boroń & Boroń, 2014; Nagajyoti et al., 2010). Historically, England's extensive industrialization, especially during the 19th and 20th centuries, contributed to atmospheric deposition of metals (Garcés-Pastor et al., 2023).

Peatlands are important ecosystems in the United Kingdom (UK)—covering about 12% of the total land area (Artz et al., 2019). Peatlands in low-lying areas cover a small proportion of this total peat area (∼15%) but have been disproportionately affected by land use pressures (JNCC, 2011). It is estimated that about 90% of UK lowland peat has been drained for agriculture (Evans et al., 2017). This drainage enhances carbon losses and peat subsidence, creating hotspots of carbon dioxide emissions from the UK land-use sector, and threatening long-term agricultural production. As a result, peatland re-wetting and restoration now form an integral component of UK's climate change mitigation strategy (Climate Change Committee, 2025). However, concerns have been raised that re-wetting of agriculturally drained peatlands could lead to the mobilization of stored contaminants, potentially impacting downstream water quality, ecosystem functioning, and human health (Apori et al., 2024). Improved understanding of the presence and distribution of contaminants within peat profiles is therefore needed in order to develop effective and sustainable peatland restoration strategies.

In this study, we investigated whether and how regional industrial pollution and local land use have altered peat chemistry. Here, we took a broad spatial approach across multiple sites and focus on comparing peat chemistry. By analyzing peat cores from different regions across England with contrasting management histories, we aimed to assess the effects of both past and present human activities, and whether this has resulted in a pollution legacy.

## 2. Methods

### 2.1. Field Collection

Peat cores were collected from 13 different lowland peatland sites, covering a range of land uses: arable, grassland, semi-natural, and rewetted (Table 1, Figure 1). Sampled sites included both bogs (ombrotrophic peatlands that receive water and nutrients almost exclusively from atmospheric deposition) and fens (minerotrophic peatlands fed by groundwater or surface water higher in dissolved ions and nutrients) (Bleuten et al., 2006). The peatland type was confirmed by the Lowland Peat Soil Survey of England and Wales (In Burton & Hodgson, 1987) and the Landis Soilscapes data set (Cranfield University, 2025). While the semi-natural sites represented relatively intact peat records, the other sites underwent varying degrees of modification, notably through drainage and (in some cases) tillage, thereby altering the peat stratigraphy. For the arable sites, the cropping type at Rosedene Farm and Wright's Farm is primarily horticulture (lettuces), while Little Common Farm and Roughs Farm grow mostly cereals.

According to some definitions of peat, for example, >30% organic material to a depth of 30 cm (Joosten & Clarke, 2002), the Wicken Baker's Fen and Rough's Farm sites would not be considered true peatlands. These sites form part of the extensive area of former thick peat in the lowlands of southeastern England that has been heavily depleted by oxidation following several centuries of agricultural drainage (Evans et al., 2017). These soils are often described as “wasted peat” in England (JNCC, 2011) or “peaty soils” in Germany, Denmark and the Netherlands, where they are also widespread (Beucher et al., 2023; Tanneberger et al., 2022). Wasted peat soils

**Table 1**
*Site Names, Locations, and Details of the Lowland Peatlands Sampled in This Study*

| Site | Region | Latitude, longitude | Peat type | Peat thickness (cm) | Land use |
|---|---|---|---|---|---|
| Little Common Farm (LC) | East Anglia | 52.4435, −0.24636 | Fen | 30 | Arable |
| Rosedene Farm (RG) | East Anglia | 52.52686, 0.477278 | Fen | >100 | Arable |
| Wright's Farm (WF) | Lancashire | 53.67711, −2.88331 | Bog | 50 | Arable |
| Roughs Farm/Sawtry Fen (SW) | East Anglia | 52.43628, −0.25922 | Fen | 37[b] | Arable |
| Middle Farm (MF) | East Anglia | 52.44883, −0.20417 | Fen | >100 | Grassland |
| Moss Side (MS) | Manchester | 53.46132, −2.45058 | Bog | >100 | Grassland |
| New Decoy (ND) | East Anglia | 52.47381, −0.20019 | Fen | 90 | Grassland |
| Railway View (RV) | Manchester | 53.46342, −2.44975 | Bog | >100[a] | Grassland |
| Wicken Baker's Fen (WBF) | East Anglia | 52.30522, 0.293667 | Fen | 40[c] | Grassland |
| Delamere Forest (DEL) | Cheshire | 53.23589, −2.68193 | Bog | >100 | Rewetted bog |
| Wicken Sedge Fen (WSF) | East Anglia | 52.31011, 0.289194 | Fen | 60 | Semi-natural fen |
| Woodwalton Fen (WW) | East Anglia | 52.44806, −0.18644 | Fen | 116[b] | Semi-natural fen |
| Holme Fen (HF) | East Anglia | 52.48564, −0.23736 | Bog | 60 | Semi-natural bog |

*Note.* Peat thickness was estimated from our peat cores or the literature. Our sampling location at Holme Fen is classified as bog peat (as is the majority of this site) according to the Lowland Peat Soil Survey of England and Wales (In Burton & Hodgson, 1987) and Landis Soilscapes data set (Cranfield University, 2025). However, the high Ca:Mg molar ratio (>>1) is indicative of fen peat, suggesting some groundwater influence (Figure S29 in Supporting Information S1). [a]Evans et al., 2016. [b]Evans et al., 2023. [c]Peacock et al., 2019.

retain a higher topsoil carbon content than true mineral soils within the same regions, continuing to act as carbon dioxide emission sources (D'Acunha et al., 2026; Tiemeyer et al., 2016) and are therefore expected to exhibit biogeochemical behaviors distinct from those of mineral soils. Given their large extent within some English lowland peat areas, comprising two thirds of UK's cropland on peat (Evans et al., 2017), wasted peat soils are an important component of the peatland management continuum examined in this study.

Cores were taken in October and November 2024 by hand using a 0.5 m or 1.0 m Russian corer to a total depth of 28–100 cm (see Figures S1–S13 in Supporting Information S1 for photos of each core). At some locations, the depth of coring was constrained by physical limitations of the coring process, due to factors such as soil compaction and shallow organic horizons. After extraction, the peat cores were wrapped in cling film to prevent moisture loss. To ensure their integrity during transportation, the cores were placed in a rigid plastic drainpipe and kept horizontal. Peat cores were transported to the Roxby Laboratories in the Department of Geography & Planning, University of Liverpool, and kept in cold storage (4°C) before being processed in late November 2024.

