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Could shelling in the First World War have increased copper concentrations in the soil around Ypres?

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Summary

In the First World War, the region around Ypres (West-Flanders, Belgium) was a battlefield where millions of copper-containing shells were fired. To investigate the consequences of this shelling, we analysed statistically data on the copper (Cu) content in the topsoil (0–0.5 m) of the province of West-Flanders, an area of 3144 km^2. The measurements had been made on the fine earth (< 2 mm) fraction of 2786 samples. A preliminary screening of the data revealed larger concentrations of Cu in a region of approximately 625 km^2 around Ypres. These concentrations were estimated by ordinary block kriging on the logarithms of the Cu concentration with separate variograms for the battlefield area and the rest of the province and mapped. The median concentration in the battlefield area was 18.0 mg Cu kg^{-1} compared with 12.0 mg Cu kg^{-1} elsewhere. We conclude that the current Cu enrichment in the soil around Ypres is the legacy of the millions of shells that were fired in the First World War.

Introduction

During the First World War (WW I), fought between August 1914 and November 1918, an estimated 1.45 billion (1.45×10^9) shells were fired by the combined German, French and British armies on all fronts (Prentiss, 1937). Around 95% of these were conventional explosive shells; the others released toxic gasses. Attacks were usually initiated by massive artillery firing. For example, at the start of the 'Third Battle of Ypres' the British forces fired more than four million shells during the 15 days preceding the first infantry attack on 31 July 1917 (Keegan, 2000, p. 361). Every shell, whether conventional or toxic, contained a considerable amount of Cu. Whereas the body of the shell was made of iron or steel, the top fuse and some internal parts were made of brass, an alloy of about 70% Cu and 30% zinc (Zn). The rotating band, which had to be softer, contained 90% Cu and 10% Zn (see http://www.madehow.com/Volume-7/Shrapnel-Shell.html on 22/6/2007 for details). A typical shell weighed about 8 kg. The fuse and the rotating band weighed about 1 kg (Lt A. Loncke, personal communication). A typical shell is therefore estimated to have contained about 0.75 kg of Cu.

One might expect that so many shells would leave substantial amounts of Cu as pollutant in the soil. However, there have been few reports on the matter. Bausinger & Preuss (2005) investigated a site near Ypres where left-over ammunition had been destroyed after the war. They found unusually large concentrations of Cu and lead (Pb), and also increased amounts of arsenic, which was used in chemical warfare to produce nerve gasses. More recently, they did a similar study near Verdun, France, and reached similar conclusions (Bausinger *et al.*, 2007). Pirc & Budkovič (1996) reported that concentrations of Cu and Pb, among other elements, were more or less anomalously large in soils along the Italian–Slovenian front of the war. The same front was further investigated by Souvent & Pirc (2001), mainly with a focus on corrosion of the metallic fragments. These studies concluded that warfare could enhance concentrations of heavy metals in soil locally. As far as we know, no one has evaluated the spatial extent of the pollution or environmental impact of shelling over a large area.

With this in mind we wanted to assess to what extent shells fired during the First World War could have resulted in enhanced concentrations of Cu in soil today. The area around Ypres, where battle was prolonged and intense, seemed well suited for our investigation. We report our findings below.

Study area and Cu threshold

The province of West-Flanders (Figure 1) covers 3144 km^2. Except for polders and dunes along the coastline, the largest

