

Pedological Factors on the Leaching of Heavy Metals from First World War Battlefields

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Abstract:

At the time that the armistice was signed in November 1918, what would become known as the First World War was the single most destructive conflict in human history. While millions were left dead on the battlefields of a conflict that spanned the globe, one unsung victim is seldom discussed: the environment. This study examines the impact that soil has on the concentrations of heavy metals that were left behind once the guns fell silent at a handful of locations that saw heavy fighting throughout the War. Heavy metal concentrations were found to be significantly different ($p < 0.1$) when compared to the background values of the heavy metals that were examined in this study. Sites that had higher amounts of clay in the soil were found to be more polluted than those that had a coarser texture due to a higher surface area and decreased material mobility.

Introduction:

Over the course of four years, what would become known as the First World War, became one of the most destructive and costly conflicts in human history. Between the two opposing blocs, the Entente and Central Powers, every major world power would become involved with over 68 million people being mobilized¹. As this was the first modern and properly industrialized war, a state of total war rapidly developed as every nation involved poured all its manpower and resources into the fight. In most cases, the distinction between military and civilian resources became blurred as nothing short of a complete victory could be accepted².

A deadly combination of tactical inflexibility combined with revolutionary new methods and technologies to wage war meant that millions of people who did not have to die, did. Although it is impossible to accurately know the total cost and level of destruction, it is estimated that the conflict resulted in some 40 million casualties: with 20 million dead¹. The First World War was notorious for the trenches that resulted from the stalemates that developed across the globe. Because of the nature of the conflict, hundreds of thousands of men would meet violent ends to fight for these small slivers in the Earth; only for them to be retaken the same day. The intensity and longevity of the stalemate resulted in a unique circumstance in which

some of the longest, largest, and most costly battles in human history, or in some instances multiple battles occurred on the same pieces of land, were able to occur. For example, at Ypres, between October 1914 and October 1918, there were five battles; and at Verdun, the battle there lasted for almost ten months. For nearly three and a half years, this stalemate would grind down the opposing armies until the manpower and resources advantages of the Entente were able to overwhelm the Central Powers in the closing months of 1918³.

It is impossible to understate the impact that the First World War had on the course of world history. The conflict completely tore apart the political, economic, social, and cultural fabric of the world. Institutions that had been around for hundreds of years were dismantled by the treaties that followed over the next few years. The Habsburgs, who had been at the helm of European politics for several hundred years, were overthrown. The Ottomans, who had been responsible for the final fall of the Roman Empire, were also gone³. Four major Empires ceased to exist (German, Russian, Austro-Hungarian, and Ottoman) and the nations that rose from their ashes had the long and difficult process to find their place in the world, which often led to even more bloodshed⁸. While the aftermath of the First World War could fill an entire series of books, ultimately the greatest legacy of the conflict is that it created the conditions necessary for the outbreak of a Second World War that would begin a mere 20 years later².

While most contemporary historians focus on the human and economic damages of modern war, there is one victim of every conflict that very few tend to explore: the environment. On the Western Front alone, it is estimated that 1.45 billion rounds of artillery shells, gas canisters, bullets, bombs, etc., were expended in anger¹. These munitions did not simply disappear once they were expended. To this day, many of them remain. As many of the trench networks on the Western Front carved their way through the farmland of Belgium and France,

what has become known as the “Iron Harvest” occurs annually; in which farmers tilling their land will uncover munitions that have been left forgotten. In the immediate aftermath of the war, the French and Belgian Governments established “Le Zone Rouge” (the Red Zone)⁴.

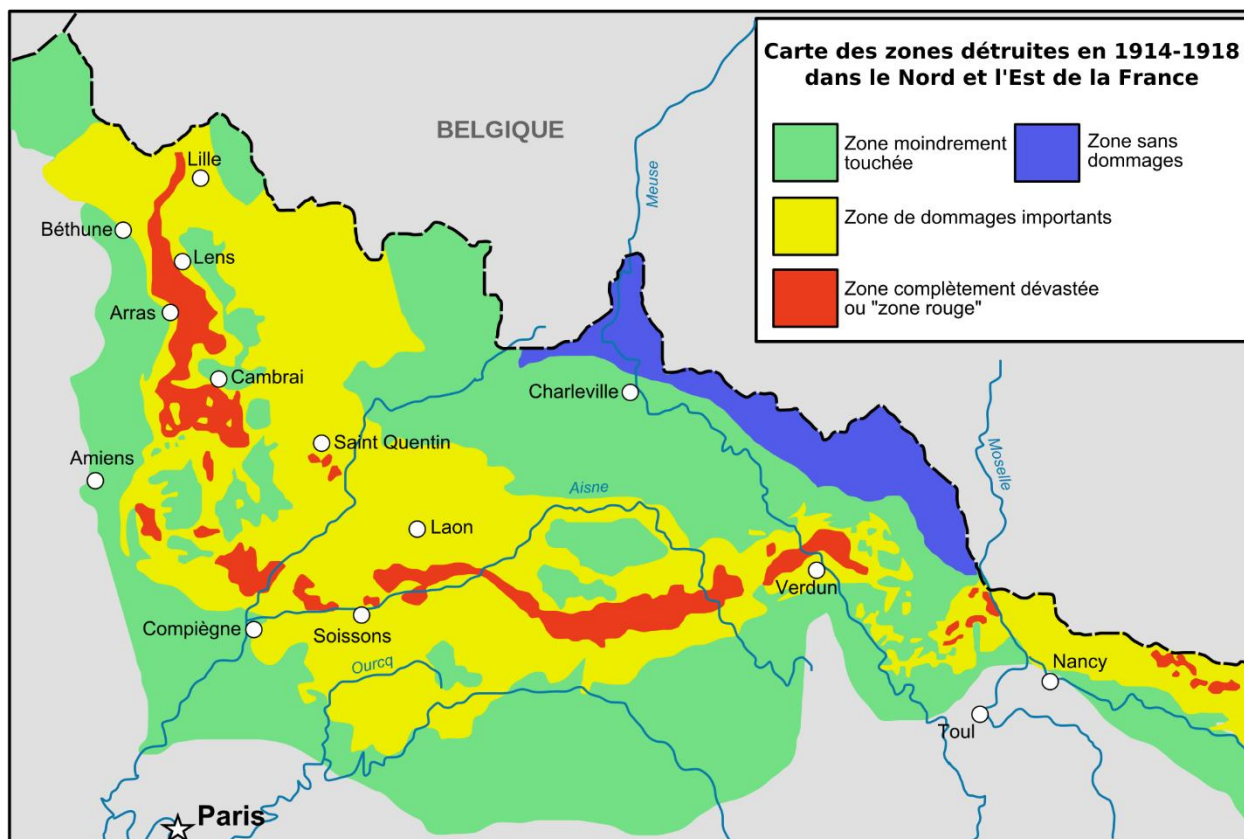


Figure 1. The Red Zone within the modern borders of Belgium and France

The Red Zone originally covered around 1,200 square kilometers (460 sq. mi.). The Red Zone was defined as “Completely devastated. Damage to properties: 100%. Damage to Agriculture: 100%. Impossible to clean. Human life impossible”. This area forbids such human activities such as housing, farming, and forestry. Because of the munitions that were used, the soil and water supply of the affected areas are heavily contaminated by lead, mercury, iron, copper, zinc, arsenic, and other heavy metals. While some of these heavy metals are necessary for basic functions in all life, high enough amounts can prove deadly⁵.

Despite the levels of destruction being relatively consistent, the levels of contamination in the present day are not. In this paper, the heavy metals that contaminate the affected areas will be examined and the reasoning as to why some areas are remain more contaminated will be determined.

Literature Review:

1. Heavy Metals:

By definition, heavy metals are metals with a relatively high density, atomic weight, and atomic number. Heavy metals vary greatly in both physical and chemical properties. Some, such as iron, are harmless to the touch; while others, such as uranium, are highly radioactive.

Although they are relatively rare within the Earth's crust, they are highly valued commodities in the modern world. Heavy metals were some of the earliest known elements to man. Elements such as iron, tin, and copper were instrumental in the building of civilization, while silver and gold were used to finance that construction. Heavy metals are used in almost everything from something as simple as cutlery, to particle accelerators. The world in which we live is built upon these elements⁶.