## 2.2. Laboratory Analysis

In the laboratory, we sliced the cores at 1-cm intervals (Figure S14 in Supporting Information S1). For analysis, we used samples at 2 cm resolution after the top 20 cm—which was sampled at 1 cm contiguous resolution—to have a representative but manageable number of samples ($n = 639$). Each sample was divided into two roughly equal sub-samples, one of which was freeze-dried for analysis by X-ray fluorescence (XRF) and the other analyzed for loss-on-ignition (LOI).

To estimate LOI, each sample was weighed before being oven dried at 105°C for 24 hr and weighed to estimate initial mass and moisture content. The sample was then combusted at 450°C for 4 hr and weighed to determine the organic matter content (Chambers et al., 2011). Variations in organic matter content can influence the reliability of XRF analysis on peat soils (Longman et al., 2019); therefore, LOI values were used to correct the XRF outputs via the internal device software.

Samples were freeze-dried, hand-ground and compressed—the samples were sufficiently homogenous not to require mechanical grinding. The samples were analyzed for 50 chemical elements via XRF using a SPECTRO XEPOS 3 ED-XRF analyzer (Ametek, Kleve, Germany) at the University of Liverpool Roxby Laboratories. The XRF analyzer converts count rates of secondary x-rays into element concentrations (Boyle, 2000). For quality

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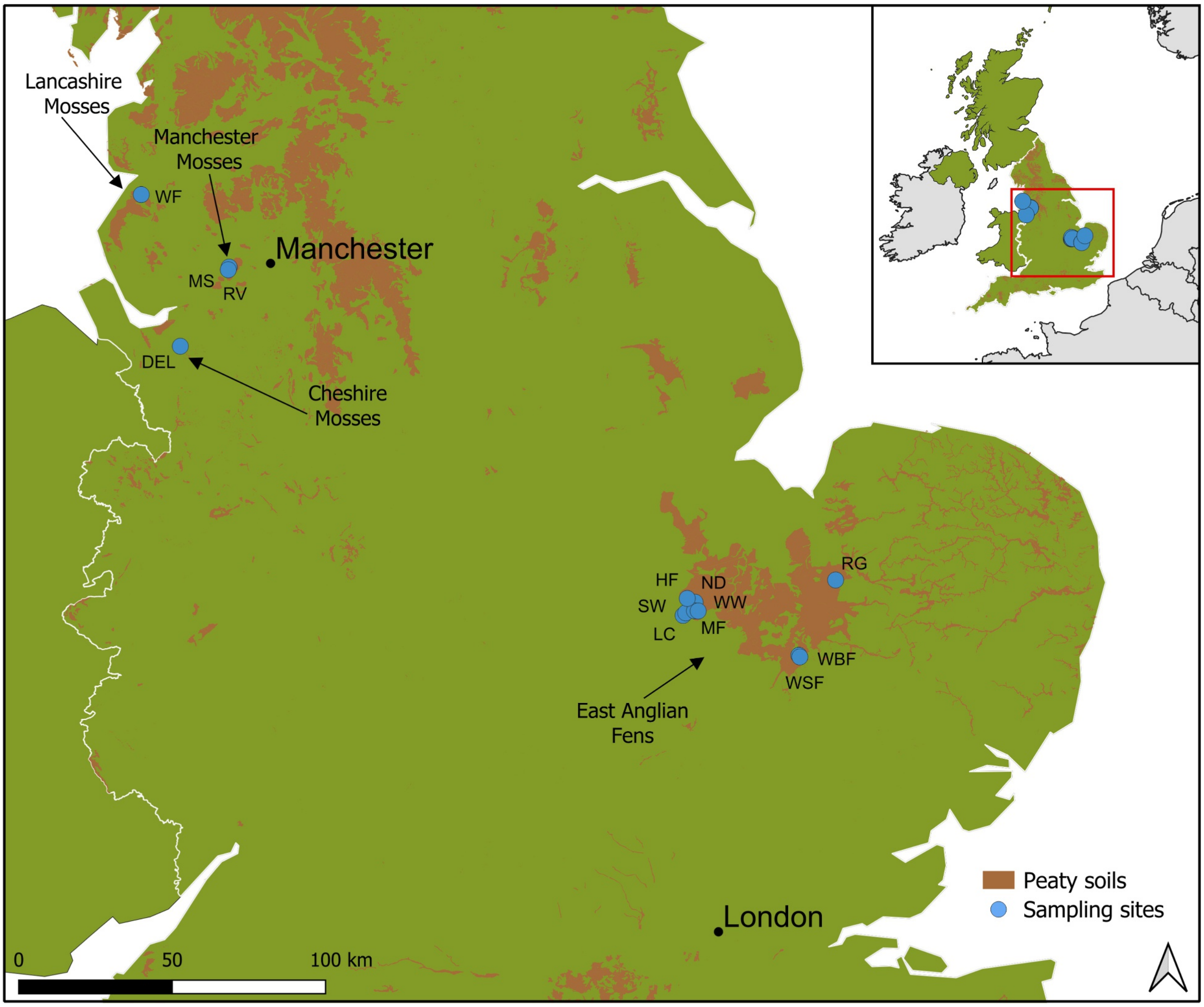


**Figure 1.** Peat core sampling locations with their site codes. In the north-west (Lancashire, Manchester and Chesire Mosses): WF, Wright's Farm; MS, Moss Side Farm; RV, Railway View; DEL, Delamere Forest; in the south-east (East Anglian Fens): HF, Holme Fen; SW, Roughs Farm; LC, Little Common Farm; ND, New Decoy; WW, Woodwalton Fen; MF, Middle Farm; WSF, Wicken Sedge Fen; WBF, Wicken Baker's Fen; RG, Rosedene Farm. England peaty soil extent from Natural England (2025). Inset map shows the UK with a red box outlining the main map extent.

control, the XRF undergoes regular standardization procedures and has accuracies verified using eight certified reference standards. For mercury (Hg), all reference materials were below the detection limit, but for concentrations above 1 μg $g^{-1}$, we expect Hg concentrations to be accurate and precise. Of the elements, 7 key elements were selected for interpretation, including those that are known indicators for industrial pollution: copper (Cu), iron (Fe), lead (Pb), mercury (Hg), zinc (Zn); and agricultural amendments: phosphorous (P) and potassium (K). We also present and discuss the ratio of metals from industrial sources (Cu, Pb, and Zn) to the lithogenic metal rubidium (Rb) (Shotyk, 1996), as a marker of industrially derived pollution.

