

Effects of Soil Property and Soil Amendment on Weathering of Abraded Metallic Pb in Shooting Ranges

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Abstract Weathering of abraded metallic Pb from bullets is a significant source of Pb contamination in shooting range soils. Weathering studies were performed using metallic Pb powder to simulate the fine-size fraction of metallic Pb found in shooting range soils. The effects of soil properties (moisture, organic matter-[OM] and pH) on weathering of abraded metallic Pb were examined by incubating a typical Florida soil for 5 to 12 days at 100% or 80% field capacity (FC) after spiking with 5% metallic Pb, after removal of soil OM at 100% FC, and after adjusting the soil pH to 4.8, 6.1 or 8.5 at 100% FC. The weathering products were examined using X-ray diffraction (XRD). Transformation of metallic Pb to secondary Pb-minerals was more rapid at 100% FC, in the presence of OM, and at lower pH. While little transformation of Pb occurred in the absence of soil OM and mostly litharge (PbO) was found at higher pH, both hydrocerussite and litharge formed at lower pH. A three-step weathering mechanisms of metallic Pb

including oxidation, carbonation and dissolution was proposed. Addition of both calcium carbonate and phosphate rock was effective in reducing water-soluble Pb, though the effect was minimal after 11 weeks of incubation, attributing to the liming effect of metallic Pb added to the soil. While reducing soil moisture and organic matter and increasing soil pH slowed weathering of metallic Pb in a soil, the effect of calcium carbonate and phosphate rock on Pb solubility in soils highly contaminated with Pb was limited.

Keywords metal contamination · shooting range · lead · hydrocerussite · pyromorphite · phosphate rock

1 Introduction

The mechanisms by which metallic Pb bullets transform to more reactive Pb compounds in shooting range soils, as well as the influence these soils have on the transformation have not been well documented. Weathering of Pb bullets leads to the accumulation of Pb in shooting range soils (Cao, Ma, Hardison, & Harris, 2003a), while transformation of Pb bullets into soluble secondary minerals may provide a mechanism for mobilization of Pb into the vadose zone (Murray et al., 1997). Most importantly, weathering of Pb bullets may increase Pb bioavailability to organisms that come into contact with contaminated soils. The health of individuals that work and participate in recreational shooting at these ranges may be at risk

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due to the secondary minerals that are present in Pb contaminated soils.

Metallic Pb is unstable under typical soil conditions (Cao et al., 2003a; Luo & Hong, 1997), and as a result, it readily undergoes weathering after depositing in a soil (Graedel, 1994). In stability diagrams for metals, there exists a passive zone where the stable solid is not the metal but a metal oxide, hydroxide or salt (Pourbaix, 1966). Under these conditions the metal becomes coated with these secondary minerals, forming a non-porous film to separate the metal from solution, and/or a porous film to partially separate the metal from solution (Pourbaix, 1966). In the case of Pb, there are only small regions for stability for surface oxides, and as a result Pb-oxides are typically too soluble to provide any protection against further weathering (Graedel, 1994). However, Pb-carbonates, such as cerussite (PbCO_3) and hydrocerussite [$\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$] generally form a protective layer that prevents further weathering of metallic Pb (Edwards, Bordass, & Farrel, 1997; Pourbaix, 1966).

These protective layers have been found on the surface of metallic Pb bullets in shooting range soils. White crust material found on the surface of Pb bullets were identified as secondary Pb minerals such as hydrocerussite, cerussite, anglesite (PbSO_4), and occasionally massicot (PbO) in shooting range soils (Craig, Rimstidt, Bonnaffon, Collins, & Scanlon, 1999; Murray et al., 1997; Scheuhammer & Norris, 1995). Lin (1996) found that the crust material consisted of two layers with the inner layer being predominantly massicot, and the outer layer being predominantly hydrocerussite. This suggested that Pb-oxides were being replaced by Pb-carbonates in shooting range soils.

Immobilization of heavy metals via soil amendments has been used extensively in remediating contaminated soils. It has been suggested that soil amendments such as phosphorus and lime can reduce Pb solubility and mobility in shooting range soils (USEPA, 2001). The relationship between Pb solubility and soil pH has been well documented. The addition of lime to soil has been shown to reduce Pb availability due to an elevation in soil pH (Geebelen, Van Gronsveld, Adriano, Carleer, & Clijters, 2002), however it may increase Pb solubility at high pH due to the formation of organo-Pb complexes (Turpeinen, Salminen, & Kairselo, 2000). Lead phosphates are

extremely insoluble, and may be important in controlling Pb in soil environments (Nriagu, 1974). Phosphorus in the form of phosphate rock (Cao, Ma, Chen, Singh & Harris, 2002; Ma & Rao, 1999) has been used to effectively reduce the solubility of Pb in contaminated soils.