1.1 Heavy Metals in Biology

While most would associate heavy metals with tangible objects, they are also fundamental in basic cellular processes. The Table below lists a sample of essential nutrients and what functions they perform in the human body:

Element	Functions in the Human Body
Iron	Cellular Respiration Oxygen Transport

Zinc	Enzyme Function Protein Function Gene Expression
Copper	Organ Function Metabolic Processes Fetal Development
Chromium	Glucose and Lipid Metabolism
Magnesium	Required for Processing ATP

Table 1. List of essential nutrients in the human body⁷

These and a variety of other heavy metals are known as trace elements. Although these are needed for life to function, high amounts of heavy metals are extremely toxic. Other heavy metals, no matter the concentration, are toxic to humans⁷.

Element	Acute Exposure	Chronic Exposure
Lead	Diarrhea Fever Vomiting	Anemia Encephalopathy Foot drop/wrist drop Nephropathy
Mercury	Encephalopathy (brain dysfunction) Nausea Vomiting	Stomatitis Nausea Nephrotic syndrome Neurasthenia Parageusia Pink Disease Tremor
Arsenic	Nausea Vomiting Diarrhea Encephalopathy Multi-organ effects Arrhythmia Painful neuropathy	Diabetes Hypopigmentation/Hyperkeratosis Cancer

Table 2. List of heavy metals that are harmful to humans⁷

1.2 Heavy Metals in Munitions

In the decades preceding the First World War, military technology had advanced more rapidly than in any other point in history. Armies that had numbered in the tens of thousands that had been equipped with black powder rifles and cannons that were capable of firing a handful of lead projectiles every minute had evolved into mobile population centers that numbered in the millions that used materials that had been unobtainable in the centuries prior. With the onset of the industrial revolution, the materials and technology which could be used to wage wars changed very rapidly. Comparatively slow moving and short-range lead musket balls had evolved into high velocity copper jacketed bullets that would not melt under the heat and pressure of being fired from a gun barrel and could travel distances farther than the human eye could see. Cast iron or bronze artillery pieces that launched projectiles a few dozen kilograms in weight only several hundred meters at slow moving infantry columns, were now steel monstrosities, capable of firing projectiles that weighed hundreds of kilograms dozens of kilometers with almost pinpoint accuracy. This mass advancement was due to the newly available materials that these weapons could be constructed of. At the turn of the 19th century, the strongest materials available to arms manufacturers were cast iron and bronze. While both capable materials, all of it had to be made by hand, which inevitably led to inconsistencies in strength; often resulting in catastrophic failures. While stronger materials did exist, such as steel, the costs to produce better alloys made it impractical for large scale production. The industrial revolution substantially decreased the production costs for better materials to the point where by 1914 every nation could produce millions of guns and ammunition every month⁸.

This paper will primarily focus on the usage of several key heavy metals: Iron, Zinc, Copper, Nickel, Chromium, Lead, Mercury, and Arsenic. Iron was by far the most widely used material in the conflict. Everything from steel helmets to tanks used iron in its construction to

some degree. Zinc was used in the construction of mechanical fuzes, a relatively new addition to munitions manufacturing. Fuzes are used to detonate an explosive payload within something like an artillery shell or grenade⁹. Because of the relatively new introduction of these mechanical fuzes, many would malfunction under the thousands of G's of acceleration from being fired from a gun. This was so prevalent, that it is estimated that up to one-third of all shells fired during the war failed to detonate. Zinc was also a component in the brass shell casings that were used in the hundreds of millions. Many of these casings were buried in the mud of the trenches and no mans land; only to be blown to bits¹.

Copper was used very extensively in all forms of munitions. The musket balls that had preceded modern munitions were made of lead. Since the arms revolution of the 19th century, the velocity, and pressures which munitions were now fired had increased rapidly. Being a comparatively malleable material, lead projectiles began to melt under these new stresses. To combat this, the soft lead projectiles were coated in copper and other copper alloys. The most popular alloy is known as gilding metal, a combination of copper and zinc. The British War Office at the time of the war defined gilding metal as "8 parts copper to 1 of zinc" (11% zinc)¹⁰. Another popular alloy was cupronickel, a copper-nickel alloy. Nickel and Chromium were not used in their pure forms but were rather used in alloys. Both elements were used to strengthen certain materials, such as bullet casings or highly machined equipment⁹.

Lead, as stated earlier was used primarily in the manufacture of bullets. Artillery shells also used lead in the form of shrapnel balls, primary explosives, and chemical warfare equipment. Mercury in the form of Mercury (II) fulminate is used as a primary explosive. Primary explosives are used to detonate the explosive charge in artillery shells or propellant charges in bullets⁸.

Arsenic and the variety of compounds that it was produced in, was used as a raw material primarily in the production of chemical warfare agents, lead alloys, and smoke generators. Approximately 480,000 tonnes of nitroaromatic explosives and intermediates were produced by Germany alone between 1914 and 1918. The two main arsenical warfare agents produced by Germany, diphenylchloroarsine and diphenylcyanoarsin, were manufactured in quantities of nearly 7,000 tonnes. In the immediate aftermath of the war, one of the main safety issues was disposing of these arsenical munitions. Most of these were disposed of in Belgium and France through burning. The combustion of arsenical compounds produces arsenic trioxide (As_2O_3) and arsenic pentoxide (As_2O_5). When combined with hydrochloric acid (HCL), the highly volatile arsenic trichloride (AsCl_3) is produced and carried down wind to be deposited in other areas¹¹.

2. Soil:

Soil is defined as the combination of minerals, gases, liquids, organic matter, and organisms that supports life. The pedosphere, which is the Earth's entire body of soil has four main functions: a habitat for organisms, a medium for plant growth, to serve as system for water storage, supply and purification, and as a modifier of the atmosphere. In combination with the lithosphere, hydrosphere, atmosphere, and biosphere, the pedosphere is a critical component in what makes the Earth capable of supporting life¹².

2.1 Soil Formation

Soil formation (pedogenesis) is an incredibly complex and drawn out process that combines physical, chemical, biological, and in many cases anthropogenic processes. Vasily Dokuchaev, a Russian geologist who is considered the father of pedology, determined that

pedogenesis occurs over time under the influence of several factors: climate, vegetation, topography, and parent material. He quantified his theory with the soil forming equation:

$$\text{Soil} = f(\text{cl}, \text{o}, \text{p}) \text{ tr}$$

Where cl is climate, o is organisms, p is biological processes, and tr is relative time. In contemporary pedology, this equation has been further refined into the mnemonic device Clorpt. Clorpt is defined as:

$$S = f(\text{cl}, \text{o}, \text{r}, \text{p}, \text{t})$$

Where S is soil, cl is climate, o is organisms, r is relief, p is parent material, and t is time.

Climate affects soil by altering the rate of biological activity and chemical reactions within the soil itself. Rainfall influences the water content and movement, which in turn affects the rates of macro and micronutrient cycles within the ecosystem. Climate extremes such as ice, wind, flooding, etc., can cause physical weathering and soil erosion. Overall, higher temperatures and rainfall will produce more developed soils.

The combination of microbial, fungal, plant, animal, and anthropogenic influences deeply influences many characteristics of soil. Microbial and fungal influences are particularly important as they can increase such processes as nitrogen fixation and phosphorous extraction. Plants contribute heavily to the level of humus (compost) in the organic layer and the roots help anchor the soil in place; reducing the rate of soil erosion. Animals such as earthworms and other bioturbators rework soils and sediments to improve nutrient availability throughout the soil structure. The presence of certain organisms can help define the overall soil type of an

ecosystem. Inceptisols are a result of the acidic leaf litter of coniferous forests, while prairie grasses create mollisols.

The relief is simply the effects that topography has on the soil. Topography determines how soil is moved, distributed, and retained within the landscape as gravity will pull water and other nutrients to lower elevations. Higher relief soils are much more susceptible to adverse environmental conditions such as extreme weather, fire and other forces of nature that may damage the soil or increase the rate of erosion. Relief will also affect the types of vegetation and other organisms that will be able to exist there.

The parent material of a soil is the underlying geological material that forms the basis of the soil itself. Soil very often inherits many physical and chemical characteristics from the parent material. Parent material can be divided into two distinct classes: consolidated and unconsolidated. Consolidated parent material is composed from consolidated rock which can be igneous, sedimentary, or metamorphic rock. Chemical and physical weathering will break down the parent material until it can be incorporated into the soil itself. Unconsolidated materials are transported materials and are classified by its means of transport: ice, water, gravity, and wind. Ice transported material comes in the form of glacial till that was dragged by a moving ice sheet. Water transported come in several forms; the most important of which are alluvium (stream transport), lacustrine (lake deposits), and marine sediments (ocean deposits). Gravity transported materials (colluvium), are rock fragments that have journeyed downslope. Wind transported materials (aeolian) are extremely small particles that are no larger than sand.