### 2.3. Statistical Analysis

We used the programming software *R* (version 4.5.0) to make all the figures and conduct all analyses (R Core Team, 2025). We used linear mixed effects models (LMMs) to evaluate the effect of land use on peat chemistry, with site as a random intercept to account for the non-independence of samples. Models were fitted for each response variable using *lmer* function from the "lme4" *R* package (Bates et al., 2015), and *p*-values for fixed effects were obtained using the "lmerTest" *R* package. Because each peatland type was not represented within each land use, we were unable to test the interactive effect of peat type and land use. For LOI, which is a proportional variable (0%–100%) and therefore violates assumptions of LMMs, we fitted a beta generalized linear mixed-effects model

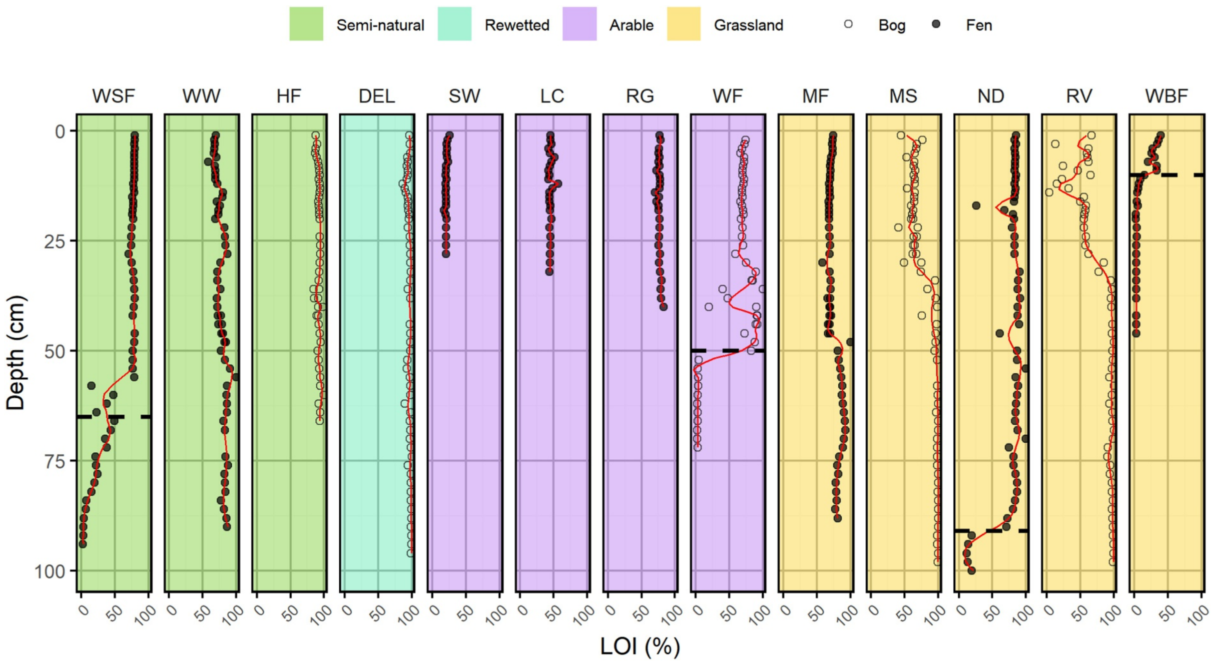


**Figure 2.** Peat core depth profiles of loss-on-ignition (%). The dashed horizontal line on some cores indicates the organo-mineral soil transition. Site codes are as follows: DEL, Delamere Forest; WSF, Wicken Sedge Fen; WW, Woodwalton Fen; HF, Holme Fen, SW, Roughs Farm; LC, Little Common Farm; RG, Rosedene Farm; WF, Wright's Farm; MF, Middle Farm; MS, Moss Side Farm; ND, New Decoy; RV, Railway View; WBF, Wicken Baker's Fen.

(beta GLMM) using *glmmTMB* from the "glmmTMB" package (Brooks et al., 2017). Spearman ($R_S$) correlations were used to test for monotonic relationships between variables, displayed as a correlation matrix using the corrplot package (Wei & Simko, 2024). To account for multiple comparisons in the correlation matrix, *p*-values were adjusted using a Bonferroni correction. We used a principal components analysis (PCA) on scaled and centered variables to visualize differences and similarities between sites. For the PCA, we kept the first two principal components, based on a visual inspection of the scree plot using the broken-stick method (Figure S15 in Supporting Information S1), which together explained 89% of the variance in the data. Down-profile concentrations are presented graphically with a Locally Estimated Scatterplot Smoothing (LOESS) smoothing function (degree of smoothing = 0.15). The horizontal line on certain cores approximates the transition from organic to mineral soils as indicated by visual observation of the core and organic matter content. Peat profile figures are organized by element; for figures by site, see (Figures S16–S28 in Supporting Information S1).

## 3. Results

### 3.1. Loss-On-Ignition (LOI)

Loss-on-ignition (LOI; %), a proxy for organic matter content, was highest (in the top 30 cm) on average at the rewetted site (95% ± 3; mean ± SD), followed by the semi-natural (81% ± 9), grassland (56% ± 25), and arable sites (53% ± 22) (Figure 2). A beta GLMM showed that LOI differed among land use types, with significantly lower values at grassland sites compared to semi-natural sites ($\beta = -1.3$, SE = 0.71, $p = 0.047$). LOI at arable and rewetted sites did not significantly differ from semi-natural sites.

### 3.2. Metals

The sum of (relatively immobile) metals (Cu, Pb, Hg, and Zn) showed notable peaks in surface peat at the bog sites Delamere Forest, Railway View, and Moss Side Farm in north-west England (Figure 3), with much lower concentrations at the remaining sites. These metal concentrations were all significantly positively related to each other (Spearman correlations in Figure S30 of Supporting Information S1). Land use had a significant effect on Cu and Fe concentrations according to our LMMs but not on the other metals (Table S1 in Supporting Information S1). The patterns of the individual metals are discussed in the subsequent sections.