In a study to determine the significance of abrasion of metallic Pb bullets in contributing to soil Pb contamination, Hardison, Jr., Ma, Luongo, and Harris, (2004) have shown that up to 1.5% bullet mass was physically removed as bullets passed through a soil berm, forming coating on the surface of soil particles as fine-size fraction. This was further confirmed by determining total Pb concentrations in the soil of a shooting range that has been open for only three months. The fact that as high as $1,142 \text{ mg kg}^{-1}$ Pb was detected in the soil fraction (<2 mm) attests the significance of abraded Pb in contributing Pb contamination in shooting range soils. However, little information is available on factors influencing weathering of the abraded Pb in soils, which may shed light on the weathering of Pb bullets in shooting range soils.

Since a significant fraction of mass of Pb bullets can be abraded as they pass through a soil berm (Hardison, Jr. et al., 2004), it is important to understand the factors impact the weathering of abraded metallic Pb. A typical Florida soil was spiked with 5% metallic Pb powder and then incubated under different conditions. The objective of the present study was to determine the effects of soil properties (moisture, organic matter and pH) and soil amendments (calcium carbonate and phosphate rock) on weathering of abraded Pb in a typical Florida soil.

2 Materials and Methods

In this study, we evaluated the effects of soil properties and soil amendments on the weathering of abraded Pb in soils by spiking a typical Florida surface soil with 5% metallic Pb powder (Alfa Aesar, MA, 99.9% Pb, < $53 \mu\text{m}$). The high Pb concentration was used to facilitate the detection of potential Pb minerals formed in the soil after incubation. In addition, Pb concentration as high as 5% in berm soil of shooting ranges is not uncommon (Cao, Ma, Chen, Hardison, & Harris, 2003b). The soil used in this study had a pH of

4.16, total organic matter (OM) of 1.81%, and total Pb and P concentrations of 3.69 and 498 mg kg⁻¹ (data not shown).

2.1 Effects of soil property on weathering of metallic Pb in a soil

Soil moisture: Triplicates of the amended soils (100 g soil plus 5% Pb) were incubated in glass beakers at 25 ± 2 °C for five days at 100% or 80% field capacity (FC). Soil moisture was adjusted on a daily basis using deionized water. At the end of five days, an aliquot of the soil was sampled, air-dried overnight, passed through a 53 µm sieve, and subjected to X-ray diffraction (XRD) analysis.

Soil organic matter: Soil OM was removed from the soil by digestion in H₂O₂ (Kunze & Dixon, 1986), resulting in soil OM of 0.15%. Triplicates of the amended soils (30 g digested soil plus 5% Pb) were incubated in glass beakers at 100% FC. At the end of 5, 9 and 12 days, an aliquot of the soil was sampled, air-dried overnight in weighing boats, passed through a 53 µm sieve, and subjected to XRD analysis.

Soil pH: Soil pH was adjusted to 4.8, 6.1 or 8.5 with the addition of 0.1 M NaOH. Triplicates of the amended soils (30 g soil plus 5% Pb) were incubated in glass beakers at 100% FC. At the end of nine days, an aliquot of the soil was sampled, air-dried overnight, passed through a 53 µm sieve, and subjected to XRD analysis.

2.2 Effects of soil amendment on weathering of metallic Pb in soil

Triplicates of the amended soils (150 g soil plus 5% Pb) with the following treatment 1) no amendment; 2) addition of 2% CaCO₃ and 3) addition of 2% phosphate rock were incubated in glass beakers at 100% or 80% field capacity for 11 weeks. Soil moisture was adjusted on a daily basis using deionized water. Calcium carbonate was purchased from Fisher Scientific (Hanover Park, IL) whereas phosphate rock (PR, <60 µm) was obtained from PCS Phosphate (White Springs, FL). A total of eight aliquots of soil samples were taken over the 11 weeks and they were air-dried overnight in weighing boats. In addition to XRD analysis, both pH and water-soluble Pb were determined in the soil.

2.3 Identification of weathered products using XRD

To separate the metallic Pb (<53 µm) that was spiked to the soil, the soil fraction (>106 µm and <2 mm) was used in all experiments except for the amendment experiment (<2 mm). The fraction <53 µm containing Pb powder was examined using XRD to determine potential formation of Pb minerals.

The XRD was performed using a computer-controlled X-ray diffractometer equipped with a stepping motor and graphite crystal monochromator. Samples were scanned from 2 to 50° 2θ using Cu Kα radiation at 35 kV and 20 mA. Soil aggregates removed at the end of the soil amendment study were broken apart, and the finer material was suspended in solution via ultra sonification and characterized using XRD.

