

Impacts of Historic Arsenical Pesticide Use on Residential Soils in Denver, Colorado

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ABSTRACT

A variety of arsenical compounds were used as pesticides in the U.S. during the first half of the 20th century. Until recently, the impacts of these practices were thought to be limited to orchard soils and other agricultural lands. However, recent investigations of metal contamination of soils near a smelter have revealed that use of a widely available crabgrass killer and insecticide (PAX) during the 1950s and 1960s resulted in arsenic concentrations of up to several thousand parts per million in the soils of residential properties over a large area of Denver, Colorado. Discrimination of pesticide and smelter impacts was a challenging process. Impacts due to smelter emissions were finger-printed by concentrations that decreased with distance, maintained constant metal ratios, and were consistent with modeling of historic emissions and deposition. Pesticide impacts were identified by their random distribution, spatial patterns that were controlled by property line features, and arsenic concentrations that were disproportionately high compared to other metals emitted by the smelters. Air photo analysis showed that high arsenic concentrations associated with pesticide use only occurred on developed properties with well established turf. PAX was finger-printed by the presence of commercial-grade arsenic trioxide crystals, co-location of high arsenic and the perlite filler used in PAX, and arsenic to lead ratios similar to the product formula. Similar arsenic contamination likely exists on numerous residential properties throughout the Denver area and in other cities with similar climatic and soil conditions. These findings raise important public health, logistical, and funding questions.

Keywords:

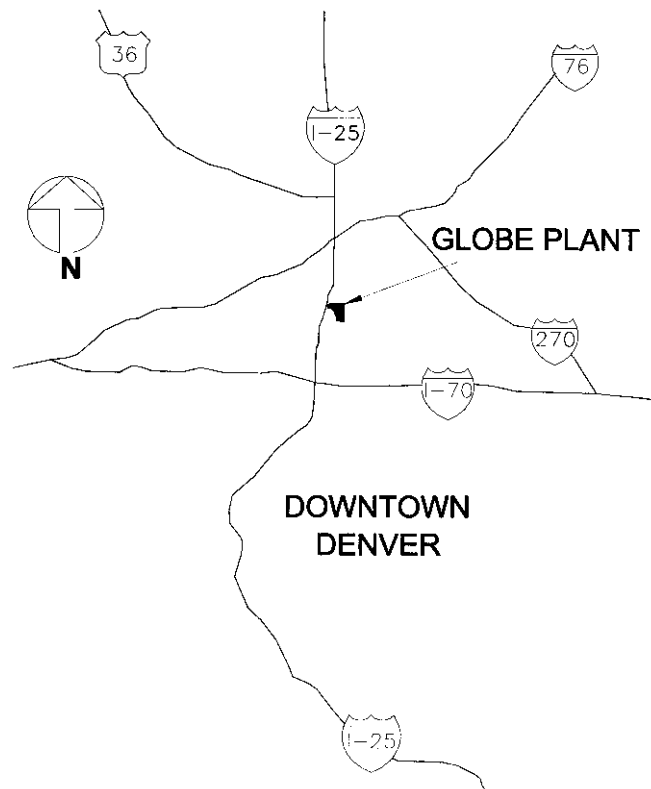
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INTRODUCTION

Recent investigations near a former smelter site in Denver, Colorado, have revealed high arsenic concentrations in soils on certain residential properties due to the historic application of a commercial crabgrass killer during the 1950s and 1960s. Although the potential impacts of arsenical pesticides on soils have been known for many years (e.g., McMurtrey and Robinson, 1938), cases in the literature have been largely confined to orchards and not residential properties without a history of this land use. Further, many of the arsenic concentrations caused by herbicide use in Denver significantly exceed those due to smelter emissions and likely occur in other neighborhoods of the city. This paper discusses the nature of the herbicide contamination and the forensic methods that were used to separate impacts due to herbicide application from those due to smelter emissions.

The pesticide impacts were inadvertently discovered while investigating soil contamination around a former smelter in Denver, Colorado. The ASARCO Incorporated (Asarco) Globe Plant was originally built in a rural area in 1886. Today, the site is located within an urban area of the city along the South Platte River valley, a major transportation and industrial corridor with a mixture of residential, commercial, and industrial land use (Fig. 1). Soils in the site vicinity are neutral to alkaline sandy to clayey loams with organic concentrations typically exceeding 1% in the surface horizons and clay accumulations in the B-horizons (SCS, 1974). The climate is semiarid with a mean annual precipitation of 13.8 inches and a mean annual temperature of 52 degrees F (TRC, 1988).

Fig. 1. Site location.



The Globe Plant smelted ore to produce lead bullion, silver, and gold until 1919, when lead-smelting operations ceased. From approximately 1912 until 1927, the plant produced arsenic trioxide by refining bag house dust from other lead smelters. From 1927 until 1993, cadmium refining was the principal operation at the Globe Plant. Since 1993, only relatively small scale, high-purity metal refining has been conducted at the plant.

The State of Colorado sued Asarco in 1983 under the Natural Resource Damages (NRD) provision of the Comprehensive Environmental Reclamation, Cleanup, and Liability Act of 1980 (CERCLA). In an effort to settle the lawsuit, a Remedial Investigation and Feasibility Study (RI/FS) was carried out between 1985 and 1990 to identify, among other things, the nature and extent of soil contamination in the surrounding community due to historic emissions of arsenic, cadmium, lead, and zinc from the facility (TRC 1988, 1990). Soil cleanup or action levels for each metal were set by the State of Colorado (CDH, 1993) based on risk assessment calculations (Putnam, 1989). The primary action level for arsenic is 70 mg/kg, while a voluntary or secondary arsenic action level was set equal to the 'upper limit of background' for arsenic, or 28 mg/kg. The primary action levels for cadmium and lead are 73 mg/kg and 500 mg/kg, respectively.

The community soil cleanup program was subsequently defined by a Statement of Work (SOW), as part of a Consent Decree entered by the U.S. District Court on July 15, 1993 that settled the NRD lawsuit. The SOW requires sampling of every property surrounding the Globe Plant in each direction until a 'clean block' is reached. A provision in the SOW allows Asarco to petition the State to not clean up properties that were contaminated by other sources not related to the Globe Plant.