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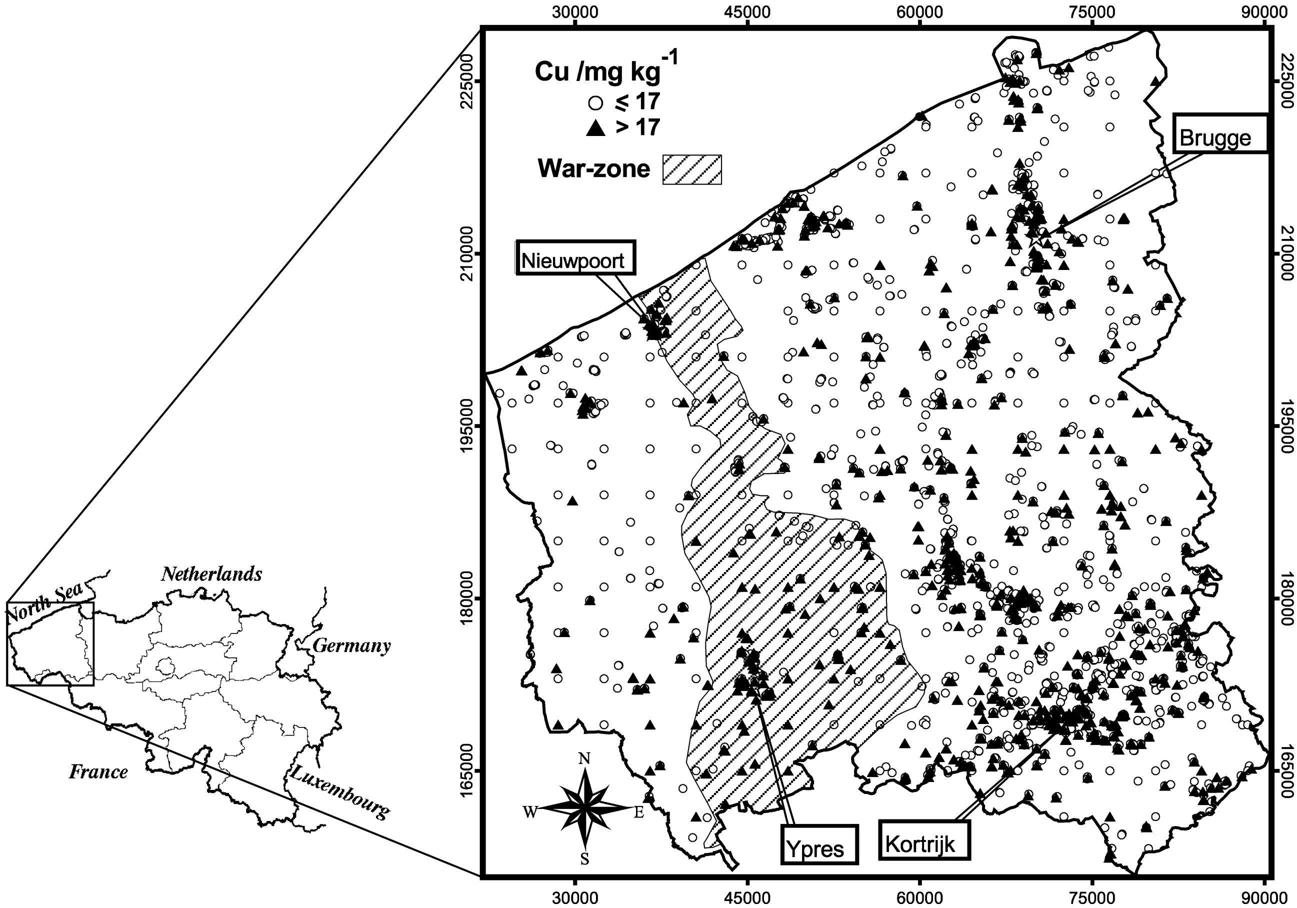

Figure 1 (a) Belgium with identification of West-Flanders (left), and (b) West-Flanders with points of topsoil Cu analyses split according to the background threshold value of 17 mg kg^{-1} and with the delineation of zone identified as 'totally destroyed land' after WW I (coordinates are according to the Belgian Lambert-72 metric projection).

part of the province is covered by Pleistocene wind-blown sediments deposited over Tertiary marine sediments. Generally, from north to south the soil texture changes from sand over silty sand, sandy silt to silt. Locally this trend is disturbed as a result of small differences in topography, but transitions between the wind-blown sediments are gradual (Boucneau *et al.*, 1998b). Around Ypres topsoil texture is mainly sandy silt, and the topography is weakly undulating with elevations mostly between 10 and 30 m. In the south of the province is a chain of hills, formed by resistant Tertiary layers. The highest of these hills is the 'Kemmelberg', to the southwest of Ypres and reaching an elevation of 151 m.

The Flemish Government published official threshold values for background concentrations of several heavy metals in soil (Vlaamse Gemeenschap, 1996). For Cu this value is 17 mg kg^{-1} for a standard soil, defined as a soil containing 10% of clay and 2% of organic matter. This value is confirmed by the geochemical atlas of Europe (Salminen *et al.*, 2005), which indicates a Cu baseline concentration in the topsoil of Flanders that fluctuates around 17.5 mg kg^{-1}. Any substantially larger value is considered to be man-induced.

