Received: 19 January 2022 | Revised: 9 July 2022 | Accepted: 29 July 2022

DOI: 10.1111/ejss.13297

SHORT COMMUNICATION

European Journal of Soil Science WILEY

Legacy of war: Pedogenesis divergence and heavy metal contamination on the WWI front line a century after battle

Owain H. Williams | **Naomi L. J. Rintoul-Hynes**

Section of Natural and Applied Sciences, School of Psychology and Life Sciences, Canterbury Christ Church University, Canterbury, UK

Correspondence
Naomi L. J. Rintoul-Hynes, Section of Natural and Applied Sciences, School of Psychology and Life Sciences, Canterbury Christ Church University, Canterbury CT1 1QU, UK.
Email: naomi.rintoul@canterbury.ac.uk

Abstract

In Europe, the First World War left a legacy on the environment due to the extensive and intense use of artillery during this period. This study examined a small wooded area in the Pas-de-Calais region in France which was subject to considerably less intense fire than previously studied WWI battlefields. In a process named "bombturbation," significant physical changes have occurred to the landscape subject to artillery fire, resulting in a divergent soil development in craters. Cratering led to higher organic matter and electrical conductivity values, but—unlike other studies—no significant difference in soil pH. Soil heavy metal concentrations did not differ within craters compared to the flat landscape. However, lead (Pb) and copper (Cu) enrichment was observed above the baseline values for the region. Despite the average concentrations of Cu and Pb being within legal limits for soils in the UK and European Union, it is likely that enrichment of Cu and Pb in the concentrations observed has caused detrimental ecotoxicological and human health effects.

Highlights

- Few studies investigate the legacy of WWI on soil, particularly from low intensity fighting.
- WWI bomb craters alter soil development, resulting in changes to organic matter and salinity.
- Cu and Pb enrichment of soil from WWI may lead to ecotoxicological and human health impacts.

KEYWORDS

contamination, copper, lead, pedogenesis, soil, war

1 | INTRODUCTION

1.1 | Historical context

Environmental damage has been a by-product, and sometimes a deliberate strategy, of war since the ancient world. The scale of warfare increased to an industrial level in the 20th Century (Francis & Krishnamurthy, 2014). The former battlefields of the First World War are of particular interest due to the nature of this war: a "static front" formed on the Western Front (Boff, 2018) that remained in place for almost the entire duration of the war (Keegan, 1994).

This front involved soldiers in close contact with each other, launching offences in increasingly extreme efforts to break the stalemate (Watson, 2015). This resulted in an unparalleled concentration of artillery and small arms fire on the western front, with 1.45 billion shells fired during WWI (Prentiss, 1937).

1.2 | Bombturbation

Bombturbation, a term coined by Joseph Hupy (Hupy & Koehler, 2011), is a form of soil disruption caused using explosive munitions, ranging from grenades to heavy artillery. Following this, the physical structure of the soil may be severely disrupted or completely destroyed (Hupy & Schaetzl, 2008). The new topographical landscape established—a change from a smooth to an irregular slope or the formation of craters—will result in new hydrological and weathering conditions (Hupy & Koehler, 2011) and a divergence in pedogenesis (Hupy & Schaetzl, 2008).

1.3 | Chemical disruption

Anthropogenic sources of heavy metals in the environment typically include industrial processes, agriculture, wastewater, mining and metallurgical processes (Hasnine et al., 2017; Masindi & Muedi, 2018; Wuana & Okieimen, 2011). However, studies into the chemical legacy of WWI have already established the presence of metallic contaminants such as copper, lead, arsenic and zinc from munitions in multiple theatres of the conflict (Baba & Deniz, 2004; Bausinger et al., 2007; Bausinger & Preuß, 2005; Meerschman et al., 2010; Souvent & Pirc, 2001; Thouin et al., 2016; Van Meirvenne et al., 2008). As a result of intense fighting, deposition of bullets, shrapnel and powder casings caused heavy metal enrichment of the soil (Hardinson Jr et al., 2004; Souvent & Pirc, 2001) as these were primarily composed of lead (Pb), copper (Cu), zinc (Zn) and steel (War Office, 1915; Watson, 2015).