Yard-by-yard soil sampling began in late 1993, as described below. Within two years, very high arsenic concentrations exceeding levels adjacent to the Globe Plant were found at distances beyond the expected area of smelter impact. The remaining sections of this paper describe the forensic process that eventually identified historic application of a crabgrass killer on lawns as the source of these anomalous arsenic concentrations.

INVESTIGATION PROCEDURES

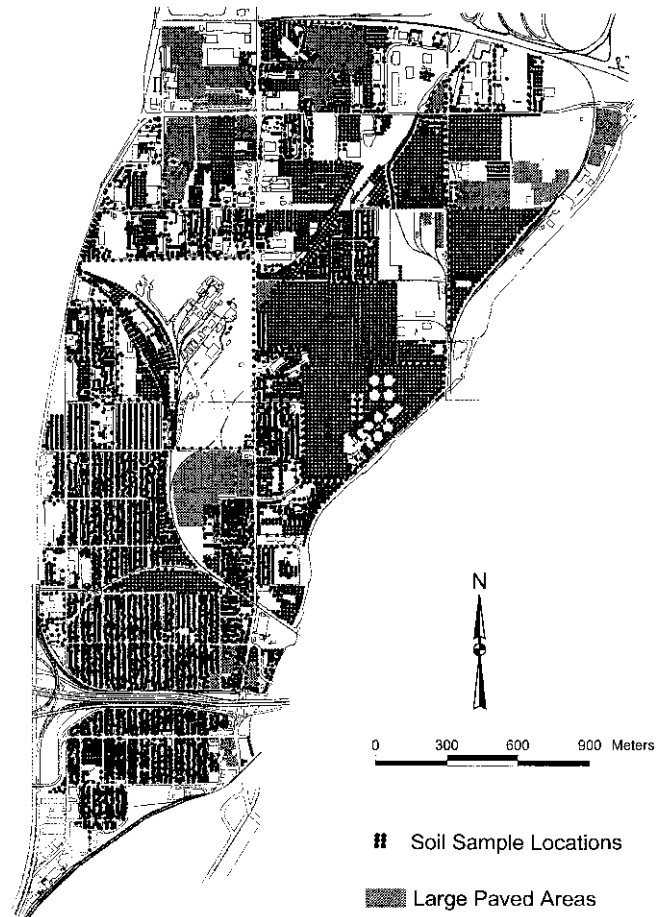
RIFS Investigation

RI/FS soil samples were collected at approximately 150 locations within two miles of the Globe Plant over 0 to 5 cm and 5 to 20 cm depth intervals, based on a polar grid system that resulted in a greater sample density near the plant. The sampling program was deliberately biased or stratified to select sites with the least amount of apparent disturbance (e.g., vacant lots) to maximize the likelihood that metals due to deposition of historic air emissions would still be present and not removed or obscured by recent development or landscaping activity (TRC, 1988). Therefore, established lawns and other landscaped areas were not sampled during the RIFS. Discrete samples were collected at each site from random locations within an 8 m by 8 m area judged to be relatively undisturbed. The minus 2 mm fractions of all soil samples were analyzed for arsenic, cadmium, lead, and zinc concentrations. Arsenic analyses were conducted by EPA Methods 206.1 and 206.2, with a detection limit of 0.5 mg/kg. More detailed information is provided in TRC (1988, 1990).

SOW Investigation

To date, over 20,000 samples have been collected at residential and commercial properties over an area of approximately 5 km² during the SOW cleanup program (Fig. 2). Properties were divided into at least four sectors not exceeding 2500 ft² (232 m²) in size. Core samples were collected at four random locations within each sector over the 0 to 5 cm and 0 to 15 cm depth intervals and composited to create one sample for laboratory analysis for each depth interval in each sector. The samples were air-dried and sieved through a #10 mesh screen (minus 2 mm fraction) prior to aliquoting for digestion by SW-846

Fig. 2. SOW soil sample locations.



Method 3050B. Samples were then analyzed for arsenic, cadmium, lead and zinc by either inductively coupled plasma–atomic emission spectrometry (ICP) by EPA Method 6010A (6010B after 1998) or laboratory X-ray fluorescence (XRF), with arsenic detection limits of 6 and 10 mg/kg, respectively, following standard EPA method laboratory quality control procedures. During the time period the XRF was used, one in twenty samples were split and also analyzed by ICP, with ICP arsenic concentrations generally being about 5 to 10% lower than XRF concentrations. This difference in the two techniques should not affect any of the observations or conclusions presented herein, which are based on very large concentration differences between properties. The results of all tests are available in the Design Investigation Reports (DIRs) for the project submitted by EnviroGroup Limited every year to the Colorado Department of Public Health and Environment beginning in 1994.

Arsenic Anomaly Investigation

When the results of the SOW investigations revealed the presence of anomalously high arsenic concentrations on various residential properties south of the Globe Plant, additional investigations were conducted to determine the source of the anomalous arsenic.

TABLE 1
Chemical and physical test methods

Parameter	Test method
Arsenic, cadmium, lead, zinc, phosphorus	EPA 6010A/B, XRF
Total Kjeldahl nitrogen	EPA 4500
Ammonia	EPA 350.3
Nitrate	EPA 300.0
Organic matter	ASTM D 2974
Cation exchange capacity	EPA 9081
pH	AASHTO T289
Organochlorine pesticides	EPA 8081
Gradation – sieve and hydrometer	ASTM D 422-63
Atterberg limits	ASTM D 4318-95

Additional samples were collected at various depth intervals on selected anomalous and neighboring properties using core samplers and digging instruments, without compositing. Samples were analyzed for arsenic, cadmium, lead, and zinc by ICP, as described above, and for other chemical and physical parameters as shown in Table 1. Arsenic phases were determined by computer-controlled scanning electron microscope (CCSEM) analyses on one gram of minus 250 micron dry soil, performed in backscattered electron imaging mode using aluminum and carbon backscatter intensity standards, at 200× and 600× magnification. Petrographic analyses were performed using stereomicroscope to detect mineral phases in soil samples. Perlite was identified by analyzing samples prepared in 1.550 refractive index liquid by polarized light microscopy and comparing glassy fragments to known perlite standards, which are isotropic and have a refractive index lower than 1.550. More detailed information on these procedures is provided in EnviroGroup (1997).