WW I and related activities around Ypres

After the initial attack in August 1914, the western front of WW I stabilized in a narrow belt of country running from the North Sea coast at Nieuwpoort, Belgium, south-eastwards into northern France and then eastwards to the Swiss border in October 1914. This frontline remained largely static during the next 4 years, despite massive attacks by both opponents. One of the zones of intense battle was around Ypres. Most of the time, the frontline formed a narrow belt of country curved along the north-eastern side of the city, known as the 'Ypres salient'. In this particular area the three 'Battles of Ypres' were fought in 1914, 1915 and 1917, as well as the 'German Spring Offensive' in 1918 (Keegan, 2000).

After the war, a zone where most of the villages were completely ruined was delineated by the Belgian Government as 'totally destroyed land' (Belgian Law of 15 November 1919; Dendooven, 2006). This zone is indicated in Figure 1 as the WW I front zone. The rather narrow part between Nieuwpoort and approximately halfway to Ypres, which is slightly below sea level during high tides, was kept inundated between 1914 and 1918, and no major attacks were launched there. Further south the war zone widened as a result of the more intense conflicts around Ypres. During most of the war the front line was within this zone, although it moved several times to the east and back to the west. The city of Ypres itself was never taken by the German army, but it was completely destroyed by artillery fire (see http://www.greatwar.be for an overview of the successive battles).

Upon explosion most parts of a shell fragmented and spread out. But the brass parts were often deformed and fragmented only partly. After the war, people searched for these deformed pieces of brass and sold them. Also, a large-scale clean-up and an overall reconstruction of the landscape took place. Land was levelled and deep tilled to mix the soil to 0.5–0.6 m and to remove larger pieces of ammunition. Even today the Belgian army maintains a special unit in the area dedicated to the removal and dismantling of unexploded WW I shells. This unit still handles 250 to 300 t of ammunition annually (Lt A. Loncke, personal communication). At present most of the area is used for agriculture.

Sampling, data and exploratory analysis

Most data for this study originate from a geographical data base maintained by the Public Waste Agency of Flanders (OVAM), where data from soil pollution investigation studies are systematically recorded. Since 2000 it is required that data submitted are located precisely by their geographical coordinates by GPS, whereas earlier samples were linked only to the cadastral unit in which they were collected.

The required procedure for total Cu analysis involves microwave destruction of 0.5 g of the air-dry fine-earth fraction (< 2 mm) of soil with 6 ml 37% HCl, 2 ml 65% HNO_3 and 2 ml 40% HF (OVAM, 1992; method CMA/2/II/A.3). In the digest metals are analysed by either ICP-AES (OVAM, 1992; method CMA/2/I/B.1) or graphite furnace atomic absorption spectrometry (OVAM, 1992; method CMA/2/I/B.2). An additional 176 observations were available from a study in 1998, which aimed to assess baseline trace element concentrations in Flanders (Tack *et al.*, 2005). In total 2786 Cu determinations in topsoil samples (0–0.5 m) of West-Flanders (Figure 1) were available. Where subsamples were provided, a depth-weighted pooled value was calculated to ensure a uniform data support over the upper 0.5 m of soil. The horizontal support of the samples was typically restricted to a single auger hole, typically of 7 cm diameter. Given the heterogeneous sources of the data, some data refer to pooled samples taken within a few m^2.

There had been preferential sampling in areas of unusually large concentrations of Cu because of the general interest in pollution. So we first used a cell-declustering algorithm (Goovaerts, 1997, p. 81; Deutsch & Journel, 1998) to counter the effects. We used square cells of side 2400 m for the purpose. This reduced the calculated mean concentration from 37.5 to 24.8 mg Cu kg^{-1}. Figure 2 shows the histogram of the 2786 declustered Cu data, and Table 1 summarizes the statistics. The values ranged between 0.2 and 3600 mg kg^{-1} with a median of 12.6 mg kg^{-1}, which was about half the mean value. The distribution is strongly positively skewed and corresponds reasonably well with the lognormal distribution (Figure 2). About one-third (32.6%) of the data exceeded the background threshold of 17 mg kg^{-1} and only 1.2% exceeded the Flemish sanitation threshold for Cu for agricultural land use, which is 200 mg kg^{-1}.

Although in general about one-third of the observed Cu data exceeded the background threshold of 17 mg kg^{-1}, regional differences in the density of observations exceeding this threshold occurred, as can be observed in Figure 1. Many samples with Cu > 17 mg kg^{-1} were found in the eastern half of the province, especially around the larger cities of Kortrijk and Brugge. Several exceptionally large Cu concentrations were measured, but they were typically surrounded by measurement points with Cu concentrations less than 17 mg kg^{-1}. In contrast, west of the line between Ypres and Nieuwpoort only a few locations with Cu concentrations exceeded the background threshold. Around Ypres itself, the pattern is different: most of the samples exceeded 17 mg kg^{-1}.

