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Legacy of conflict in South Lebanon's soils

Technical report from the *Turabna – Janoub Soil Monitoring* pilot

August 2025 campaign

Nabatieh and Marjaayoun Districts,
Nabatieh Governorate, Lebanon

May 2026

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Executive summary

This report presents the results of a pilot soil monitoring campaign conducted in August 2025 in the Governorate of Nabatieh, South Lebanon. This project – a collaboration between Amel Italia, Amel Association International, and Source International – was initiated in response to widespread concerns among local communities regarding the long-term environmental impacts of the Israeli attacks that began in October 2023.

During the August 2025 campaign, we collected 40 topsoil samples across the Marjaayoun and Nabatieh Districts. Results were compared with soil samples collected in 2001 from the same area and with international soil guidelines from Germany and Canada.

Across the study area, **we observed a statistically significant increase in several metals commonly associated with warfare from 2001 to 2025**. Among other metals, lead, antimony, copper, and zinc – well-established markers of military activity – showed clear enrichment across the years. While the median increases were generally moderate, a small number of sites emerged as contamination hotspots, with concentrations far exceeding both historical baselines and international guidelines. Overall, **our results reveal a pattern of diffuse, low-to-moderate contamination at the regional scale overlaid by hotspots with markedly elevated metal concentrations** – a spatial pattern consistent with observations from other post-conflict settings.

In contrast, **we found no substantial evidence of soil contamination that can be uniquely attributed to the use of white phosphorus**. All proxies of white phosphorus analyzed so far have shown no systematic differences between 2001 and 2025, nor between sites with confirmed white phosphorus strikes and other locations. On the other hand, some sites suspected to be affected by white phosphorus strikes displayed a clear signature of war-related metal contamination. Together, these findings confirm previous investigations suggesting that **white phosphorus residues and their degradation products are transient** and that the **long-term environmental impacts are likely dominated by the toxic metals co-released during explosions**, not by white phosphorus itself.

Likewise, **analysis of total uranium revealed no significant differences between 2001 and 2025**. Strong correlations between uranium and phosphorus further support a geogenic, rather than anthropogenic, origin. These results are consistent with a previous national assessment that found no evidence of depleted uranium use in Lebanon.

Overall, this first assessment shows a **moderate but widespread deterioration of soil quality in South Lebanon over the past two decades**. While most sites show limited exceedances, a small number of contamination hotspots pose potential environmental and public-health concerns and warrant priority attention. **The findings highlight the need for continued, systematic soil monitoring, targeted investigations at hotspot locations, and integration of environmental assessments into post-conflict recovery and land-use planning.**

Table of contents

Introduction

The context

Since October 7, 2023, the Southern regions of Lebanon have been severely impacted by Israeli attacks and subsequent military invasion, resulting in widespread destruction of civilian property, infrastructure, and livelihoods. The Governorate of Nabatieh was among the most affected areas, with more than 8500 attacks, including airstrikes, bombardments, and 247 documented incidents of white phosphorus use (until November 2024).[1–3] These attacks resulted in nearly 4000 fatalities and the displacement of over 1.2 million people.[1]

Beyond the direct humanitarian impacts, **military operations have had dramatic consequences for local ecosystems**. Wildfires burned more than 2200 hectares of forests and arable lands, disrupting agricultural activities across nearly one quarter of Lebanon's farming areas.[1] **Attacks involving white phosphorus have raised particular concerns** not only for their immediate destructive effects but also for the possibility of long-term soil contamination.[4,5] Farmers and landowners fear that pollution caused by white phosphorus strikes could compromise food safety and agricultural productivity, now and in the future.[4,5] While evidence remains limited, **allegations of the use of depleted uranium ammunitions** during the September 2024 offensive have further intensified these concerns.[1]

The report

In this context, the project *Turabna – Janoub Soil Monitoring* aims to initiate a systematic soil monitoring program in areas of Southern Lebanon impacted by the last Israeli invasion. The overall goal of this initiative is to support humanitarian responses and future remediation efforts while also

Figure 1. The impact of building destruction on surrounding soil.

providing accessible, evidence-based knowledge to local communities engaged in post-conflict recovery. *Turabna* is a project of Amel Italia, Amel Association International, and Source International.

This report presents the scientific results of the first sampling campaign, conducted in August 2025 in Nabatieh and Marjaayoun Districts, within the Governorate of Nabatieh. This initial effort was intended as the pilot of a larger monitoring program, and specifically aimed to:

1. Qualitatively and quantitatively assess the type and extent of potential warfare-related contaminants in soils, with a focus on heavy metals and proxies for white phosphorus and depleted uranium.
2. Disseminate preliminary findings to local communities in an accessible format.
3. Inform the design and implementation of future monitoring activities.

Selection of war-related soil contaminants

To guide the selection of contaminants, we referred to the existing literature on the environmental impacts of war – e.g., the reviews by Certini et al.[6], Broomandi et al.[7], von Stackleberg[8], and others. Although the available information is often constrained by site access, heterogeneous methodologies, and site-specific results, these reviews provide a useful starting point for identifying common processes and sources of soil contamination.

Soil is the environmental compartment most susceptible to contamination during military operations, with **heavy metals and explosives being the most ubiquitous war-related soil pollutants** (Figure 2).[6–8]

Heavy metals are primarily introduced into soils through military ordnance. Following detonation or impact, fragments of shells, bullets, and unexploded ammunition that remain on the ground progressively release their constituent metals through weathering and leaching. Studies conducted at military training ranges and conflict sites indicate that **lead, antimony, zinc, and copper** are the most common elements associated with war-related soil contamination.[6,7] The

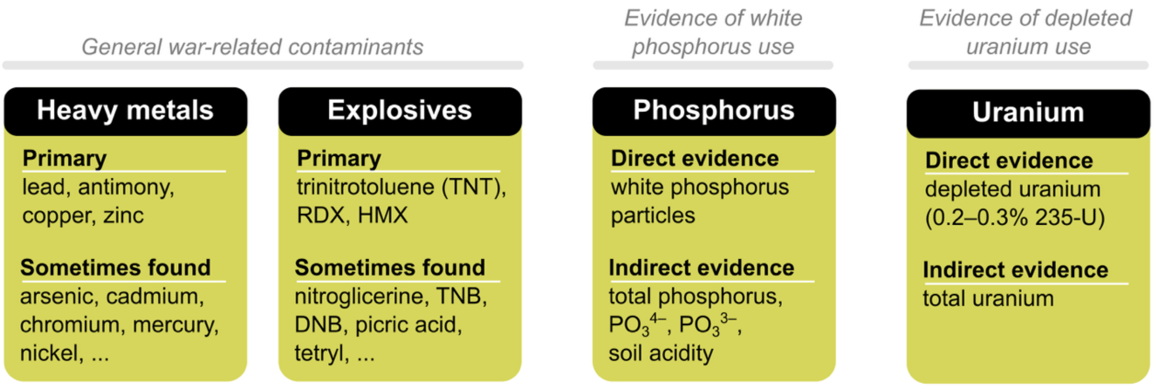

Figure 2. Overview of expected and proposed contaminants in South Lebanon. We based this selection of soil contaminants and proxies on the scientific literature (e.g., Certini et al.[6], Broomandi et al.[7], and others[8–11]; see text).

prevalence of these metals reflects the typical composition of military equipment: lead and antimony are major components of most bullet types,[12–15] while copper and zinc are derived primarily from brass alloys of bullet jackets, cartridge cases, shrapnel, and other military materials.[6,7,12] Other metals frequently but not always detected include **arsenic, cadmium, chromium, mercury, and nickel**,[6,7] which may occur as minor constituents in specific ammunition types or alloys used in military equipment. Due to its widespread occurrence in military-impacted soils, high toxicity, and environmental persistence, lead is the most concerning pollutant on this list.[6,7] Arsenic, cadmium, and mercury also warrant attention because of their high toxicity and potential for long-term human and ecological exposure.[16] Although the environmental impacts of the other metals may depend strongly on soil properties and chemical speciation, elevated concentrations commonly reported in conflict-affected soils may substantially increase their associated risk. For these reasons, all of the above metals were included within this study.

Explosives constitute a second major class of contaminants linked to military activities.[6–8] Substances like trinitrotoluene (TNT), RDX, and HMX have been frequently detected in soils from military areas in Korea, Canada, and the US.[7] Unlike heavy metals, some explosives can be broken down by soil microorganisms. However, this process can generate by-products that are even more toxic than the original explosive, creating potential issues for the soil microbiome and subsequent impacts on agricultural productivity.[8] Due to insufficient funding at the pilot stage, explosives will be analyzed on a subset of samples during a subsequent phase of the project.

To specifically address the concerns of local communities, **we also included pollutants specifically associated with the use of white phosphorus and depleted uranium**. After detonation, white phosphorus ammunition leaves uncombusted particles scattered unevenly within a few meters of the impact crater.[17,18] White phosphorus is unstable when exposed to air: within days, these particles will transform into phosphorus oxides and subsequently into phosphonic acid and phosphoric acid (Figure 3).[10,17] These acids also form directly in air during the explosion of white phosphorus ordnance and are later deposited onto surrounding soils through atmospheric fallout (Figure 3).[10]

Figure 3. Expected environmental effects of white phosphorus use. The photo was taken during a white phosphorus strike in South Lebanon (reproduced from WhitePhosphorus.info[2]). The schematic on the left summarizes the processes occurring in the soil after fallout of white phosphorus uncombusted particles and oxidation products. The schematic on the right depicts a simplified view of the reactions occurring in air after detonation, which are responsible for the white smoke. This overview does not include heavy metals and explosives that are co-released during explosions.

Once onto the ground, these acids may make the soil more acidic and increase the amount of total phosphorus, including phosphites (formed from phosphonic acid) and phosphates (formed from phosphoric acid). Phosphites are uncommon in natural soils and will slowly transform into phosphates,[19,20] which are well-known soil nutrients and fertilizers.[6,21] **The use of white phosphorus ammunition is thus expected to enhance soil concentration of total phosphorus, phosphates, phosphites, and make the soil's pH more acidic**: these are the proxies we included in *Turabna*. Shortly after explosions, unreacted white phosphorus particles may be detectable near craters.[9,17,18,22] However, as our sampling took place more than 6 months after the last reported strike, we did not investigate the presence of intact residues as we deemed their persistence over this timeframe unlikely.

Since the first Gulf War, depleted uranium has been used in certain types of military equipment due to its unique physical properties, which make it extremely effective in armor-penetrating applications – for this reason, it is used in tank ammunition and armor-piercing shells.[11,23] Depleted uranium is different from *enriched* uranium used in nuclear weapons. Although both are forms of the same element, their isotopic composition is different: enriched uranium has a higher proportion (from 3.5–5% in power plants to > 90% in bombs) of uranium-235, the most radioactive isotope, while depleted uranium has a lower amount of this isotope (0.2–0.3%) as compared to the element naturally found in rocks (0.7%).[11,24] Distinguishing between natural, depleted, and enriched uranium therefore requires precise measurement of uranium isotopes, which are technically complex and costly. Furthermore, uranium toxicity is primarily driven by its chemical form – i.e., whether it occurs as metallic uranium or as a component of salts and minerals –, not isotopic composition.[25,26] For this reason, in *Turabna*, **we measured total uranium as an indirect proxy for depleted uranium**.

Previous studies in South Lebanon

A few Lebanese actors and institutions – including the National Council for Scientific Research (CNRS), the American University of Beirut (AUB), and the Lebanese Ministry of Agriculture – have already conducted soil analyses in South Lebanon in the aftermath of the attacks.