1.4 | Aim

This study determined whether physical and chemical forms of disruption were evident over an area with relatively minor cratering than has been left largely undisturbed. First, by examining pH, soil organic matter and electrical conductivity (EC) in samples from craters and from flat, relatively undisturbed ground (non-craters), the study established whether the physical effects are likely to have led to a divergence in pedogenesis. Next, the study investigated whether soil contamination (Pb and Cu) was higher in craters compared to the undisturbed ground (direct enrichment). It determined whether there has been enrichment of heavy metals more generally at the site above expected (baseline) concentrations. As with Van Meirvenne et al. (2008) and Meerschman et al. (2010), this experiment used nickel (Ni) as a control as this metal is not associated with warfare activities and should therefore be within the baseline range.

2 | MATERIALS AND METHODS

2.1 | Site description

The study site is within Sheffield Memorial Park, a wooded area located near the village of Puisieux, France. The site formed part of the British front line during 1916 and was involved in the series of battles known collectively as the Battle of the Somme (Greatwar.org, 2020; Figure 1). The area has not been relandscaped or decontaminated (Blake, 2020).

2.2 | Sample collection

A clustered sampling method was used to account for the localised nature of the cratering (Jianwei, 2019), where a soil corer was used to extract 22 soil cores from the centre point inside 11 craters likely caused by bombturbation. Conversely, 50 soil cores from flat, relatively undisturbed ground with no physical evidence of bombturbation were collected across the site using a random sampling method, accounting for the heterogenous nature of the soil. Cores were taken to a depth of 15 cm as most metal fragments deposited from warfare are found up to this depth (Souvent & Pirc, 2001). Samples were dried at 60°C in a Memmert 500 oven for 72 h then stored at room temperature for 6 months prior to analysis.

2.3 | Laboratory analysis

The loss on ignition (LOI) method was used to measure the organic matter content in the soil samples. 1 g (±0.1 g) of oven-dried soil were heated in a Carbolite ELF 11/6 muffle furnace at 550°C for 8 h. After cooling, the samples were removed and re-weighed, with the difference in mass being used to determine the LOI %, a proxy for soil organic matter (SOM). To analyse for pH and EC, 5 g (±0.5 g) of each soil sample was mixed with 25 ml of deionised water and shaken at 100 rpm for 30 min. The pH was measured using a glass electrode Jenway 3510 pH meter and the EC was then measured using a Hanna H199301 electrical conductivity meter. For each soil sample, 1 g (±0.1 g) was