2.4 Chemical extraction and analysis

Soil organic matter was determined using the Walkley–Black procedure (Nelson & Sommers, 1982). Soil pH was determined after equilibrating a 1:1 mixture of soil to deionized water for 24 h. Total phosphorus was measured colorimetrically with a Shimadzu 160U spectrometer using the molybdate/ascorbic acid method (Olsen & Sommers, 1982). Total soil Pb were determined by flame atomic absorption spectrometry (Varian 220 FS with SIPS, Walnut Creek, CA) after digesting the soil with HNO₃ and H₂O₂ using the hot-block digestion procedure (USEPA Method 3050a). Water-soluble Pb was extracted by the method detailed in Ma and Rao (1997). Lead concentrations <1.0 mg l⁻¹ were reanalyzed by graphite furnace atomic absorption spectrometry (Perkin-Elmer SIMMA 6000, Norwalk, CT).

Quality control samples including standard reference material for soil (2709 San Joaquin soil and 2710 Montana soil) were used with sample digestion (US Department of Commerce National Institute of Standards and Technology, Gaithersburg, MD 20899). Satisfactory precision (reproducibility) and accuracy (percent of recovery) within ± 20% were obtained.

2.5 Data analysis

The effects of treatments were determined by analysis of variance with the generalized linear model procedure using the Statistical Analysis System (SAS

Institute Inc.) computer program. Significance was tested at the 0.01 probability level.

3 Results and Discussion

3.1 Impact of soil moisture

Transformation of metallic Pb to more reactive Pb compounds in the soil was rapid and influenced by soil moisture. After five days of incubation at 80% or 100% field capacity (FC), both hydrocerussite [$\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$] and litharge (PbO) were formed as suggested by their peaks from the XRD patterns (Figure 1a). However, the soil incubated at 80% FC (lower moisture level) showed a considerable amount of metallic Pb remaining. The XRD data may suggest that most of the metallic Pb has been converted in the soil incubated at 100% FC, but this was not the case at 80% FC.

This was most likely due to less water to coat the surface of metallic Pb in the 80% FC treatment. It has been shown that weathering of metallic Pb depends on a water layer that forms on its surface, acting as a medium for the diffusion of atmospheric gases (O_2 and CO_2), which attack the metal surface and lead to the formation of secondary Pb minerals and subsequent dissolution of Pb into solution (Graedel, 1994; Rocca & Steinmetz, 2001). It must be noted that pure water is not corrosive to metallic Pb, but the oxidizing agents that diffuse through this water layer are what lead to the formation of secondary Pb minerals (Pourbaix, 1966). The impact of moisture on the weathering of metallic Pb has been seen in the natural environment in the form of damp roof conditions that have been shown to increase the failure of Pb roofs on historical buildings due to ‘condensation corrosion’ (Edwards et al., 1997).

3.2 Impact of soil organic matter

The presence of soil OM was necessary for the transformation of metallic Pb to more reactive Pb compounds in the soil. The soil used in this experiment contained only 0.15% OM compared to

1.8% for the one in the moisture experiment. Even after incubation for 12 days at 100% FC, significant peaks of metallic Pb remained in the soil (Figure 1b). In addition, no peaks for secondary Pb minerals were present except minium (PbO).

These results suggest that the removal of soil OM impeded the transformation of metallic Pb to Pb-oxides or Pb-carbonates. This result was confirmed by another experiment where a pure sand was spiked with 5% Pb and incubated at 100% FC. Except for an insignificant peak for cerussite and litharge, the XRD patterns were dominated by peaks from metallic Pb even after 62 days of incubation (data not shown). This was most likely due to a lack of CO_2 in the sand as well as the soil. Lin, Comet, Ovarfort, and Herbert, (1995) noted that the rate of Pb transformation to secondary minerals was 15.6% in a soil rich in humus compared to 4.8% in a mineral soil.

Microbial communities in soil are responsible for the oxidation of organic matter to CO_2 . As a result, CO_2 in soil air is often several hundred times more concentrated than what is typically found in the earth’s atmosphere (Brady & Weil, 2000). This suggests that as organic matter content increases in soil, the rate of metallic Pb transforming to Pb carbonates will also increase (Lin, 1996).