Between the end of 2024 and the beginning of 2025, AUB sampled more than 250 sites across the southern neighborhood of Beirut, the Beqaa Valley, and other areas of South Lebanon (personal communication). This investigation included soil, vegetation, and other debris and focused on white phosphorus' contaminants, namely heavy metals, total phosphorus, available phosphorus, soil pH, and explosives. While the full study is not yet available, AUB shared some key findings in the local news, including the 100 to 400-fold increase in total phosphorus compared to the natural background in sites affected by white phosphorus use.[5] According to AUB's experts, the most long-term impact of white phosphorus ammunition must be looked for in the heavy metals co-released with bombing, not in unburned white phosphorus residues or its degradation products.[4,5] Ongoing analyses also include heavy metals and changes in soil microbial activity.[5]

The Lebanese CNRS in collaboration with the United Nations Development Program (UNDP) has also released an overview document that surveys the damages of the Israeli attack until the ceasefire of

November 27, 2024[1]. The report also includes the results of analyses aimed at detecting evidence of depleted uranium use at 8 suspected sites in the southern suburbs of Beirut and in the Beqaa valley. None of the 14 samples showed uranium-235 to uranium-238 ratios different from those of the natural element. Likewise, no occurrence of depleted uranium was found in particulate matter samples that were collected nearby.

Normative and historical reference

To evaluate the results of this pilot survey, we employed two different frameworks. First, we considered selected **international guidelines** from Canada and Germany. Canada has one of the most comprehensive soil quality frameworks, which is widely used worldwide. The Canadian Environmental Quality Guidelines for soils set recommended maximum values for pollutants in 4 use-based classes, taking into account both environmental protection and human health.[27] Values for selected pollutants in residential soils are reported in Table 1. In addition to Canada, we used the German normative framework, which is commonly applied in soil quality evaluations by the Lebanese CNRS. Germany defines precautionary values ("Vorsorgewerte") for 9 heavy metals across 3 soil types. These values are intended for soils with low organic carbon content (< 9% by mass).[28] Table 1 reports the value for loam/silt ("lehm/schluff") soils, which best match the characteristics of our study site. While regulating fewer elements, the German values are broadly comparable to the Canadian normative.

We used international guidelines because of the lack of both national[29] and global values. Unlike air[30] and drinking water[31], there are no universally accepted soil pollution thresholds due to the influence of local geology, soil properties, soil biodiversity, and legacy use on pollutants' behavior. Even the recent European Soil Monitoring Law (Directive EU 2025/2360)[32] does not specify fixed threshold concentrations but only identifies the variables that individual states must monitor.[32–34]

For these reasons, **we use as primary reference the median values from soil samples collected in 2001** (Table 1). These samples were kindly provided by Prof. Talal Darwish (CNRS) and analyzed using the same procedure applied to the 2025 soils. These samples were collected in the context of a large project intended to create the first soil chemistry database of Lebanon (see Darwish et al.[35]). Compared to the German and Canadian reference normative, the 2001 samples were more alkaline (median of 8.1), reflecting the calcareous nature of South Lebanese soils.[36] While their median values were not concerning, a few samples showed elevated concentrations of chromium, nickel, and/or selenium relative to international guidelines, hinting at either legacy pollution or naturally enriched geologic conditions.

Table 1. Overview of normative and historical reference used for evaluating soil quality. For historical data, we report the median (black) and the range (in grey) of the 7 samples from 2001 (Table A4); values starred with a red asterisk have at least one sample above the selected international normative. [a] Lowest Provisional Final Soil Quality Guideline value between the 0.5-IQ and 1-IQ pt decrement[37]. n.s. = not set; n.d. = not determined

	International normative		Historical values
Parameter	**Canadian Soil Quality Guidelines – residential (mg/kg)**	**German Provisional Values – loam/clay soil (mg/kg)**	**Median and range (mg/kg)**
Soil pH	6 to 8	n.s.	8.1 [7.0 – 8.2] *
Aluminum	n.s.	n.s.	12543 [8071 – 18765]
Antimony	20	n.s.	0.21 [0.08 – 0.71]
Arsenic	12	20	4.6 [1.0 – 7.9]
Barium	500	n.s.	87 [66 – 154]
Beryllium	4	n.s.	0.97 [0 – 1.2]
Boron	n.s.	n.s.	3.3 [1.8 – 4.6]
Cadmium	10	1	0.31 [0 – 0.51]
Cobalt	50	n.s.	7.7 [3.9 – 24]
Chromium	64	60	47 [26 – 95] *
Phosphorus	n.s.	n.s.	900 [460 – 3800]
Iron	n.s.	n.s.	7429 [6100 – 9613]
Manganese	n.s.	n.s.	883 [343 – 1283]
Mercury	6.6	0.3	n.d.
Molybdenum	n.s.	n.s.	0.34 [0.17 – 0.86]
Nickel	45	50	36 [11 – 58] *
Lead	61[a]	70	7.9 [3 – 18]
Copper	63	40	14 [8.1 – 34]
Selenium	1	n.s.	0.42 [0 – 1] *
Tin	50	n.s.	1.5 [0.91 – 1.8]
Thallium	1	1	0.11 [0 – 0.14]
Uranium	23	n.s.	1.7 [0.48 – 3.5]
Vanadium	130	n.s.	57 [19 – 66]
Zinc	250	150	42 [23 – 86]

Sampling site and methods

Sampling site

Between August 13 and 18, 2025, we sampled 40 sites in the Governorate of Nabatieh, of which 20 were in the Marjaayoun District and 20 in the Nabatieh District (Figure 4 and Table A2). Of these, 33 sites were directly impacted by the most recent conflict (filled brown circles in Figure 4), while 7 were control sites (open circles). We based the distinction between impacted and control sites on the presence of craters, bombed houses and infrastructures, and residents' accounts. Although not exactly matching the 2025 locations, samples from 2001 were overall from the same general area (green points in Figure 4). Three 2001 sites were within 1 km of some sampled in 2025 – i.e., 253/L05, 267/L33, and 274/L32 –, allowing for direct, point-by-point comparisons. Field conditions during the 2025 campaign were consistently sunny, hot, and dry (total absence of rain in the previous month).

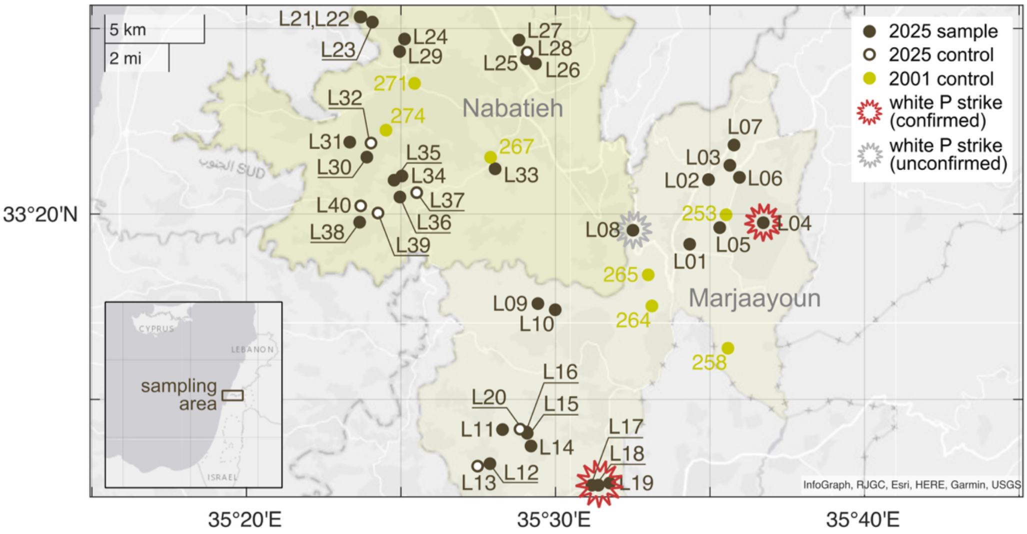

Figure 4. Overview of sampling locations in 2001 and 2025. Brown filled and open circles indicate impacted and control sites sampled in 2025, respectively, while green filled circles represent historical samples from 2001. For the 2001 sites, we maintained the original numbering convention. Local communities reported white phosphorus strikes at 5 locations since the onset of the most recent conflict; 4 of these were confirmed with an independent dataset[2] (see Figure A1 in the Appendix).

The 40 sites visited in 2025 were well distributed across land uses and settings (Table A2). Most locations were private (90%, 36 samples) and evenly spread across rural (40%), urban (30%), and urban-rural interface (30%) areas. Land cover included gardens (45%), permanent crops like olive trees (45%), arable crops such as cereals (18%), barren soil (10%), forests (4%), and buildings (4%; examples in Figure 5). Some sites had mixed classification, most commonly garden + permanent crops (15%).

We recorded white phosphorus use at 5 sites in the Marjaayoun District (L04, L08, L17, L18, and L19; Figure 4 and Table A2). In 4 cases, we confirmed this information using an independent online database of white phosphorus strikes in South Lebanon[2] (Figure A1). L08 could not be confirmed; it

Figure 5. Overview of representative sampling sites in the Marjaayoun (A to C) and Nabatieh (D to F) Districts. Locations L20 (C) and L32 (F) are control sites, while L17 was impacted by white phosphorus use. L02 was classified as "garden", L17 as "barren soil", L20 as "forest", L24 as "permanent crops", L31 as "arable crops" (now destroyed), and L32 as "unused soil".

is possible that white phosphorus use occurred after November 2024 or that local accounts misattributed explosions to this ordnance. All impacted sites had been exposed to military operations since October 7, 2023; according to local accounts, the last military operations in L01 and L09 took place less than 6 months before our campaign. No unexploded ordnance was observed or reported near any sampling site.

Based on visual analysis, soils were primarily loamy (80%); one site was sandy (L19), one clayey (L16), and 8 contained a mix of rocky debris and other materials.

General site characterization

At each site, we recorded general field data with ODK Collect,[38] which was used to fill a questionnaire previously set up in KoboToolbox.[39] The questionnaire had 29 queries, including date, GPS coordinates and altitude, present and past weather conditions, information on location, sample ID, sampling details, land type and use, soil type and appearance, recent occurrence of military operations and white phosphorus strikes, and presence of unexploded ordnance.

Soil sampling

We collected top-soil samples (0–10 cm) using a well-cleaned metal shovel (e.g., Figure 5A–D). At each site, we gathered several soil aliquots within 2 to 5 meters of the target point and transferred them into a plastic bucket. We homogenized the soil, removed stones and large aggregates, quartered the mixture, and created 3 sub-samples of approximately 100-150 g each. Sub-samples A and B were placed into new vacuum sampling bags (Wevac, 15 × 25 cm), sealed with a portable vacuum sealer (Elma V Go), labeled, and stored. Before sealing, we added a small oxygen absorber (Midukit, tuoyangji-500cc) to sub-sample B to limit the oxidation of phosphite to phosphate during transport and storage. Sub-sample C was placed into a regular sampling bag, labelled, and stored away from direct sunlight. Sub-samples A and B were brought to Italy for chemical analyses, while sub-sample C was left at AUB for future complementary analyses.

At the end of each sampling day, we stored all samples in a refrigerator at 4 °C. During national and international transports, samples stayed at room temperature in the dark.