RESULTS OF INVESTIGATIONS

The results of the RI/FS investigations indicated that arsenic concentrations decreased from levels of approximately 100 to 200 mg/kg near the Globe Plant to levels typically 20 mg/kg or less within 2000 m of the site (Fig. 3a). Cadmium concentrations decreased with distance in a similar manner (Fig. 3b). Similar findings were expected at the start of the SOW investigations. Indeed, cadmium concentrations during the SOW investigations did decrease with distance from the Globe Plant (Fig. 4a), consistent with the results of the RI/FS investigations. Arsenic concentrations, however, continued to remain elevated during the SOW investigations and even increased with distance, as shown in Fig. 4b. In fact, arsenic concentrations were much higher at properties more than 1000 m from the Globe Plant than found near the Globe Plant during either the RI/FS or SOW investigations, exceeding 1000 mg/kg on several properties (Fig. 5).

The impacts of smelter emissions on soil generally decrease rapidly with distance from the site because of dilution caused by the geometrically expanding air volume, plume dispersion due to air turbulence, and plume depletion due to fallout, as observed at numerous smelter sites reported in the literature (e.g., Balsley and Caldwell, 1974; Bolter et al., 1974; Temple et al., 1977; Ball et al., 1983; Kuo et al., 1983; Brams, 1985; Karczewska et al., 1998; and others). Because the randomly located, high arsenic concentrations encountered during the SOW were not consistent with air emissions from the Globe Plant smelter, further investigations were conducted to determine the source of the anomalous arsenic.

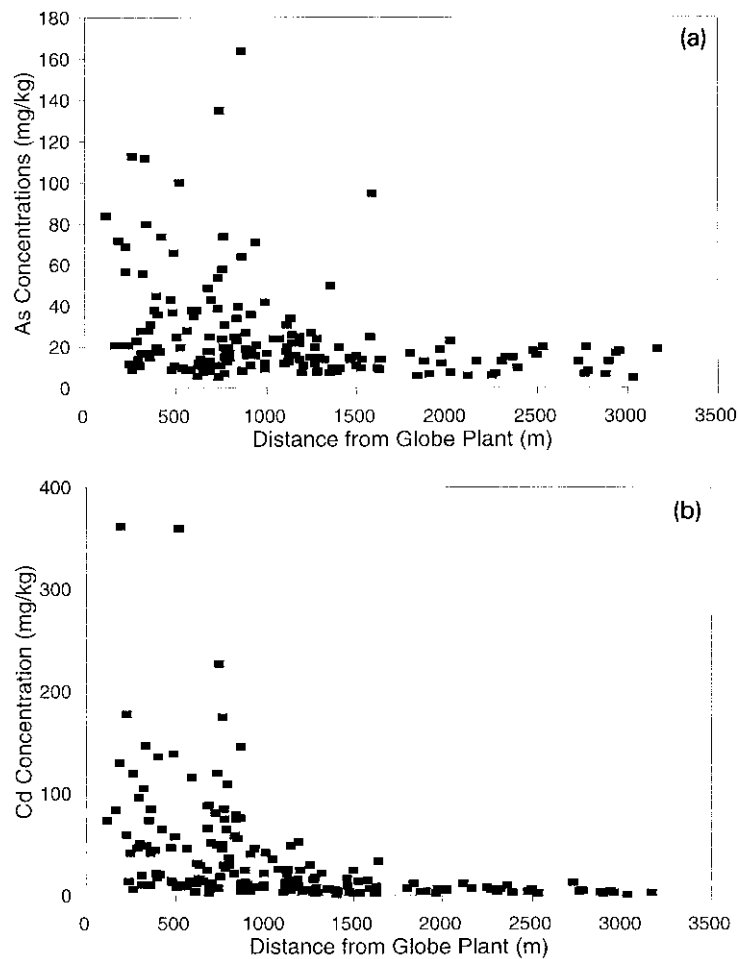


Fig. 3. (a) RIFS arsenic concentrations vs. distance. (b) RIFS cadmium concentrations vs. distance.

SOURCE EVALUATION

Potential sources of the anomalous arsenic concentrations that were considered during the source evaluation included air emissions from the Globe Plant (perhaps under gaseous transport conditions), application of pesticides, and placement of contaminated fill. A variety of evaluation procedures were used to fingerprint the source of the anomalous arsenic concentrations by testing for these various characteristics, as described below.

Spatial Patterns

Kriging analyses were conducted to see whether spatial correlations would indicate the source of the anomalous arsenic. On a large scale, cadmium concentrations decrease with distance, as discussed above, and show strong correlations with the Globe Plant and predominant northeast–southwest wind directions (Fig. 6a), consistent with a smelter emission source. Arsenic concentrations, however, are randomly distributed and, except in the immediate vicinity of the Globe Plant, have no spatial relationship with the plant