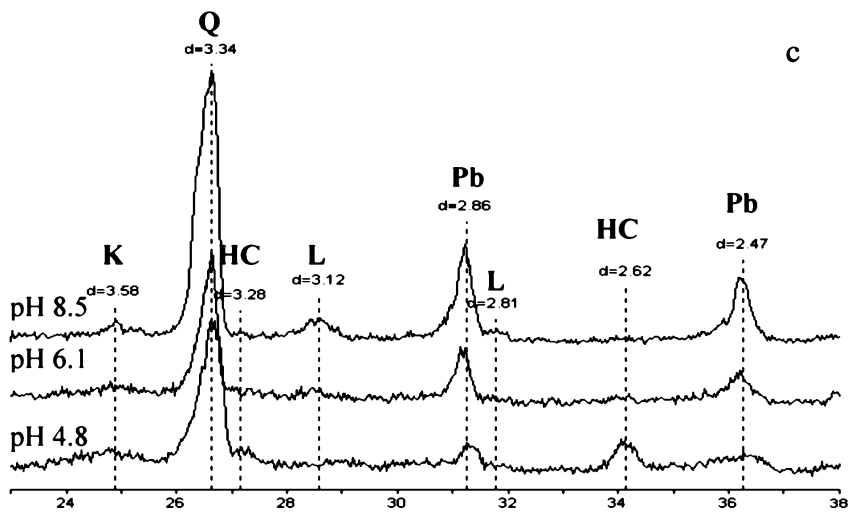
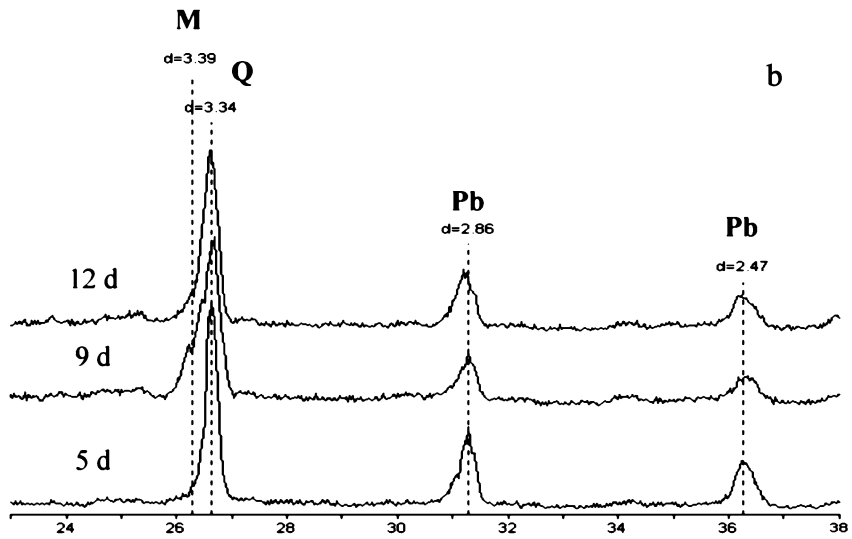
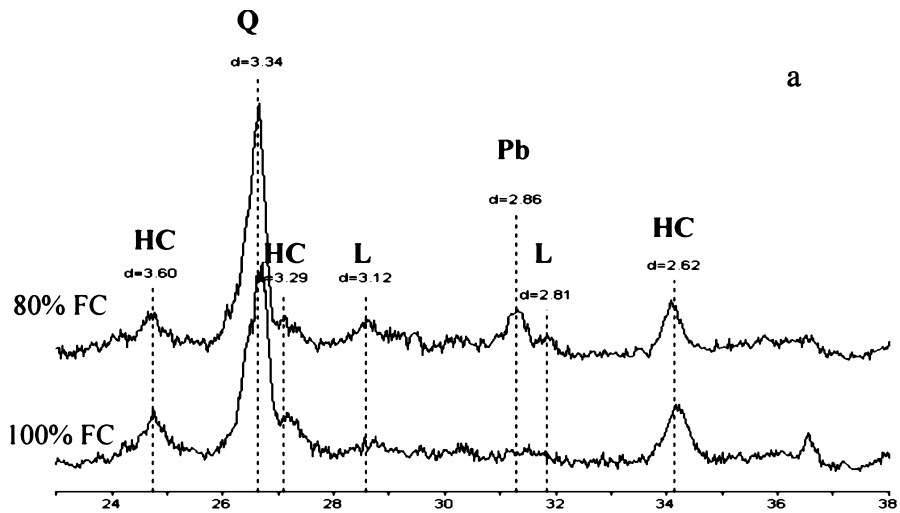
In addition, organic acids have been implicated in the accelerated weathering of Pb bullets in shooting range soils (Jorgensen & Willems, 1987), as well as the accelerated corrosion and failure of Pb roofs on historic buildings (Edwards et al., 1997; Graedel, 1994). This is most likely due to the destruction of the protective layer (mostly secondary Pb minerals) formed on the surface of metallic Pb during the weathering process (Edwards et al., 1997). Humic and fulvic acids may bind with Pb formed on the surface of metallic Pb, accelerating weathering of metallic Pb by exposing new surfaces (Jorgensen & Willems, 1987).