Historical samples

Samples from 2001 were collected by Prof. T. Darwish (CNRS) and collaborators following standard soil sampling protocols. At each site, they manually excavated the soil to a depth of up to 200 cm (or until the bedrock or water table was reached). Locations were carefully selected to be representative of the local soil type. They then collected samples from each horizon, proceeding upward to minimize cross-contamination. Back to the laboratory, each sample was quartered, and one half was cleaned from roots and gravel, air dried, grinded, sieved (2 mm), and subjected to further analyses. The remaining half was air-dried as received, packed in a hermetic plastic container, labeled, and placed in a dedicated archive at the National Center for Remote Sensing-CNRS in Mansourieh, Lebanon.

In August 2025, we retrieved 100–150 g of these archived samples and transferred them into our regular sampling bags. From the original dataset, we selected only 7 samples from the uppermost horizon collected in the Maryaajoun and Nabatieh Districts. These soils were brought to Italy and subjected to the same treatments as sub-samples A.

Chemical analyses

We sent sub-samples A and the 2001 soils to an Italian commercial laboratory (accredited by ACCREDIA), which analyzed soil pH, heavy metals, and total phosphorus. Soil pH in water was obtained via the procedure D.M. 13/09/1999 SO n° 185 GU n° 248 21/10/1999 Met. III.1, which involves measuring the pH of a soil-water suspension.[40] Metals, metalloids, and essential elements – including total phosphorus and uranium – were measured on dry and sieved soils (< 2 mm) using microwave-assisted acid digestion (EPA 3051 A 2007) followed by elemental determination via inductively coupled plasma mass spectrometry (ICP-MS, EPA 6020 B 2014). The results were reported as mg/kg of dry weight of *total* soil, in compliance with the Italian normative. Table A1 reports the limits of detection and average estimated measurement uncertainties of the ICP-MS analyses as provided in the laboratory test reports. For pH measurements, the reported uncertainty was 0.5 pH units.

Sub-sample B was brought to the University of Turin (Italy) for the analysis of phosphate and phosphite in aqueous soil extracts via ion chromatography. These analyses are still ongoing and will be included in an upcoming update.

Data analysis

We analyzed all data using Excel and Matlab (R2012b). We computed boxplots and medians using all available concentrations, also when the analyte was not detected (n.d.; value set to 0) or was below its limit of detection (raw data in Table A3).

For statistical analyses, we first tested the data normality of the 2025 and 2001 datasets using the Lilliefors test ("lillietest" function in Matlab).[41] As most parameters did not follow a normal distribution, we applied non-parametric tests: the Mann-Whitney U test[42] for pairwise comparisons ("ranksum" function) and the Kruskall-Wallis test[43] ("kruskalwallis" function) followed by post-hoc pairwise comparisons ("multcompare" function) for differences among more than two groups (see the footnote[1] for a simpler explanation). In all cases, we set the significance level at $p < 0.05$. Correlation coefficients between elements were obtained on the combined 2001+2025 dataset with the "corrcoef" function. We excluded boron, mercury, and molybdenum from all statistical analyses, as these elements were absent or below their limit of detection in 100% of the samples.

For the 3 sites measured in 2001 and 2025, we computed 2001-to-2025 ratios by dividing the value of each parameter in 2025 by that in 2001 (i.e., 2001-to-2025 ratio = (value in 2025)/(value in 2001)). A ratio > 1 indicates an increase over the years, while a ratio < 1 a decrease, and a ratio = 1 no change.

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[1] These tests are statistical tools used to check whether different groups of data show meaningful differences among themselves, rather than differences that could be explained by chance alone. The Mann-Whitney U test is used to compare 2 groups of data (e.g., group A vs. group B), while the Kruskall-Wallis test is employed when comparing more than 2 groups (e.g., group A vs. group B vs. group C). The post-hoc comparisons were then applied to identify which group pairs drive the Kruskall-Wallis test's outcome.

Results

General overview

Soils collected in 2025 contained almost all of the analyzed elements and were slightly alkaline (Table A3). Of the 23 chemical elements measured, 11 were above their limits of detection in 100% of the samples. Boron, mercury, and molybdenum were always absent or below detection, while beryllium, cadmium, copper, nickel, lead, selenium, tin, thallium, and uranium were detected in most – but not all – samples. The most abundant elements were consistently aluminum (5670–21670 mg/kg), iron (3150–14620 mg/kg), phosphorus (270–8200 mg/kg), manganese (107–970 mg/kg), and barium (40–352 mg/kg), reflecting the typical elemental distributions in the Earth's crust. Among the heavier metals, zinc (33–1500 mg/kg), chromium (11–200 mg/kg), vanadium (8.5–160 mg/kg), and nickel (4.3–110 mg/kg) occurred at the highest concentrations. Soil pH measured in water ranged from 7.3 to 8.6 (median of 8.1), confirming their alkaline nature – indeed, most soils in South Lebanon sit on a calcareous bedrock.[36]

Statistical analyses indicate that **the chemical composition of soils collected in 2025 was generally homogeneous**. Soil pH was the only parameter that differed significantly between impacted and control sites ($p = 0.010$; Table A4), with control soils being slightly more acidic. In contrast, **several key parameters were significantly higher in 2025 as compared to 2001** (Table A4; discussed below). **Selected outliers were also at least an order of magnitude higher than both control groups**; these highly impacted locations are discussed in detail in the following sections.

Within the 2025 dataset, several elements varied significantly across sites with different classification. Rural sites had overall higher concentrations of beryllium, cobalt, manganese, and vanadium than urban areas (Table A7). A few elements were also different between municipalities (Table A6): aluminum, cadmium, and zinc were higher in the Marjaayoun District, whereas uranium was more abundant in that of Nabatieh. On the other hand, we found no significant differences among soils with different uses (e.g., garden, crops, etc.), for any of the variables (Table A7).

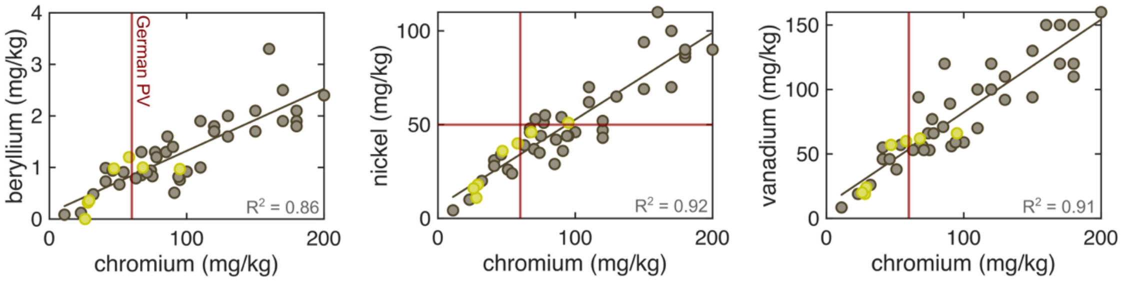

Figure 6. Correlation between chromium and other elements with likely geogenic origin. When available, German Precautionary Values (PVs) are shown as red lines: values above or to the right of these lines exceed the limit. Data points from 2001 and 2025 are shown in green and dark brown, respectively. The R^2 of the linear regression line is shown in the lower right corner: values closer to 1 indicate stronger correlations and a higher likelihood that the elements share the same origin.

Within the dataset, certain elements showed strong correlations with each other. The most evident involved chromium, beryllium, nickel, and vanadium (Figure 6 and Table A8). This pattern applied both in 2001 and 2025, suggesting a potential influence of local geology. Notably, the 2001 values were consistently at the lower end of the range, possibly reflecting increased mobilization of bedrock elements due to war-related activities (see below).

Comparison with historical data

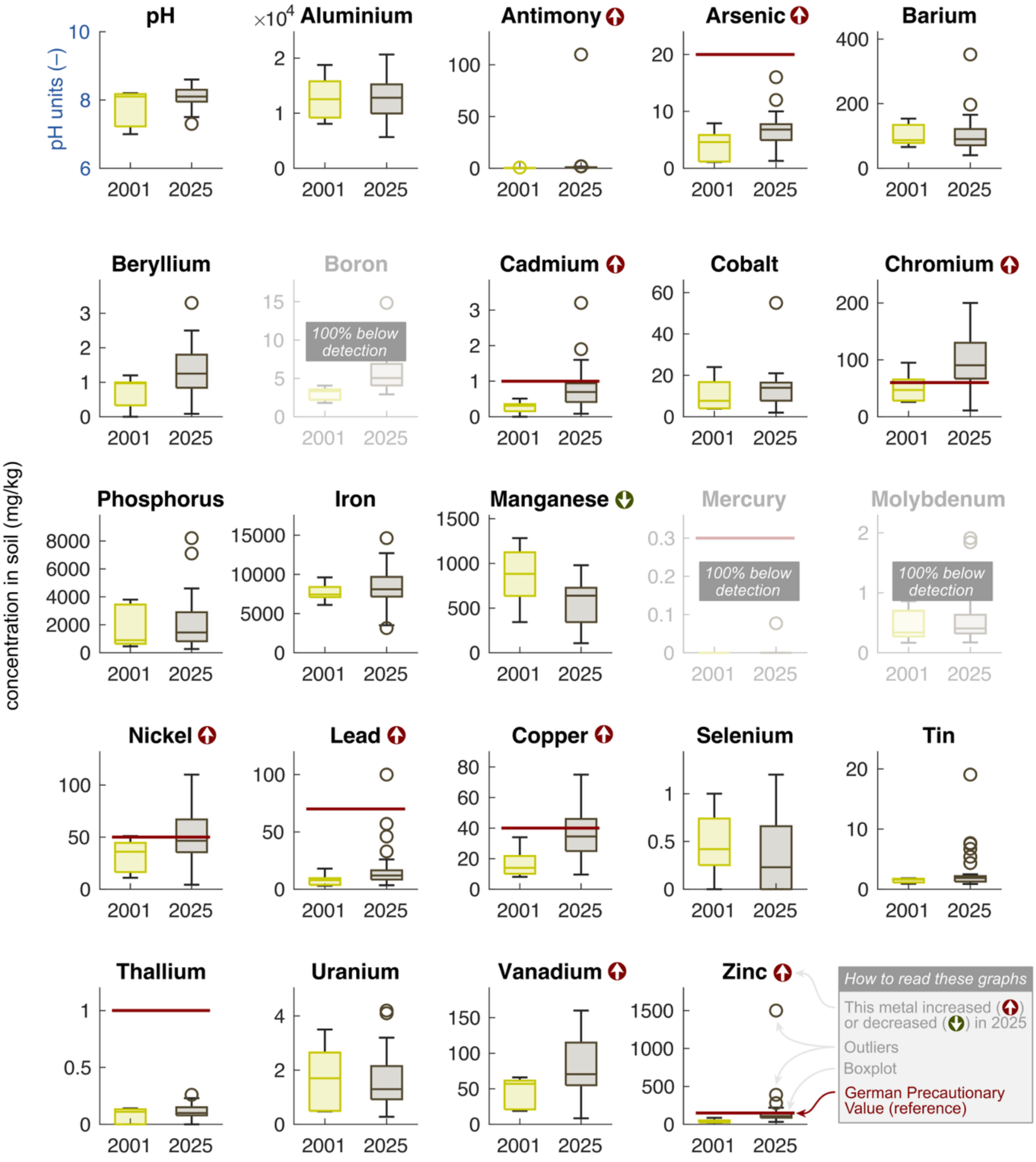

Figure 7. Comparison of pH and concentrations of metals, metalloids, and other elements in soils between 2001 and 2025 (green and dark brown boxplots, respectively). The first graph shows pH values, not concentrations. Elements consistently below detection limits – boron, mercury, and molybdenum – are shaded and excluded from the discussion. Elements that increased or decreased significantly between 2001 and 2025 ($p < 0.05$) are indicated with a red or green arrow, respectively, next to the element's name (see also Table A6). When available, Germany's Precautionary Values are shown as dark red lines. Raw data are in Table A3.