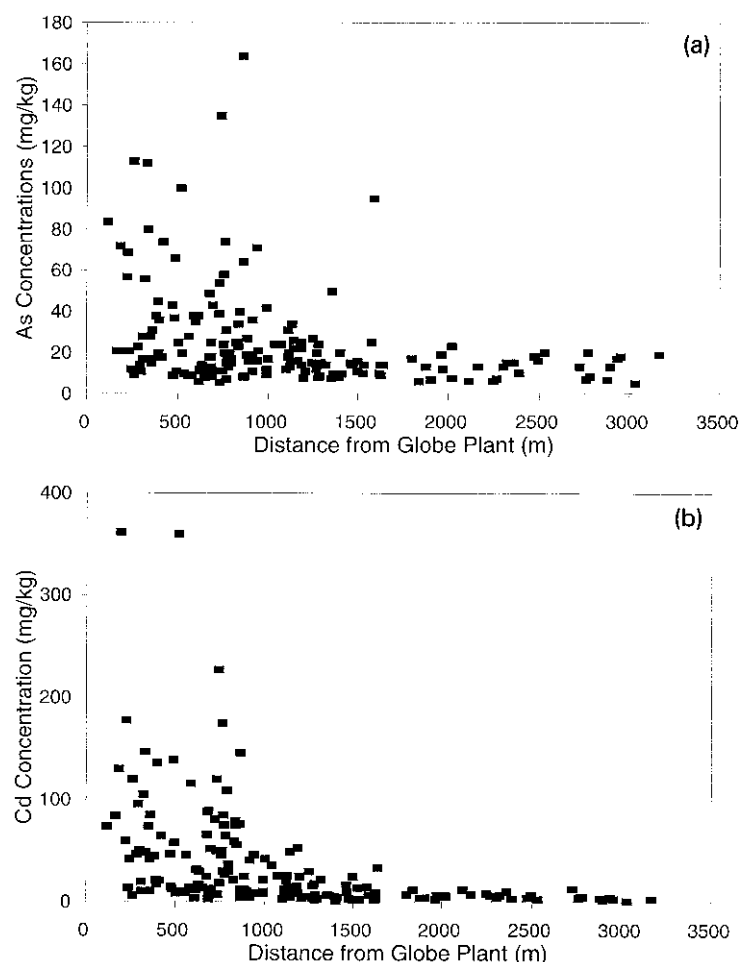
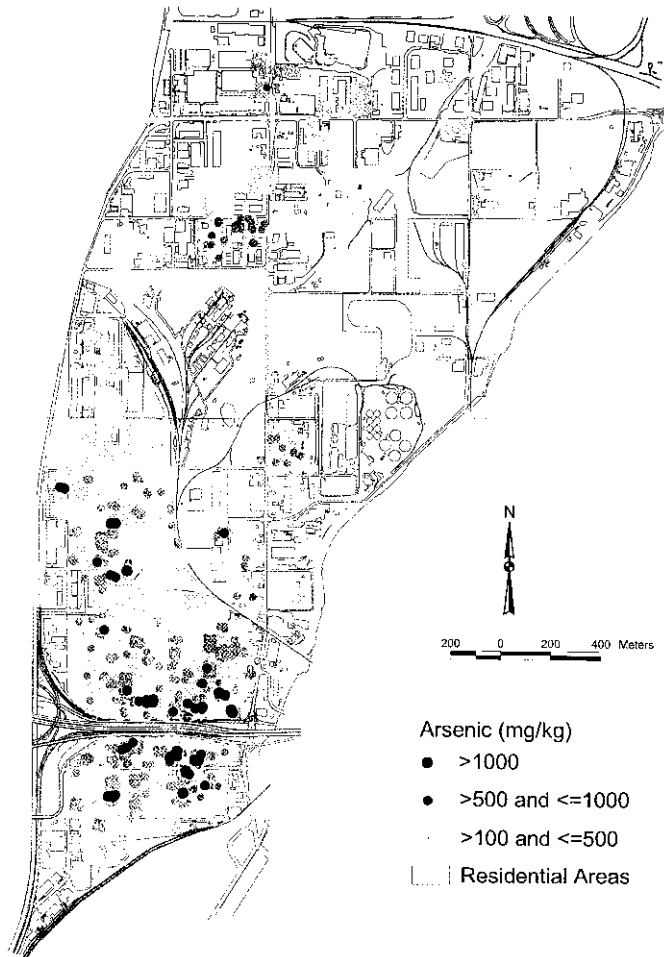


Fig. 4. (a) SOW cadmium concentrations vs. distance. (b) SOW arsenic concentrations vs. distance.

site (Fig. 6b). Most elevated arsenic concentrations are found in the southern, residential portion of the study area, while no anomalous arsenic concentrations are observed in the predominantly commercial and industrial area to the northeast (and downwind) of the Globe Plant.

The data set collected in the neighborhood contained several samples per yard allowing interpolation on a much finer scale than is generally performed in environmental investigations. A variogram analysis indicated an east–west anisotropy on a scale of 100 ft east–west, and 50 ft north–south, which corresponds with the approximate dimensions and orientation of individual residential properties. In order to incorporate the observed anisotropy into a kriging interpolation of the data, a search ellipse of 100×50 ft (30×15 m) was used with a 10×10 ft (3×3 m) grid. The resulting map of soil arsenic shows rectangular areas of arsenic that correspond with residential property boundaries (Fig. 7), strongly suggesting an arsenic source that was applied to specific properties and not to others. Furthermore, the east–west anisotropy observed in the data is inconsistent

Fig. 5. Arsenic concentrations on residential properties.



with an airborne source located to the north, where the Globe Plant is located. The most striking feature of the map of soil arsenic is the readily apparent grid pattern of the arsenic corresponding with property boundaries, streets, alleys, and vacant lots.

These spatial patterns are consistent with pesticide application or contaminated fill placement on residential properties, and not airborne deposition, unless arsenic concentrations were altered after deposition by property-specific events, such as soil removal, fill placement, or activities that would enhance (or delay) the subsequent leaching of arsenic into the soil (see below). On the other hand, applications of arsenical products would be more likely to follow property boundaries.