To reveal the broad pattern, we did a preliminary screening with a GIS-based moving window (Zhang *et al.*, 2007). Our window was 6 km $\times$ 6 km and our pixels were 500 m $\times$ 500 m. Within each window the number of Cu data was counted. If there were fewer than four observations, no result was displayed. In a window with at least four observations the proportion of the data exceeding 17 mg kg^{-1} was counted.

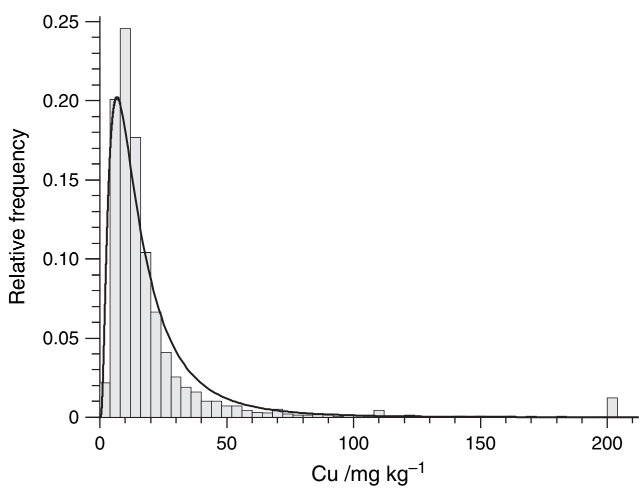

Figure 2 Histogram of declustered Cu data in topsoil of West-Flanders (last bar groups all data exceeding 200 mg kg^{-1}) with corresponding lognormal distribution fitted to it.

Table 1 Descriptive statistics of Cu (mg kg^{-1}) of the declustered complete data set and the two subsets: inside and outside the war zone (subsets both in original units and after logarithmic transformation)

		Inside war zone		Outside war zone	
	Complete data set	Original units	ln transformed	Original units	ln transformed
No of data	2786	199		2587	
Minimum	0.20	4.50	1.50	0.20	−1.61
Median	12.6	18.0	2.89	12.0	2.48
Maximum	3600.0	830.0	6.72	3600.0	8.19
Mean	24.8	26.9	2.87	23.9	2.57
Variance	9191.6	3786.8	0.561	9186.0	0.689
Standard deviation	95.9	61.5	0.749	95.8	0.830
Skewness	19.8	11.4	1.02	21.1	0.95

Figure 3 shows the result classified according to a proportion of 75% exceeding, or not, the 17 mg kg^{-1} threshold. Two large contiguous areas are apparent. Both were inside the battle zone near Ypres. The area shown in black north of the city corresponds with the ridge of Langemark–Passendale where, as part of the 'Third Battle of Ypres', the 'Battle of Passchendaele' was fought. The second area shown black south of the city is where during the 'Battle of the Messines Ridge' in 1917 and the 'German Spring Offensive' of 1918 there was intense shelling and deep mining. In the rest of the province only a few isolated cells with a proportion of observations > 75% exceeding the 17 mg kg^{-1} threshold were identified. There are some much larger Cu concentrations than around Ypres, but most are isolated spots mostly surrounded by observations with Cu contents less than the background threshold. In contrast, most of the data exceeded the official threshold around Ypres. This suggests that we should consider the Cu in the topsoil to be non-stationary in mean, and that for a more formal analysis (see below) we should distinguish two zones, namely the battlefield around Ypres, and the remainder of the province.

The selected area within the war zone included 199 Cu data, and 2587 data were outside it. Table 1 lists the descriptive statistics of these two subsets. The Cu concentrations inside the war zone varied between 4.5 and 830 mg kg^{-1} with a median of 18.0 mg kg^{-1}. Those outside varied between 0.2 and 3600 mg kg^{-1} with a median of 12.0 mg kg^{-1}, 6 mg kg^{-1} less. Both distributions were strongly positively skewed. As Figure 4a