The last, and most important factor, in soil formation is time. The formation of soil is a painfully slow process in natural conditions and can often take thousands of years to form even the poorest of soils. Agricultural soils, notably mollisols, take even longer. The process of

breaking down parent material into usable sizes and combining it with enough organic material is no easy process¹².

2.2 Soil Classification

The classification of soil is in many ways like biological taxonomy. The USDA lists soil taxonomical levels from the most general to specific as Order, Suborder, Great Group, Subgroup, Family, and Series. In this paper, soils will be examined at the Family level. Taxonomical level in soil is determined by a variety of factors including the variations in clorpt, as well as characteristics such as depth, moisture, texture, cation exchange capacity, salt content, etc.

Soil orders are the largest and most general grouping in soil taxonomy. Orders describe the general development and properties of the soil. Below is a simplified guide to the major soil orders and some of their characteristics:

Soil Type	Characteristics
Entisols	<ul style="list-style-type: none"> • Recently formed soils • Lack well-developed horizons
Inceptisols	<ul style="list-style-type: none"> • Young soils • Have very little horizon formation
Aridisols	<ul style="list-style-type: none"> • Soils in desert conditions
Mollisols	<ul style="list-style-type: none"> • Soils associated with grasslands • Very deep and fertile
Alfisols	<ul style="list-style-type: none"> • Soils with high amounts of aluminum and iron
Spodosols	<ul style="list-style-type: none"> • Acidic soils • Associated with coniferous and deciduous forests
Ultisols	<ul style="list-style-type: none"> • Acidic soils in the tropics • Very weathered
Oxisols	<ul style="list-style-type: none"> • Heavily weathered • Rich in iron and aluminum oxides
Histosols	<ul style="list-style-type: none"> • Soils found in bogs

Vrtisols	<ul style="list-style-type: none"> • Inverted soils • Very clay rich
Andisols	<ul style="list-style-type: none"> • Soils made from volcanic ash • Young and very fertile
Gelisols	<ul style="list-style-type: none"> • Soils with permafrost

Table 3. Major soil types with defining characteristics¹³

Soil Suborders are divided based on soil properties and horizon which are determined by temperature and moisture profiles. Great Groups are a subdivision of Suborders in which the order and makeup of each horizon differentiates one soil from another. Distinguishing features such as the amount of iron, clay, organic material, temperature, etc., are all used to identify a soil. Soil subgroups are generally divided into three categories: typic, intergrade and extragrade. Typic soils represent the typical description of the great group which it is part of. Intergrade soils represent properties which suggest how it is similar to other soil great groups, suborders, or orders. Extragrade soils represent soils that are too different to be included in another soil classification.

Soil families are categorized based on the physical and chemical properties of a soil that influence its ability to interact with agricultural and engineering applications. The main characteristics that influence the family are texture, mineralogy, pH, permeability, structure, consistency, the amount of precipitation, soil temperature, and the percentage of silt, sand, and more coarse fragments such as gravel. The soil series is simply the location in which the soil was found¹³.

2.3 Heavy Metals in Soil:

Heavy metals in soils are an integral part in how soils interact other parts of the ecosystem. All naturally occurring heavy metals originate from the lithosphere. Through

weathering and erosion, the parent material is broken up and eventually the metals that were in the parent material will become available in the soil¹⁴.

	Upper Crust	Sandstone	Shales	Limestone	Granite
As	2	0.5	13	1.5	3
Cd	0.1	<0.04	0.25	0.1	0.1
Cr	35	35	100	5	10
Cu	14	2	45	6	12
Ni	19	2	2	0.3	5
Pb	17	10	22	5	20
Zn	52	20	100	40	50

Table 4. Lithogenic sources of heavy metals in mg/kg¹⁵

There are several factors that determine what heavy metals and how much of that metal are present. Depending on the parent material, certain heavy metals will be prevalent more so than others. Most metalloids that are naturally present in soil are in the forms of cations and anions and a soils ability to adsorb these cations and anions is crucial in their availability to whatever organism needs them¹⁵. Anthropogenic influences are also a source of heavy metals. Many fertilizers, pesticides, and herbicides introduce many heavy metals that would otherwise not naturally find their way into the soil¹⁶.

2.4 Other factors affecting soil

There are several other factors that will affect how soil develops and behaves. Chiefly among these factors is texture. Texture is quantified by the ratio of sand to silt to clay¹².

Name of soil separate	Diameter limits (mm)
Clay	less than 0.002
Silt	0.002 – 0.05
Very fine sand	0.05 – 0.10
Fine sand	0.10 – 0.25
Medium sand	0.25 – 0.50
Coarse sand	0.50 – 1.00
Very coarse sand	1.00 – 2.00

Table 5. Particle sizes that determine texture¹²

Texture varies wildly between soil types and there are ranges that a description of texture may fall into¹³.

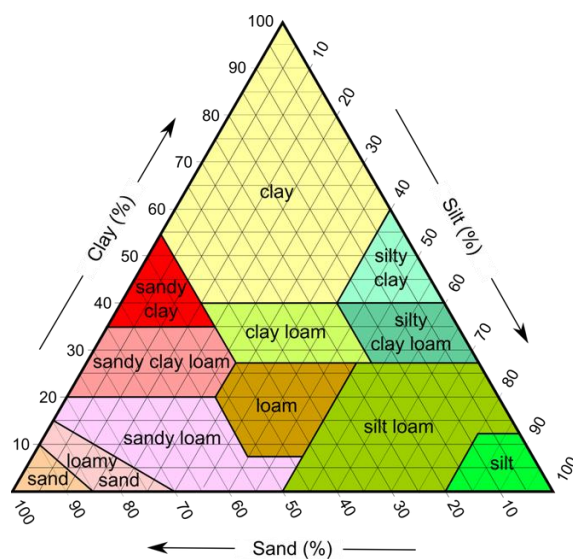


Figure 2. Texture triangle used to define texture¹³

Another factor on the way that soil behaves is the Cation Exchange Capacity (CEC). Measured in cmol/kg, the CEC is a measurement of the number of cations that can be retained on soil particle surfaces. The negative charges on soil particles such as clay, attract positively charged cations. In general, clay and organic matter are responsible for the CEC, although this is not always the case. CEC is a general measurement of fertility as it increases the bioavailability of several key nutrients such as potassium and calcium. Conversely, it also increases a soils ability to retain pollutant cations such as lead. pH has a profound effect on the CEC as an increase in pH increases the amount of positive charge within the soil, thus increasing the CEC¹⁵.

Methods:

It should be noted that the data used in this paper is not original. Data was gathered at each location by the respective authors who penned the papers *Geostatistical Assessment of the Impact of World War I on the Spatial Occurrence of Soil Heavy Metals*, *Exposure assessment of a burning ground for chemical ammunition on the Great War battlefields of Verdun*, *Pollution caused by metallic fragments introduced into soils because of World War I activities*, and *Effect of Warfare Waste on Soil: A Case Study of Gallipoli Peninsula (Turkey)*.

1. Sampling Locations

The scale of the First World War is truly unfathomable. From the fields of Flanders to pieces of coral in the South Pacific, the war was fought on four continents². For the purposes of this study, four locations have been selected: Ypres, Verdun, the Isonzo, and Gallipoli.



Figure 3. Map of Eurasia (with sample areas denoted by arrows) with 1914 National Borders

1.1 Ypres

The study at Ypres was done over an area of 640 km² in the south of West-Flanders, Belgium. This area represents the entire warzone of the four major engagements, the First (1914), Second (1915), and Third Battles (1917) of Ypres, and the German Spring Offensive (1918), that occurred in the area over the course of the war. While the city of Ypres itself was

never conquered by the advancing Germans, the city was destroyed by artillery fire³.