3.3 Impact of soil pH

The transformation of metallic Pb to reactive Pb-minerals was influenced considerably by soil pH, as the case with soil moisture and soil OM. Increase in soil pH increased the amount of metallic Pb remained

Figure 1 Effects of soil moisture after 5 days of incubation (a), soil organic matter after 5–12 days of incubation (b), and soil pH after 9 days of incubation (c) on X-ray diffraction patterns of a soil spiked at 5% metallic Pb. Experiment A were incubated at

100% and 80% field capacity (FC) whereas b and c at 100% FC. ► Soil organic matter was removed in experiment b. *Q* – quartz; *Pb* – metallic Pb; *M* – minium (Pb_3O_4); *K* – kaolinite; *HC* – hydrocerussite; *L* – litharge (PbO).



in the soil after incubation for nine days at 100% FC (Figure 1c). At pH 4.8, metallic Pb rapidly transformed to hydrocerussite. However, as pH increased to 8.5, less Pb was converted (larger metallic Pb peaks), and less hydrocerussite was produced. In addition, soil pH also influenced the weathering products of metallic Pb. The predominate peaks in the soil at pH 4.5 were Pb carbonate, i.e., hydrocerussite, whereas in the soil at pH 8.5, the predominate peaks were Pb oxides, i.e., litharge. It appeared that at elevated soil pH, Pb weathered to Pb-oxide where the transformation seemed stopped.

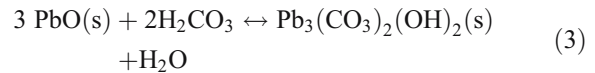
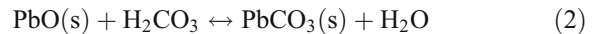
In addition, a lower pH will also influence the rate of metallic Pb transformation to secondary minerals by solubilizing these secondary minerals formed on the surfaces of metallic Pb, thereby exposing new metallic Pb surfaces for weathering. Soil pH plays an important role in the solubility of Pb in shooting range soils (Jorgensen & Willems, 1987; Lin, 1996). The dissolution of both cerussite and hydrocerussite require 2 moles of H^+ per mole of Pb when CO_2 is the product (Jorgensen & Willems, 1987). Thus, at higher pH values the solubility of Pb is repressed (Zimdahl & Skogerboe, 1977), and Pb minerals are more stable and may form a protective layer to prevent further weathering.

Regardless of soil pH, transformation of metallic Pb to reactive Pb-minerals was minimal in the absence of soil OM (Figure 1b). The digested soil after removing soil OM had a low pH of 4.74 (data not shown). However, the fact that little weathering of metallic Pb took place suggested that soil OM is a more important factor than soil pH in controlling the weathering of metallic Pb. In a separate experiment determining the role of microorganisms in transformation of metallic Pb in soil, we found that autoclaving the soil had little effect, i.e., soil OM was more important than the abundance of soil microorganisms in controlling weathering of metallic Pb in a soil (data not shown). This is important when considering that soils in Florida are typically sandy with low soil OM and pH. This should also be considered when trying to develop best management practices for shooting range operators.

3.4 Mechanisms of weathering of metallic Pb in a soil

Based on our study and literature (Cao et al., 2003b; Craig et al., 1999; Lin, 1996), a three-step mechanism for the weathering of metallic Pb in a soil is proposed,

i.e., oxidation, carbonation and dissolution (Figure 2). The transformations can be described by the following chemical equations:



First of all, a layer of water on the surface of metallic Pb is necessary for the diffusion of gases that will react with metallic Pb, which is consistent with our moisture data (Figure 1a). Oxygen diffuses through this layer of water and oxidizes metallic Pb to the divalent Pb form [Equation (1)], which is typically found in the environment (Brown, Foster, & Ostergen, 1999). Gaseous CO_2 will dissolve within the aqueous surface layer and form carbonate ligands that will react with Pb oxides to form Pb carbonates [Equations (2) and (3)] (Graedel, 1994). Dissolution to secondary Pb minerals will occur due to acidity within the soil water (Luo & Hong, 1997), or through ligands and chelating agents that will react with secondary species (Jorgensen & Willems, 1987).

The chemical transformation of PbO to hydrocerussite requires protons [Equations (2) and (3)]. At higher pH the hydronium ion concentration is low, and protons are in demand. The transformation of metallic Pb to hydrocerussite was impeded by the lack of protons at a higher soil pH, therefore only Pb-oxides were formed (Figure 1c).

3.5 Impact of soil amendments

The effects of soil amendments (2% calcium carbonate or 2% phosphate rock) on the weathering of metallic Pb under two moisture levels (80% and 100% FC) were monitored over a period of 11 weeks. Soil pH in the treatments incubated at 80% FC rose considerably within the first week (Figure 3a). Soil pH then decreased before increasing back above 7 after week 6. However, no significant difference in soil pH was seen between the treatments. This suggests that Pb ultimately buffered the soil pH at these high concentrations in the soil (spiked at 5%). Elevated soil pH has been associated with soils contaminated with Pb shot, with greater amount of Pb concentrations being

associated with higher soil pH (Astrup, Boddum, & Christensen, 1999; Chen, Ma, & Harris, 2001). As previously discussed, the conversion of Pb oxide to Pb carbonate [Equations (2) and (3)], and the dissolution of these solids could ultimately cause pH to increase (Luo & Hong, 1997). Gee, Ramsey, and Thomson, (2001) concluded that the role of Pb secondary minerals as natural metal ion buffers is often overlooked. Therefore, it appears that metallic Pb has a natural liming effect when a soil is contaminated with Pb bullets, and it will ultimately prevent further weathering due to this process.