Correlation with Land Use

Airborne emissions are expected to impact all types of properties, whether developed or undisturbed. This was observed to be the case for cadmium, when concentrations were compared to land use (Fig. 8a). A comparison of arsenic concentrations and land use, however, indicated that anomalous arsenic concentrations only occurred on developed

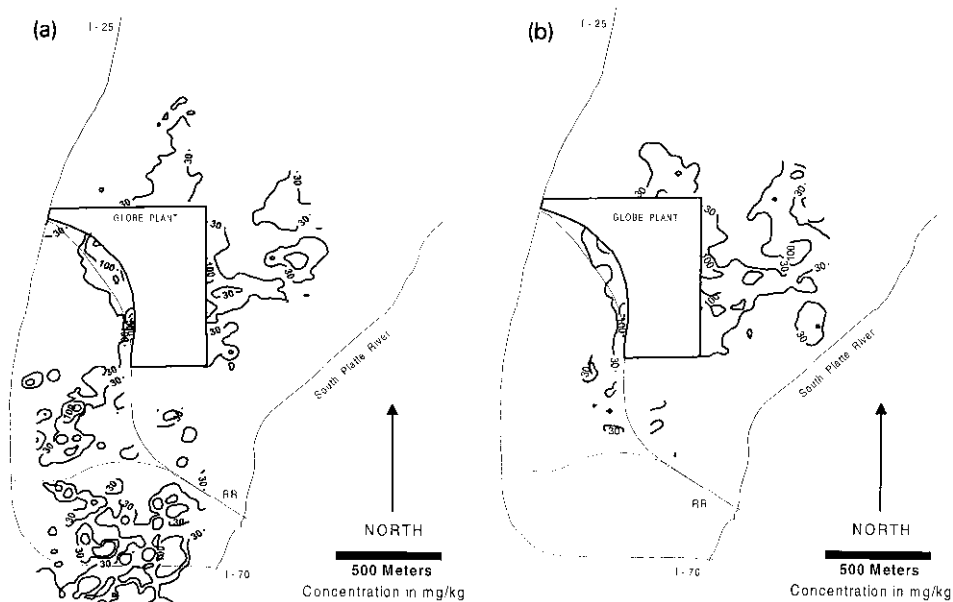


Fig. 6. (a) Kriging contours of cadmium concentrations. (b) Kriging contours of arsenic concentrations.

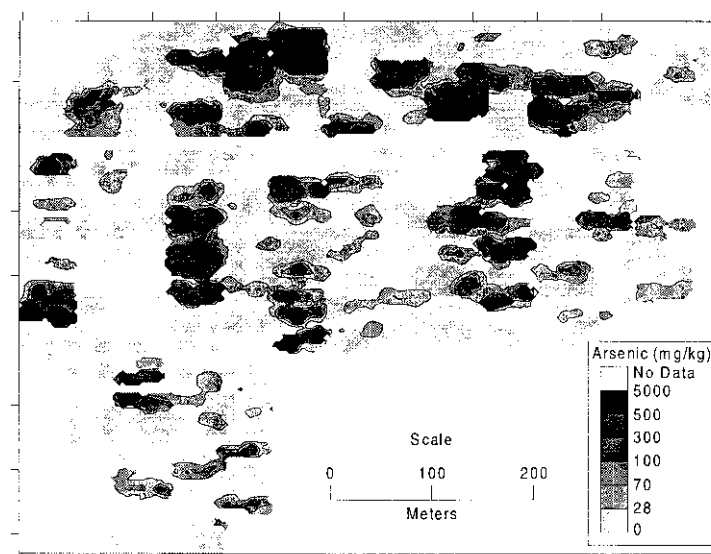


Fig. 7. Small-scale arsenic kriging contours.

residential properties. Arsenic concentrations on undeveloped land (e.g., historically vacant lots, parks) and historically commercial properties (excluding properties where Globe Plant wastes and materials were directly placed by mechanical or waterborne means) were low (Fig. 8b). This bias toward developed properties explains why the RIFS samples,

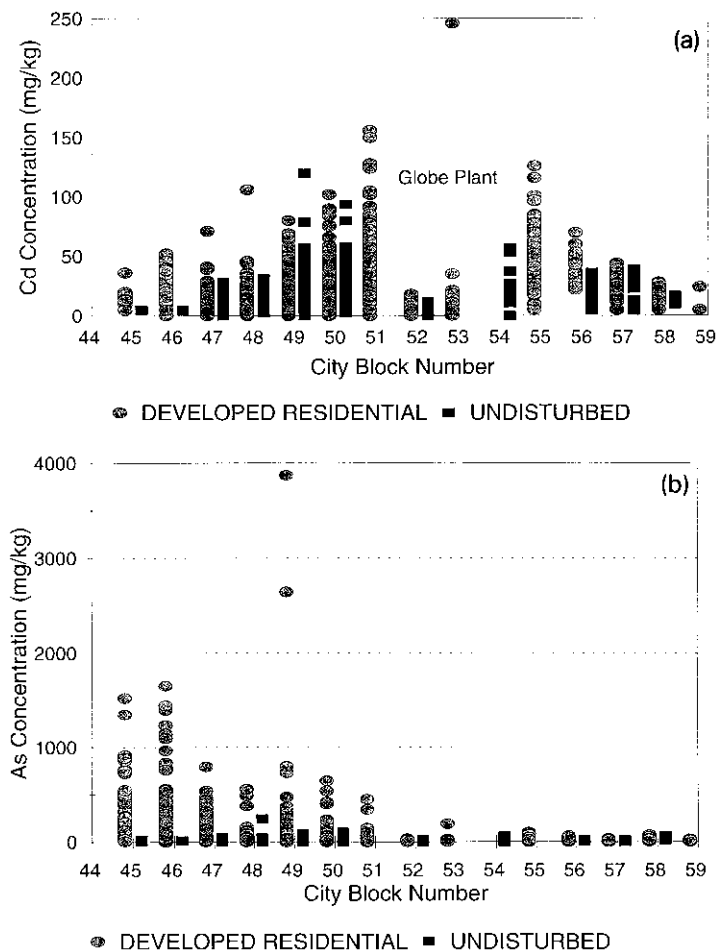


Fig. 8. (a) Cadmium concentrations vs. land use. (b) Arsenic concentrations vs. land use.

which were collected from relatively undisturbed sites, did not include anomalous arsenic concentrations (Fig. 3a). The correlation between the anomalous arsenic concentrations and developed residential properties is not consistent airborne deposition but is consistent with the application of herbicides to residential lawns or the placement of contaminated fill.