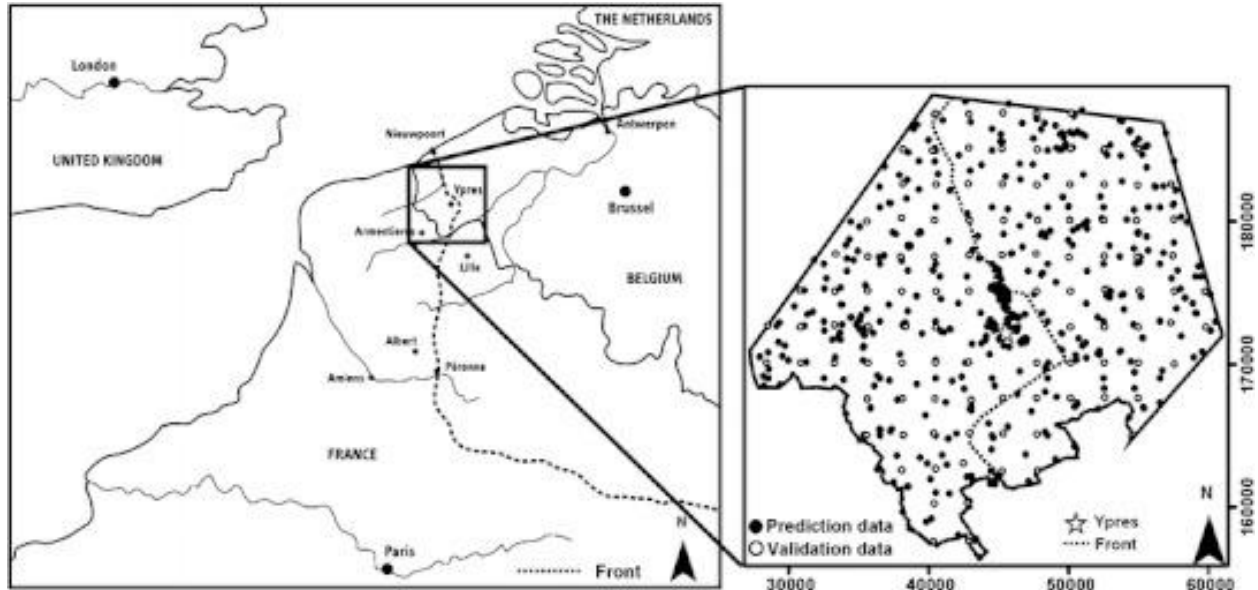


Figure 4. Study area located within Flanders and the frontline relative to the city¹⁷

The soil located around Ypres is classified as “Pleistocene (Weichsilian) wind-blown sediments deposited over Tertiary marine clayey sediments (Ypresian).” The texture profile gradually shifts from being a sandy-silt in the north and center to a silt in the south. Clayey profiles are present in the extreme south and north-east. The topography of the area is relatively flat, ranging between 10 and 30m above sea level with a chain of hills in the southwest rising to 151m. At present, most of the land is used for agriculture¹⁷.

1.2 Verdun

Verdun was the site of the longest and one of the most costly battles of the entire war. Over the course of 302 days, over 300,000 soldiers lost their lives. Unlike the other sites which occurred over hundreds of kilometers, the entire battle at Verdun was fought in the space equivalent to that of modern metropolitan Berlin (about 30 km²)¹.

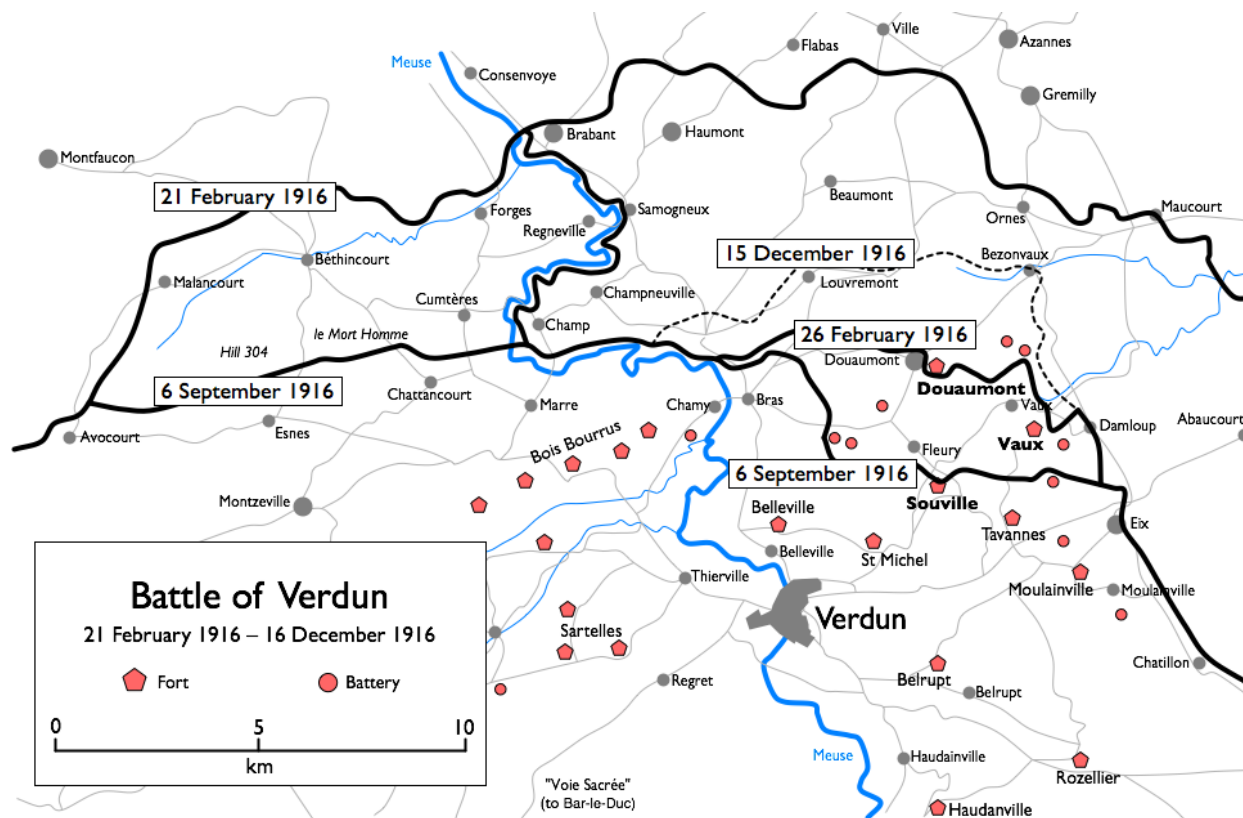


Figure 5. Verdun and frontline movement

This study was conducted in the northeast of Verdun, in an oak-hornbeam forest of the Woëvre-plain. The exact location being at a place referred to as "place à gaz" (place to gas) in the western edge of the Spincourt Forest. This site was the location of a former German ammunition dump with many of the munitions being arsenic laden gas shells. The area itself is rather small, measuring 70m in diameter, with little vegetation. The center of the opening is covered in a layer of ash, charcoal, scoria and various elements of ammunition.

Pedologically, the soils surrounding Verdun are mostly Hapludalfs, which are better drained Alfisols. The study area in question has incredibly clay rich soils formed from Callovien bedrock that contains lime, gypsum, and iron-rich layers. The heavy clay layers prevent precipitation from infiltrating deeper into the soil¹¹.

1.3 Isonzo

The Isonzo River played witness to a series of twelve battles over the course of the war from June 1915 to November 1917. Some 500,000 soldiers met their ends fighting for the sixty-mile long Isonzo Valley¹.