Water-soluble Pb over the 11-week incubation at 80% FC was presented in Figure 3b. There was no significant difference between the treatments at 100% FC over time (data not shown). However, there was a significant difference between the treatments at 80% FC over time, with the unamended soil typically having the highest concentration of water-soluble Pb. The PR-amended soil typically had lower water-soluble Pb, and the CaCO₃-amended soil generally had the lowest water-soluble Pb. However, at week 11, water-soluble Pb in the CaCO₃-amended soil has increased, suggesting that soil amendments had less influence on water-soluble Pb on a long-term basis in the soil studied.

Past studies have shown that the presence of carbonate species in soils leads to elevated pH levels, which enhance the precipitation of metal-carbonates (Maskall & Thornton, 1998). Zimdahl and Skogerboe

(1977) concluded that liming a soil reduced the solubility of Pb due to the formation of Pb-carbonate, and subsequently reduced the availability of Pb to plants. However, in the present study, the formation of Pb-carbonates was suppressed at higher pH since transformation from Pb-oxides to Pb-carbonates requires available protons [Figure 1b; Equations (2) and (3)]. This suggests that the suppression of Pb solubility at high pH in these soils results from a lack of transformation from metallic Pb to Pb-carbonates. Liming soils may also increase Pb solubility. Turpeinen et al., (2000) found that in soils of a former shooting range, liming significantly increased the water-soluble Pb in amended soils. They concluded that it was most likely due to an increase in dissolved organic carbon in the soil as pH increased.

The XRD patterns of the unamended and PR-amended soil incubated for one week at 100% FC were shown in Figure 4a. It is evident that while there were no peaks for metallic Pb, peaks for hydrocerussite, massicot, litharge and possibly minium were visible in both soils. This suggests that the dramatic increase in soil pH in all treatments (Figure 3a) resulted from transformation of virtually all metallic Pb to secondary Pb minerals. This reaction consumed protons, which accounts for the rise in pH [Equations (2) and (3)]. It should be noted that neither metallic Pb nor hydrocerussite was seen in the XRD pattern for the CaCO₃-amended soil (data not shown).

Figure 2 Proposed three-step mechanism for the weathering of metallic Pb in soil.