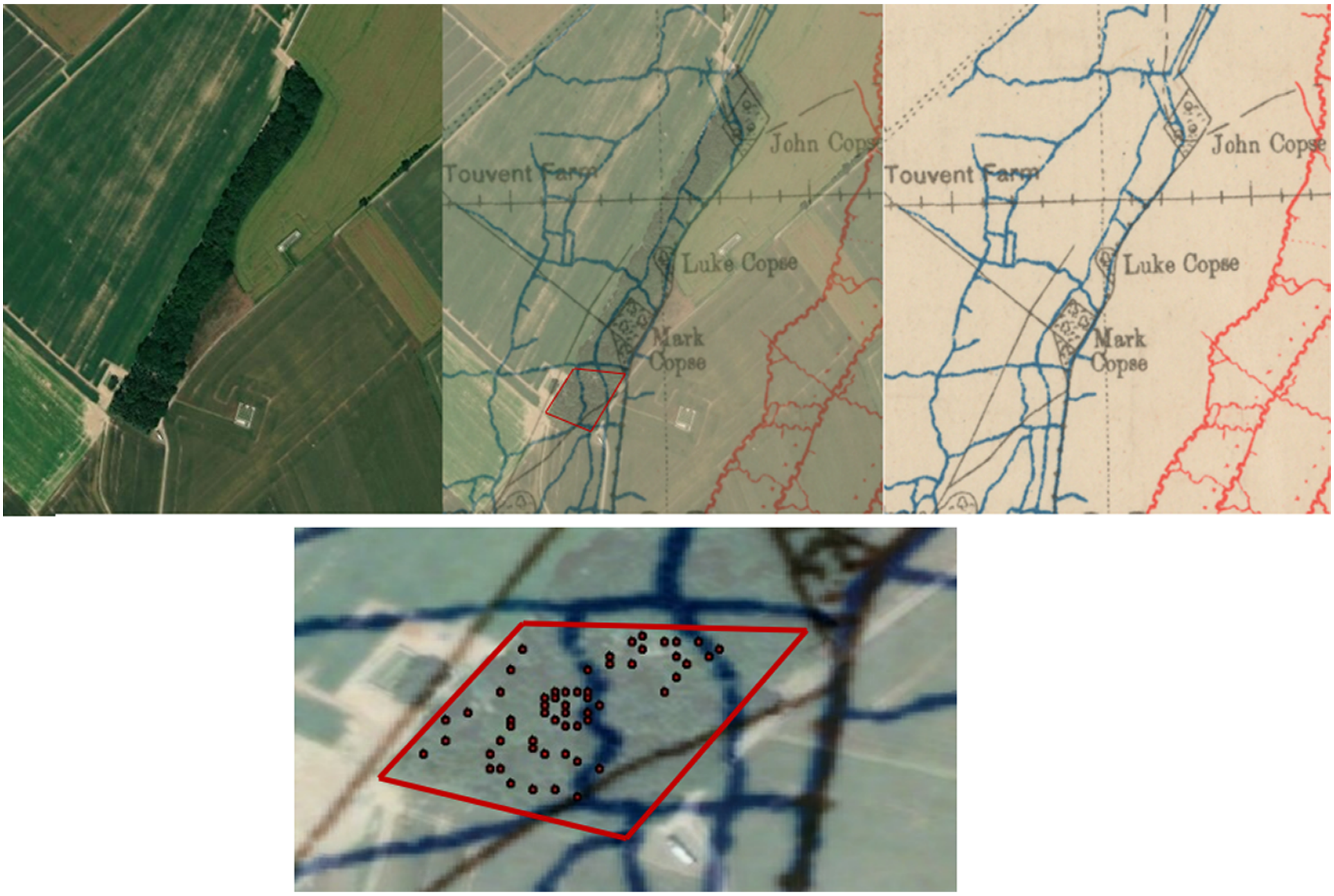

FIGURE 1 Evidence that the field site is located at the former front line. Image created using Google maps and a historical map reproduced with the permission of the National Library of Scotland (2020), with data sampling points created using ArcGIS 10.8.1

TABLE 1 Average values for crater and non-crater samples (±SE)

	pH	EC (μs)	Organic matter (%)	Pb (mg/kg)	Cu (mg/kg)	Ni (mg/kg)
Crater	7.23 (±0.14)	339.25 (±20.31)	19.73 (±1.84)	162.00 (±99.85)	42.52 (±1.51)	19.31 (±0.88)
Non-crater	6.72 (±0.17)	223.07 (±11.08)	10.80 (±0.44)	49.49 (±8.67)	43.90 (±1.65)	18.95 (±0.50)

added to a solution of 2.5 ml of 65% HNO_3 and 7.5 ml of 37% HCl and digested in a Berghof Speedwave 4 microwave digester. After filtration with Whatman 100 filter paper, the samples were diluted to 50 ml. A Perkin Elmer Optima 8000 Inductivity Coupled Plasma—Optical Emission Spectrometer (ICP-OES) was used to measure the concentration of heavy metals in the digested samples.

3 | RESULTS

3.1 | Effects of bombturbation on soil chemistry: Craters versus non-craters

Following Anderson-Darling normality tests, data that were normally distributed (EC and nickel)—or where transformations subsequently gave a normally distribution (organic matter and lead)—were subject to an unpaired t-test. Non-parametric data (pH and copper) were analysed using a Mann–Whitney test. These were used to assess whether there was a statistically significant difference between data for soil properties in crater and non-crater samples at the 5% level to reject the null hypothesis of no difference in means. The mean and SDs for each soil property are shown in Table 1. Soil EC ($p < 0.001$) and SOM ($p < 0.001$) were both significantly different, however pH ($p = 0.166$) was not. Mean soil EC was 52% higher in craters than non-craters and mean SOM content was 1.8 times higher in craters than non-crater samples. There was no significant difference between crater and non-crater samples for Ni ($p = 0.703$) or Cu ($p = 0.599$). Although not significant at the 5%

Element	Topsoil concentrations after *aqua regia* extraction and ICP-AES (mg/kg)	Mean concentration in this study (mg/kg)	Range in this study (mg/kg)
Pb	15–21	93.24	9.75–2471.00
Cu	12–16	43.37	32.45–110.25
Ni	14–21	19.09	7.2–27.75

TABLE 2 Figures for regional baseline topsoil levels of some heavy metals from the geochemical atlas of Europe (Salminen, 2005) compared to the mean and range at Puisieux for Cu, Pb and Ni

level, Pb showed a *p*-value that approaches the conventional threshold for statistical significance ($p = 0.094$).