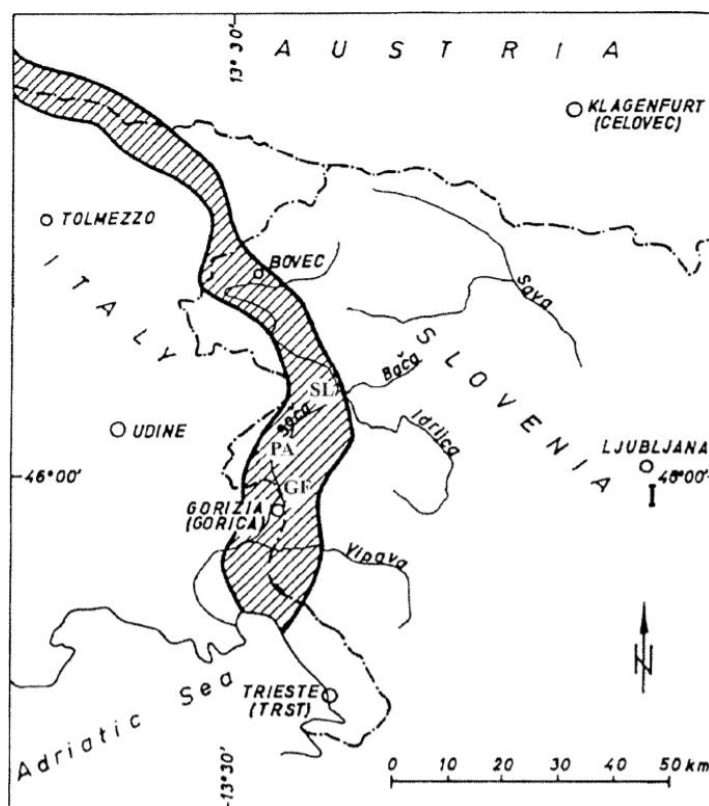


Figure 6. The Isonzo Front with sample site locations (Denoted by GF, PA, and CL)¹⁸

The three sample sites at Sela pri Volčah (SL), Prižnica (PA), and Nova Gorica (GF) were selected to diversify the geology and soil type of each sample. The site at Sela pri Volčah has a Late Cretaceous marlstone parent material that contains calcite, quartz, feldspar, muscovite, and chlorite. The main soil type found in this area is classified as a rendzina; a very humus and lime-rich soil. At Prižnica, the parent material is an Early Cretaceous limestone with calcite, with some quartz, feldspars, muscovite or illite and chlorite. The soil type is a cambisol. At Nova

Gorica, the parent material is a sandstone bedrock containing quartz, calcite, feldspars. The soil type is also a cambisol¹⁸.

1.4 Gallipoli

The Gallipoli Peninsula was the sight of a futile 11-month campaign by the British Empire to force the Dardanelles in order to take Constantinople and force the Ottomans out of the war. This coincidentally the first time the Australia and New Zealand had fought under their own flags as part of the Australian and New Zealand Army Corps (ANZAC).

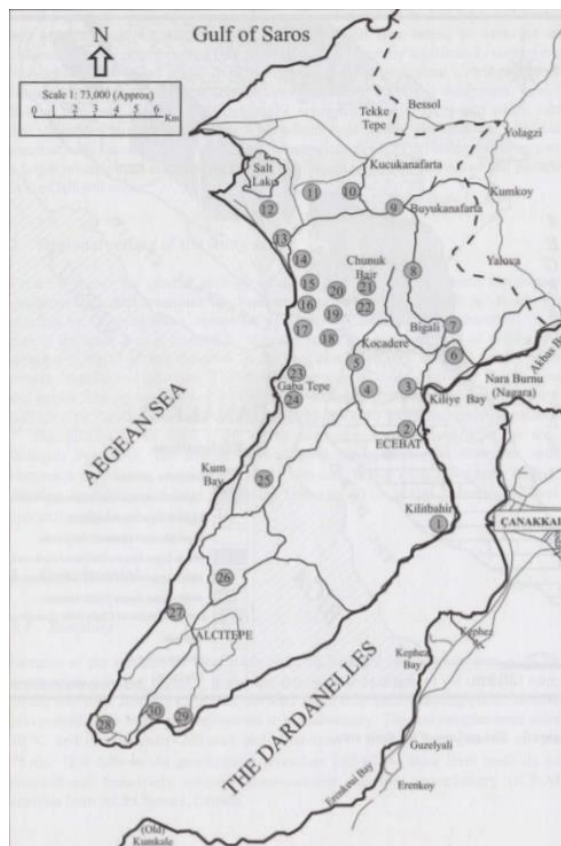


Figure 7. The Gallipoli Peninsula with sample sites¹⁹

Soil samples were taken from 30 locations throughout the peninsula, mainly at Cape Helles, ANZAC Cove, and Sulva Bay, as is marked in Figure 6. These three landing sites saw

the greatest intensity of fighting. The parent material of the entire peninsula is quite diverse, with Upper Miocene Neritic limestone around the southern ANZAC landing sites at Cape Helles and Upper Miocene Pliocene undifferentiated rocks and Quaternary Alluvium at ANZAC Cove and Sulva Bay in the North. The soil type throughout the area is entirely Noncalciic Brown and Redzina¹⁹.

2. Field Methods

2.1 Ypres

Data on heavy metal concentrations in the study area came from four sources: 392 samples from the Public Waste Agency of Flanders (OVAM), 38 samples from Ghent University, 102 samples from a grid of independent validation data, and 199 samples selected based on geostatistical criteria from the authors of *Geostatistical Assessment of the Impact of World War I on the Spatial Occurrence of Soil Heavy Metals* for a total of 731 samples.

The concentration of heavy metals from all of the soil samples were determined by a microwave digestion of the air dry fine-earth fraction (<2 mm) using HCl, HNO₃, and HF. During the digestion, the concentrations of heavy metals were analyzed by inductively coupled plasma atomic emission spectrometry (ICP-AES). In ICP-AES, inductively coupled plasma is used to produce excited atoms and ions to emit electromagnetic radiation that is characteristic of a specific element. In this study, the ICP-AES was used to test for several elements: Arsenic, Cadmium, Chromium, Copper, Mercury, Nickel, Lead, and Zinc.

Once these samples had been processed, they were compared to the legal thresholds of heavy metals in agricultural land, defined as containing 10% clay and 2% organic matter, as provided by the OVAM. As the data provided by the OVAM regarding Arsenic, Cadmium, and

Mercury is censored, Indicator Kriging (IK), a geostatistical modeling program, was applied to fill in the gaps as a result of these censors¹⁷.

2.2 Verdun

To fully understand the quantitative and qualitative nature of heavy metal contamination this study was divided into two stages. The first stage involved taking 500 g samples of the scoria and upper ash layers on the test site. In the central burn zone, ten samples of the scoria were taken at a depth of 0-5 cm. Two 500 g samples were taken from the Bv horizon at a depth of 10-15 cm. Lastly, two 500 g samples were taken from the edge of the burning ground. One of these samples was taken from a pit filled with humic material and the other was taken 10 m away from the burning ground from the Bv horizon.

The second phase examined the mobility of the heavy metal contaminants. Three boreholes were drilled, one in the center of the burning ground and two others at the edge of the burning ground and the soil cores removed. The soil horizons of each borehole were separately examined in a laboratory. These boreholes were filled with ceramic suction cups that had pore sizes of 1 μm . Bentonite was used to fill each borehole and the leachate was collected in 500 mL bottles. Leachate was collected every two weeks from each borehole. This phase saw an additional eight soil samples taken from the root zones and mosses on the edge of the burning ground at a depth of 0-2.5 cm.

All soil samples were air dried and was ground in a mortar to a particle size of <200 μm . The soil samples from the first phase was analyzed using a Carbon, Hydrogen, and Nitrogen Analyzer (CHNS). Aliquots of the soil samples were extracted with aqua regia to determine the

concentrations of heavy metals and a 1 M ammonium nitrate solution to calculate the mobile fraction in the liquid samples¹¹.

2.3 Isonzo

At the Isonzo, samples of both parent materials and soil were taken from each of the three locations at Sela pri Volčah, Prižnica, and Nova Gorica. At Sela pri Volčah and Prižnica, a metal detector was used to identify and collect all metallic fragments at and just below the soil surface.

All geochemical soil samples were air dried and sieved through a 2-mm sieve. Further grinding, milling, and quartering reduced the grain size to 63 μm . The parent materials were also ground, milled, and separated to 63 μm . After aqua regia digestion that was performed at 95 °C with 3-1-2 HCl–HNO₃–H₂O, inductively coupled plasma emission spectrometry (ICP) was used to analyze 31 different elements (apart from mercury). Mercury levels were analyzed using atomic absorption spectrophotometry (AAS).

Pedological soil samples were oven dried for three days at 35 °C. After drying, all samples were sieved through a 2-mm sieve. Pedological analyses were performed according to Sparks and others (1996), Blum and others (1986), Head (1984) and Grasshoff (1976). pH was determined by soil suspension in 0.1 mol/l KCl. For texture, 10 g soil samples were first treated with 25 ml 0.4 mol/l Na₄P₂O₇/ 10 H₂O and then fed through a Kohn pipette device. To determine organic matter, the Walkley-Black method was used with oxidation in 0.5 mol/l K₂CrO₇ and in the presence of H₂SO₄. Nitrogen was measured using the Kjeldahl procedure with a TiO₂ catalyst.