Overall, **we found the most significant differences between samples collected in 2001 and 2025**. For simplicity, we thus consider the 2025 dataset as a single group; similar results were obtained when separating impacted and control sites (Table A6 and Table A7).

Almost all variables that were statistically higher in 2025 compared to 2001 were heavy metals directly or indirectly associated with warfare. Heavy metals consistently found in battlefields and military training ranges – i.e., antimony, copper, lead, and zinc (Figure 3) – were all statistically higher in 2025 relative to the historical control (Figure 7 and Table A6). Additional metals that increased significantly over the 20-year period include arsenic, cadmium, chromium, and nickel, which are also common in conflict areas (Figure 3).[6,7] These same results were also observed in the pointwise comparisons (Table A5). In our case, increased chromium and nickel in 2025 may additionally reflect the mobilization of bedrock due to explosions or other war-related activities rather than solely the use of weapons containing these metals. This interpretation is further supported by elevated levels of vanadium ($p = 0.03$) and, though less significantly, beryllium ($p = 0.058$; the limit for significance is 0.05) in 2025 compared to 2001. As we showed in Figure 6, we suspect all these metals share the same natural origin. Manganese was the only element that significantly decreased between 2025 and 2001 and had no strong link to warfare based on the available literature.[6,7,12] Overall, these findings hint at a legacy of war-related pollution that extends beyond the most recent conflict and impacts the whole study area.

Comparison with international standards

As Lebanon does not have established environmental quality standards for soil, we used the German Precautionary Values[28] (PVs) as the primary benchmark and the Canadian Environmental Quality Guidelines for soils[27] as a secondary reference. Since these guidelines are not specific to the background chemistry of the study site, the discussion below must be considered only indicative.

Germany sets Precautionary Values only for arsenic, cadmium, chromium, mercury, nickel, lead, copper, thallium, and zinc (Table 1). While arsenic, mercury, and thallium were consistently below their PVs, **chromium, nickel, copper, and zinc exceeded the recommended values in more than a quarter of the 2025 sites** (Figure 7 and Table A3). Specifically, we found exceedances in 80% of the samples for chromium, 45% for nickel, 35% for copper, and 25% for zinc. Cadmium and lead, exceeded the PVs only at 8 and 1 sites, respectively. According to the German guidelines, the most polluted site was L33 – the private garden of a bombed house in the Nabatieh District – with 5 exceedances. Sites with 4 exceedances included 5 locations in the Marjayoun District (L02, L05, L06, L13, and L14) and 2 in the Nabatieh District (L32 and L35), notably featuring 2 control sites (L13 and L32). In contrast, in 2001, exceedances were limited to chromium (2 of 7 sites) and nickel (1 of 7 sites), the two metals that we tentatively attributed to local geology rather than direct pollution (Figure 6).

Comparison with the Canadian guidelines led to comparable conclusions. Chromium and nickel were again the elements with the most exceedances in 2025 (78% and 55% of sites, respectively) and the only metals above the guidelines in 2001 (2 sites). Due to more permissive thresholds than the German PVs, we observed exceedances in less than 10% of the sites for vanadium (10%), copper

(8%), zinc (8%), antimony (3%), arsenic (3%), cobalt (3%), lead (3%), and selenium (3%). By far, the most impacted location was L02, with 8 exceedances, followed by L33, with 4; both were private gardens of bombed houses.

Heavy metals associated to warfare

Heavy metals are major soil contaminants in military training areas and in sites affected by current or past conflicts.[6,7] **Primary heavy metals** directly attributable to armed conflicts **include lead, antimony, zinc, and copper** (Figure 3).[6,7,12] Other elements frequently detected in war-affected areas – such as arsenic, cadmium, chromium, mercury, and nickel (Figure 3) – have a more nuanced link to warfare and may reflect indirect effects rather than direct contamination.[6,7,12]

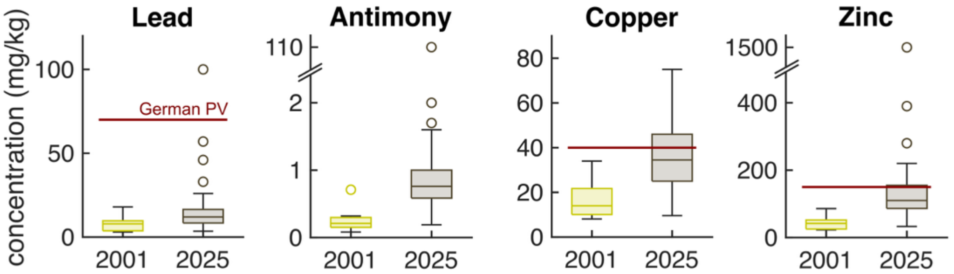

Figure 8. Changes in heavy metals directly associated with warfare between 2001 and 2025. Red lines indicate the German Precautionary Values (PVs). For antimony and zinc, the y-axis is cut to include the highest outlier.

All metals highly specific to warfare were statistically higher in 2025 compared to 2001 (Figure 8 and Table A3). Copper and zinc exceeded the German PVs in a significant fraction of the 2025 samples (35% and 25%, respectively) but were consistently below this threshold in 2001 (Figure 8). These elements did not differ significantly between municipalities or between impacted and control sites in 2025 (Table A6), reinforcing the idea of a progressive worsening of environmental quality *over the entire study area* since 2001. Except for a few notable outliers (discussed below), this increase was within the order of magnitude: concentrations increased 1.5-fold for lead, 3.6-fold for antimony, 2.5-fold for copper, and 2.6-fold for zinc in 2025 vs. 2001 (median values; Table A5). This trend was also evident at the 3 sites visited in both campaigns, where average 2001-to-2025 ratios were 4.0 for lead, 4.6 for antimony, 4.4 for copper, and 5.3 for zinc (Table A5).

The 2025 dataset included a few outliers with a clear warfare signature (Figure 9). **The most evident was L17**, which was collected at a small plot at the side of a damaged building in Houla (Marjaayoun District) and was one of the sites impacted by white phosphorus strikes. Houla had been almost completely destroyed during the Israeli invasion and was the most devastated village visited in 2025. This sample exhibited the highest concentrations of antimony (110 mg/kg vs. a median of 0.76 mg/kg; 520-fold higher than the 2001 median), lead (100 mg/kg vs. a median of 12 mg/kg), and copper (75 mg/kg vs. a median of 34 mg/kg), **clearly reflecting an ammunition-related fingerprint. L02** and **L33**, collected in the gardens of bombed houses in Qlaiaa and Choukine, showed the second-highest concentrations of lead (57 and 33 mg/kg, respectively), copper (64 and

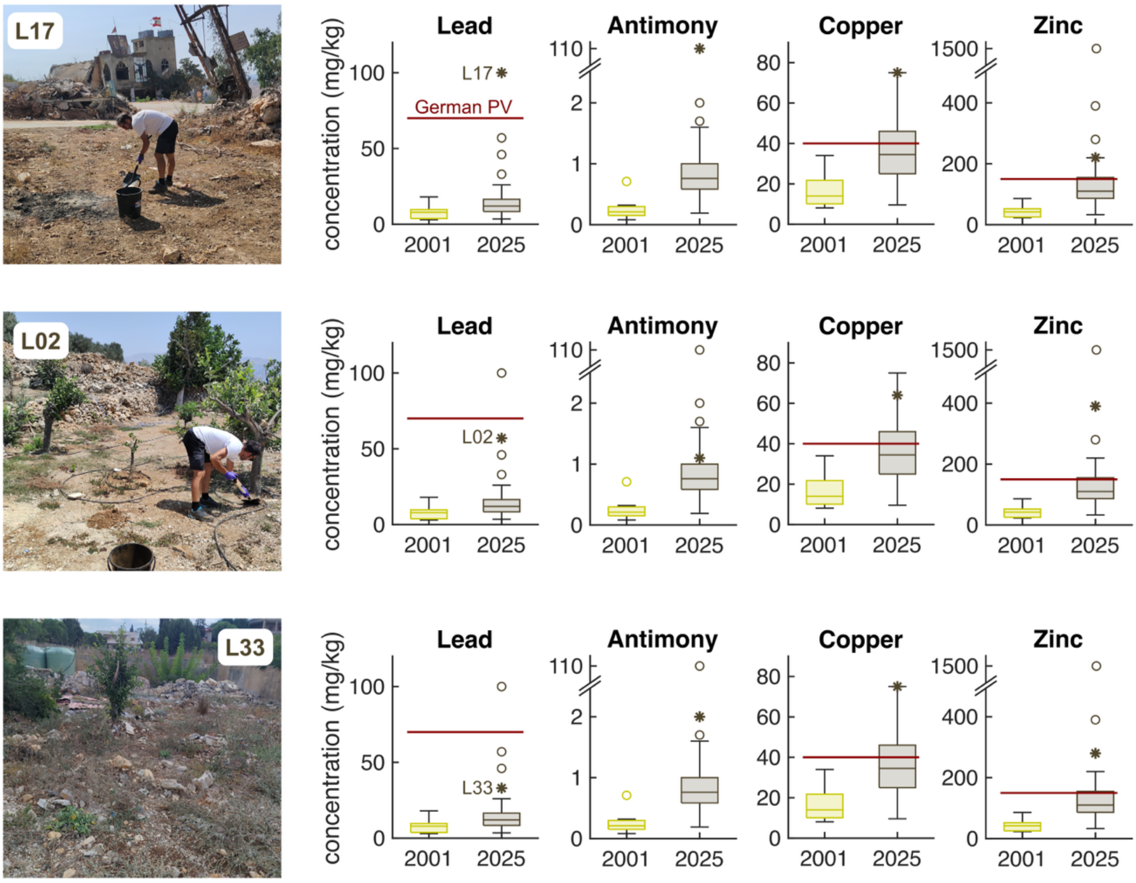

Figure 9. Sites with a strong fingerprint of war-related contamination. The boxplots on the right side are a reproduction of Figure 8 with data points corresponding to each hotspot highlighted.

75 mg/kg), and zinc (390 and 280 mg/kg), along with some of the highest antimony levels in the dataset (1.1 and 2.0 mg/kg).

Most of the additional metals commonly detected in war-impacted areas were also statistically higher in 2025 compared to 2001. While mercury was constantly below its detection limit, arsenic, cadmium, chromium, and nickel showed significant increase over this period – both across the whole dataset (Table A6) and in the pointwise comparisons (average 2001-to-2025 ratios of 3.9–5.5; Table A5). As explained above, we attribute the increase in chromium and nickel primarily to indirect impacts – e.g., enhanced mobilization of local bedrock due to explosions and other soil disturbance during post-2001 conflicts. Although cadmium and arsenic may be present in ordnance – they are common impurities of, respectively, lead ammunition and propellants/explosives –, they also correlate with chromium, nickel, and other elements linked to local bedrock (Table A8). For this reason, we suspect that the enrichment of these secondary war-related contaminants is only indirectly related to warfare.

