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Grenade Range Management Using Lime for Metals Immobilization and Explosives Transformation

Treatability Study

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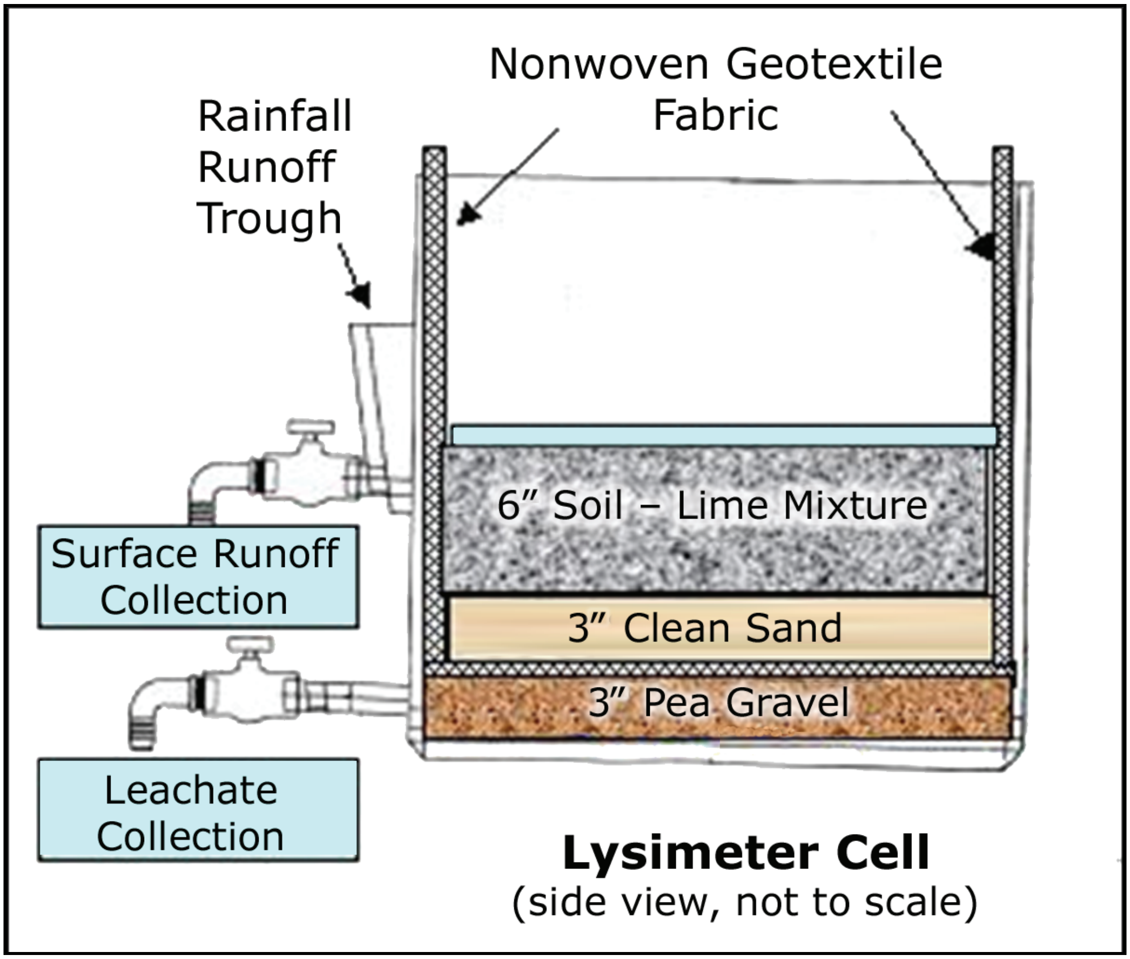
June 2007