The correlation between anomalous arsenic concentrations and land use was examined on a smaller scale by looking at two blocks where both developed residential and historically vacant lots were present. Prior to plotting the arsenic data (to avoid biased interpretations), historic aerial photographs were used to delineate the portions of properties on these two blocks where well-established turf was present in the 1950s and 1960s. Arsenic concentrations that exceeded 70 mg/kg (the action level) were then plotted. As shown in Fig. 9, all arsenic concentrations exceeding 70 mg/kg fell on sectors with well-established turf, consistent with the application of herbicides on lawns and inconsistent with airborne deposition.

Fig. 9. Arsenic correlation with well established turf.

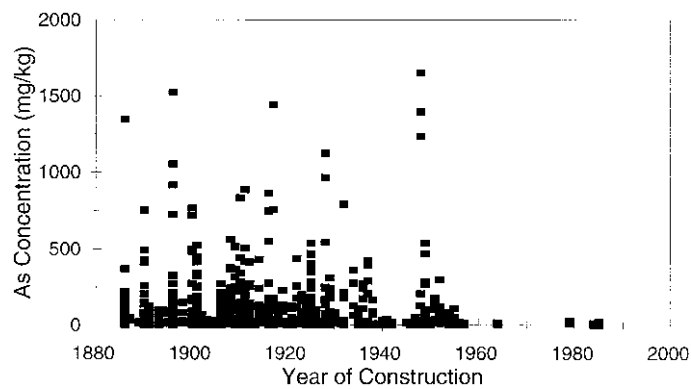
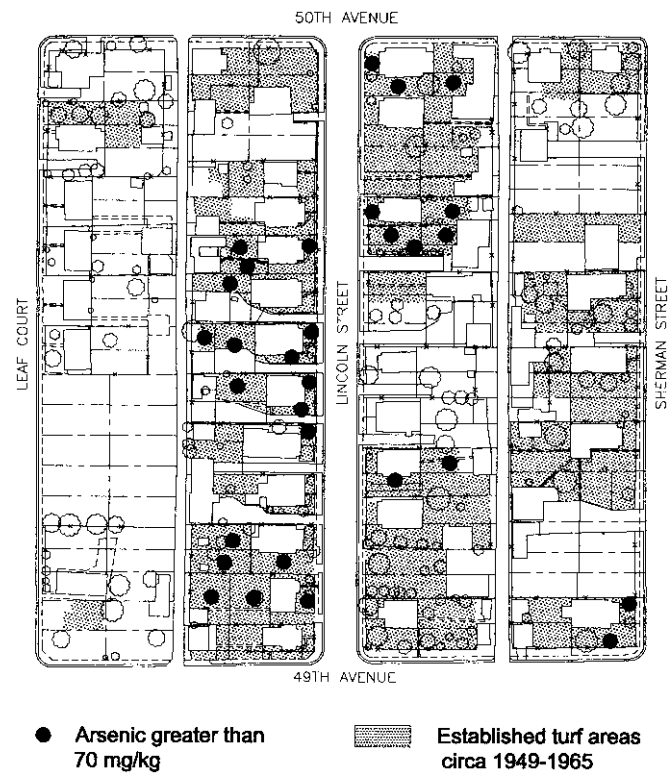
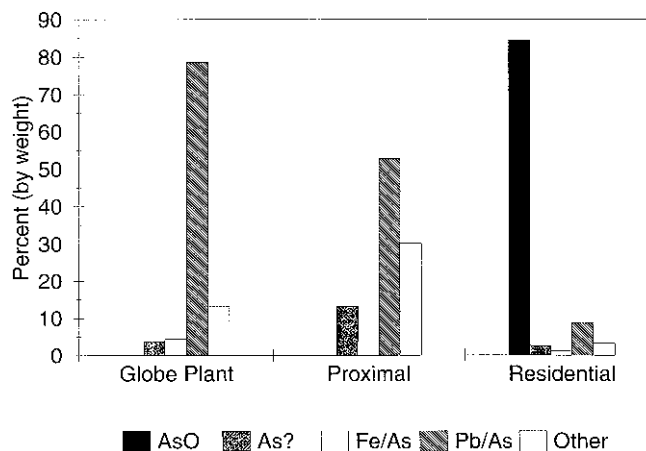


Fig. 10. Arsenic correlation with construction date.

Correlation with Construction Date

Arsenic concentrations were compared to the date of initial property development, based on tax records. Anomalous arsenic concentrations were observed on properties developed from the 1880s through the early 1950s (Fig. 10), with no particular trend over time. Because the highest arsenic concentrations were found in the 0–5 cm depth interval,

Fig. 11. Arsenic phases.



including the root mat of the lawns, it is safe to conclude that contamination occurred no earlier than the date of property development. The impacts of earlier contamination, while potentially existing at depth, would likely be disturbed by house construction and should not present in subsequently placed sod (see discussion of depth profiles, below). Therefore, at least some properties were being impacted as late as the early 1950s. If the arsenic had been applied at the time of house construction, we would expect the arsenic on older properties to be lower on average than arsenic on younger properties, because arsenic dissolution and leaching over time. Similarly, if the arsenic was the result of deposition over a long period of time, we would expect arsenic concentrations to be higher on older properties.

Because arsenic concentrations do not show any trend with the date of house construction, it is likely that all of the anomalous arsenic applications occurred after the early 1950s. This time period is not consistent with Globe Plant arsenic refining operations, which ended in 1927. While cadmium calcining operations included arsenic emissions, this time period is also not consistent with these operations because the greatest potential for emissions was in the 1930s and 1940s prior to the installation of modern air pollution control equipment. However, application of arsenical pesticides on lawns would have occurred in the late 1950s and 1960s (see below), consistent with the observed time trends.

Arsenic Speciation

Arsenic from smelter emissions and commercial pesticides might be expected to have different arsenic phases, or phase ratios. Therefore, soil samples were selected from residential properties with anomalous arsenic concentrations, the Globe Plant, and properties immediately downwind of the Globe Plant and analyzed by CCSEM. The arsenic on the anomalous residential properties was found to be predominantly arsenic trioxide, with small amounts of metal-arsenic phases, such as lead arsenate and clay mineral phases (Fig. 11). In contrast, no significant amounts of arsenic trioxide were found in Globe Plant soils or in the soils of properties immediately downwind of the plant (and likely to have been impacted by airborne emissions from the plant).