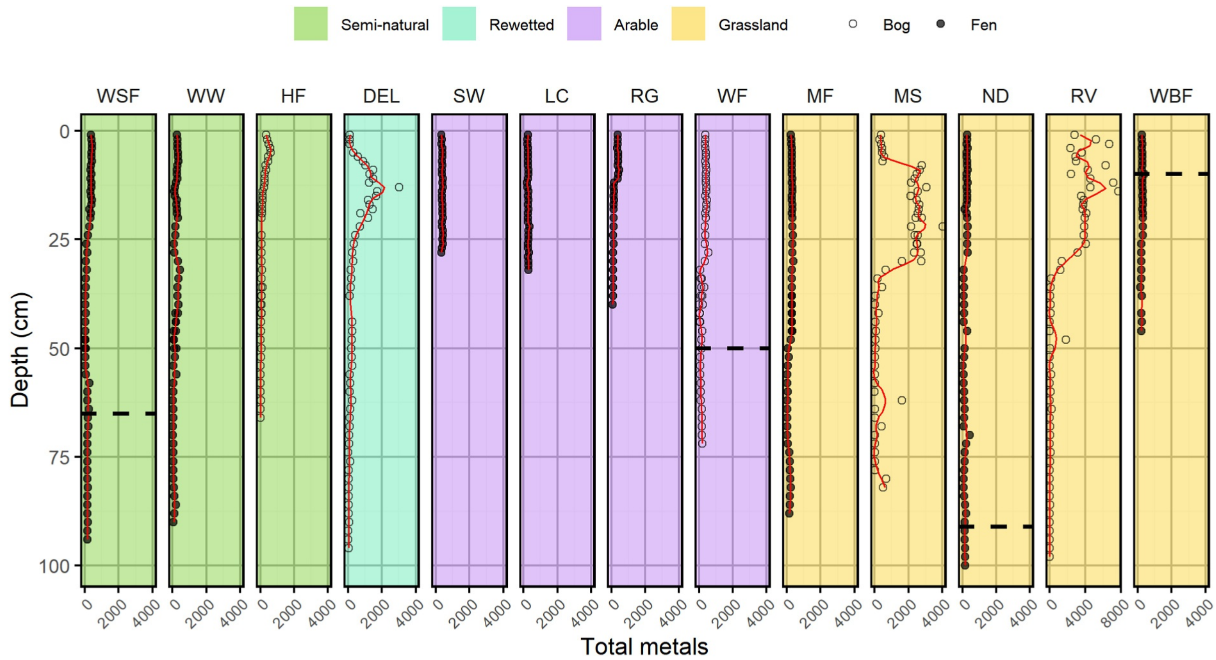


**Figure 3.** Peat core depth profiles of the sum of copper (Cu), mercury (Hg), lead (Pb), and zinc (Zn) concentrations (μg $g^{-1}$). The dashed horizontal line on some cores indicates the organo-mineral soil transition. Site codes are as follows: DEL, Delamere Forest; WSF, Wicken Sedge Fen; WW, Woodwalton Fen; HF, Holme Fen; SW, Roughs Farm, LC, Little Common Farm; RG, Rosedene Farm; WF, Wright's Farm; MF, Middle Farm; MS, Moss Side Farm; ND, New Decoy; RV, Railway View; WBF, Wicken Baker's Fen. Note that RV has a scale of 0–8,000.

#### 3.2.1. Copper (Cu)

Land use had a significant effect on Cu concentrations according to our LMM ($p = 0.02$; Table S1 in Supporting Information S1), with significantly higher values at arable ($\beta = 0.79$; $p = 0.01$) and grassland ($\beta = 0.80$, $p = 0.008$) sites compared to semi-natural sites. The two Manchester Mosses sites (Moss Side Farm, Railway View) and Delamere Forest site had consistent large peaks in Cu (~300–1,000 μg $g^{-1}$) concentrations in the top 30 cm of peat (Figure S31 in Supporting Information S1). Elevated Cu (albeit at lower concentrations: ~200 μg $g^{-1}$) was observed in the top 15 cm in the southeastern England sites Holme Fen (semi-natural) and Rosedene Farm (arable). The ratio of Cu to Rb (indicative of atmospheric vs. lithogenic sources) was consistent with these results, showing elevated Cu:Rb at Moss Side Farm, Railway View, and Delamere Forest (Figure S32 in Supporting Information S1).

#### 3.2.2. Iron (Fe)

Land use had a significant effect on Fe concentrations according to our LMM ($p = 0.03$; Table S1 in Supporting Information S1), with significantly lower values at the rewetted site compared to semi-natural sites ($\beta = -1.82$; $p = 0.04$). The Manchester Mosses sites had peaks in Fe concentrations (~75–150 mg $g^{-1}$) in surface layers (Figure S33 in Supporting Information S1). Wright's Farm (arable), Wicken Sedge Fen (semi-natural), New Decoy (grassland) sites all showed slightly elevated concentrations (50–75 mg $g^{-1}$) but only in deeper layers (30 cm+). Indeed, the Wright's Farm core had a visible orange band at the organic-mineral transition at this depth (Figure S3 in Supporting Information S1), while the ND core also featured a transition to denser, mineral soil with an orange color at depth (Figure S9 in Supporting Information S1). In addition, slightly elevated Fe concentrations in the peat profile (~55 mg $g^{-1}$ at ~25 cm) were observed at the grassland site Wicken Baker's Fen. Although down-core patterns of Fe generally followed Hg ($R_S = 0.39$), Pb ($R_S = 0.42$) and Cu ($R_S = 0.56$), they marginally diverged in some cases. For example, at Delamere Forest (rewetted bog), Fe peaked earlier (6–9 cm) compared to Cu (13 cm). Likewise, at Holme Fen (semi-natural) Fe was already elevated at the surface, while Cu did not peak until 5 cm. At New Decoy, Wicken Sedge Fen, and Wright's Farm, surface Fe was not elevated as seen for the other metals at those sites.