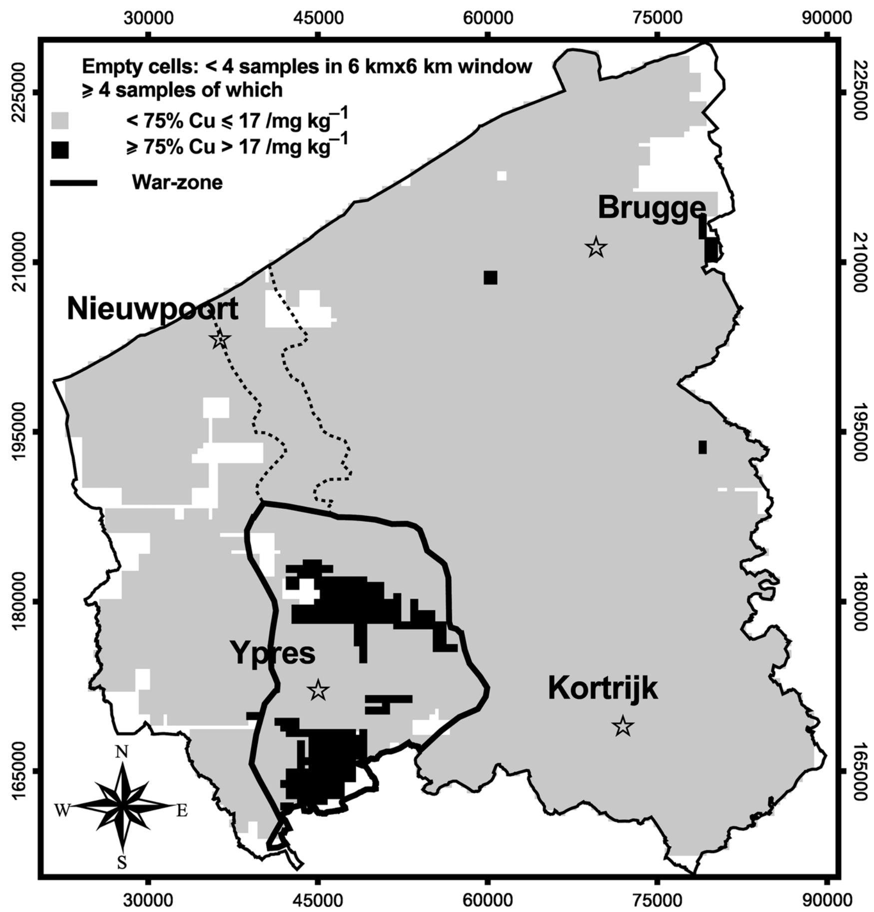

Figure 3 Result of a 6 km × 6 km moving window operation around 500 m × 500 m cells identifying cells with less than four samples within this window (white cells) and cells with at least four samples, of which less than 75% exceeds the background threshold (grey cells) or more than 75% exceeds the background threshold (black cells). The full curve inside the province delineates the selected war zone around Ypres.

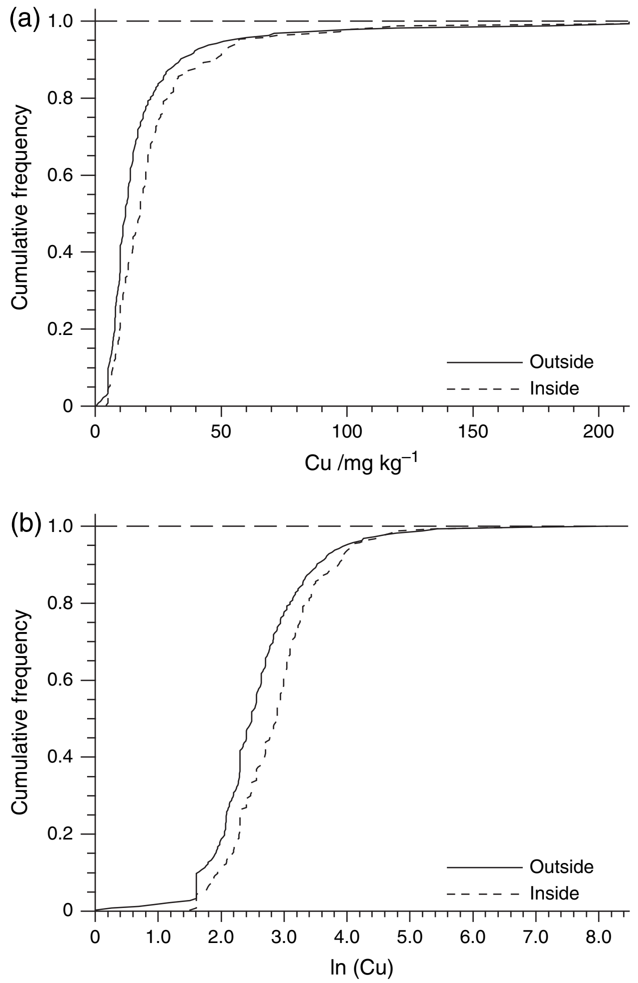

Figure 4 Cumulative frequency distributions, using declustering weights, of (a) the Cu observations in original units (restricted to < 210 mg kg^{-1}), and (b) the ln-transformed Cu observations, both located inside or outside the war zone around Ypres.