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Abstract: The Department of Defense operates hundreds of hand grenade ranges (HGRs) for training purposes. Live fire training is a necessary function to maintain mission readiness for our Nation's warfighters, but it creates a potential source zone for munitions constituents such as metals and explosives. Fragmentation grenades — typically containing composition B within a steel shell casing — constitute the majority of hand grenades used at fixed position ranges. Explosives have been detected in HGR soils at levels in the low parts per billion (µg/kg) up to percent levels. Two mechanisms with potential for offsite migration of metals and explosives from HGR soil are transport in surface water and subsurface transport in leachate or pore water. Simple, innovative, and cost-effective technologies are being developed that can break down munitions constituents quickly at the training sites and prevent residues from migrating to local surface water or groundwater supplies. The application of hydrated lime to HGRs provides both a mechanism for metals immobilization and explosives transformation. The results from this treatability study indicate that the application of lime can be incorporated into range sustainability operations and the management practices for active HGRs.

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Preface

The work reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. The Environmental Security Technology Certification Program (ESTCP) funded the project, which is designated field demonstration project ER-0216.

The work presented in this report was part of an effort to investigate the applicability of lime application to immobilize metals and transform explosives on active hand grenade ranges. Dr. Steven L. Larson, Dr. Jeffery L. Davis, W. Andy Martin, Deborah R. Felt, and Dr. Dennis L. Brandon of the Environmental Laboratory (EL), Vicksburg, MS, and Catherine C. Nestler of Applied Research Associates, Inc., Vicksburg, MS, prepared this report. Assisting were Gene Fabian, Aberdeen Test Center, Aberdeen Proving Grounds, MD; Gregory O'Connor, Army Materiel Command; Kerry Taylor, Jackson State University; Jennifer Butkus, Environmental Office, U. S. Military Academy (USMA), West Point, NY, and Beth-Anee Johnson, Integrated Training Area Management Office, Fort Jackson, SC. Technical assistance was provided by Milton Beverly, Environmental Research and Development, Inc.; Chris Griggs and Michelle Thompson, Applied Research Associates, Inc.; LeeAnn Riggs and Deborah Regan, SpecPro; Casey Trest, Mississippi State University; and Tarmiko Graham, Alcorn State University, MS. The gracious participation of the USMA and Fort Jackson range control personnel for the assistance with obtaining range samples in support of this project is also acknowledged.

This study was conducted under the direct supervision of Dr. Patrick N. Deliman, Chief, Environmental Engineering Branch, EL, and Dr. Richard E. Price, Chief, Environmental Processes and Engineering Division, EL, and under the general supervision of Dr. John M. Cullinane, Technical Director, EL. Dr. Beth Fleming was Director, EL.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Notation

ASTM	American Society for Testing and Materials
ATC	Aberdeen Test Center
ATSDR	Agency for Toxic Substances and Disease Registry
Avg	Average
bgs	Below ground surface
BMP	Best management practice
CEC	Cation exchange capacity
cm	Centimeter
DDI S&S	Distilled and de-ionized suspend and settle
DoD	Department of Defense
ERDC-EL	Engineer Research and Development Center - Environmental Laboratory
ESTCP	Environmental Security Technology Certification Program
g	Gram
gal	Gallon
HE	High explosive
HGR	Hand grenade range
HPLC	High performance liquid chromatography
HQDA	Headquarters, Department of the Army
IARC	International Agency for Research on Cancer
ICP	Inductively coupled plasma
ID	Internal diameter
IDL	Instrumental detection limits
in.	Inch
kg	Kilogram
L	Liter
mg	Milligram
mL	Milliliter
mm	Millimeter
MS	Mass spectrometry

n.a.	Not applicable
n.c.	No change
n.d.	Not determined/non detect
NPL	National Priority List
ORC	Organic related compounds
PBET	Pb bioavailability test
pH	-$\log_{10}$ (H activity); or –$\log_{10}$ (H^+ molarity) at low ionic strength
ppm	Parts per million
RDX	Hexahydro-1,3,5-trinitro-1,3,5-triazine
RL	Reporting limit
RO	Reverse osmosis
SAS	Statistical Analysis System
SOP	Standing operating procedure
SPE	Solid phase extraction
Std	Standard deviation
TCLP	Toxicity Characteristic Leaching Procedure
TNT	2,4,6-trinitrotoluene
TOC	Total organic carbon
TSS	Total suspended solids
USACE	United States Army Corps of Engineers
USEPA	United Sates Environmental Protection Agency
USMA	United States Military Academy
UXO	Unexploded ordnance
v	Volume
w	Weight
w:w	Weight to weight
µm	Micrometer