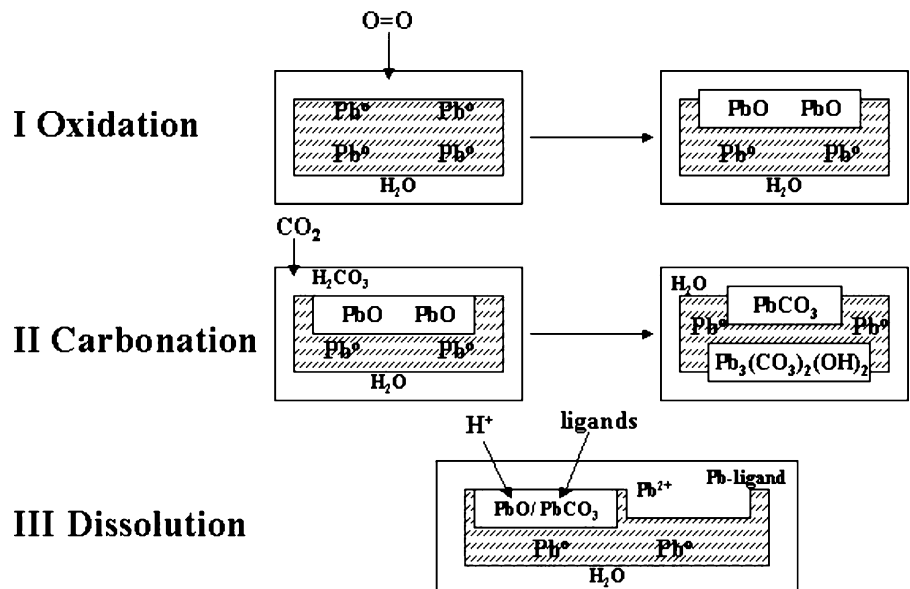
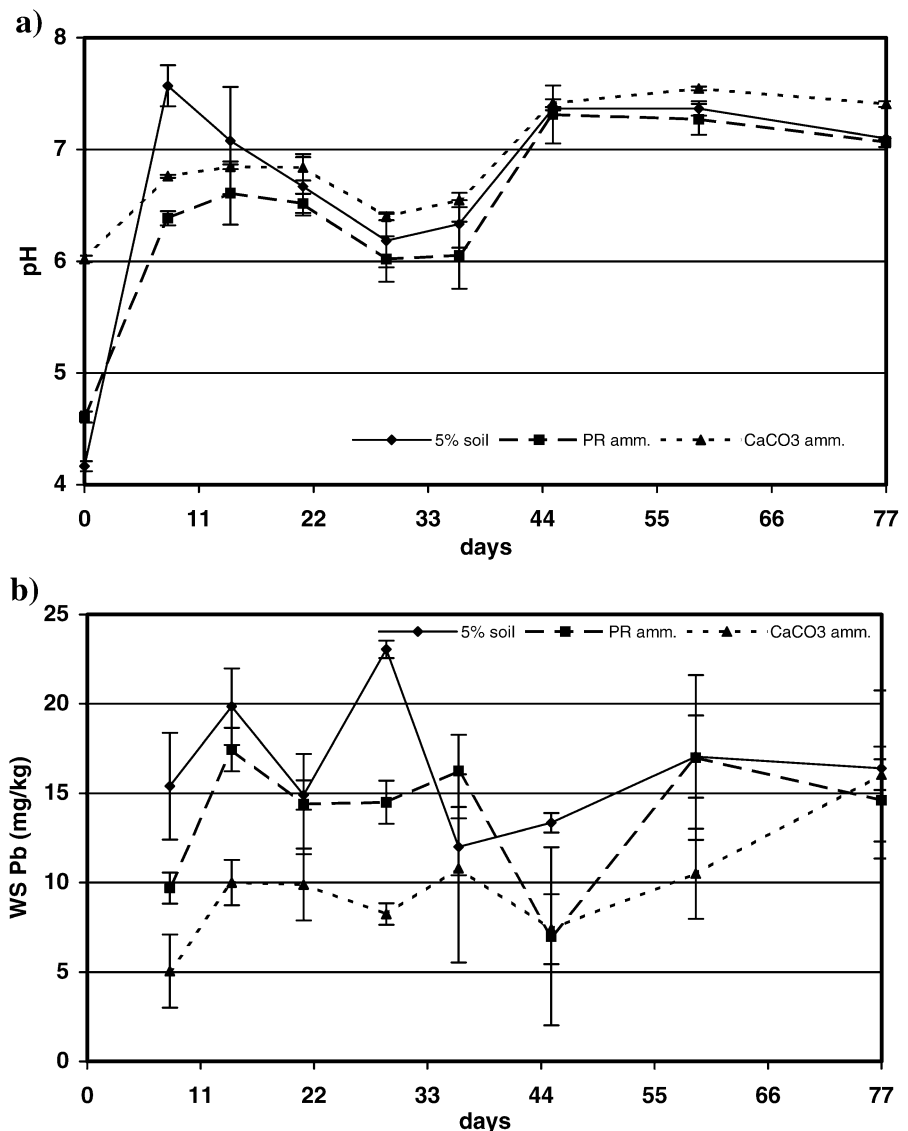


Figure 3 Effects of soil amendments (calcium carbonate and phosphate rock) on pH (a) and water soluble Pb (b) in a soil spiked with 5% metallic Pb and incubated at 80% field capacity for 11 weeks.



After 11 weeks of incubation, aggregates formed in the PR-amended soil were characterized. It can be seen that the aggregates appeared to be composed of quartz that has been cemented together by a precipitate (Figure 4b). It should be noted that those aggregates removed from the unamended as well as the PR-amended soils were much more unyielding, whereas the aggregates from the CaCO₃-amended soil broke apart easily. The aggregates in the unamended and PR-amended soils were composed of quartz being cemented together by hydrocerussite, massicot as well as possibly pyromorphite (Pb-phosphate) in the PR-amended soil, whereas the sample collected from the

CaCO₃-amended soil was dominated by calcite (data not shown).

The main peaks for pyromorphite are at 2.95 (100%) and 2.89 Å (60%). It is common to observe only one primary peak of pyromorphite in soil samples, i.e., 2.95 Å (Cao et al., 2002; 2003a, b). This is because the quantity of pyromorphite formed is often limited and the formed pyromorphite is not well crystallized. The absence of a clearly distinguishable second peak at 2.89 Å for pyromorphite may not allow a definitive conclusion that pyromorphite has formed. However, the size of the primary peak suggests that pyromorphite appeared to have