Arsenic trioxide was produced at the Globe until 1927. Arsenic was also emitted from the cadmium calcine stack during later years and white crystals (likely amorphous form) were observed to form at the top of the stack and fall on the plant and nearby properties during the 1930s and early 1940s. Nevertheless, it appears that most residues of this process have dissolved over time and become associated with other metal and mineral

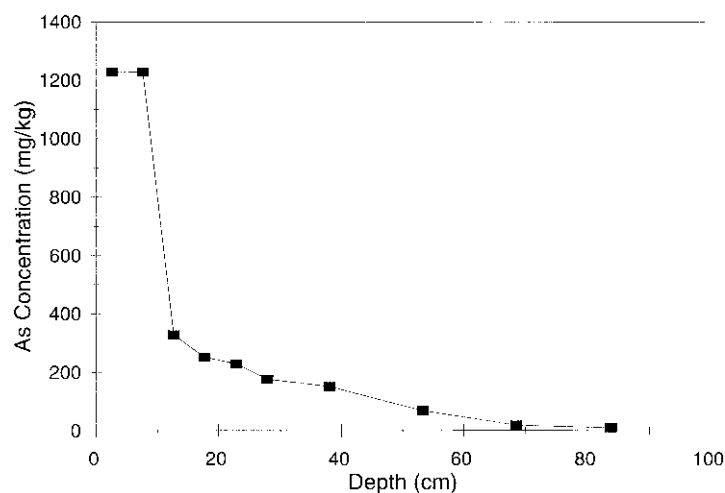


Fig. 12. Typical arsenic concentration depth profile.

phases. The arsenic trioxide observed in the anomalous soil was in the form of relatively large (up to and occasionally exceeding 100 μm) crystals (rather than amorphous) and more indicative of commercial product than emission particles.

Depth Profiles

Arsenic concentrations were measured at discrete depth intervals on several properties. In all cases where anomalously high arsenic concentrations were found in the upper 0–5 cm depth interval, concentrations decreased rapidly with depth (Fig. 12). This depth profile indicates that the anomalous arsenic concentrations resulted from surface application of arsenic, rather than placement of arsenic-contaminated fill, because concentrations in fill materials would tend to be random with depth throughout the fill zone. Evaporative forces (which can draw salts to the ground surface in arid climates) would not explain this depth profile, because the arsenic in the upper 0–5 cm was predominantly in the original arsenic trioxide crystal form (see discussion of arsenic speciation) and had not been dissolved. Further, the examination of neighboring properties with anomalous and low arsenic concentrations did not reveal the presence of any fill horizons that would explain the difference in arsenic concentrations.

While spatial and land use correlations indicate that the anomalous arsenic was applied to the surface individual residential lawns, additional data were required to evaluate the alternative hypothesis that arsenic due to airborne deposition was preferentially retained on (rather than applied to) these yards because of some property-specific condition. If this were the case, elevated arsenic concentrations would be expected at depth on properties where arsenic concentrations in the 0–5 cm depth range were low (i.e., by this hypothesis, already leached). Testing to depths of approximately 1 m did not reveal any significant arsenic at depth on several properties with low surficial values, including properties immediately adjacent to those with anomalously high arsenic concentrations, indicating that high arsenic concentrations never existed on these properties and that the preferential leaching (or retention) hypothesis is not valid.

Geochemical Profiles

If preferential leaching or retention of arsenic was the explanation for the property-specific distribution of the anomalous arsenic concentrations, some geochemical or textural char-

TABLE 2
Soil conditions at neighboring properties

Parameter	Property 44K05	Property 44K06
Maximum arsenic concentration (mg/kg)	12	1440
Dominant arsenic phases in upper 5 cm	Pb, Si-Fe	AsO (>90%), Pb
Soil type (Unified Classification System)	CL	CL
Plasticity index (%)	18	14–17
Organic matter (%)	3.9–6.4	3.3–4.2
Mineralogy	Similar	Similar
Perlite present	No	Yes
Chlordane, total (μg/kg)	97	198

acteristic should explain this difference in the leaching behavior. Therefore, metals concentrations, nutrients, pH, organic content, grain size, and Atterberg limits were measured at anomalous and neighboring, otherwise similar, residential properties with low surficial arsenic concentrations. As shown in the example in Table 2, the physical and geochemical properties of the soils were nearly identical. Further, no correlation was found between phosphorous, iron, or nitrogen and arsenic concentrations. Therefore, none of the data supported the hypothesis of historic, widespread arsenic contamination (e.g., by airborne emissions) that was subsequently leached at all properties but those with anomalously high concentrations today.

Correlation with Pesticide

Because of the evidence suggesting the anomalous arsenic had been applied to specific residential properties in the 1950s or later, as discussed above, the literature was reviewed for information on arsenical products applied to turf. Historians at PHR Environmental Consultants identified a lawncare product called PAX, which contained arsenic trioxide (25.11%) and lead arsenate (8.25%), and was used for crabgrass control in Denver and other cities in the 1950s and 1960s (U.S. Patent 3057709, 1962; Stadtherr, 1963; Frost et al., 1973). PAX was a solid, granular product that was typically applied by a drop spreader at rates of about 10 to 12 kg/100 m² of lawn, depending on the version of the product.

A single application at a rate of 12 kg/100 m² would theoretically increase the arsenic concentration in the upper 5 cm of soil by approximately 350 mg/kg (assuming a typical loamy soil dry density of about 1400 kg/m³), while ten applications over a decade would theoretically increase arsenic concentrations by 3500 mg/kg. Dissolution and leaching of arsenic, however, would reduce concentrations in the upper 0–5 cm over time. Measured concentration profiles with depth (e.g., Fig. 12) indicate that approximately 30% of the arsenic was retained in the upper 5 cm at the time of testing, with the remainder typically distributed over the upper 30 to 60 cm (EnviroGroup, 1997). Therefore, modern-day arsenic concentrations of 100 to 1000 mg/kg are consistent with one to ten applications of PAX in the 1950s and 1960s, assuming that about 30% of the arsenic remained in the upper 0–5 cm. This range is consistent with the average observed range of anomalous arsenic concentrations on most properties. The occasional higher, individual concentrations are explained by overlap of drop spreader paths and deliberate over-application in areas with thick crabgrass. We can also imagine that some home owners applied PAX at rates that were higher than recommended due to miscalculation, incorrect spreader settings, a desire (perhaps misguided) for better performance, or to completely use up a bag of PAX (19 kg).