shows, the Cu distribution inside the war zone shows an increased frequency of samples with Cu concentrations between 10 and 60 mg kg^{-1}, whereas, to a lesser extent, the area outside the war zone contains more samples with larger Cu contents (> 120 mg kg^{-1}). The variance of the data outside the war zone was much larger than that inside it (Table 1).

To stabilize the variances of the data sets we transformed them to their natural logarithms:

$$y(\mathbf{x}_\alpha) = \ln[z(\mathbf{x}_\alpha)], \quad (1)$$

where $z(\mathbf{x}_\alpha)$ are Cu observations obtained at the locations $\mathbf{x}_\alpha$ ($\alpha = 1,2,\ldots, n$) and $y(\mathbf{x}_\alpha)$ are their logarithms. Figure 4 shows that both cumulative frequency distributions of the ln-transformed Cu data inside and outside the war zone approach the S-shape of a Gaussian distribution. Both distributions have strongly reduced coefficients of skewness (Table 1). Therefore, further analysis was done on the transformed data.

Geostatistical analysis

Variograms

Because our aim was to estimate the Cu content from our data over the entire study area the variogram $\gamma(\mathbf{h})$ had to be estimated and modelled. We computed the experimental variogram $\hat{\gamma}(\mathbf{h})$ of the logarithmically transformed Cu data for each of the two zones we distinguished by the usual method of moments:

$$\hat{\gamma}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})}\sum_{\alpha=1}^{N(\mathbf{h})}\{y(\mathbf{x}_\alpha + \mathbf{h}) - y(\mathbf{x}_\alpha)\}^2, \quad (2)$$

in which $N(\mathbf{h})$ is the number of pairs of data $\{y(\mathbf{x}_\alpha), y(\mathbf{x}_\alpha+\mathbf{h})\}$ separated by the vector $\mathbf{h}$. The largest value inside the war zone was observed near a car assembling site. It was masked to stabilize the variogram. Also outside this zone a few outliers, directly related to industrial activities, were masked. As there were no differences between directions in either set of data we treated the variation as isotropic. The experimental variogram, $\hat{\gamma}(h)$, was therefore computed with $h = \|\mathbf{h}\|$ for lags in distance only. To both estimated variograms the spherical function

$$\begin{aligned}\gamma(h) &= C_0 + C_1\left\{\frac{3h}{2a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right\} \text{ if } 0 < h \le a\\ \gamma(h) &= C_0 + C_1 \text{ if } h > a, \text{ and}\\ \gamma(0) &= 0 \end{aligned} \quad (3)$$

was fitted, with C_0 the nugget variance, $C_0 + C_1$ the sill and a the range of spatial autocorrelation. The best fit was obtained with the 'Indicator Goodness of Fit' parameter of Variowin (Pannatier, 1996) as a guide. The model parameters are given in Table 2, and both variograms are plotted in Figure 5. The variogram inside the war zone had a longer range and a smaller nugget : sill ratio. This indicates that the Cu content has a stronger spatial structure inside the war zone; it behaves spatially in a more continuous way and has a smaller short-range component than that outside.

Mapping the Cu content

With the variograms and the data we estimated $Y(B)$ by ordinary block kriging for blocks B of 500 m × 500 m over the whole province. This involved solving the kriging system to

Table 2 Parameters of the spherical models fitted to the experimental variograms of ln(Cu) inside and outside the battle zone with C_0 as the nugget variance, C_1 as the sill of the autocorrelated variance and a as the range. The NSR is the nugget : sill ratio