Chemical symbols

Al	Aluminum
As	Arsenic
Ca	Calcium

Cd	Cadmium
Cr	Chromium
Cu	Copper
Fe	Iron
Hg	Mercury
K	Potassium
Mn	Manganese
Mo	Molybdenum
Na	Sodium
Ni	Nickel
Pb	Lead
Sb^2	Antimony
Si	Silica
V	Vanadium
Zn	Zinc
$CaCO_3$	Calcium carbonate
$CaOH_2$	Calcitic hydrated lime
K_2CO_3	Potassium carbonate
KOH	Potassium hydroxide
NaOH	Sodium hydroxide
NH_3-N	Nitrogen-ammonia
NO_2/NO_3	Nitrite/nitrate
OH^-	Hydroxide
OPO_4	Orthophosphate in soil water
SO_4	Sulfate
TKN	Total Kjehldahl nitrogen
TP	Total phosphorus

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
gallons	3.785412	cubic meters
inches	0.0254	meters
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Munitions on hand grenade ranges

Most munitions-impacted soils on training ranges contain a mixture of contaminants. Fragmentation grenades, which constitute the majority of hand grenades used at fixed position ranges, are typically composed of a steel shell and composition B explosive material. Studies performed on ranges in both the United States and Canada have shown that munition constituents, concentration, fragment size, and spatial distribution vary widely within individual ranges, as well as between different ranges (Pennington et al. 2001, 2002). Jenkins et al. (2001) described hand grenade ranges (HGRs) they studied as small in size (only a few hectares), poorly vegetated, with high explosive (HE) contamination concentrated in an area 15 to 35 m from the throwing pit, that is 20 to 60 m wide and mixed 10 to 15 cm deep. Composition B is a 60:39:1 percent by weight mixture of hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), 2,4,6-trinitrotoluene (TNT), and wax binder, respectively. The primary HE contaminant is the RDX. It was found at concentrations ranging from <0.01 to 51 mg/kg [n=13] (Jenkins et al. 2006). Jenkins et al. (2006) further concluded that low-order detonations contributed most of the HE contamination on HGRs. Low-order detonations are discrete, point sources of munitions constituents with residue concentrations possible in the percent range in the immediate vicinity of the armament.

Environmental fate and transport

Brannon and Pennington (2002) have summarized the fate and transport processes for explosives in soil and water, providing descriptors for dissolution, adsorption coefficients, and transformation rates. Many of the munitions constituents occurring on training ranges have slow dissolution rates and low partition coefficients with a high potential for long-term contamination of ground and surface water (Brannon and Pennington 2002; Lynch 2002). The combination of a high, but reversible, sorption coefficient and the magnitude of contamination at many sites results in a high potential for continuous percolation of contaminated water from near-surface sources through the unsaturated zone to the groundwater. RDX has a low soil adsorption potential, which leads to a high potential of migration and contamination of groundwater. Jenkins et al. (2001) and

Pennington et al. (2001, 2002) reported RDX-contaminated groundwater from several of the sites they tested, confirming the transport potential of energetics into groundwater.

The fate of metals in soils depends on the physical and chemical properties of both the specific metal and the soil. Metals occur in the form of discrete particles (intact munitions or fragments), as well as metal salts (weathering products) and dissolved metal or metallic complexes adsorbed to the soil matrix. Transport is more likely when the metals are in a soluble form; for example, at low pH levels. Significant downward migration of metals from the soil surface can also occur when the metal retention capacity of the soil is exceeded. The capacity of soil to adsorb Pb and Zn increases with increased pH levels. Controlling soil and pore water pH can, therefore, directly impact the fate and transport of metals associated with munitions residues.