Proxies for white phosphorus

In addition to heavy metals and explosives, white phosphorus ordnance can leave on the ground uncombusted particles and oxidation products, primarily phosphonic acid and phosphoric acid

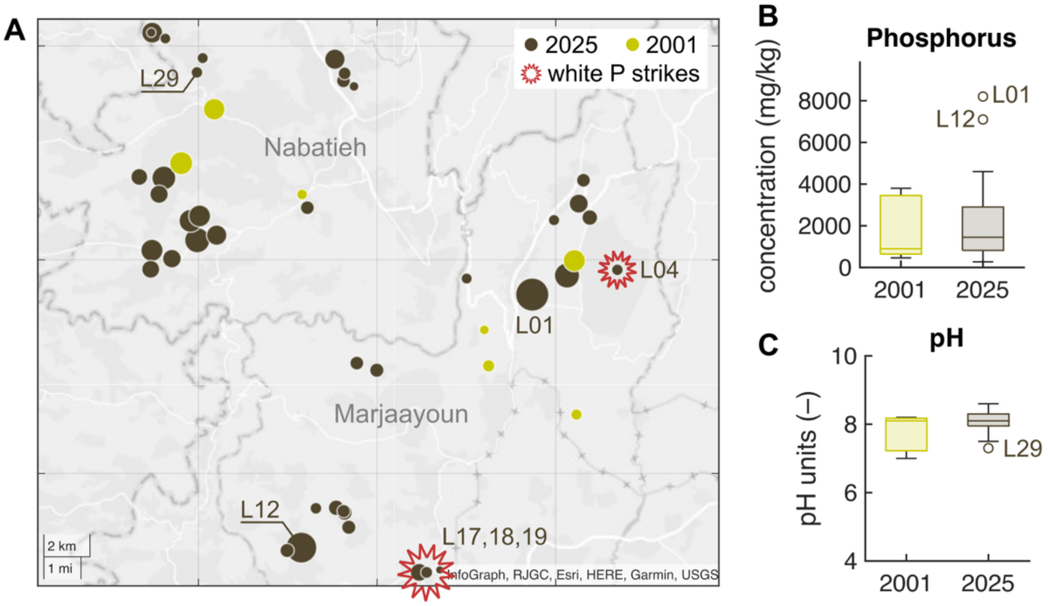

Figure 10. Proxies of white phosphorus use. A Spatial distribution of total phosphorus in soils collected in 2001 (light green) and 2025 (brown); larger circles indicate higher concentrations (range: 270–8200 mg/kg). The map reports only sites with confirmed white phosphorus strikes. Boxplot summarizing total phosphorus concentrations (**B**) and soil pH (**C**) for the 2001 and 2025 datasets. Outliers are labeled both in the boxplot and the map.

(Figure 4).[9,10,17] Due to sampling and analytical constraints, our assessment relied only on indirect proxies of white phosphorus use: total phosphorus, soil pH, phosphate (the most likely form of phosphoric acid in soil), and phosphite (the most likely form of phosphonic acid in soil). We hypothesized that sites affected by white phosphorus strikes would exhibit higher concentrations of total phosphorus (as reported in previous work by AUB)[5] and phosphate compared to 2001; acidic pH; and detectable levels of phosphite, which is uncommon in undisturbed soils[19,20].

The data that we collected so far did not support these hypotheses. Total phosphorus showed no consistent trend with ordnance use. We found no differences in total phosphorus between 2001 and 2025 (Figure 10B) nor in any other statistical test (Table A6 and Table A7). Despite being closer to the border and more impacted by white phosphorus strikes than the Nabatieh District,[1,2] the Marjaayoun District had overall lower levels of total phosphorus (Figure 10A). Only two sites – L01 (near Borj El-Moulouk) and L12 (near Majidel Selm) – deviated from this pattern: although we were not aware of white phosphorus use at these sites, total phosphorus was respectively 9 and 8 times higher than the 2001 median. While these increases are modest compared to those reported previously (100- to 400-fold),[5] a more in-depth analysis suggests an anthropogenic contribution – which may be white phosphorus ordnance, but also fertilizers, wastewater, or other[21] (Figure 11; details in the following section). On the other hand, sites with confirmed white phosphorus use – L04, L17, L18, and L19 (Figure A1) – were well within the median of the dataset (270–2200 mg/kg). Likewise, total phosphorus in sites measured in 2001 and 2025 had a varied trend: increased slightly in the Marjaayoun District (253/L05, 2001-to-2025 ratio of 1.3), decreased at the impacted site in the Nabatieh District (274/L33, ratio of 0.3), and increased strongly at the nearby control site (267/L32, ratio of 6.6; Table A5). Overall, these results indicate that **total phosphorus is largely controlled by geogenic inputs rather than direct anthropogenic sources related to ordnance use**.

Soil acidity showed patterns consistent with the results for total phosphorus. Soils were overall alkaline (Figure 10C) with a single outlier in L29, a site in the Nabatieh District with no reported white phosphorus use. Locations with documented strikes also exhibited alkaline pH, with values clustered close to the 2025 median (8.0–8.3, median 8.1). Likewise, in the sites measured in both campaigns, pH remained stable or increased slightly over time (average 2001-to-2025 ratio of 1.1; Table A5).

Although ongoing analyses of phosphates and phosphites may yield additional insights, **the current dataset does not provide clear evidence of environmental impacts uniquely attributable to white phosphorus strikes**. A likely explanation – consistent with the literature[9,17,44] – is that the effects of white phosphorus are highly localized and heterogeneous, making them particularly sensitive to sampling artifacts. This limitation was compounded by the small number of sites with confirmed white phosphorus use and the relatively long interval between the last attacks and our sampling campaign. Given the instability of uncombusted white phosphorus and the mobility of its degradation products, any transient increase in total phosphorus may have been attenuated through weathering or leaching. In addition, the calcareous nature of soils in South Lebanon likely buffered any temporary decrease in soil pH caused by deposition of white phosphorus oxidation products. Notably, site L17 – one of the locations suspected to be affected by white phosphorus – displayed the clearest signature of war-related contamination (Figure 9). Taken together, these findings support previous studies[5,6] indicating that the **environmental impacts associated with white phosphorus use primarily arise from the toxic heavy metals contained in the ordnance rather than from phosphorus itself**.

Proxies for depleted uranium

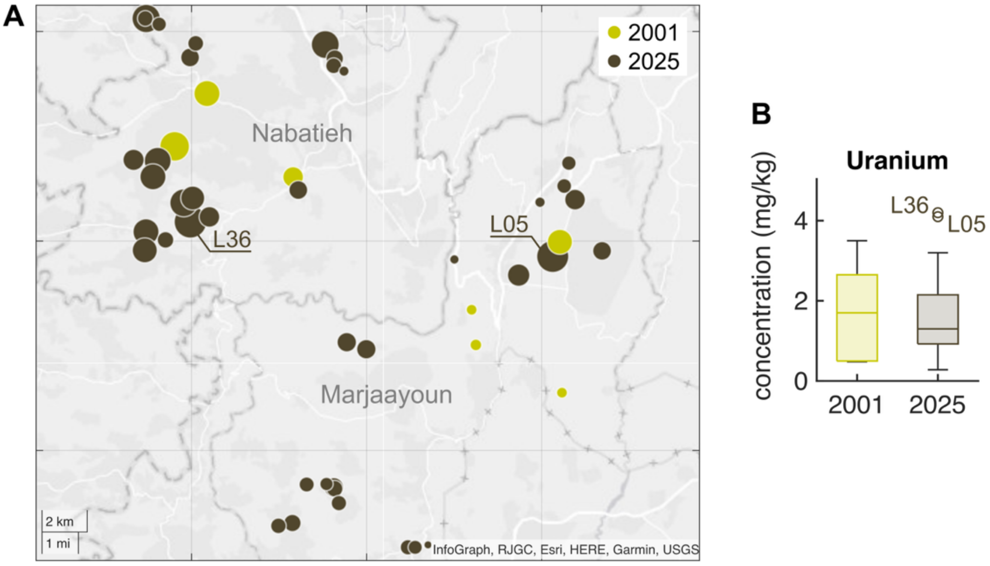

Figure 11. Proxies for depleted uranium. A Spatial distribution of total uranium in soils collected in 2001 (light green) and 2025 (brown); larger circles indicate higher concentrations (range: 0.28–4.2 mg/kg). **B** Boxplot summarizing uranium concentrations in the 2001 and 2025 datasets. Outliers are labeled both in the boxplot and the map.

Depleted uranium, a by-product of uranium enrichment, is used in tank armor, armor-piercing munitions, and other military equipment.[11,23] Since distinguishing between isotopes of the same element requires expensive and complex analyses, we used *total* uranium as a proxy for depleted uranium (Figure 3).

Our data showed no evidence of depleted uranium use in South Lebanon. Total uranium did not differ significantly between 2025 and 2001 (Figure 11 and Table A6). Concentrations were 0.5–3.5 mg/kg in 2001 and 0.3–4.2 mg/kg in 2025 (Table A3), remaining always well below the Canadian guideline of 23 mg/kg (Table 1) and within typical background ranges found worldwide (0.3–12 mg/kg).[26] We detected a significant difference only between the two districts (Table A6 and Figure 11), with lower concentrations in Marjaayoun (closer to the border) and higher in Nabatieh. This spatial pattern, opposite to what we expected, suggests either legacy contamination or differences in bedrock geology. While not statistically significant (p = 0.11), the same geographic distribution was also observed in 2001, supporting this interpretation. At sites sampled in both years, changes in total uranium were modest, with an average 2001-to-2025 ratio of 1.2 (Table A5).

An in-depth look at the data revealed a **strong correlation between phosphorus and uranium** (R^2 = 0.77; Figure 12) **that reinforces the hypothesis of a geogenic origin**. Phosphate rocks are known to contain traces of uranium and have historically been exploited as uranium sources,[45,46] justifying their co-occurrence. Two sites (L01 and L12) deviate markedly from this correlation, showing phosphorus concentrations substantially higher than predicted from their uranium content. Notably, these same sites correspond to the outliers of the total phosphorus dataset (Figure 10B), supporting our attribution of excess phosphorus at these locations to anthropogenic sources.

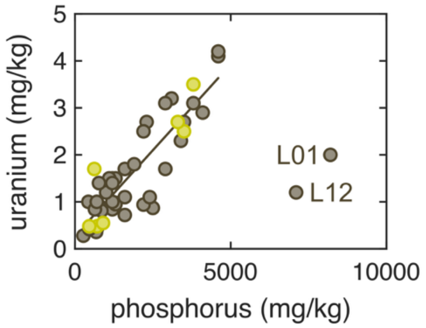

Figure 12. Correlation between total phosphorus and uranium in 2001 (light green) and 2025 (brown). The line is a linear regression obtained excluding samples L01 and L12 (R^2 = 0.77).

Overall, our results strengthen previous findings indicating no evidence of depleted uranium use in South Lebanon. A 2024 investigation from the Lebanese National Council of Scientific Research and UNDP reported no detectable depleted uranium in 14 soil samples collected from areas where use of these weapons was suspected.[1] Earlier studies focusing on the 2006 conflict likewise found limited evidence of depleted uranium use in the region.[47–49]

Key findings

Heavy metals

We found an **increase in selected metals and metalloids across the entire sampling area between 2001 and 2025**. The large majority of these elements have been directly or indirectly associated with warfare in the scientific literature,[6–8] supporting a link between recent military operations and changes in soil chemistry.