	C_0	C_1	a/m	NSR
Inside	0.216	0.316	2220	0.406
Outside	0.646	0.178	1480	0.784

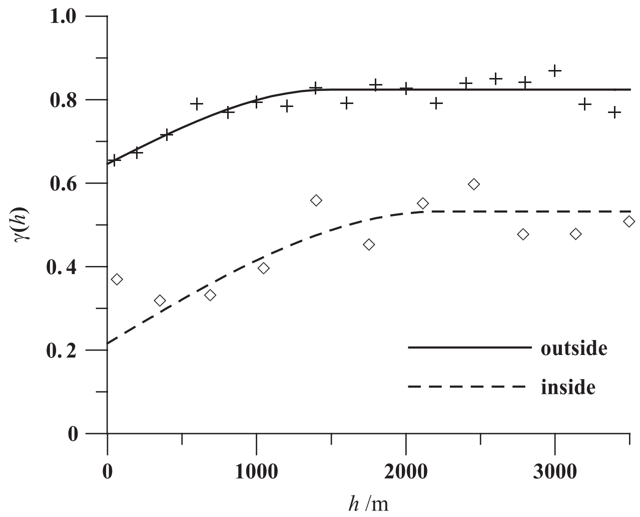

Figure 5 Experimental (points) and theoretical (curves) variograms of the ln (Cu) data located inside or outside the war zone around Ypres.

obtain interpolation weights λ_α attributed to the $n(B)$ observations within the neighbourhood around the centre of the block

$$Y^*(B) = \sum_{\alpha=1}^{n(B)} \lambda_\alpha y(\mathbf{x}_\alpha), \tag{4}$$

with $Y^*(B)$ being the block estimate of ln(Cu). Because different variogram structures were identified in the two zones, we kriged within each zone with its own variogram but using all data within each neighbourhood. This was to avoid abrupt and unrealistic discontinuities at the borders of the zones (Boucneau *et al*., 1998b).

The final step is to back transform $Y^*(B)$ to the original scale. According to Webster & Oliver (2001) the following formula may be used

$$Z^*(B) = \exp\left\{Y^*(B) + S^2_{\mathrm{OK}_Y}(B)/2 - \psi\right\}, \tag{5}$$

in which $S^2_{\mathrm{OK}_Y}(B)$ is the ordinary kriging variance of $Y^*(B)$ and ψ is the Lagrange parameter required in the ordinary kriging system to ensure that the weights sum to 1. However, because this back-transformation depends on the magnitude of the kriging variance, fluctuation in the estimates might reflect variation in sampling density. To avoid such an effect Pebesma & de Kwaadsteniet (1997) recommend that one takes the simple anti-logs of the estimates

$$\widehat{\mathrm{me}}_{\mathrm{Cu}}(B) = \exp\left\{Y^*(B)\right\}. \tag{6}$$

If the distribution is truly lognormal then this quantity estimates the median of the distribution. It is biased somewhat towards smaller values, but not seriously.

The resulting map is presented in Figure 6. Over most of the province the estimated median Cu contents were less than the threshold of 17 mg kg^{-1}. However, locally small patches, usually covering only a few pixels, had much larger values reaching in some places > 60 mg kg^{-1}. Most of these patches could be associated with industry around the bigger cities, Brugge, Roeselare and Kortrijk, or near the harbours of Zeebrugge, Oostende and Nieuwpoort. Also near Ypres there are a few such patches related to isolated factories. However, over almost the entire delineated war zone the predicted values were in the range 17–25 mg Cu kg^{-1}. Generally, this area coincides more or less with the boundaries of the war zone, except in the southwest where the larger Cu concentrations extend beyond its limits.

Discussion and conclusions

Given the similarity of the parent material throughout the province and the lack of metallurgical industry in and around the study area, we can discount the differences in Cu concentrations caused by changes in geology or manufacturing industry. Pig slurry and sewage sludge, which are potential sources of Cu in soil (Xue *et al*., 2003), have been spread on the land, but although strong links have been found between the increased phosphate and organic matter contents in soil and intensive pig breeding in West-Flanders, maps of these two properties (De Smet *et al*., 1996; Van Meirvenne *et al*., 1996) show no similarity with the patterns of Cu. Thus the shells seem to have been the only significant cause of the increased Cu in the area.

The difference in the median concentrations was 6 mg kg^{-1}. The war zone covers approximately 625 km^2. If we consider the top 0.5 m with an average density of 1.5 g cm^{-3} (Boucneau *et al*., 1998a) then that 6 mg kg^{-1} corresponds to an input of 2813 t of Cu. This is comparable to a contamination produced by a large metallurgical factory. For example, Rawlins *et al*. (2006) estimated the Pb deposited in the soil around a smelter that had operated for 53 years to be 2500 t. Because a shell contained on average 0.75 kg of Cu this input of Cu would correspond to approximately 3.7 million shells. This number would be a gross underestimate of the true number of shells fired in the zone for the following reasons.