Current remediation technologies

The optimum treatment technology for successful remediation of distributed energetics and metals contamination on training ranges should be inexpensive, easily applied in remote locations, effective on heterogeneous contaminant distributions, effective over large areas, effective on multiple compounds, as nonintrusive as possible, and able to be incorporated into normal range operations. Technologies currently available for the remediation of munitions-contaminated soil and groundwater have been reviewed by Stratta et al. (1998), the National Research Council (1999), Rodgers and Bunce (2001), Weeks et al. (2003), the U.S. Government Accountability Office (2005), and the Federal Remediation Technology Roundtable (FRTR), updated in 2006. Few remediation alternatives are available to treat soil and sediments, and most of these involve ex-situ treatment. Inherent in all ex-situ processes is the required excavation and transport of the contaminated soil with the associated health and safety risks. Ex-situ systems are often part of a treatment train and, as such, are expensive to initiate and often produce residuals that also must be treated (Weeks et al. 2003). Therefore, a minimally disruptive, in-situ technology is preferable. Two in-situ processes reviewed favorably by Rodgers and Bunce (2001) and the FRTR (2006) are enhanced bioremediation and phytoremediation. The length of time and the effects of climate on cleanup are disadvantages shared by these methods. In summary, no technology is currently available that can effectively remediate the HE contamination found on active training ranges or to prevent transport of these contaminants into the groundwater.

Unlike the hazardous organic contaminants associated with munitions residues, metals are not degraded or easily detoxified. The most commonly used treatment technologies for metals in soils on firing ranges include solidification/stabilization, excavation and offsite disposal, and acid extraction (Larson et al. 2006, in press). Other remediation technologies include electrokinetics and phytoremediation (FRTR 2006). These technologies, however, do not meet the optimum remediation requirements of an active firing range.

Alkaline hydrolysis

The use of the hydrolysis reaction as a means to degrade various environmental contaminants is reviewed in the USEPA report on Fate, Transport, and Transformation Test Guidelines (1998). The neutralization of HE by alkaline hydrolysis is presented by the National Research Council (1999) in their investigation of alternative technologies available to clean up chemical weapons. To summarize the reaction, alkaline hydrolysis decomposes the explosive to organic and inorganic salts, soluble organic compounds, and various gases. Heaton (2001) proposed the commercial use of base hydrolysis in an ex-situ mode to remove explosive residues from scrap ordnance.

Brooks et al. (2003) and Hansen et al. (2003) investigated the removal of RDX from soil by alkaline hydrolysis. The efficiency of the alkaline hydrolysis reaction to remove explosive compounds from soil depends on bringing the explosive into direct contact with the hydroxide ion, which takes place within the soil pore water. The alkaline hydrolysis reaction removed nitroaromatics and nitramines from a variety of different soil types, although the reaction rate was slower in soils with high clay content (i.e., high cation exchange capacity, CEC). At pilot-scale, the reaction performed best when the lime was mixed well into the soil, bringing the hydroxide ion into close contact with the explosive material. Toxicity testing showed that the reaction reduced soil toxicity and mutagenicity.

Amendments used to raise the pH in liquid and soil systems conventionally include metal oxides, hydroxides (e.g., NaOH, KOH), and carbonates (e.g., $CaCO_3$, K_2CO_3). These materials have been used in a variety of applications, including domestic and industrial wastewater treatment, acid mine drainage, and agricultural soil treatment. Several formulations of lime have been investigated for their ability to increase soil pH and degrade HE (Brooks et al. 2003). The calcitic, hydrated lime ($Ca(OH)_2$), used primarily in engineering applications, proved most amenable to soil treatment for alkaline hydrolysis (Brooks et al. 2003). This application has now been used in field-scale studies (Thorne et al. 2004; Johnson et al. 2006, in press).