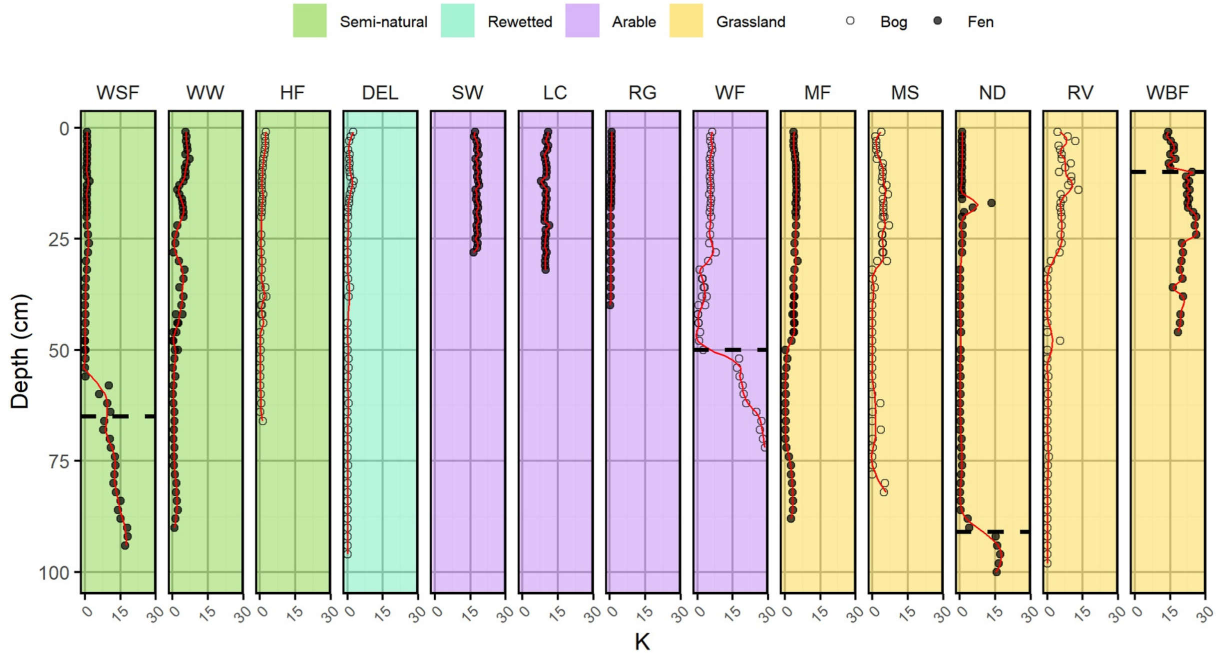


**Figure 4.** Peat core depth profiles of potassium (K) concentrations (mg $g^{-1}$). The dashed horizontal line on some cores indicates the organo-mineral soil transition. Site codes are as follows: DEL, Delamere Forest; WSF, Wicken Sedge Fen; WW, Woodwalton Fen, HF, Holme Fen, SW, Roughs Farm; LC, Little Common Farm, RG, Rosedene Farm; WF, Wright's Farm; MF, Middle Farm; MS, Moss Side Farm; ND, New Decoy; RV, Railway View; WBF, Wicken Baker's Fen.

### 3.2.3. Lead (Pb)

Consistent with Cu ($R_S = 0.79$) and Hg ($R_S = 0.68$), Moss Side Farm, Railway View, and Delamere Forest had peaks of Pb (1500–3,000 μg $g^{-1}$) in the top 30 cm of peat (Figure S34 in Supporting Information S1). The remaining bog site, Wright's Farm (arable), showed slightly elevated concentrations of Pb in the top ~30 cm but at much lower levels (~200 μg $g^{-1}$) than the other three bog sites. The eastern England fen sites all displayed comparatively low levels of Pb, besides some small surface peaks at Holme Fen (semi-natural) and Wicken Sedge Fen (semi-natural) (both ~200 μg $g^{-1}$). The ratio of Pb to Rb only showed elevated Pb:Rb at Delamere Forest (Figure S35 in Supporting Information S1).

### 3.2.4. Mercury (Hg)

Hg was detected (peaking at 6–10 μg $g^{-1}$) at Moss Side Farm, Railway View and Delamere Forest, in the upper ~30 cm of peat (Figure S36 in Supporting Information S1), in parallel with Pb ($R_S = 0.68$) and Cu ($R_S = 0.67$). The remaining sites all had lower Hg concentrations <2 μg $g^{-1}$. Down core patterns in Hg were largely similar to those of Pb ($R_S = 0.68$) and Cu ($R_S = 0.67$), as reflected in their positive relationships in the PCA (Figure 6).

### 3.2.5. Zinc (Zn)

High concentrations of Zn (750–2,000 mg $g^{-1}$) were detected in the top 30 cm of peat in the Manchester Mosses (Moss Side Farm, Railway View) (Figure S37 in Supporting Information S1). The remaining sites all had lower Zn concentrations <250 mg $g^{-1}$. The ratio of Zn to Rb was consistent with these results, showing elevated Zn:Rb at Moss Side Farm, Railway View, and additionally, Delamere Forest (Figure S38 in Supporting Information S1).

## 3.3. Nutrients

### 3.3.1. Potassium (K)

K concentrations were elevated (10–24 mg $g^{-1}$) throughout the shallow (~30 cm) core profiles at the arable sites Roughs Farm and Little Common Farm, as well as the former arable grassland site Wicken Baker's Fen (Figure 4). K concentrations peaked at depths of 50–100 cm at Wicken Sedge Fen (semi-natural), Wright's Farm (arable on bog peat), New Decoy (grassland on fen peat), and Wicken Baker's Fen (grassland on fen peat), which correlated

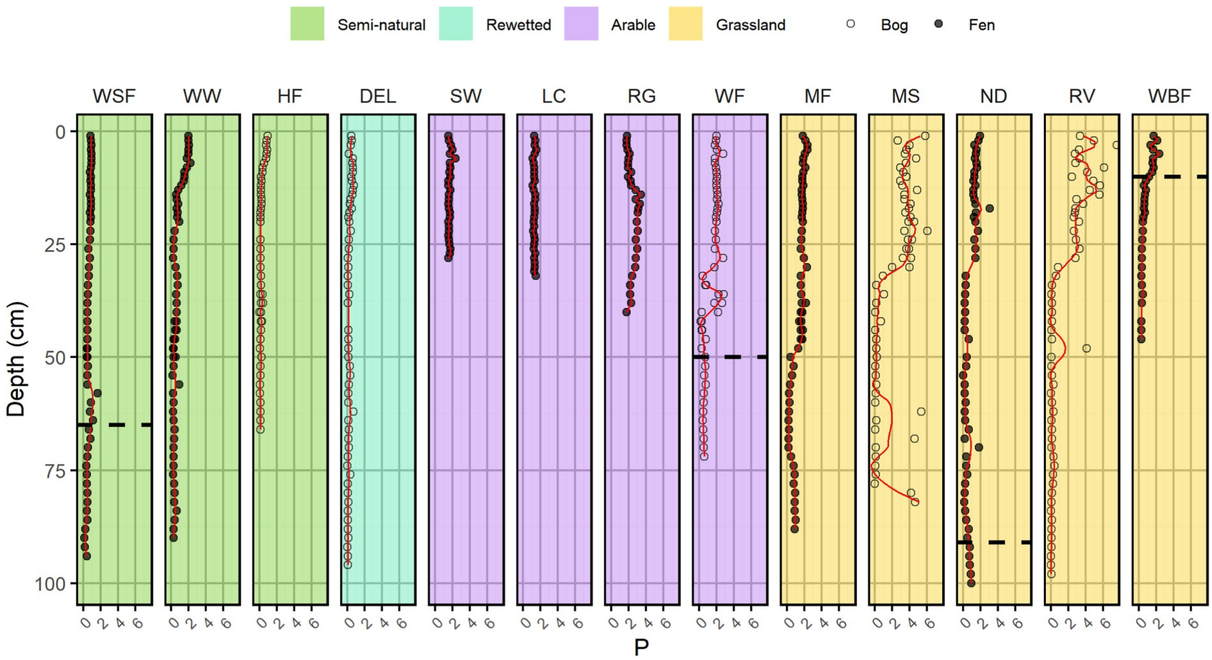


**Figure 5.** Peat core depth profiles of phosphorus (P) concentrations (mg $g^{-1}$). The dashed horizontal line on some cores indicates the organo-mineral soil transition. Site codes are as follows: DEL, Delamere Forest; WSF, Wicken Sedge Fen; WW, Woodwalton Fen; HF, Holme Fen; SW, Roughs Farm; LC, Little Common Farm; RG, Rosedene Farm; WF, Wright's Farm; MF, Middle Farm; MS, Moss Side Farm; ND, New Decoy; RV, Railway View; WBF, Wicken Baker's Fen.