Lead, antimony, copper, and zinc – direct fingerprints of ammunition use (Figure 3) – **increased significantly in 2025 compared to the historical reference** (Figure 8). While copper and zinc were also above the German precautionary values in 35% and 25% of the 2025 samples, respectively, **the overall increase was modest** (1.5-fold to 3.6-fold compared to the 2001 median). In contrast, **a small number of sites emerged as clear contamination hotspots**. The most striking case was L17, in Houla (Marjaayoun District), where antimony concentrations were 500-fold higher than the 2001 median, and lead exceeded the German PV of 70 mg/kg (Figure 9). Following was L02, showing the second-highest concentrations of lead, copper, and zinc of the dataset, and L33, with the highest concentration of copper and the second-highest concentration of antimony (Figure 9). Among these elements, **lead is of the greatest concern** due to its persistence and well-acknowledged toxicity to soil biota and humans.[14,16,37]

Additional metals commonly detected in military training ranges and conflict-impacted areas – e.g., arsenic, cadmium, chromium, and nickel (Figure 3) – **were also significantly higher in 2025 than in 2001** (Figure 7). For some of these elements – chromium and nickel in particular – we suspect that their increase reflects the enhanced mobilization of local bedrock caused by explosions, not direct leaching from abandoned military equipment. Among these elements, **arsenic and cadmium are of greatest concern** due to their carcinogenicity.[50,51]

Taken together, these findings indicate a **diffuse but moderate deterioration of soil quality over the past 24 years** in the Marjaayoun and Nabatieh Districts. Levels of toxic metals that raise particular concern are limited to a small number of contamination hotspots. These hotspots typically occurred in areas subjected to intense military activity (e.g., L17) or near locations where spent ammunition may have remained on the ground (though we did not find evidence of this latter case during our campaign).

This pattern of diffuse contamination overlayed over heterogeneously distributed hotspots has been reported in other post-conflict settings, including depleted uranium contamination in Serbia and Montenegro[11] and white phosphorus pollution in Alaska[17]. This unique pattern likely reflects the combined effect of two processes. First, military explosions generate dust and aerosols that disperse contaminants over a broad area, whose extent depends on prevalent wind conditions, particle size, and co-occurring disturbance. This process is responsible for the diffuse pollution background. Second, corrosion of residual ammunition and other metal fragments may leach contaminants locally over time, leading to sharply elevated concentrations of their constituent elements in a localized area – these are the contamination hotspots.

White phosphorus

We did not find evidence of environmental impacts uniquely attributable to white phosphorus use. Although we did not directly detect white phosphorus particles, all indirect proxies analyzed so far provided a consistent picture: we observed no systematic increases in total phosphorus (the largest increase was 9-fold at site L01) and no change in soil pH between 2001 and 2025 (Figure 10). Likewise, sites with confirmed white phosphorus strikes did not exhibit higher levels of phosphorus nor more acidic soil pH than unimpacted locations.

These findings contrast with previous research conducted by AUB, which reported a 100- to 400-fold increase in total phosphorus compared to the natural background in Dahyeh, Bekaa, and other areas of South Lebanon.[5] A key difference between the two studies was timing: the AUB campaign took place between late 2024 and early 2025, only a few weeks after the last reported strike.[2] Given the transient nature of white phosphorus residues and their rapid oxidation into more mobile compounds,[10,17] the longer delay between attacks and our sampling campaign may have attenuated or erased direct contamination signals. In contrast, L17, one of the sites with confirmed white phosphorus use, emerged as a contamination hotspot for lead, antimony, copper, and zinc (Figure 9).

Taken together, **our results reinforce the idea that the environmental impacts of white phosphorus use evolve over time.**[5,6] In the short-term, white phosphorus ordnance causes devastating wildfires and direct ecosystem damage;[2,5,52] in the mid-term, it may temporarily disrupt soil chemistry and biological processes by altering the natural phosphorus cycle;[19,21,53] and in the long-term, its environmental footprint may be dominated by the toxic and persistent metals (e.g., lead, cadmium, and arsenic) co-released during explosions. **Given the limited academic literature on this topic,[5,6] these conclusions should be regarded as a working hypothesis requiring further investigations.**

Depleted uranium

Likewise, **we found no evidence of depleted uranium use in South Lebanon**. Total uranium, an indirect proxy of depleted uranium, did not change significantly between 2001 and 2025 and had always been at levels compatible with natural abundances found worldwide (Figure 11). The natural origin was further corroborated by the strong correlation between uranium and phosphorus (Figure 12).

This result mirrors previous findings from the Lebanese National Council of Scientific Research and UNDP that showed no evidence of depleted uranium use at 8 suspected sites in Beirut and its southern suburbs and in the Bekaa valley.[1]

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Appendix

Table A1 Overview limits of detection and average measurement uncertainty for metals, metalloids, and other elements detected via ICP-MS.

Table A2 Selected properties of soil samples collected in 2025.

Table A3 Chemical composition and pH of soils collected in 2025 and comparison with historical values and international normative.

Table A4 Chemical composition and pH of soils collected in 2001 and comparison with the international normative.

Table A5 Comparison between 2001 and 2025.

Table A6 Results of selected Mann-Whitney U tests (comparison between 2 groups).

Table A7 Results of selected Kruskal-Wallis tests (comparison among 3 groups or more).

Table A8 Selected correlation coefficients between elements in the combined dataset.

Figure A1 Confirmation of sites with white phosphorus use.

Table A1. Overview of limits of detection and average measurement uncertainty for metals, metalloids, and other elements detected via ICP-MS (values provided by the laboratory). When not available (n.a.), analytes were always > their limits of detection. The average relative error was calculated as reported uncertainty / measured value for each element, averaged over the 47 samples of the study.

	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Iron	Manganese	Mercury	Molybdenum	Nickel	Lead	Phosphorus	Copper	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
Limit of detection (mg/kg)	n.a.	0.1	n.a.	n.a.	0.1	100	0.1	n.a.	n.a.	n.a.	n.a.	0.5	10	10	10	n.a.	10	0.5	n.a.	0.025	0.5	n.a.	n.a.
Average relative error (%)	n.a.	32%	29%	29%	26%	n.a.	25%	30%	30%	41%	26%	n.a.	n.a.	36%	37%	n.a.	29%	24%	27%	27%	28%	26%	27%

Table A2. General properties of soil samples collected in 2025 the Marjaayoun and Nabatieh Districts.

ID	Sample or *control*	District	Ownership	Land type	Land use	Military operations in the last 6 months?	White phosphorus strike?	Latitude	Longitude
L01	Sample	Marjaayoun	Private	Rural	Permanent crops	**Yes**	No	33.31978	35.57237
L02	Sample	Marjaayoun	Private	Rural	Garden	Not known	No	33.34879	35.58253
L03	Sample	Marjaayoun	Private	Rural	Arable crops	No	No	33.35523	35.59404
L04	Sample	Marjaayoun	Private	Urban	Other (building)	No	**Yes**	33.32943	35.61207
L05	Sample	Marjaayoun	Private	Rural	Garden	No	Not known	33.32722	35.58858
L06	Sample	Marjaayoun	Private	Rural	Permanent crops	No	Not known	33.34981	35.59921
L07	Sample	Marjaayoun	Private	Interface	Permanent cr. + garden	No	No	33.36433	35.59627
L08	Sample	Marjaayoun	Private	Rural	Permanent crops	No	**Yes**	33.32602	35.54177
L09	Sample	Marjaayoun	Private	Rural	Permanent crops	**Yes**	No	33.29307	35.49054
L10	Sample	Marjaayoun	Private	Rural	Permanent crops	No	No	33.29029	35.49985
L11	Sample	Marjaayoun	Public	Rural	Barren soil	No	No	33.23643	35.47145
L12	Sample	Marjaayoun	Private	Interface	Garden	No	No	33.22108	35.46465
L13	*Control*	*Marjaayoun*	*Private*	*Rural*	*Permanent crops*	*No*	*No*	*33.21996*	*35.45802*
L14	Sample	Marjaayoun	Private	Interface	Permanent crops	No	No	33.22903	35.48680
L15	Sample	Marjaayoun	Private	Interface	Permanent crops + garden	No	No	33.23477	35.48476
L16	Sample	Marjaayoun	Private	Interface	Garden	No	No	33.23531	35.48439
L17	Sample	Marjaayoun	Public	Urban	Garden + barren soil	No	**Yes**	33.21140	35.52310
L18	Sample	Marjaayoun	Private	Urban	Garden	No	**Yes**	33.21142	35.51964
L19	Sample	Marjaayoun	Private	Urban	Barren or unused soil	No	**Yes**	33.21239	35.52923
L20	*Control*	*Marjaayoun*	*Public*	*Rural*	*Forest*	*No*	*No*	*33.23663*	*35.48091*
L21	Sample	Nabatieh	Private	Urban	Garden	No	No	33.42183	35.39507
L22	Sample	Nabatieh	Private	Interface	Garden	No	No	33.42185	35.39464

L23	Sample	Nabatieh	Private	Interface	Garden	No	No	33.41954	35.40123
L24	Sample	Nabatieh	Private	Interface	Permanent crops	No	No	33.41193	35.41863
L25	Sample	Nabatieh	Private	Urban	Permanent cr. + garden	No	No	33.40306	35.48430
L26	Sample	Nabatieh	Private	Urban	Permanent + arable cr.	No	No	33.40090	35.48922
L27	Sample	Nabatieh	Private	Urban	Garden	No	No	33.41148	35.48032
L28	*Control*	*Nabatieh*	*Public*	*Urban*	*Permanent cr. + garden*	*No*	*No*	*33.40595*	*35.48484*
L29	Sample	Nabatieh	Private	Interface	Permanent cr. + garden	No	No	33.40634	35.41595
L30	Sample	Nabatieh	Private	Rural	Garden	No	No	33.35890	35.39828
L31	Sample	Nabatieh	Private	Rural	Barren or unused soil	No	No	33.36563	35.38906
L32	*Control*	*Nabatieh*	*Private*	*Rural*	*Barren or unused soil*	*No*	*No*	*33.36523*	*35.40051*
L33	Sample	Nabatieh	Private	Urban	*Garden*	No	No	33.35364	35.46747
L34	Sample	Nabatieh	Private	Interface	Permanent crops	No	No	33.35043	35.41719
L35	Sample	Nabatieh	Private	Interface	Arable crops	No	No	33.34853	35.41297
L36	Sample	Nabatieh	Private	Interface	Permanent + arable cr.	No	No	33.34098	35.41611
L37	*Control*	*Nabatieh*	*Private*	*Rural*	*Arable crops*	*No*	*No*	*33.34294*	*35.42517*
L38	Sample	Nabatieh	Private	Urban	Permanent cr. + garden	No	No	33.32965	35.39438
L39	*Control*	*Nabatieh*	*Private*	*Rural*	*Arable crops*	*No*	*No*	*33.33379*	*35.40427*
L40	*Control*	*Nabatieh*	*Private*	*Urban*	*Garden*	*No*	*No*	*33.33701*	*35.39497*

Table A3. Chemical composition and pH of soils collected in 2025 (Marjaayoun: L01 – L20; Nabatieh: L21 – L40) **and comparison with historical values and international normative**. pH is in arbitrary units, metal concentrations are in mg/kg. Values in dark red exceed the German Precautionary Values for type 2 soils (Table 1). Control samples are highlighted in green and italics. Values in grey were either not detected ("n.d.", reported as zeros by the laboratory) or were below their limits of detection (see Table A1).