3.2 | Heavy metal enrichment of soils

To determine whether enrichment of Pb, Cu and Ni has occurred, Table 2 compares the regional baseline values to the mean values and concentration range found in this study. Although there were no significant differences in Cu or Pb for craters compared to non-craters, the mean values for Cu and Pb suggest soil contamination has occurred. There has been enrichment of soil Pb by 72–78 mg/kg, equivalent to more than four times the top baseline value. Soils have also been enriched with 27–31 mg/kg Cu, or 2.5 times the top baseline value. For copper, every sample was above the baseline value. Although two thirds of samples were below the baseline for lead, some had concentrations 100 times greater than the baseline. The average nickel concentration of 19.1 mg/kg was within the expected range for the region; therefore the results are as expected for the control.

4 | DISCUSSION

4.1 | Impacts of physical disturbance on soil development

4.1.1 | Crater size

The size of craters at Puisieux is similar to those found in similar studies (Hupy & Schaetzl, 2008; Meerschman et al., 2010; Souvent & Pirc, 2001; Van Meirvenne et al., 2008). However, Puisieux was not subject to the same intense and concentrated fire and has just four craters >1 m. This site is therefore representative of lower-impact WWI battlefield sites in terms of the damage from cratering and bombturbation. As well as the intensity of gunfire or explosions, bomb crater size will differ depending on the type of explosion and the physical and mechanical properties of the soil (Ambrosini et al., 2002; Payne et al., 2019).

4.1.2 | Organic matter

Previous studies investigating bombturbation found that the physical disturbance altered the course of soil development, acting as a catalyst for pedogenesis (Shaw et al., 2001). These explosions caused craters to develop a thicker organic soil layer (Hupy & Schaetzl, 2006, 2008) and higher nutrient concentrations (Shaw et al., 2001) in craters. Similar results have been recorded at Puisieux, where the organic matter content is significantly higher in craters. This is likely caused by craters becoming the focal points for runoff, litter and sediment deposits (Hupy & Schaetzl, 2006, 2008; Seibert et al., 2007). Other factors that could have affected the organic matter content include the position, slope or elevation of the craters (Guo et al., 2013), soil moisture and surface runoff into craters (Seibert et al., 2007; Zhang et al., 2012), plant growth favouring depressions rather than flat areas (Hupy & Schaetzl, 2008; Vicentini et al., 2020), earthworm activity (Hupy & Schaetzl, 2008), soil type and underlying geology (Zhang et al., 2012).

4.1.3 | Salinity

At Puisieux the soil salinity is greater within craters than non-crater sites. Cratering could affect salinity via leaching, transporting and accumulation (Karaca et al., 2018). Salinity correlates positively with cation exchange capacity and organic matter content of soil (Valente et al., 2012), thus changes in organic matter may be driving increases in salinity. Other factors affecting salinity include soil moisture content affecting the cations in solution (Heiniger et al., 2003; Seladji et al., 2010), lower soil compaction in disturbed soils increasing salinity (Seladji et al., 2010), or soil texture, particularly clay content, affecting conductivity readings (Schjønning et al., 2017).

4.1.4 | pH

In contrast to Hupy and Shaetzl (2006, 2008), there was no significant difference in soil pH in the craters compared with the flat areas. Soil organic matter has been shown to cause acidification of soil in many environments (Ritchie & Dolling, 1985) due to the production of acids from biological activity and decomposition of organic matter (Jørgensen & Willems, 1987; Paul, 2015; Tukura et al., 2007). As munitions smash the underlying bedrock, rock fragments are more exposed to weathering in the bottom of craters and weathering processes occur more quickly due to increased runoff (Hupy & Schaetzl, 2008; Runge, 1973). Thus, the high chalk content of the weathered parent material could act as a buffering agent (Goulding, 2016). As several acids are found in explosives, acidification of the soil would most likely occur across entire area historically associated with warfare (Certini et al., 2013), not just in bomb craters.

4.2 | Contamination with heavy metals due to WWI activities

4.2.1 | Identification of battlefield sites using heavy metals

Of the various anthropogenic sources of heavy metals (Hasnine et al., 2017; Masindi & Muedi, 2018; Wuana & Okieimen, 2011), there is no historical evidence of wastewater, mining or metallurgical activity that could cause contamination above the regional baseline, but agricultural sites are within close proximity. However, the fact that lead and copper concentrations are elevated, but not nickel, is evidence that the WWI related activity is the cause of the contamination. Therefore, soil copper and lead can be used to identify historic battle sites from WWI, using nickel as a control. Because fragments of shells, grenades, bullets and other munitions can be distributed in the soil more sporadically (Meerschman et al., 2010), this lack of homogenisation may explain the similarity between craters and non-craters. Material will not only land in the craters themselves but will also be blasted a considerable distance from the depressions they create. Thus, rather than identifying and testing craters specifically, sampling across the entire site is recommended.