Mineral concentrations and corrosion products of alloys in both parent materials and soil samples were determined by x-ray diffraction at 40 kV and 20 mA. From the metallic fragments

collected at the sites at Sela pri Volčah and Prižnica, elements in those fragments were determined by determined by optical emission spectrometry (OES). Bi, Cu, Fe, Sb, Sn and Zn in cast iron, Pb-alloy and brass metallic fragments were measured by infrared absorption spectrometry (IRS)¹⁸.

2.4 Gallipoli

Samples from the peninsula were taken from 30 locations. From a depth ranging between 0-20 cm about 5 kg of soil was taken from each location using a shovel. All samples were oven dried at 40 °C. Once dried, the samples were sieved through a <200 µm sieve and ground to achieve a grain size of 75 µm.

A microwave digestion technique was used for the total dissolution of each sample. .1 g of each soil sample was digested using a combination of hydrofluoric, nitric, and hydrofluoric acids. This solution was then placed into Teflon beakers and dried on a heating plate. 5 mL of concentrated HCl was twice added to the dried solution to remove any lingering fluoride ions. Once this final solution was fully dried, ICP-AES was used to analyze each sample for 12 chemical elements (As, Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sr, V, Zn)¹⁹.

2.5 Statistical Analysis

With all of the data collected from each site by the respective studies, each site must be compared to the background values for each element to determine if the values found at each site are statistically significantly higher than the background values to prove if there is indeed an abnormally high concentration of heavy metals in these areas. Three tests were conducted: one for the median values, one for the mean values, and one for the proportional value of those samples that tested above the background value. Background values were determined using soils

maps that had a range of values over an area. The midpoint of each range was used when plugged into each formula.

For the hypothesis for the median and mean is as follows:

$$H_0: \mu \leq \text{Background Value}$$

$$H_1: \mu > \text{Background Value}$$

For the median and mean values, the equation below was used to determine the Z-Score.

$$Z = \frac{\bar{x} - u_0}{(\sigma / \sqrt{n})}$$

\bar{x} = median or mean μ = background value σ = Standard Deviation n = number of data points
--

For the hypothesis for each proportion is as follows:

$$H_0: p \leq 0.5$$

$$H_1: p > 0.5$$

For the proportion of those samples that were measured to be over the background values, the equation below was used with a population proportion of 0.5.

$$Z = \frac{\hat{p} - p}{\sqrt{\frac{pq}{n}}}$$

\hat{p} = sample proportion p = population proportion $q = 1-p$ n = number of data points
--

Once the Z-Scores from all data sets have been calculated, the P-Value will be calculated with a significance value of 0.1 to determine if the concentration of each metal is statistically significant. Any P-Value that is greater than 0.1 is statistically significant.

Results:

Since each paper that these concentrations were sourced from were completed by different authors with different research criteria, the elements that were tested for are not consistent and thus some have been left out. For the purposes of this study, the elements that will be analyzed only contain As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, and Fe. The tables below for each site are presented as background values, summary statistics, and the Z-Scores and P-Values. Some background values for certain elements were not obtainable. In the tables containing Z-Scores and P-Values, values that are highlighted in red are significantly low and those in green are significantly high. All concentrations below are in mg/kg.

1.1 Ypres

As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
16	0.7	62	20	0.1	16	31	77

Table 6. Background Values of Heavy Metal Concentrations at Ypres¹⁷

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Min	3.7	0.01	5.9	0.85	0.04	1	1	6.7
Median	10	0.43	38	18	0.1	12.8	31	60
Max	70	2.5	210	250	1	70.2	950	620
Mean	10.5	0.52	40.7	23.3	0.14	14.2	47.6	81.9

Proportion	<0.3	<0.3	<0.3	0.46	N/A	<0.3	0.58	0.4
SD	4.63	0.3	16.49	20.57	0.1	7.71	61.85	76.12

Table 7. Summary Statistics of Heavy Metal Compounds within the Ypres study area¹⁷

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Z-Score (Median)	-18.28	-12.70	-20.53	-1.37	N/A	-5.85	0.00	-3.15
P-Value (Median)	<0.001	<0.001	<0.001	0.085	N/A	<0.001	0.500	0.001
Z-Score (Mean)	-16.76	-8.46	-18.22	2.26	N/A	-3.29	3.77	0.91
P-Value (Mean)	<0.001	<0.001	<0.001	0.012	N/A	0.001	<0.001	0.181
Z-Score (Prop)	-5.64	-5.64	-5.64	-1.13	N/A	-5.64	2.26	-2.82
P-Value (Prop)	<0.001	<0.001	<0.001	0.129	N/A	<0.001	0.012	0.002

Table 8. Z-Scores and P-Values from Ypres

From *Geostatistical Assessment of the Impact of World War I on the Spatial Occurrence of Soil Heavy Metals*, it was found that at the regional level, the median concentrations for all metals measured were found to be equal to or lower than the background values determined by the OVAM. Despite the medians, the means for Cu, Hg, Pb, and Zn were all higher than the background values. The levels of Hg in the soil were considered misleading as the background were so low, making an accurate measurement extremely different. After using their spatial model, it was determined that the increased levels of Cu, Pb, and Zn were linked to WWI activities, especially in the areas around the Ypres salient¹⁷. The Z-Scores and P-Values indicate that there is lead pollution throughout the study area. These values however are misleading as the authors of the original data clearly stated that the concentrations of Cu, Pb, and Zn were all statistically much higher around the front line as shown in Figure 7. There was a particularly high concentration of arsenic behind the line in the southern part of the study area, but this was

determined to be because of an ammunition burning site that was established post-war. Soil texture seemed to have an effect on the element concentrations being studied, most of the soil within the study area was found to be a sandy-silt, with bands of silt and clay towards the southern tip of the study area. It was found that as the percentage of clay increased, so too did the concentrations of heavy metals¹⁷.

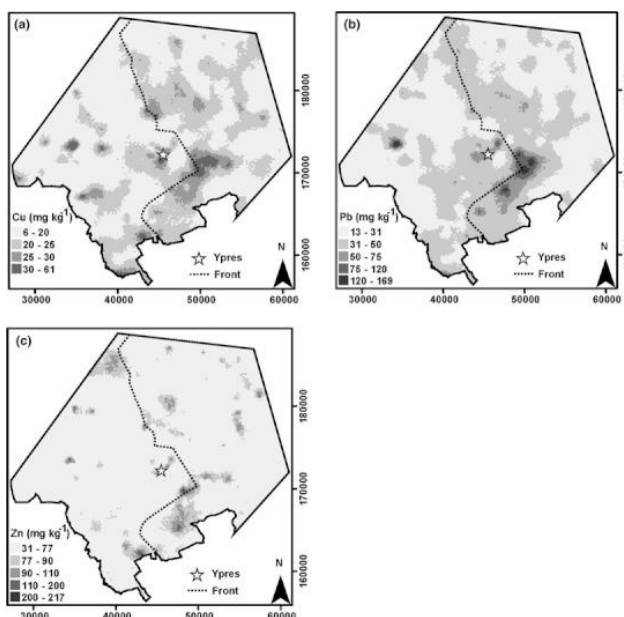


Figure 8. Cu, Pb, and Zn concentrations around the Ypres salient¹⁷

1.2 Verdun

The results from the Verdun site came in two separate studies: one at the topsoil and one in the soil cores. This was done primarily to see how mobile the metals being observed had been since the cease of hostilities.

As	Cr	Cu	Ni	Pb	Zn
15	60	15	75	32.5	55

Table 9. Background values of heavy metal concentrations at Verdun²⁰

	As	Cr	Cu	Ni	Pb	Zn	Fe
Min	59	18	20	8	176	289	14,695
Median	24,811.5	25.5	3,754.5	12	5,576	16,565.5	30,967.5
Max	175,907	39	16,877	17	26,398	113,237	96,900
Mean	52,362.57	26.57	5,744.43	11.79	6,942.36	34,018.21	44,061.07
Proportions	1.0	0.0	0.93	0.0	1.0	1.0	N/A
SD	58,204.66	29.19	5,974.24	3.21	6,988.88	39,251.71	26,895.86

Table 10. Summary Statistics of Heavy Metal Compounds in the topsoil samples at Verdun

	As	Cr	Cu	Ni	Pb	Zn	Fe
Z-Score (Median)	1.59	-4.42	2.34	-73.43	2.97	4.29	N/A
P-Value (Median)	0.056	<0.001	0.010	<0.001	0.002	<0.001	N/A
Z-Score (Mean)	3.37	-4.29	3.59	-73.68	3.70	3.24	N/A
P-Value (Mean)	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	N/A
Z-Score (Prop)	3.74	-3.74	6.95	-3.74	3.74	3.74	N/A
P-Value (Prop)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	N/A

Table 11. Z-Scores and P-Values of heavy metals at Verdun (Surface)

As shown in Table 7, the figures at this site compared to the others is much more toxic. Although there is a significant amount of variation within the concentrations of each respective element, the overall levels on contamination are much higher. Except for Cr, Cu, and Ni, each element is much higher than those found at the other sites. The Z-Score and P-Values also show that almost every element tested was statistically higher than the background values of the area. If it were not for the extreme variability in the sample values, the Z-Scores would have been

much higher. Through these values, it is evident that the site is extremely toxic even to this day.