Hydroxide fate and transport in soil

During lime applications, the fate of hydroxide ions (OH^-) during transport through the soil will presumably be an important aspect of this proposed management technology. The alkaline hydrolysis reaction occurs in the aqueous phase. Therefore, the lime amendments and the munitions constituents must first dissolve into the soil pore water before the reaction can take place. Advective and dispersive processes will transport the hydrated lime cationic (i.e., Ca^{2+}) and alkaline anionic species (i.e., OH^-). Cations may undergo ion exchange with other cations sorbed at exchange sites in the soil, including hydrogen (low pH soils) and aluminum (high clay soils). Reaction with H^+ exchanged from low pH soils inhibits the alkaline hydrolysis of the explosive munitions constituents by neutralizing the OH^- ions, effectively buffering the system. Base cations can also interact with the OH^- ions to form insoluble hydroxides, again removing them from potential munitions constituent hydrolysis. Furthermore, hydrogen ions associated with various functional groups in humic matter may also dissociate under elevated pH conditions, and likewise inhibit alkaline hydrolysis of the explosive munitions constituents. Clearly, soil chemistry plays an important and complex role in energetics management through alkaline hydrolysis.

Range management of metals and explosives laden soils

Munitions residues are potential sources for soil and water contamination by heavy metals. The addition of lime is currently being used to treat heavy metals contamination in a variety of applications: wastewater treatment (Charerntanyarak 1999; Kurniawan et al. 2006), treatment of sewage sludge solids (Fang and Wong 1999; Wong and Selvam 2006), and treatment of soils (Mckinley et al. 2001; Geebelen et al. 2003; Gray et al. 2006). Reviewing several treatment techniques for treating wastewater contaminated with heavy metals, Kurniawan et al. (2006) found that lime precipitation was the most effective method to treat effluent with a metal concentration >1,000 mg/L. The advantages of the lime treatment included the low capital cost and simplicity of operation. Charerntanyarak (1999), using $Ca(OH)_2$ as the precipitant, reported an optimum treatment pH of 11 and a removal efficiency of 99.3 to 99.8 percent for Mn, cadmium (Cd), and Zn.

Fang and Wong (1999) and Wong and Selvam (2006) investigated the use of lime in composting sewage sludge. The lime stabilized the heavy metals in the sludge (copper (Cu), Mn, Zn, and nickel (Ni)), significantly reducing the concentrations of water and acid-extractable metals. The lime amendment had no adverse side effects on the overall system, as it did not slow compost maturation or interfere with seed germination. The authors recommended a lime addition of <1.0 percent (w:w).

Highway construction projects have turned to contaminated soils (such as river silt and sewage sludge) to use as backfill material. Construction projects also use lime as a soil strengthener and conditioner. Mckinley et al. (2001) investigated the cementitious reaction that stabilizes the metals in the soil. They found that lead (Pb), arsenic (As), mercury (Hg), and Fe concentrations were very low in the leachate from the treated soil. The authors suggested that metals complex with the soil organic matter in the silt and sludge. At high pH, the organic matter dissolves, leaving the metal in solution as a metal-organic complex. Although the leachate did not contain metals in concentrations high enough to be an environmental concern, McKinley et al. (2001) concluded that stabilization of contaminated soil using lime will perform best in soils with low organic matter content.

Dermatas and Meng (2003) added fly ash to contaminated soil in order to determine the effects on soil strength and heavy metals containment. Class C fly ash contains at least 30 percent calcium oxide as well as silica (Si), aluminum (Al), and Fe oxides up to 50 percent, and is used primarily in construction and geotechnical applications. Dermatas and Meng (2003) concluded that the addition of fly ash increased the soil strength and enabled the containment of heavy metals. Lead and hexavalent chromium were immobilized and trivalent chromium immobilization was enhanced by fly ash addition to the soils.

Geebelen et al. (2003) compared various bioassays to evaluate the success of soil lead immobilization treatments. Three amendments were evaluated: $Ca(CO_3)$, cyclonic ash and steel shot, and phosphate rock. Lead immobilization was tested using single and sequential extractions together with a microbiological sensor, a phytotoxicity test, plant uptake, and a Pb bioavailability test (PBET). Lime decreased the phytotoxicity and plant Pb uptake and passed the microbiological sensor. The authors did report that different amendments did not behave the same way in different soils with different sources of contamination. They suggested the use of a wide suite of indices to evaluate Pb availability after treatment. Field studies comparing red mud (high pH bauxite refining residue) and lime to remediate heavily contaminated soils found no difference in their performance (Gray et al. 2006). The authors reported a decrease in soluble and extractable metals concentrations in the treated soil. The amendments also reduced plant uptake of the metals as well as allowing re-vegetation of the soil.