4.2.2 | Copper enrichment

Although copper is essential for human health at trace amounts (Bost et al., 2016), it poses a health risk when ingested in larger quantities through direct exposure via contaminated soil, water or air, or through the ingestion of contaminated plant or animal matter. A range of copper toxicity symptoms in humans include long-term gastrointestinal system and liver damage, cognitive symptoms, paralysis or death (Jadoon et al., 2017; WHO, 2004). Based on these human health concerns, legislation provides a threshold dose that soils should not exceed 135 mg/kg at pH 6–7 in the UK and 50–140 mg/kg in the EU (Nicholson & Chamber, 2008; Tóth et al., 2016). As the maximum concentration for Cu was 110.25 mg/kg, all samples are within an acceptable range according to UK and European guidelines.

Trace amounts of copper serve important functions in the growth, development and functioning of plants (Olivares & Uauy, 1996; Yruela, 2009). However, copper can be toxic to plants at concentrations as low as 20 mg/kg (Borkert et al., 1998). Similarly, there is a detrimental impact on soil biota at concentrations as low as 10 mg/kg (El-Ghamry et al., 2000). Thus, copper is likely having a detrimental ecological impact at Puisieux.

4.2.3 | Lead enrichment

Lead serves no useful function in the human body and is considered toxic at any concentration (Wani et al., 2015; WHO, 2019), damaging renal and nervous systems, particularly in children (Adriano, 2001). Legislation sets threshold concentrations for lead in soil of 200 mg/kg above pH 5.0 in the UK and 50–300 mg/kg for EU countries (Nicholson & Chamber, 2008; Tóth et al., 2016). The maximum values found in the soil are at least nine times the maximum threshold value, suggesting that remediation is necessary.

Lead has no biological function but can cause a variety of morphological, physiological and biochemical dysfunctions in plants and soil organisms (Fahr et al., 2013; Lanno et al., 2019; Sharma & Dubey, 2005). Effects have been recorded at concentrations as low as 35–50 mg/kg (Lanno et al., 2019; Pan & Yu, 2011; Zhang et al., 2016), therefore there have probably been detrimental ecological impacts due to lead enrichment at Puisieux.

4.2.4 | Soil properties and heavy metal availability

Soils with a high organic matter content will immobilise heavy metals (Fayiga & Saha, 2016; Hernandez et al., 2003). Organic matter also affects the transformation rate of metallic compounds (Ma et al., 2007), with high organic matter resulting in less leaching of metal contaminants. Soils retain these metallic compounds for long periods, however, high organic matter correlates with increased solubility of lead but not copper (McBride et al., 1997).

High soil salinity leads to a release of heavy metals and thus higher heavy metal mobility. (Acosta et al., 2011;

Du Laing et al., 2009). Soil pH affects the bioavailability of heavy metals by affecting their solubility, sorption/desorption, complexation and redox potential (Fayiga & Saha, 2016). Each metal has its own leaching profile related to soil pH (Król et al., 2020; Zhang et al., 2018), where heavy metals tend to be more bioavailable in acidic soils (Dijkstra & Johannes, 2004).

5 | CONCLUSION

Differences in organic matter and salinity in the craters suggest that physical disturbance led to a divergence in soil development at a site that received less munitions than in previous studies. Soil pH was similar in craters and non-crater areas, possibly due to acidification of the soil by the explosives. Enrichment of copper and lead is due to warfare rather than natural or other anthropogenic causes. Although copper was below the threshold for UK and EU soils, some samples had lead concentrations above these limits. Therefore, this must be considered when considering a change in land use (i.e., to agriculture).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Naomi Rintoul, upon reasonable request.

ORCID

Naomi L. J. Rintoul-Hynes https://orcid.org/0000-0002-8096-5552

REFERENCES

Acosta, J. A., Jansen, B., Kalnitz, K., Faz, A., & Martínez-Martínez, S. (2011). Salinity increases mobility of heavy metals in soils. *Chemosphere*, *85*(8), 1318–1324.