The pH at the surface was also found to be slightly acidic, ranging between 4.8 and 5.8¹¹.

	As	Cu	Pb	Zn	Fe
Min	26	8	11	52	25,960
Median	115.5	115.5	17.5	241	36,793
Max	2,477	30	104	1,604	41,123
Mean	525.58	14.75	28.08	552.67	35,122.25
Proportions	1.0	0.17	0.83	1.0	N/A
SD	842.40	6.17	26.1	574.64	5,075.93

Table 12. Summary Statistics of Heavy Metal Compounds in the soil core samples at Verdun

	As	Cu	Pb	Zn	Fe
Z-Score (Median)	0.41	56.42	-1.99	1.12	N/A
P-Value (Median)	0.341	<0.001	0.023	0.131	N/A
Z-Score (Mean)	2.10	-0.14	-0.59	0.00	N/A
P-Value (Mean)	0.018	0.444	0.278	0.500	N/A
Z-Score (Prop)	3.46	-2.31	0.57	3.46	N/A
P-Value (Prop)	0.500	0.010	0.284	0.500	N/A

Table 13. Z-Scores and P-Values of heavy metals at Verdun (Soil Cores)

Within the soil cores, it was found that the level of contamination decreased as depth increased; although there was still a significant amount of iron found. The Z-Scores and P-Values also reflect this decrease in pollution with depth, although some elements are still significantly higher than the background values. One reason for the vast change in pollution was

the fact that this particular site was a former ammunition burning site. The combustion of the materials, particularly arsenic containing gas canisters, created a burned layer on the surface that prevented much of the material from absorbing into the lower layers of the soil. The soil textures from these samples were determined to be a silty-clay with the pH being a much more neutral 7.1¹⁷.

1.3 Isonzo

As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
7.5	0.45	32.5	30	<0.5	75	32.5	75

Table 14. Background Values of heavy metal concentrations at the Isonzo²⁰

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Fe
Min	2	0.2	30	44	0.27	30	120	53	28,200
Median	6	0.7	47	56	9.28	72	143	118	31,700
Max	10	2.2	73	225	9.28	75	1,005	278	42,400
Mean	6	1.03	50	108.33	3.46	59	422.67	149.67	34,100
Proportions	0.0	0.66	0.33	1.0	0.66	0.0	1.0	0.66	N/A
SD	4	1.04	21.67	101.21	5.05	25.16	504.45	115.79	7,397.97

Table 15. Summary Statistics of Heavy Metal Compounds within the Isonzo study area

	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	Fe
Z-Score (Median)	-0.65	0.42	1.16	0.45	3.01	-0.21	0.34	0.64	N/A
P-Value (Median)	0.259	0.337	0.123	0.326	0.001	0.417	0.367	0.261	N/A
Z-Score (Mean)	-0.66	0.97	1.40	1.34	1.02	-1.1	1.34	1.12	N/A
P-Value (Mean)	0.255	0.166	0.081	0.090	0.154	0.136	0.090	0.131	N/A

Z-Score (Prop)	-1.73	0.55	-0.59	1.73	0.55	-1.73	1.73	0.55	0.N/A
P-Value (Prop)	0.042	0.291	0.278	0.278	0.291	0.042	0.042	0.291	N/A

Table 16. Z-Scores and P-Values of heavy metals at the Isonzo

At the Isonzo, there was much lower levels of pollution than found at Ypres or Verdun. Despite this, it was found that the levels of pollution, particularly of Cu, Hg, Pb, and Zn, were still much higher than the background values. It was concluded that the elevated levels of these pollutants were directly because of wartime activities, particularly heavy artillery bombardment. Being a rather mountainous region, soil horizons are relatively thin and contain upwards of 60% stones by mass. Despite this, soil still played a role in the levels of pollution. It was found that overall, soils tested were found to be silty-loam, loam, or sandy-clay-loam and were overall well aerated and permeable. The pH values varied between 3.2 and 6.5, with the brown soil being the most acidic. Plant life was also found to play a part in the levels of pollution. The study found that the sites with more vegetation, particularly at the sites containing rendzina soil, many free-floating ions prefer adsorption into organic matter¹⁸.

1.4 Gallipoli

Cd	Cr	Cu	Ni	Zn
<0.5	35.1	15.1	67.7	36.7

Table 17. Background Values of heavy metal concentrations at Gallipoli¹⁹

	As	Cd	Cr	Cu	Ni	Pb	Zn
Min	2	<0.5	22	8	42	2	22
Median	6	<0.5	33.5	15	66.5	10	35
Max	72	<0.5	58	23	118	68	56

Mean	8.07	<0.5	35.07	15.07	67.7	13.87	36.67
Proportions	N/A	0.0	0.47	0.47	0.43	N/A	0.4
SD	12.63	<0.5	7.96	3.89	15.86	13.85	8.18

Table 18. Summary Statistics of Heavy Metal Compounds within the Gallipoli study area

	As	Cd	Cr	Cu	Ni	Pb	Zn
Z-Score (Median)	N/A	0.00	-1.1	-0.14	-0.41	N/A	-1.14
P-Value (Median)	N/A	0.500	0.136	0.444	0.341	N/A	0.127
Z-Score (Mean)	N/A	0.00	-0.02	-0.04	0.00	N/A	-0.02
P-Value (Mean)	N/A	0.500	0.492	0.484	0.500	N/A	0.492
Z-Score (Prop)	N/A	-5.48	-0.36	-0.36	-0.73	N/A	-1.10
P-Value (Prop)	N/A	<0.001	0.359	0.359	0.233	N/A	0.136

Table 19. Z-Scores and P-Values of heavy metals at Gallipoli

At Gallipoli, this site was found to be by far the least polluted out of the sites examined. Overall, the concentrations of each element were found much lower than was originally anticipated. There was one site that tested extremely high for As, but it was later determined that this was from a Turkish hospital that had been at that location. Several other elements, particularly of Pb, Cu, and Cr, were also shown to have a slight spike around the three main areas of battle at Sulva Bay, ANZAC Cove, and Cape Helles; but not enough to cause concern¹⁹. The Z-Scores and P-Values for the site also show that there are no significant levels of contamination. The soils on the peninsula are mostly sandy-silts in texture with a highly porous parent material.

Discussion:

1.1 Discussion of Results

The data collected and analyzed clearly shows that there are discrepancies of the pollution of heavy metals at each site. As originally hypothesized, there are differences in the overall level of contamination at each site. Overall, the sites at Ypres and Verdun were much more polluted than the sites at the Isonzo and Gallipoli. Although some of the data, specifically the Z-Scores and P-Values at each site could be misleading, further reading of the original data and publications revealed that there was more pollution than the analysis might have indicated. The $p=0.1$ significance level proved to be sufficient to determine if the samples were significantly high or not, although more vigorous testing would give a more accurate picture of the levels of contamination at each site.

There are several possible explanations as to why some sites were more contaminated than others. One factor could have been the climate that each site resides in, specifically the amount of precipitation that each area experiences. At first glance, it would make sense that with more rainfall, the pollutants of each area would simply be washed away over time. However, upon closer examination, the sites with the highest amount of precipitation, Ypres and Verdun, were also the most polluted. The amount of organic matter and plant life at each location could have also had an effect. In, theory, some plant life could remove some of the pollutants from the soil. Again, this cannot possibly be the reason as the areas that have the most vegetation, Ypres and Verdun, are the most polluted. The Isonzo is much more mountainous and Gallipoli is much dryer, both scenarios that are not good for plant growth and thus the concentration of organic matter in their respective soils.