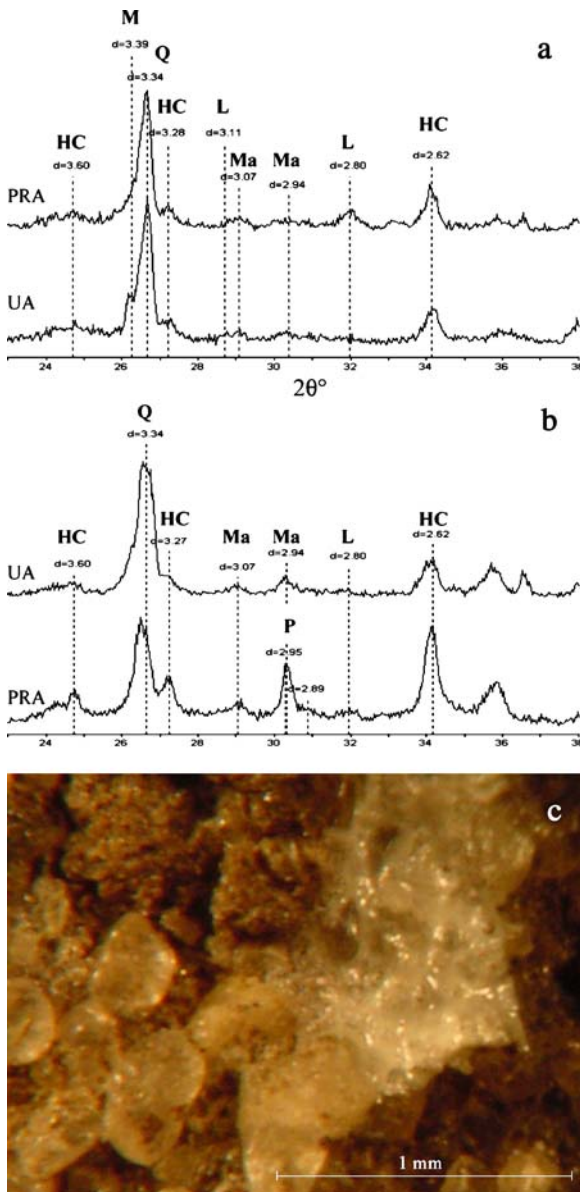


Figure 4 Effects of soil amendments (calcium carbonate and phosphate rock-PR) on the X-ray diffraction (XRD) patterns of a soil spiked with 5% metallic Pb and incubated for 1 week at 100% field capacity (a); XRD patterns of soil aggregates formed after incubation for 11 weeks at 100% field capacity (b); and photography of soil aggregates at 2 \times magnification from the PR-amended soil after incubation for 11 weeks at 100% field capacity. UA – unamended soil; PRA – phosphate rock amended soil; HC – hydrocerussite; L – litharge (PbO); Ma – massicot (PbO); Q – quartz; P – Pyromorphite.

been formed in the PR-amended soil. Based on previous studies, phosphorus amendments may be considered as a possible approach for immobilizing Pb in shooting range soils. Pyromorphite is the least

soluble mineral under most anaerobic and aerobic conditions (Nriagu, 1974), as well as more importantly over a wide pH range (Traina & Laperche, 1999). Amending soils with phosphate rock has previously been identified to significantly reduce the solubility of Pb in different types of Pb contaminated soils (Cao et al., 2002; Ma & Rao, 1999). In addition, hydroxypyromorphite has been found in the phosphorus-rich berm soil of a shooting range in Florida (Cao et al., 2003a, b).

While pyromorphite appeared to have formed in the PR-amended soils in the present study, Pb solubility was not reduced significantly when compared with other treatments (Figure 3b). This suggests that the dominant Pb species in these soils were still Pb-carbonates. This is most likely due to the highly insoluble nature of PR. Ma, Logan, & Traina, (1995) concluded that the primary mechanism for the immobilization of Pb by PR was through dissolution of phosphate rock, and then precipitation of pyromorphite. The presence of 5% metallic Pb significantly increased soil pH (Figure 3a), thus hindered the dissolution of PR in the soil. This result suggest that addition of PR would not be effective in treating soils highly contaminated with Pb in a shooting range due to their high pH. While studies have shown PR may not be as effective as phosphoric acid in immobilizing Pb in soils (Cao et al., 2002; Hettiarachchi, Pierzynski, & Ransom, 2001), it is possible that, when used in conjunction, Pb immobilization will be more effective.

4 Conclusions

Soil properties and soil amendments both influenced weathering of metallic Pb in a soil. It was found that higher soil moisture level increased the weathering rate of metallic Pb to Pb-carbonates. When soil OM was absent from the soil, there was little transformation of metallic Pb to secondary Pb-minerals. Soil pH significantly influenced the weathering products of metallic Pb, with lower weathering rate at higher pH. At a higher soil pH (8.5), only Pb-oxides were formed whereas both Pb-carbonates and Pb-oxides were formed at lower pH (4.8). Soil amendments influenced the formation of secondary minerals resulting from metallic Pb weathering. Water-soluble Pb was decreased in a soil treated with CaCO₃ and PR. After

11 weeks of incubation, pyromorphite was present in the PR-amended soil. This study clearly demonstrated that soil properties and amendments both influenced the weathering of metallic Pb in soils. Best management practices for shooting range soils should be established with these factors in mind.

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