Adriano, D. (2001). *Trace elements in terrestrial environments* (2nd ed.). New York.

Ambrosini, R. D., Luccioni, B. M., Danesi, R. F., Riera, J. D., & Rocha, M. M. (2002). Size of craters produced by explosive charges on or above the ground surface. *Shock Waves*, *12*, 69–78.

Baba, A., & Deniz, O. (2004). Effect of warfare waste on soil: A case study of Gallipoli peninsula (Turkey). *International Journal of Environment and Pollution*, *22*, 657–675.

Bausinger, T., Bonnaire, E., & Preuß, J. (2007). Exposure assessment of a burning ground for chemical ammunition on the great war battlefields of Verdun. *Science of the Total Environment*, *382*, 259–271.

Bausinger, T., & Preuß, J. (2005). Environmental remnants of the first world war: Soil contamination of a burning ground for arsenical ammunition. *Bulletin of Environmental Contamination and Toxicology*, *74*, 1045–1052.

Blake, J. (2020). Access to memorial site for scientific research [email].

Boff, J. (2018). Fighting the First World War: Stalemate and attrition, *British Library*. https://www.bl.uk/world-war-one/articles/fighting-the-first-world-war-stalemate-and-attrition#.

Borkert, C., Cox, F., & Tucker, M. (1998). Zinc and copper toxicity in peanut, soybean, rice, and corn in soil mixtures. *Communications in Soil Science and Plant Analysis*, *29*(19–20), 2991–3005.

Bost, M., Houdart, S., Oberli, M., Kalonji, E., Huneau, J. F., & Margaritis, I. (2016). Dietary copper and human health: Current evidence and unresolved issues. *Journal of Trace Elements in Medicine and Biology*, *35*, 117–115.

Certini, G., Scalenghe, R., & Woods, W. (2013). The impact of warfare on the soil environment. *Earth-Science Reviews*, *127*, 1–15.

Dijkstra, J., & Johannes, C. (2004). Leaching of heavy metals from contaminated soils: An experimental and modelling study. *Environmental Science and Technology*, *38*(16), 4390–4395.

Du Laing, G., Ricklebe, J., Vandecateele, B., Meers, E., & Tacka, F. M. G. (2009). Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review. *Science of the Total Environment*, *407*(13), 3972–3985.

El-Ghamry, A. M., Subhani, A., Moh'd, W., Changyong, H., & Zhengmiao, X. (2000). Effects of copper toxicity on soil microbial biomass. *Pakistan Journal of Biological Sciences*, *3*(6), 907–910.

Fahr, M., Laplaze, L., Bendaou, N., Hocher, V., El Mzibri, M., Bogusz, D., & Smouni, A. (2013). Effect of lead on root growth. *Frontiers in Plant Science*, *4*, 175–182.

Fayiga, A. O., & Saha, U. K. (2016). Soil pollution at outdoor shooting ranges: Health effects, bioavailability and best management practices. *Environmental Pollution*, *216*, 135–145.

Francis, R., & Krishnamurthy, K. (2014). Human conflict and ecosystem services: Finding the environmental price of warfare. *International Affairs*, *90*(4), 853–869.

Goulding, K. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use and Management*, *32*, 390–399.

Greatwar.org. (2020). Sheffield Memorial Park, Somme Battlefields, France. http://www.greatwar.co.uk/somme/memorial-sheffield-park.htm

Guo, P.-T., Wu, W., Sheng, Q.-K., Li, M.-F., Liu, H.-B., & Wang, Z.-Y. (2013). Prediction of soil organic matter using artificial neural network and topographic indicators in hilly areas. *Nutrient Cycling in Agroecosystems*, *95*, 333–344.

Hardinson, D. W., Jr., Ma, L. Q., Luongo, T., & Harris, W. G. (2004). Lead contamination in shooting range soils from abrasion of lead bullets and subsequent weathering. *Science of the Total Environment*, *328*((1–3)), 175–183.

Hasnine, T., Huda, E., Khatun, R., & Saadat, A. (2017). Heavy metal contamination in agricultural soil at DEPZA, Bangladesh. *Environment and Ecology Research*, *5*(7), 510–516.

Heiniger, R. W., McBride, R. G., & Clay, D. E. (2003). Using soil electrical conductivity to improve nutrient management. *Agronomy Journal*, *95*, 508–519.

Hernandez, L., Probst, A., Probst, J. L., & Ulrich, E. (2003). Heavy metal distribution in some French forest soils: Evidence for atmospheric contamination. *Science of the Total Environment*, *312*, 195–219.