The only two sensible factors for heavy metal contamination are soil texture and to a much lesser degree pH. Soil texture, as discussed before, is the ratio of sand to silt to clay. As a unit of clay has more surface area than silt or sand, it can be assumed that soils with higher amounts of clay have a higher surface area. This increase in surface area results in more places for heavy metals to latch onto and stay in the soil. Soils with greater clay concentrations are also less porous, therefore decreasing the rate at which water and other materials can move through the soil. To prove this point, the soil in Ypres around the Ypres salient, which had statistically higher amounts of Cu, Pb, and Zn, had a texture that was described as clay. Conversely, the soils on the Gallipoli Peninsula had a soil texture that was described as silty-sand while the soils at the Isonzo were varied between a silt-loam and a sandy-clay-loam. The CEC of these soils can also be assumed to be higher as clay increases the total cation availability. The sites at Ypres and Verdun are also now mostly used as agricultural land, further increasing the CEC of the soil as there is much more organic matter in the soil. A higher CEC would surely increase the concentrations of heavy metals broken down from munitions. The pH of each sites also affects the CEC as an increase in pH increases cation exchange. Ypres and the Isonzo proved to be slightly acidic while Verdun was neutral. pH also influences the overall movement of heavy metals as more acidic soils will break down wartime materials at a greater rate. But because the rates of pollution are higher at Ypres than at the Isonzo, it can be inferred that the texture must have a greater effect on the overall concentrations.

Looking at each individual site, there are also discrepancies of which metals were much more prominent than others. At Ypres for example, the data collected indicated that Cu, Pb, and Zn were present in the greatest concentrations in the area surrounding the Ypres salient. The maps as shown in figure 8 show that these metals are found in the highest concentrations in what

can be assumed to have been no mans land or the German front lines as it was general practice for the British artillery at the time to heavily bombard areas of no mans land with lead containing shrapnel shells to cut a path through the fields of barbed wire for the advancing troops. Arsenic also tended to concentrate in specific areas as well. In the cases at Ypres and Verdun, these were proven to be from ammunition burning sites while at Gallipoli it was due to what was determined to be a hospital. Unfortunately, maps were not available at the Isonzo so it is impossible to determine what might have caused certain elements to be more present than others.

1.2 Future Work

The greatest limitation for this study was the overall lack of available data. There were not as many sources as were initially hoped as any federally acquired data that was “supposed” to exist proved impossible to track down. Most of the sources provided only summary statistics which in turn limited that statistical analysis that could be done. If this work were to continue, more samples would need to be taken at each location. Some other factors to look into would be how topography affects the movement of material. Focusing on the frontlines and the areas that constituted no mans land would also be desirable as it can be assumed that these areas would have seen especially intense bombardment by artillery fire and fighting between troops. Lastly, expanding the number of sites tested would give a better picture of the global level of contamination. Sites such as ones along the Somme and Marne Rivers, as well as the areas where the Brusilov Offensive occurred or areas in Africa and the Middle East would give a much better representation of how the conflict affected the environment on a more global scale.

While this study demonstrated that there is still contamination that is directly contributed to the First World War, this would be the mere beginning of efforts to remediate those locations that are affected. Ideally, this study and studies at other sites could be used to determine

techniques for remediation to lessen the levels of contamination so that it is once again safe to live there. There are several such remediation techniques such as phytoremediation or perhaps fungi but that is a discussion for another study.

Conclusion

This study clearly supports that there is indeed a significant amount of heavy metal contamination at First World War battlefields and that soil is instrumental in just how contaminated each site is. While the amount of data that was available was sparse, what was there clearly indicated that there is a disparity between sites and that soil is a factor in that. With more data in terms of specificity and volume, a better understanding how just how much contamination is present and where it is located will be possible.

It is important to remember that this study only examined a small number of sites with a limited amount of data and that the scale of the conflict that caused this issue was much larger than a handful of locations. While this study did not show a complete picture of how or why these battlefields are still contaminated to this day, it is certainly a first step in remembering environmental legacy of the Great War.

References

1. Tucker, Spencer. World War I. Encyclopedia. ABC-CLIO, 2005.
2. Keegan, John. The First World War. The Bodley Head, 2014.
3. Gilbert, Martin. The First World War: A Complete History. RosettaBooks, 2014.
4. Heiderscheidt , Drew. “The Impact of World War One on the Forests and Soils of Europe.” *Digscholarship.unco.edu*, University of Northern Colorado, July 2018, digscholarship.unco.edu/cgi/viewcontent.cgi?article=1175&context=urj.
5. Gębka, Karolina, et al. “The Impact of Military Activities on the Concentration of Mercury in Soils of Military Training Grounds and Marine Sediments.” *Environmental Science and Pollution Research International*, Springer Berlin Heidelberg, Nov. 2016, www.ncbi.nlm.nih.gov/pmc/articles/PMC5101266/.
6. Minkina, Tatiana M. Heavy Metal Compounds in Soil: Transformation Upon Soil Pollution and Ecological Significance. Nova Science, 2010.
7. Zoroddu MA, Aaseth J, Crisponi G, Medici S, Peana M, Nurchi VM (June 2019). "The essential metals for humans: a brief overview". *J. Inorg. Biochem.* **195**: 120–29. doi: 10.1016/j.jinorgbio.2019.03.013. PMID 30939379
8. Hamilton, Douglas T. *Shrapnel Shell Manufacture: a Comprehensive Treatise on the Forging, Machining, and Heat-Treatment of Shells, and the Manufacture of Cartridge Cases and Fuses for Shrapnel Used in Field and Mountain Artillery, Giving Complete Direction for Tool Equipment and Methods of Setting up Machines, Together with Government Specifications for This Class of Munitions*. The Industrial Press, 1915.
9. Hamilton, Douglas T. *High-Explosive Shell Manufacture; a Comprehensive Treatise on the Forging, Machining and Heat-Treatment of High-Explosive Shells and the Manufacture of Cartridge Cases, Primers, and Fuses, Giving Complete Directions for Tool Equipment and Methods of Setting up Machines, Together with a Review of the Making of Powders, High Explosives, and Fulminates*. The Industrial Press, 1916.
10. Great Britain. War Office. Dress Regulations for the Officers of the Army. (Including the Militia), 1900. London: Printed for H.M.S.O. by Harrison and Sons, 1900.
11. Bausinger, Tobias, et al. “Exposure Assessment of a Burning Ground for Chemical Ammunition on the Great War Battlefields of Verdun.” *Science of the Total Environment*, vol. 382, no. 2, 2007, pp. 259–271., doi: 10.1016/j.scitotenv.2007.04.029.
12. Buol, Stanley W., et al. *Soil Genesis and Classification*, John Wiley & Sons, Incorporated, 2011. ProQuest Ebook Central, <https://ebookcentral.proquest.com/lib/hedberg-ebooks/detail.action?docID=1138972>.
13. *Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys*. U.S. Dept. of Agriculture, Natural Resources Conservation Service, 1999.
14. *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and Their Bioavailability*. Netherlands, Springer Netherlands, 2012.
15. Brady, Nyle C.; Weil, Ray R. (2008). *The nature and properties of soils* (14th ed.). Upper Saddle River, USA: Pearson.
16. Selim, H. Magdi, and Michael C Amacher. *Reactivity and Transport of Heavy Metals in Soils*. CRC/Lewis, 1997.

17. Meerschman, Eef, et al. “Geostatistical Assessment of the Impact of World War I on the Spatial Occurrence of Soil Heavy Metals.” *Ambio*, Springer Netherlands, June 2011, www.ncbi.nlm.nih.gov/pmc/articles/PMC3357735/#CR11.
18. Souvent, P, and S Pirc. “Pollution Caused by Metallic Fragments Introduced into Soils Because of World War I Activities.” *Environmental Geology: International Journal of Geosciences*, vol. 40, no. 3, 2001, pp. 317–323., doi:10.1007/s002540000156.
19. Baba, Alper, and Ozan Deniz. “Effect of Warfare Waste on Soil: A Case Study of Gallipoli Peninsula (Turkey).” *International Journal of Environment and Pollution*, vol. 22, no. 6, 2004, pp. 657–657., doi:10.1504/IJEP.2004.006056.
20. Tóth, Gergely, et al. “Maps of Heavy Metals in the Soils of the European Union and Proposed Priority Areas for Detailed Assessment.” *Science of The Total Environment*, vol. 565, 2016, pp. 1054–1062., doi: 10.1016/j.scitotenv.2016.05.115.