The arsenic to lead ratio in PAX would theoretically result in the following relationship between the total lead (Pb) and total arsenic (As) concentration in soil:

$$\text{Total Pb} = \text{Background Pb} + (\text{Total} - \text{Background As})/4.2 \quad (1)$$

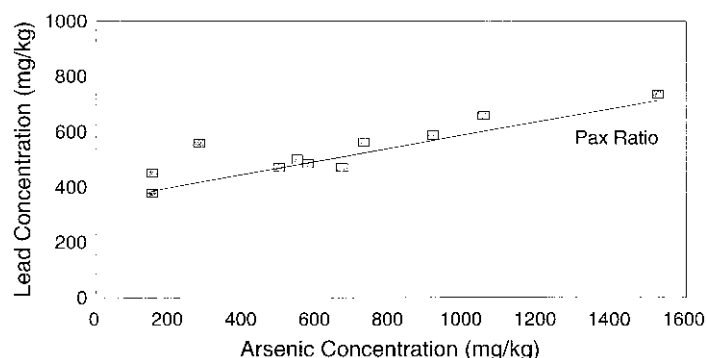


Fig. 13. Correlation with PAX lead/arsenic ratio.

The background lead concentration is the lead concentration prior to the application of PAX, due to natural soil levels and anthropogenic contributions (e.g., leaded gas, lead paint). If the background lead concentration was the same at all points on the property, the lead and arsenic concentrations after the application of PAX would fall along a straight line defined by equation 1. In reality, the background lead concentration will vary from point to point across a yard, resulting in departure from a straight line. Nevertheless, the lead and arsenic ratios in samples at several properties with anomalous arsenic concentrations were similar to the slope of this line, or the PAX lead to arsenic ratio, as shown in Fig. 13.

On other properties, we observed a greater scatter of the data, but always to the left of a bounding line described by the PAX lead to arsenic ratio. This behavior is consistent with increased leaching of the product, and preferential leaching of the more soluble arsenic trioxide component which would cause data points to shift to the left of the PAX line in Fig. 13. Therefore, the lead to arsenic ratios on the anomalous properties are consistent with historic applications of the PAX product, and are inconsistent with applications of pure arsenic trioxide or other metal-phase arsenic (which would tend to plot below the PAX line, or randomly throughout the plot space, respectively).

A strong correlation was found between anomalous arsenic samples and the presence of perlite, one of the inactive ingredients of PAX (U.S. Patent 3057709, 1962). All residential lawn soil samples with anomalous arsenic concentrations that were examined by stereomicroscope were found to contain perlite, while no perlite was found in any of the samples with low arsenic concentrations. While perlite is also found in other products, such as potting soil, the chances of this correlation occurring by random chance are negligible.

Testing in other Areas

If the anomalous arsenic concentrations found in Globeville are due to historic applications of PAX, it is reasonable to expect anomalously high arsenic concentrations in other parts of Denver where the product was likely used, i.e., older neighborhoods that would have lawns sufficiently aged to have crabgrass infestation in the 1950s or 1960s. While random testing of other neighborhoods was difficult for Asarco to justify, a property was discovered in south Denver, approximately 8 miles south of the Globe Plant, where a former resident recalled their family using PAX on the lawn. Fortunately, the property was still in the possession of the family and sampling access was granted. Elevated arsenic concentrations (maximum 210 mg/kg), lead/arsenic ratios that fit the PAX ratio, the presence of arsenic trioxide crystals, a decreasing arsenic concentration profile with depth, and the presence of perlite, all matched the PAX finger-print that was observed in Globeville soils.

Subsequently, the U.S. EPA listed the Vasquez Boulevard – I70 Superfund Site on the National Priorities List, which included several square miles of neighborhoods to the east of Globeville where similar high arsenic concentrations were detected. While investigations were not complete at the time of this paper, the data indicate that high arsenic concentrations occur on random properties across the neighborhoods, without any apparent spatial relationship to the Globe Plant or any other point source (ISSI, 2000). Intensive sampling of selected properties shows that the arsenic concentrations are confined to property boundaries, as observed in Globeville (ISSI, 2000).

CONCLUSIONS

Several lines of evidence indicate that anomalous arsenic concentrations found in the Globeville area are due to the historic application of the crabgrass killer, PAX, although application of other arsenical products, such as lead arsenate, likely contributed to the high levels on some properties. Based on testing in other neighborhoods, and because PAX was sold throughout Denver, it is reasonable to conclude that these impacts may be relatively widespread in the older neighborhoods. Further, similar impacts may be observed in other cities where PAX was sold, depending on climate and soil conditions (i.e., the degree of leaching).

To a large degree, Globe Plant smelter impacts can be separated from pesticide impacts by the spatial correlation of the former to the Globe Plant, and the lack of spatial patterns among the latter sites. In areas of overlap, examination of the metal trends on non-residential properties should provide a good indication of smelter impacts, while the presence of perlite might be used as an indicator of PAX on pesticide-impacted properties. Careful modeling of the dispersion and deposition of historic air emissions from the Globe Plant has also shown promise as a means of separating smelter and other urban sources of arsenic and other metals (EnviroGroup, 1998).

The presence of the pesticide impacts raises important socioeconomic questions. How prevalent are the pesticide impacts, and what is a reasonable approach to evaluating this condition on the thousands of properties that could potentially be impacted? If present, to what extent is the arsenic a source of exposure to people living on impacted properties, and to what extent is remediation, if any, necessary? Finally, what cost-effective methods are available for dealing with any identified concerns, and who will provide the funding?

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