Hupy, J., & Koehler, T. (2011). Modern warfare as a significant form of zoogeomorphic disturbance upon the landscape. *Geomorphology*, *157-158*, 169–182.

Hupy, J., & Schaetzl, R. (2008). Soil development on the WWI battlefield of Verdun, France. *Geoderma*, *145*, 37–49.

Hupy, J. P., & Schaetzl, R. J. (2006). Introducing "bombturbation", a singular type of soil disturbance and mixing. *Soil Science*, *171*, 823–836.

Jadoon, Z., Rauf, N., & Syed, M. (2017). *Copper in the environment: Source, environmental impact, effect on human health and* *remediation*. 4th international water conference climate change & disaster risk management for sustainable development & businesses.

Jianwei, L. (2019). Sampling soil in a heterogeneous research plot. *Journal of Visualized Experiments*, *143*, e58519.

Jørgensen, S. S., & Willems, M. (1987). The fate of lead in soils: The transformation of lead pellets in shooting-range soils. *Ambio*, *16*, 11–15.

Karaca, S., Gülser, F., & Selçuk, R. (2018). Relationships between soil properties, topography and land use in the Van Lake Basin, Turkey. *Eurasian Journal of Soil Science*, *7*(2), 115–120.

Keegan, J. (1994). *A History of Warfare*. Alfred A. Knopf.

Król, A., Mizerna, K., & Bozym, M. (2020). An assessment of pH-dependent release and mobility of heavy metals from metallurgical slag. *Journal of Hazardous Materials*, *384*, 121502.

Lanno, R., Oorts, K., Smolders, E., & Albanese, K. (2019). Effects of soil properties on the toxicity and bioaccumulation of Lead in soil invertebrates. *Environmental Toxicology*, *38*(7), 1486–1494.

Ma, L., Hardison, D., Harris, W. G., Cao, X., & Zhou, Q. (2007). Effects of soil property and soil amendment on weathering of abraded metallic Pb in shooting ranges. *Water, Air, and Soil Pollution*, *178*, 297–307.

Masindi, V., & Muedi, K. L. (2018). Environmental contamination by heavy metals. In H. E.-D. M. Saleh & R. F. Aglan (Eds.), *Heavy metals* (pp. 115–132). IntechOpen.

McBride, M., Sauve, S., & Hendershot, W. (1997). Solubility control of Cu, Zn, Cd and Pb in contaminated soils. *European Journal of Soil Science*, *48*(2), 337–346.

Meerschman, E., Cockx, L., Islam, M., Meeuws, F., & Van Meirvenne, M. (2010). Geostatistical assessment of the impact of World War I on the spatial occurrence of soil heavy metals. *Ambio*, *40*(4), 417–424.

National Library of Scotland Map Images. (2020). National Library of Scotland. https://maps.nls.uk/geo/explore/#zoom=16&lat=50.10856&lon=2.65784&layers=101465218&b=1.

Nicholson, F., & Chamber, B. (2008). SP0547: Sources and impacts of past, current and future contamination of soil. Appendix 1: Heavy metals. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=13317&FromS.

Olivares, M., & Uauy, R. (1996). Copper as an essential nutrient. *American Journal of Clinical Nutrition*, *63*(5), 791–796.

Pan, J., & Yu, L. (2011). Effects of cd or/and Pb on soil enzyme activities and microbial community structure. *Ecological Engineering*, *37*(11), 1889–1894.

Paul, E. A. (2015). *Soil microbiology, ecology and biochemistry* (4th ed.). San Diego, USA.

Payne, J. E., Myers, W. S., Jr., Ehrgott, J. Q., Jr., Rickman, D. D., Thomas, C. D., & Windham, J. E. (2019). Investigation of relationships between soil type and condition and crater size for shallow buried explosive charges. *International Journal of Protective Structures*, *10*(2), 135–153.

Prentiss, A. M. (1937). *Chemicals in war*. McGraw-Hill.

Ritchie, G., & Dolling, P. (1985). The role of organic matter in the acidification of soil. *Australian Journal of Soil Research*, *23*(4), 569–576.

Runge, E. (1973). Soil development sequences and energy models. *Soil Science*, *115*(3), 183–193.

Salminen, R. (2005). Geochemical Atlas of Europe, Geological Survey of Finland. http://weppi.gtk.fi/publ/foregsatlas/index.php.