with low LOI ($R_S = -0.87$; Figure S21 in Supporting Information S1). For all of these sites, the increase in K concentrations coincided with visible transitions from organic to mineral profiles (Figures S3, S5, and S9 in Supporting Information S1). In contrast, K concentrations peaked toward the surface at the bog peat sites Delamere Forest, Moss Side Farm, Railway View, and Holme Fen as well as Woodwalton Fen.

### 3.3.2. Phosphorus (P)

Land use had a significant effect on P concentrations according to our LMM ($p = 0.007$; Table S1 in Supporting Information S1), with significantly higher values at the arable ($\beta = 0.55$; $p = 0.003$) and grassland ($\beta = 0.34$; $p = 0.03$) sites compared to semi-natural sites. P concentrations were elevated (maximum: 3.4 mg $g^{-1}$) throughout the 40 cm core profile at Rosedene Farm (arable) (Figure 5). At the other arable site (Wright's Farm), P concentrations were also elevated in the upper ~40 cm (although to a lower maximum: 2.8 mg $g^{-1}$). At Little Common Farm (arable; 1.5 mg $g^{-1}$ maximum) and Roughs Farm (arable; 2.4 mg $g^{-1}$ maximum), P concentrations were also elevated to a lesser degree. Concentrations of P increased toward the upper ~10 cm at Woodwalton Fen (semi-natural fen; 2.2 mg $g^{-1}$ maximum). The grassland sites (Middle Farm, Moss Side Farm, New Decoy, Railway View, Wicken Baker's Fen) all displayed elevated surface P concentrations to various degrees. Surface P concentrations were particularly elevated at the top 25 cm at Railway View (7.6 mg $g^{-1}$ maximum) and Moss Side Farm (6.1 mg $g^{-1}$ maximum).

## 3.4. Overall Trends

The first PCA axis (63.8% of variance) distinguished samples based on low to high metal content, noting that Hg, Pb, Cu, and Zn are especially closely (positively) related (Table S2 in Supporting Information S1; Figure 6). Fe fell outside of the main metal grouping (Cu, Pb, Hg, and Zn) in the PCA. The second axis (24.9% of variance) represents a gradient of low to high organic matter content, where low organic matter content is associated with high K content. The rewetted bog site (Delamere Forest) has higher soil organic matter content than most of the other land uses. The arable and semi-natural fen sites occupied a broadly similar area of the ordination space, reflecting a range of organic matter and metal concentrations. The grassland sites have the largest spread, indicating a large within-group variability in element concentrations.