Sample ID	pH	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Copper	Iron	Lead	Manganese	Mercury	Molybdenum	Nickel	Phosphorus	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
L01	7.7	15605	0.29	7.8	67	0.99	6.4	0.2	18	41	15	6451	22	581	n.d.	0.45	31	8200	0.53	1.26	n.d.	2	55	**220**
L02	8.5	17074	1.1	16	68	3.3	7.6	0.71	55	**160**	**64**	7155	57	814	0.077	0.35	**110**	710	1.2	0.88	0.19	0.44	150	**390**
L03	8.4	19887	0.6	6.1	87	1.3	6.1	0.83	16	**77**	31	7433	14	727	n.d.	0.57	**51**	2500	n.d.	2.08	0.093	0.87	77	100
L04	8	5670	0.29	1.4	53	0.12	4.1	0.47	2	23	9.6	3510	6.8	152	n.d.	0.41	10	770	0.09	1.24	n.d.	1.4	19	33
L05	8.5	9990	1	7.6	352	1.7	3.9	**1.4**	18	**150**	**50**	8008	11	799	n.d.	0.35	**94**	4600	1	1.29	0.15	4.1	94	150
L06	7.8	17622	1.1	7.7	111	1.9	3.3	**3.2**	20	**180**	**43**	9531	16	979	n.d.	0.26	**86**	1600	0.7	2.07	0.17	1.7	150	140
L07	8	20206	0.36	4.8	74	0.73	5.5	0.34	12	41	15	6218	7.3	680	n.d.	0.46	28	1200	0.19	1.89	n.d.	0.84	46	61
L08	8.2	20667	0.19	5.9	40	0.94	5.7	0.14	14	46	15	10640	5.8	632	n.d.	0.47	34	680	0.42	1.11	0.079	0.36	46	44
L09	8.3	14228	1.4	6.1	82	1.8	2.9	**1.2**	18	**120**	**43**	6455	26	759	n.d.	0.44	47	1200	0.47	6.72	0.14	1.5	120	110
L10	8	14083	0.72	5.5	65	1.7	4.6	0.96	14	**120**	33	6909	11	583	n.d.	0.26	43	1300	n.d.	1.86	0.096	1.5	120	96
L11	8.3	13712	0.86	5.1	144	1.6	3.3	0.86	14	**130**	34	9569	7.8	638	n.d.	0.24	**65**	790	n.d.	1.44	0.13	0.91	92	100
L12	7.7	11284	0.84	5	155	0.92	14.8	0.99	8.4	**70**	**45**	8297	26	640	n.d.	0.30	37	7100	n.d.	7.54	0.099	1.2	56	**190**
L13 (control)	*7.5*	*13683*	*1*	*7.3*	*103*	*2.1*	*4.7*	***1.5***	*20*	***150***	***49***	*7475*	*16*	*929*	n.d.	*0.27*	***69***	*1300*	*0.69*	*2.05*	*0.18*	*0.98*	*130*	*130*
L14	7.9	14482	0.83	7.7	82	2.5	4.4	**1.6**	20	**170**	**57**	8930	15	728	n.d.	0.20	**70**	1300	0.89	2.13	0.23	0.95	150	140
L15	8.3	12082	1.6	4.9	139	0.94	9.4	0.86	7.9	**74**	**45**	7423	46	387	n.d.	0.34	35	1600	0.43	4.35	0.079	1.1	66	**190**
L16	8.5	17361	0.77	7.9	65	2.4	4.4	0.92	16	**200**	**54**	12490	11	502	n.d.	0.17	**90**	1100	n.d.	2.24	0.17	1.5	160	130
L17	8.2	13870	110	3.3	121	0.67	8.0	0.81	6.6	51	**75**	7304	**100**	306	n.d.	0.82	26	850	0.12	7.67	0.073	0.81	38	**220**
L18	8.1	15820	1.1	8.6	106	1.9	7.9	0.64	16	**110**	39	12704	17	779	n.d.	0.70	**62**	2200	0.63	5.40	0.26	0.94	100	**1500**
L19	8.3	6829	0.48	1.3	166	0.085	6.1	0.085	2.1	11	13	3145	3.5	107	n.d.	0.36	4.3	270	0.11	1.39	n.d.	0.28	8.5	**160**

L20 (control)	*7.7*	*15605*	*0.29*	*7.8*	*67*	*0.99*	*6.4*	***0.2***	*18*	***41***	*35*	*10157*	*15*	*763*	*n.d.*	*0.26*	***65***	*1600*	*n.d.*	*2.25*	*0.17*	*0.72*	*110*	*130*
L21	8.6	8111	0.74	9	55	0.51	10.8	0.34	3.9	**91**	25	6438	7.2	142	n.d.	1.84	36	3100	0.26	1.32	n.d.	3.2	56	100
L22	8.3	16957	0.34	5.2	66	1.3	5.0	0.19	8.4	**85**	14	14622	12	332	n.d.	0.48	29	430	0.39	2.05	0.1	1.0	71	55
L23	8.2	14378	1.1	6.8	102	1.3	4.1	0.41	13	**67**	27	10901	12	686	n.d.	0.40	48	640	n.d.	1.89	0.14	0.84	94	75
L24	8.1	14875	0.72	6.9	87	1.6	3.3	0.4	16	**86**	28	9021	17	676	n.d.	0.37	42	700	n.d.	2.10	0.15	1.0	120	93
L25	8.1	12258	1.7	5.3	90	0.83	6.8	0.9	7.6	**75**	25	10106	13	354	n.d.	0.49	44	1200	0.97	2.48	0.097	1.0	53	97
L26	8.3	8656	0.49	2.7	75	0.48	4.1	0.42	5	32	15	6157	9.5	232	n.d.	0.32	20	460	n.d.	1.98	n.d.	0.42	26	73
L27	8.3	7917	0.76	6.9	101	0.92	6.9	0.59	5.9	**100**	35	7957	9.2	237	n.d.	0.81	46	2900	0.3	1.21	0.1	3.1	59	110
L28 (control)	*7.9*	*13928*	*0.61*	*7.1*	*96*	*1.7*	*5.5*	***1.9***	*17*	***120***	*36*	*7555*	*12*	*658*	*n.d.*	*0.33*	***52***	*1000*	*1*	*1.76*	*0.14*	*1.2*	*100*	*130*
L29	7.3	10959	0.52	4.7	50	0.91	5.3	0.24	7.5	54	15	8796	8.2	262	n.d.	0.70	24	770	0.36	1.05	n.d.	1.4	57	59
L30	8.3	10394	0.9	9.7	59	0.76	5.3	0.37	6.1	**95**	23	9485	24	283	n.d.	1.91	44	2300	0.9	1.42	0.09	2.7	66	71
L31	8	12146	0.7	8.3	96	1.4	4.3	0.42	14	**90**	31	9785	9	702	n.d.	0.57	**54**	1900	0.2	1.50	0.14	1.8	89	82
L32 (control)	*8*	*10850*	*0.88*	*12*	*125*	*1.8*	*4.9*	*0.74*	*17*	***180***	***52***	*10706*	*15*	*727*	*n.d.*	*1.07*	***88***	*4100*	*0.99*	*2.25*	*0.22*	*2.9*	*120*	***160***
L33	8.1	16139	2	7.9	122	1.9	3.9	**1.1**	21	**170**	**75**	9024	33	869	n.d.	0.39	**100**	1200	n.d.	19.06	0.15	1.4	120	**280**
L34	8.3	9059	0.63	6.8	80	0.82	7.4	0.48	6.1	**94**	36	9080	6.2	311	n.d.	0.84	44	3400	0.48	1.04	0.082	2.3	59	100
L35	8	11909	0.79	10	129	2.1	3.7	0.68	15	**180**	**56**	11036	12	714	n.d.	0.76	**90**	3800	n.d.	2.01	0.18	3.1	110	**160**
L36	8.2	9253	0.76	7	87	1	7.3	0.82	10	**110**	**47**	8149	8.5	468	n.d.	0.70	**70**	4600	n.d.	1.04	0.1	4.2	70	140
L37 (control)	*8.1*	*8632*	*0.75*	*5*	*90*	*0.85*	*4.0*	*0.62*	*8.1*	***67***	*34*	*7167*	*7.4*	*469*	*n.d.*	*0.32*	*46*	*2900*	*0.71*	*0.93*	*n.d.*	*1.7*	*55*	*91*
L38	8.4	9912	0.57	4.7	84	0.79	4.2	0.55	9.6	**63**	30	6525	8.3	573	n.d.	0.45	39	2200	0.11	1.27	0.087	2.5	53	77
L39 (control)	*7.6*	*10274*	*0.54*	*4.4*	*138*	*1.2*	*3.1*	*0.68*	*15*	***78***	*35*	*8051*	*11*	*877*	*n.d.*	*0.32*	***55***	*2400*	*n.d.*	*1.24*	*0.12*	*1.1*	*66*	*93*
L40 (control)	*7.9*	*9141*	*0.7*	*4.3*	*197*	*0.9*	*5.1*	*0.72*	*12*	***71***	*32*	*7304*	*14*	*657*	*n.d.*	*0.34*	***53***	*3500*	*n.d.*	*1.47*	*0.1*	*2.7*	*53*	*120*
Median	**8.1**	**12816**	**0.76**	**6.8**	**90**	**1.25**	**5.0**	**0.70**	**14**	**90**	**34**	**8100**	**12**	**639**	**n.d.**	**0.41**	**46**	**1450**	**0.23**	**1.9**	**0.10**	**1.3**	**70**	**110**
2001 median	8.1	12543	0.21	4.6	87	0.97	3.3	0.31	7.7	47	14	7429	7.9	883	0	0.34	36	900	0.42	1.6	0.11	1.7	57	42
German PVs				20				1		60	40		70		0.3		50				1			150
Canadian EQGs	6–8		20	12	500	4		10	50	64	63		61		6.6		45		1	50	1	23	130	250

Table A4. Chemical composition and pH of soils collected in 2001, including their median values in comparison with relevant international normative. pH is in arbitrary units, metal concentrations are in mg/kg. Values in dark red exceed the German Precautionary Values (PVs) for type 2 soils (Table 1). Values in grey were either not detected ("n.d.", reported as zeros by the laboratory) or were below their limits of detection (Table A1).

Sample ID	pH	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Copper	Iron	Lead	Manganese	Mercury	Molybdenum	Nickel	Phosphorus	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
253	7.2	11952	0.14	1.1	154	0.32	2.6	0.34	4	28	8.1	7150	3	1143	n.d.	0.17	11	3500	0.47	1.79	n.d.	2.5	19	26
258	8.1	15476	0.21	4.6	66	0.98	3.3	0.36	13	47	14	7077	7.9	562	n.d.	0.30	36	710	1.0	0.96	0.11	0.48	57	50
264	8.2	15906	0.32	6.2	79	1.2	3.6	0.31	18	58	21	8541	18	1069	n.d.	0.60	40	900	0.42	1.63	0.14	0.55	60	53
265	8.2	18765	0.19	4.8	87	1.0	3.4	0.2	24	**68**	22	9613	10	1283	n.d.	0.34	46	460	0.26	1.59	0.14	0.48	62	42
267	7	12543	0.23	1.4	101	0.36	2.1	0.14	4.2	29	11	7429	3.3	883	n.d.	0.26	18	620	n.d.	1.83	n.d.	1.7	24	23
271	7.3	8276	0.082	1.1	145	n.d.	1.8	n.d.	3.9	26	9.8	6100	5.2	856	n.d.	0.73	16	3300	0.25	1.56	n.d.	2.7	20	25
274	8.1	8071	0.71	7.9	78	0.97	4.1	0.51	7.7	**95**	34	7941	8.8	343	n.d.	0.86	**51**	3800	0.83	0.91	0.11	3.5	66	86
Median	**8.1**	**12543**	**0.21**	**4.6**	**87**	**0.97**	**3.3**	**0.31**	**7.7**	**47**	**14**	**7429**	**7.9**	**883**	**0**	**0.34**	**36**	**900**	**0.42**	**1.6**	**0.11**	**1.7**	**57**	**42**
German PVs				20				1		60	40		70		0.3		50				1			150
Canadian EQGs	6–8		20	12	500	4		10	50	64	63		61		6.6		45		1	50	1	23	130	250

Table A5. Comparison between 2001 and 2025 (top: pointwise comparison of sites within 1 km radius; bottom: comparison of median values). pH is in arbitrary units, metal concentrations are in mg/kg. The table summarizes 2025-to-2001 ratios calculated with concentrations reported in Table A3 and Table A4. Sample L32 was a 2025 control site. Boron, mercury, and molybdenum were always below their limit of detection or were not detected (n.d.), thus results must be considered only indicative.