Schjønning, P., McBride, R. A., Keller, T., & Obour, P. B. (2017). Predicting soil particle density from clay and soil organic matter contents. *Geoderma*, *286*, 83–87.

Seibert, J., Stendahl, J., & Sorensen, R. (2007). Topographical influences on soil properties in boreal forests. *Geoderma*, *141*, 139–148.

Seladji, S., Cosenza, P., Tabbagh, A., Ranger, J., & Richard, G. (2010). The effect of compaction on soil electrical resistivity: A laboratory investigation. *European Journal of Soil Science*, *61*, 1043–1055.

Sharma, P., & Dubey, R. (2005). Lead toxicity in plants. *Brazilian Journal of Plant Physiology*, *17*(1), 35–52.

Shaw, R. B., Doe, W. W., III, & Houston, S. (2001). *Ecological soil characterization of the Delta Creek and Washington impact areas, Fort Greely, Alaska*. North Carolina, USA.

Souvent, P., & Pirc, S. (2001). Pollution caused by metallic fragments introduced into soils because of World War I activities. *Environmental Geology*, *40*(3), 317–323.

Thouin, H., Le Forestier, L., Gautret, P., Hube, D., Laperche, V., Dupraz, S., & Battaglia-Brunet, F. (2016). Characterization and mobility of arsenic and heavy metals in soils polluted by the destruction of arsenic-containing shells from the Great War. *Science of the Total Environment*, *550*(15), 658–669.

Tóth, G., Hermann, T., Da Silva, M., & Montanarella, L. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International*, *88*, 299–309.

Tukura, B., Kagbu, J., & Gimba, C. (2007). Effects of pH and total organic carbon (TOC) on the distribution of trace metals in Kubanni dam sediments, Zaria, Nigeria. *Science World Journal*, *2*(3), 1–6.

Valente, D., Queiroz, D., Pinto, F., Santos, N., & Santos, F. (2012). The relationship between apparent soil electrical conductivity and soil properties. *Revista Ciência Agronômica*, *43*(4), 683–690.

Van Meirvenne, M., Meklit, T., Verstraete, S., & De Boever, M. (2008). Could shelling in the first world war have increased copper concentrations in the soil around Ypres? *European Journal of Soil Science*, *59*, 372–379.

Vicentini, F., Hendrychova, M., Tajovský, K., Pižl, V., & Frouz, J. (2020). The effect of topography on long-term spontaneous development of soil and woody cover on graded and untreated overburden. *Forests*, *11*(5), 602.

Wani, A., Ara, A., & Usmani, J. (2015). Lead toxicity: A review. *Interdisciplinary Toxicology*, *8*(2), 55–64.

War Office. (1915). *Treatise on ammunition* (10th ed.). War Office.

Watson, A. (2015). *Ring of steel: Germany and Austria-Hungary at war, 1914–1918*. Penguin.

World Health Organisation. (2004). *Copper in drinking-water*. World Health Organisation https://www.who.int/water_sanitation_health/dwq/chemicals/copper.pdf

World Health Organisation. (2019). *Lead poisoning and health*. World Health Organisation https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health

Wuana, R., & Okieimen, F. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *International Scholarly Research Notices*, *2011*, 1–20.

Yruela, I. (2009). Copper in plants: acquisition, transport and interactions. *Functional Plant Biology*, *36*(5), 409–430.

Zhang, C., Nie, S., Liang, J., Zeng, G., Wu, H., Hua, S., Liu, J., Yuan, Y., Xiao, H., Deng, L., & Xiang, H. (2016). Effects of heavy metals and soil physicochemical properties on wetland soil microbial biomass and bacterial community structure. *Science of the Total Environment*, *557–558*, 785–790.

Zhang, S., Huang, Y., Shen, C., Ye, H., & Du, Y. (2012). Spatial prediction of soil organic matter using terrain indices and categorical variables as auxiliary information. *Geoderma*, *171-172*, 35–43.

Zhang, Y., Zhang, H., Zhang, Z., & Liu, C. (2018). pH effect on heavy metal release from a polluted sediment. *Journal of Chemistry*, *2018*, 7597640.

How to cite this article: Williams, O. H., & Rintoul-Hynes, N. L. J. (2022). Legacy of war: Pedogenesis divergence and heavy metal contamination on the WWI front line a century after battle. *European Journal of Soil Science*, *73*(4), e13297. https://doi.org/10.1111/ejss.13297