1 Not all shells exploded, some are still found today. Karg (2005) estimated the proportion of unexploded shells to be 10–15%.

2 The Cu concentrations refer to the fine-earth (< 2 mm) fraction of the soil only. Many pieces of brass are larger than this and were therefore excluded.

3 Only the top 50 cm of the soil profile was sampled.

The exact number of shells fired in the war zone around Ypres during WW I remains unrecorded, but it must have been several tens of millions (as mentioned earlier, at the onset of the Third Battle of Ypres already four million shells were fired by the British forces alone).

As Figure 6 shows, the area with overall large Cu concentrations in the soil around Ypres coincides well with the boundaries of the war zone, except to the southwest where the larger Cu concentrations extend outside it. This extension could have been

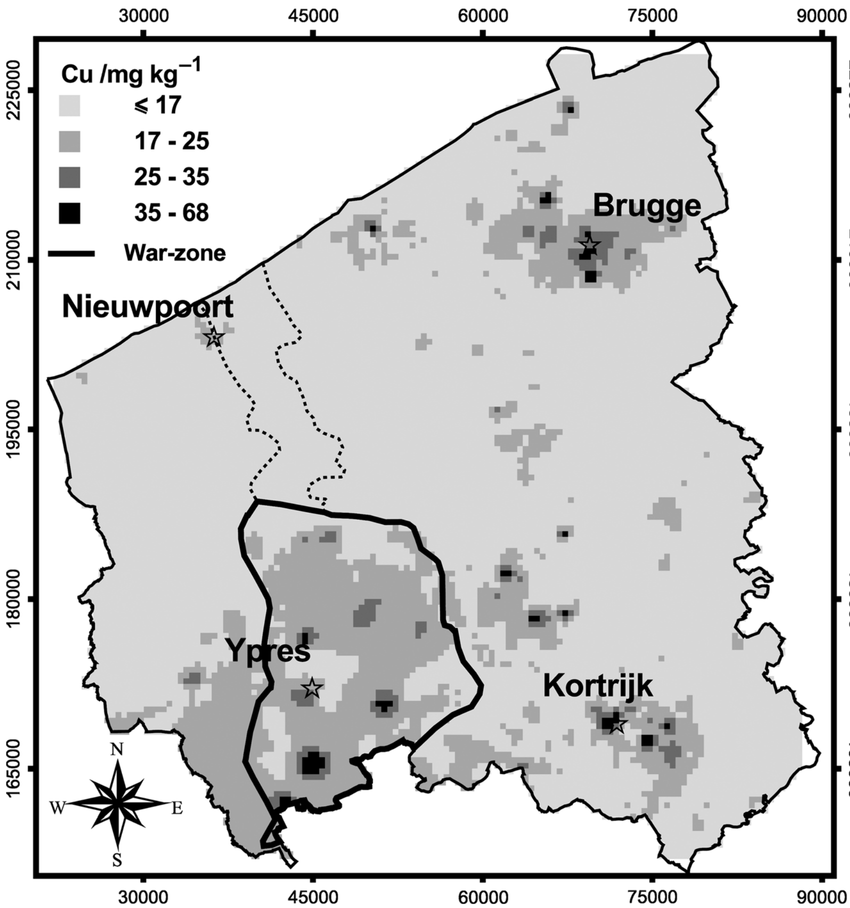

Figure 6 Estimates of the topsoil Cu content obtained with ordinary block kriging of the logarithmically transformed data, with variogram stratification according to the war zone around Ypres.

caused by the German Spring Offensive in 1918, during which large parts to the south and southwest of Ypres were occupied, including the strategically important Kemmelberg. Moreover, artillery was generally well behind the front and often targeted by the opposing artillery. Thus shelling occurred also behind the front zone.

That the overall increase of Cu content in the soil of the war zone by 6 mg kg^{-1} might have resulted from the war activities is therefore an acceptable hypothesis. There is no evidence that other factors, such as industrial contamination or use of manure, could have caused it. The zone of increase coincides remarkably with the area of the most intensive battle. The millions of shells that have been fired in this region can explain the extent of this increase. We conclude that the current enrichment of 6 mg Cu kg^{-1}, amounting to approximately 2800 t of Cu in the upper 0.5 m of soil, is the legacy of shelling in the First World War.

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