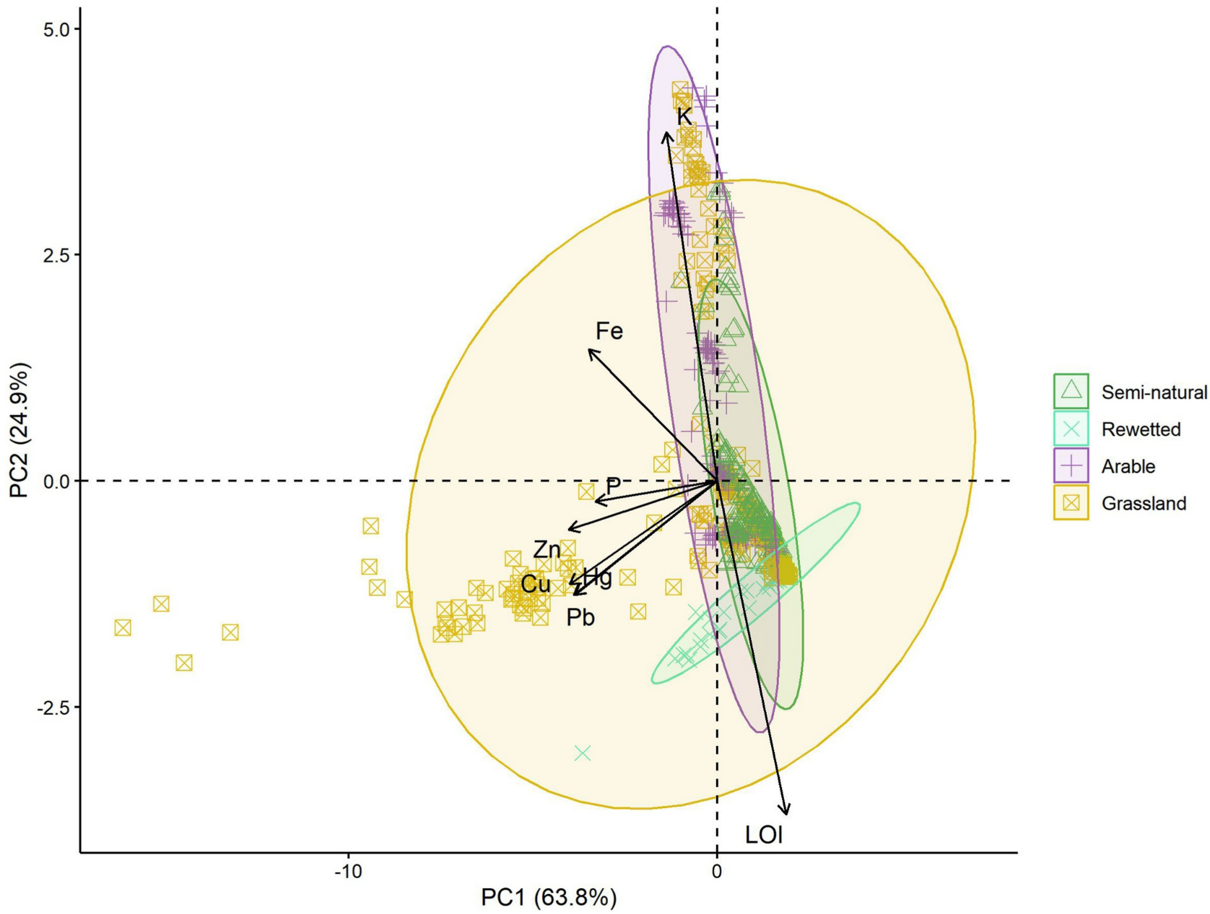


**Figure 6.** Principal components analysis of element composition of lowland peat cores across land uses.

## 4. Discussion

### 4.1. Impacts of Industrial Activities

Peatlands are effective at accumulating metals as these elements bind strongly to organic matter—making peat cores valuable archives of past atmospheric pollution (Hansson et al., 2015; Roux et al., 2004). Bogs in particular are excellent records of urban and industrially derived air pollution due to their sole reliance on atmospheric inputs (Shuttleworth et al., 2014). However, given the disturbed nature of the bogs in this study, the peat cores demonstrated that they may not be exclusively ombrotrophic, as shown by Ca:Mg molar ratios >1 (Shotyk, 1997). We focus on low-mobility metals Cu, Pb, Hg, and Zn, which are reliable indicators of atmospheric pollution in peat (Novak et al., 2011). In contrast, Fe has a very high degree of mobility in waterlogged peat, where it can be remobilized by fluctuating water columns and changing redox conditions (Novak et al., 2011). This mobility of Fe was evident at Wright's Farm (arable) and New Decoy (grassland) sites, which both showed elevated concentrations in deeper layers (below 50 cm).

In line with our expectations for low-mobility metals, we found notable peaks of metal concentrations in the surface peat of the bog cores (except for Wright's Farm). Wright's Farm (arable) had lower metal concentrations than the other three bog sites. This is likely because this site is further away and upwind of the main industrial sources of air pollution in the region (Greater Manchester). Large-scale peatland drainage schemes started in the Lancashire region of north-west England as early as the seventeenth century (Gritt, 2008). All of the bogs we sampled were located in the north-west of England, near Greater Manchester, a major hub of manufacturing during the industrial revolution (Douglas et al., 2002). These elevated concentrations therefore likely come from regional historic coal combustion and metal smelting activities (Fletcher & Ryan, 2018; A. W. Osborne et al., 2024). The ratio of predominantly industrial source metals (Pb, Cu, and Zn) to a lithogenic source metal

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(Rb) still showed localized peaks in metal concentrations, suggesting relative enrichment of industrially derived metals above background crustal inputs, consistent with atmospheric deposition (Mao et al., 2019). These metal peaks were consistently observed at Delamere Forest, a relatively intact peatland compared to the other north-west sites where peat disturbance in the last few centuries (e.g., erosion, oxidation, historical extraction) has removed or homogenized the recent peat layers that would otherwise preserve atmospheric fallout signatures. Similar peaks in Pb and Cu have been observed in other cores from the Manchester Mosses, where radiocarbon dating shows that these metal concentrations peaked in 1920 (Fletcher & Ryan, 2018; Garcés-Pastor et al., 2023). This timing coincides with the peak of the cotton textile industry in the Greater Manchester area, as well as large scale population growth and urbanization (Rodgers, 1962). In addition, sewage sludge and other urban wastes were also historically disposed of on the Manchester Mosses (until the 1950s), via plowing into the soil, so direct contamination could also be a viable route (Breward, 2003). Modern-day Manchester continues to be heavily urbanized, with atmospheric Hg emissions detected in the Manchester area today (Lee et al., 2000). We acknowledge that the natural distribution of the dominant peatland type across England (bog in the north-west and fen in the southeast) poses a limitation for disentangling the effects of industrialization, given the confounding regional differences in peat formation, climate, parent material, etc.

Intact peatlands are effective at retaining and immobilizing heavy metals (Apori et al., 2024). However, disturbance such as drainage and land use change can alter peat properties, potentially mobilizing the stored metals in peatlands (Apori et al., 2024). Elevated metal concentrations in soils can be detrimental to microbial communities, thereby disrupting biogeochemical cycling and reducing soil fertility (Abdu et al., 2017; Lenart-Boroń & Boroń, 2014). Metals can have harmful effects on plants, including altered metabolism, reduced growth, and lower biomass production (Nagajyoti et al., 2010). Metals can also leach from peat to surface waters, causing concerns for aquatic biota (Shahjahan et al., 2022). Given these concerns, governments and organizations propose safe limits for metals in soils and waters. Ambient background (rural areas away from point sources of pollution) soil concentrations of metals from the 1983 England and Wales National Soil Inventory are 116 $\mu g\ g^{-1}$ Pb, 15 $\mu g\ g^{-1}$ Cu, 52 $\mu g\ g^{-1}$, and Zn for peat/peaty soils (McGrath & Zhao, 2006). Concentrations in some subsamples at all sites exceeded these average background values for at least one of these metals. A European directive regarding the application of sewage sludge to agricultural land proposes 300 $\mu g\ g^{-1}$ as a safe limit for Pb in soils (Council Directive 86/278/EEC of 12 June 1986 on the Protection of the Environment, 1986). Core concentrations exceeded this limit at a total of 68 subsamples, all from cores collected in the Manchester and Cheshire Mosses (at Delamere Forest, Moss Side Farm, and Railway View). The same directive proposes 1 $\mu g\ g^{-1}$ as a safe limit for Hg in soils. Core concentrations exceeded this limit at a total of 79 subsamples—mostly at the Manchester and Cheshire Mosses, with three subsamples at Wicken Baker's Fen, three at Rosedene Farm, two at Wicken Sedge Fen, and one at Woodwalton Fen. Thus, with a few exceptions, peat outside of the Greater Manchester region had metal concentrations within safe thresholds.

Industrialization has been widely linked to elevated trace metal concentrations in peatlands globally. Concentrations of Pb, Cd, and Zn exceeded permissible levels in a peat bog in Poland, attributed to a metal smelting plant located 10 km away from the site (Borgulat et al., 2018). Surface Cu and Ni concentrations from peat cores near Sudbury, Canada were correlated with distance from the main smelter in the area (Barrett & Watmough, 2015). Regional-scale atmospheric deposition also plays a key role, with external inputs of Pb from soil dust and atmospheric pollution from industry, coal burning, and vehicle exhaust emissions contributing to recent Pb concentration peaks in ombrotrophic peat bogs in northern Europe (Brännvall et al., 1997; Garcés-Pastor et al., 2023; MacKenzie et al., 1998).