Samples ID	pH	Aluminum	Antimony	Arsenic	Barium	Beryllium	Boron	Cadmium	Cobalt	Chromium	Copper	Iron	Lead	Manganese	Mercury	Molybdenum	Nickel	Phosphoros	Selenium	Tin	Thallium	Uranium	Vanadium	Zinc
Pointwise comparison																								
253/L05	1.2	0.8	7.1	6.9	2.3	5.3	1.5	4.1	4.5	5.4	6.2	1.1	3.7	0.7	n.d.	2.1	8.5	1.2	0.47	1.79	n.d.	1.6	4.9	5.8
274/L33	1.0	2.0	2.8	1.0	1.6	2.0	1.0	2.2	2.7	1.8	2.2	1.1	3.8	2.5	n.d.	0.5	2.0	0.3	n.d.	20.9	1.4	0.4	1.8	3.3
267/L32 (c)	*1.1*	*0.9*	*3.8*	*8.6*	*1.2*	*5.0*	*2.4*	*5.3*	*4.0*	*6.2*	*4.7*	*1.4*	*4.5*	*0.8*	*n.d.*	*4.1*	*4.9*	*6.6*	*n.d.*	*1.2*	*n.d.*	*1.7*	*5.0*	*7.0*
Average	*1.1*	*1.2*	*4.6*	*5.5*	*1.7*	*4.1*	*1.6*	*3.9*	*3.8*	*4.5*	*4.4*	*1.2*	*4.0*	*1.4*	*n.d.*	*2.2*	*5.1*	*2.7*	*n.d.*	*7.6*	*n.d.*	*1.2*	*3.9*	*5.3*
Overall comparison (median values)																								
2025/2001	1.0	1.0	3.6	1.5	1.0	1.3	1.5	2.2	1.8	1.9	2.5	1.1	1.5	0.7	n.d.	1.2	1.3	1.6	0.6	1.2	0.9	0.8	1.2	2.6

Table A6. Results of selected Mann-Whitney U tests (comparison between 2 groups). Statistically different groups are highlighted in green ($p < 0.05$). Elements in grey were zero or below their limit of detection in 100% of the samples and were not considered in the discussion.

	p values			
	2025 vs. 2001	Samples vs. controls (2025)	Nabatieh vs. Marjaayoun (2025)	Nabatieh vs. Marjaayoun (2001)
Soil pH	0.092	0.010	0.978	0.286
Aluminum	0.940	0.149	0.008	0.114
Antimony	0.0004	0.817	0.357	0.857
Arsenic	0.030	0.845	0.675	0.971
Barium	0.869	0.091	0.818	0.857
Beryllium	0.058	0.510	0.120	0.229
Boron	0.001	0.845	0.337	0.629
Cadmium	0.002	0.130	0.048	0.629
Cobalt	0.369	0.309	0.051	0.229
Chromium	0.010	0.392	0.756	0.857
Copper	0.003	0.345	0.279	1.000
Iron	0.275	0.817	0.229	0.629
Lead	0.028	0.887	0.176	0.629
Manganese	0.019	0.130	0.114	0.229
Mercury	0.720	0.693	0.342	1.000
Molybdenum	0.665	0.219	0.008	0.400
Nickel	0.041	0.130	0.989	1.000
Phosphorus	0.622	0.117	0.432	0.629
Selenium	0.378	0.512	0.668	0.400
Tin	0.184	0.656	0.114	0.857
Thallium	0.343	0.282	0.634	0.400
Vanadium	0.034	0.630	0.371	1.000
Uranium	0.976	0.521	0.008	0.114
Zinc	0.0002	0.844	0.031	0.629

Table A7. Overview of *p* values of Kruskal-Wallis tests (comparison among 3 or more groups). Statistically different groups are highlighted in green ($p < 0.05$). Groups responsible for the test's outcome are indicated in parenthesis. Elements in grey were zero or below their limit of detection in 100% of the samples and were thus nor considered in the discussion.

	p values		
	Rural vs. urban vs. interface (2025)	Land use (2025)	Samples (2025) vs. controls (2025) vs. 2001
Soil pH	0.638	0.238	0.003 (samples ≠ controls)
Aluminum	0.071	0.131	0.468
Antimony	0.853	0.793	0.002 (samples ≠ 2001, controls ≠ 2001)
Arsenic	0.175	0.107	0.089
Barium	0.703	0.087	0.140
Beryllium	0.017 (rural ≠ urban)	0.092	0.093
Boron	0.258	0.137	0.002
Cadmium	0.465	0.855	0.002 (samples ≠ 2001, controls ≠ 2001)
Cobalt	0.009 (rural ≠ urban)	0.137	0.284
Chromium	0.132	0.201	0.022
Copper	0.611	0.836	0.007 (samples ≠ 2001, controls ≠ 2001)
Iron	0.062	0.328	0.541
Lead	0.691	0.464	0.082
Manganese	0.009 (rural ≠ urban)	0.111	0.012 (samples ≠ 2001)
Mercury	0.472	0.853	0.809
Molybdenum	0.388	0.861	0.253
Nickel	0.091	0.143	0.025 (control ≠ 2001)
Phosphorus	0.455	0.593	0.374
Selenium	0.221	0.355	0.518
Tin	0.607	0.805	0.396
Thallium	0.282	0.140	0.255
Vanadium	0.016 (rural ≠ urban)	0.093	0.080
Uranium	0.982	0.595	0.952
Zinc	0.857	0.552	0.001 (samples ≠ 2001, controls ≠ 2001)

Table A8. Selected correlation coefficients between elements in the combined dataset (2001 + 2025). Cells highlighted in light green have R^2 between 0.6 and 0.79, while values in dark green have $R^2 \geq 0.80$. Elements in grey were always below their limits of detection or were never detected.

	R^2 value		
	Chromium	Nickel	Phosphorus
Soil pH	0.23	0.27	-0.15
Aluminum	0.22	0.26	-0.30
Antimony	-0.11	-0.12	-0.11
Arsenic	0.73	0.78	0.18
Barium	0.12	0.22	0.32
Beryllium	0.86	0.86	-0.11
Boron	0.00	-0.02	0.35
Cadmium	0.66	0.57	0.00
Cobalt	0.56	0.71	-0.11
Chromium	(1.00)	0.92	0.05
Copper	0.76	0.77	0.10
Iron	0.48	0.44	-0.11
Lead	0.12	0.17	-0.06
Manganese	0.24	0.35	0.01
Mercury	n.d.	n.d.	n.d.
Molybdenum	0.00	-0.06	0.22
Nickel	0.92	(1.00)	0.11
Phosphorus	0.05	0.11	(1.00)
Selenium	0.26	0.27	0.06
Tin	0.22	0.22	-0.02
Thallium	0.79	0.78	-0.09
Vanadium	0.91	0.83	-0.1
Uranium	0.21	0.20	0.63
Zinc	0.21	0.26	0.08

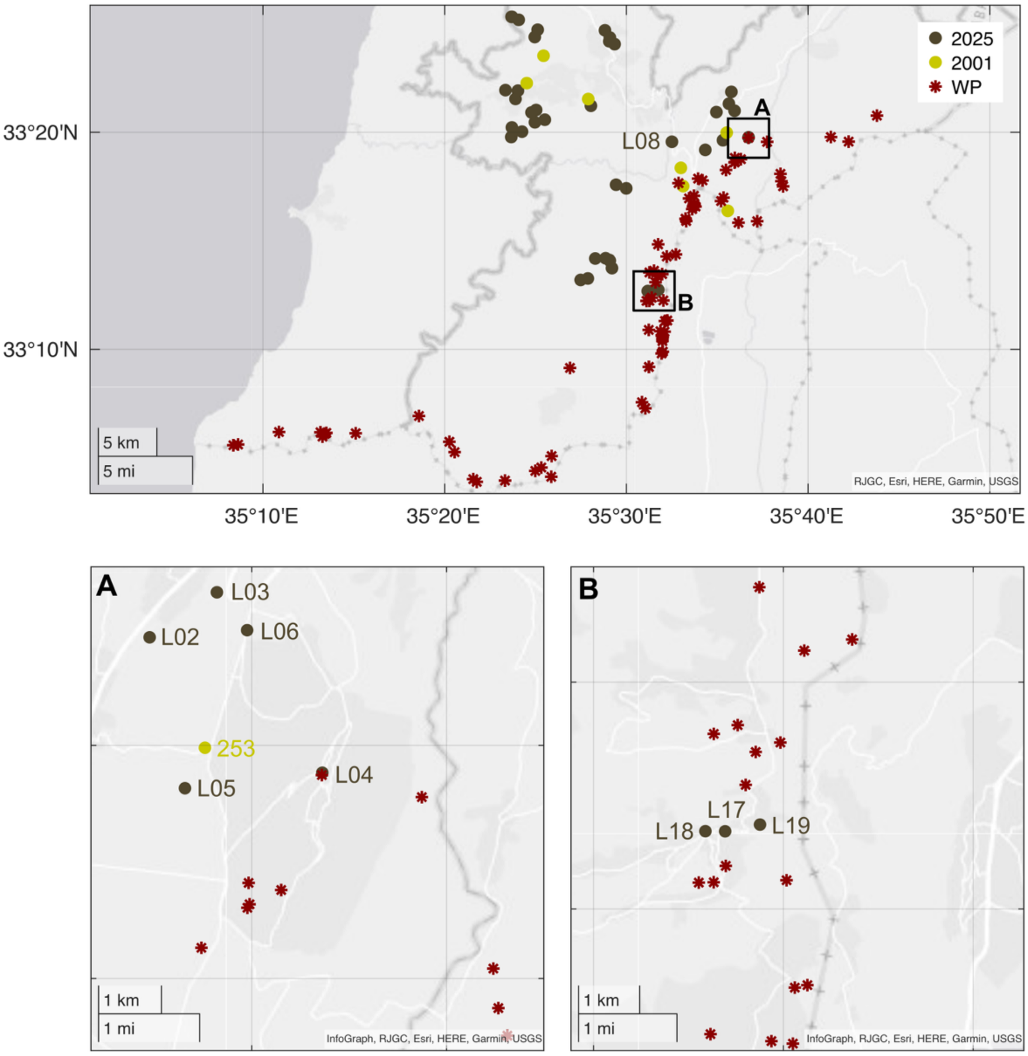

Figure A1. Confirmation of sites with white phosphorus use. The map on the top reproduces the sampling points from 2025 (brown) and 2001 (light green) overlapped with the sites of reported white phosphorus use (WP, red asterisks) according to the online database WhitePhosphorus.info[2] (data until November 2024). Among the 5 sites from the 2025 campaign, L08 was not confirmed.