### 4.2. Impacts of Land Use

Away from the historic industrial center in north-west England, we found some elevated metal concentrations, likely attributed to regional-scale atmospheric loading and local agricultural inputs. Our PCA indicates a decoupling of LOI and metals, and the ratios of predominantly industrial source metals (Pb, Cu, and Zn) to Rb further suggests relative enrichment of industrially derived metals (Mao et al., 2019). There were elevated metal concentrations at arable (Rosedene Farm) and grassland (New Decoy, Middle Farm) sites in east England in the upper 30 cm of peat. With no natural metal deposits in the region (Mayes et al., 2010), these elevated levels likely signal atmospheric loading from further away and/or local inputs. The significantly higher Cu concentrations at arable and grassland sites than semi-natural sites indicate that fertilizer and/or manure inputs could be a source of heavy metals, as has been observed elsewhere (Mantovi et al., 2003). The elevated metal concentrations at New

Decoy and Middle Farm (both grasslands) generally track P concentrations, further suggesting that inputs of diverse fertilizers or other amendments can be sources of metals at some sites. Semi-natural fen sites Holme Fen and Wicken Sedge Fen also had a small peak of metals in the upper 15 cm, which is likely attributed to regional-scale atmospheric loading, particularly for Holme Fen, which is in fact a bog. Additionally, Wicken Sedge Fen is irrigated with river water to keep water levels high (Peacock et al., 2017), which may be a source of heavy metals at this site. Similarly, elevated concentrations of metals have been observed in peat cores in remote areas away from present/historic industrial centers, for example, in central Scotland and Sweden (Brännvall et al., 1997; Farmer et al., 1997).

Elevated concentrations of K and P can be indicative of fertilizer or other agricultural inputs. Elevated K concentrations were observed at the arable sites (Roughs Farm and Little Common Farm). At the grassland site, Wicken Baker's Fen, high K concentrations could be due to a legacy of historic arable cultivation, including manure inputs from cattle and pony grazing (Heming, 2008), or enrichment from river water, which is pumped onto the site during the winter (Peacock et al., 2019). K concentrations peaked at depths of 50–100 cm at Wicken Sedge Fen (semi-natural), Wright's Farm (arable on bog peat), and New Decoy (grassland on fen peat), which correlated with low organic matter content and therefore mineral weathering, although there may also be leaching from upper organic horizons to deeper, mineral horizons. Indeed, for all three sites the increase in K concentrations coincided with visible transitions from organic to mineral profiles. In contrast, K concentrations peaked toward the surface at the bog peat sites Delamere Forest, Moss Side Farm, and Railway View. Nutrients such as K are often limited in bogs; therefore, tight internal cycling by vegetation may have led to the K enrichment in surface peat that we observed at these sites (Olde Venterink et al., 2002).

P was significantly higher at arable and grassland sites than semi-natural sites. At the arable sites, fertilizer inputs are the likely source of P. The grassland sites (Middle Farm, Moss Side Farm, New Decoy, Railway View, Wicken Baker's Fen) all displayed elevated surface P concentrations, particularly in the top 25 cm at Railway View and Moss Side Farm. This could generally be indicative of tight P cycling within the rooting zone due to nutrient limitation, as with K. At the Manchester Mosses sites, this could also be due to the historical disposal of sewage sludge and other urban wastes, which were deposited directly onto the Manchester Mosses during the 19th century (Breward, 2003). At Woodwalton Fen (semi-natural), the surface P-enrichment is possibly derived from high-P eutrophic water inputs from the ditch network outside of the fen's boundary (Mountford et al., 2002).

Down core patterns of P and K were generally not matched across sites, reflecting site-specific differences in nutrient cycling. Although P was high at the arable site Rosedene Farm, K was not—perhaps attributed to the type of fertilizer used, crop uptake of K, or acid-mediated mobility. At the other arable site (Wright's Farm), P concentrations were also elevated in the upper ∼40 cm. However, at Little Common Farm (arable) and Roughs Farm (arable), P concentrations were elevated to a lesser degree. This is likely attributed to their respective cropping regimes, where Wright's Farm and Rosedene Farm both support primarily horticulture crops which require high fertilizer inputs, while Little Common Farm and Roughs Farm grow mostly cereals which require low inputs (Liu et al., 2025; Sica & Magid, 2024).

Organic matter content was significantly higher at the semi-natural sites compared to the drained grassland sites, demonstrating that higher water tables are effective at preventing carbon losses (Evans et al., 2021). The surface layers at grassland sites Moss Side Farm and Railway View had low organic matter content, presumably due to drainage-induced carbon losses, while at greater depths (30 cm+), anaerobic conditions deeper in the peat profile likely slowed decomposition. The lowest mean organic matter content was at the former arable/now grassland site, Wicken Baker's Fen (12%), where extensive subsidence and oxidation, because long-term drainage has increased bulk density and reduced organic carbon content as the remaining peat has intermixed with underlying mineral soil (Peacock et al., 2019).

The impacts of land use on peat chemistry have been observed globally, with evidence for local management influencing various element concentrations. In Ireland, the highest peat core heavy metal concentrations were found in grasslands (both restored and semi-natural) compared to forest peatlands and cutaway bogs, attributed to higher soil organic carbon and higher pH (Apori et al., 2024). Concentrations of Cd, Hg, and Pb at the grassland sites exceeded World Health Organization (WHO) safe thresholds, and their sources were attributed to fertilizer and pesticide use as well as atmospheric deposition (Apori et al., 2024). Similarly, a review of peat chemistry studies in Southeast Asia revealed elevated K and Zn concentrations in more intensively managed peatlands compared with forest and restored sites, attributed to drainage, fertilizer applications, and ash from peat fires (Kunarso et al., 2022).

## 5. Conclusions

Peatland drainage and their subsequent use for agriculture have left a legacy on UK lowland peat, as evidenced by our peat cores. Drained grassland sites had lower organic matter content when compared to semi-natural sites, highlighting how long-term drainage and land-use change results in sustained peat carbon losses. Proximity to major urban and industrial areas left a legacy of metals in lowland peat cores, sometimes at concentrations higher than the proposed safe limits. Away from this historic industrial center we found smaller surface peaks of metals at arable and grassland sites in east England, potentially indicative of more distant regional scale atmospheric pollution or repeated use of manure or fertilizer amendments. Peatlands provide the valuable ecosystem service of retaining and immobilizing pollutants such as metals, providing additional justification for their conservation and restoration beyond carbon storage. Our findings reveal the footprint that humans have had on lowland peat, providing insights that can help inform rewetting and other restoration strategies.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Availability Statement

The data and programming code that support the findings of this study are openly available in Figshare at https://doi.org/10.6084/m9.figshare.30795122 (Silverthorn & Peacock, 2025).

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