Munitions-related contamination, initially identified at production and handling facilities, is now known to include military training ranges and demolition test areas as well (Jenkins et al. 2001; Pennington et al. 2001, 2002). The sustainability of live-fire ranges is of paramount importance to ensure continued training at Army installations. Active military ranges are crucial to military readiness, and the development of effective treatment options for energetic and heavy metal contaminants is essential for range management and sustainability (Borthwick and Beshore 2000; Jones et al. 2002). Alkaline hydrolysis has the potential to transform explosives and stabilize metals residues in range soil. The research presented here examines basic aspects of lime application as a means of reducing the metals and explosives source zone contamination on live-fire ranges.

2 Experimental Design

Design

Two separate lysimeter studies were conducted with the HGR soils. The first lysimeter study used native HGR soil from the U.S. Military Academy, NY (USMA), and Fort Jackson, SC. The USMA HGR soil mixed with hand grenade residue containing composition B with a decreased volume of simulated rainfall was used for the second lysimeter study.

In Lysimeter Study I (Table 1), eight lysimeters were loaded with HGR soil from USMA and Fort Jackson. One of the four lysimeters was a control with no addition of hydrated lime. The three other lysimeters had a lime dose equal to 50 percent (i.e., ½ times the lime dosage), 100 percent (1×), and 200 percent (2×) of the lime dosage requirement as determined by a modified American Society for Testing and Materials (ASTM) method D6276-99a (ASTM 1999). The lime dosage requirement was defined as the amount of lime necessary to bring the soil pH to above 11.5, a level that aggressively promotes alkaline hydrolysis of explosives (Davis et al. 2006, in press). These lime dosages (in dry weight percent) were 0.15, 0.30, and 0.60 percent lime for the native USMA soil and 0.5, 1, and 2 percent lime addition for the Fort Jackson soil, respectively. On a weekly basis, 46.3 L of reverse osmosis (RO) water of approximately 5.5 pH was applied to each of the four lysimeter cells for a total of 16 rain events. The lysimeter cells were left uncovered after each weekly rain event. The USMA cells were loaded with 210 kg of HGR soil while the Fort Jackson lysimeter cells were loaded with approximately 170 kg of HGR soil. The difference in the soil mass is due to the soil density and compaction within the lysimeter cells.

Lysimeter Study II (Table 1) was similar to Lysimeter Study I except the total rainfall was reduced by 75 percent and the amount of lime added to the cells was increased. The reasons for the second lysimeter study were to reduce the potential flushing of the lysimeter cells and to observe the possible effects of different lime dosages within the cells. Three lysimeter cells were loaded with 200 kg of crushed rock HGR soil from USMA. One of the three lysimeters was a control with no addition of hydrated lime. The other two lysimeters were dosed with 0.83 and 1.66 percent hydrated lime, respectively (for a 200- and 400-percent lime dose required to elevate the pH above 11.5). On a weekly basis, 11.6 L of RO water was supplied to each of the three lysimeter cells and the lysimeters were left uncovered after each weekly rain event.

Table 1. Experimental design for Lysimeter Studies I and II.

Lysimeter Cell	Project Description			
	Study I		Study II	
	% Lime Added to Soil	Water Addition	% Lime Added to Soil	Water Addition
1	USMA Control no lime	2.94 in. (46.3 L) of RO water applied per week for 16 rain events	USMA Control no lime	0.734 in. (11.6 L) of RO water applied per week for 16 rain events
2	USMA 0.15% (1/2x lime dose) (0.315 kg total)		USMA 0.83% (2x lime dose) (1.745 kg total)	
3	USMA 0.30% (1x lime dose) (0.630 kg total)		USMA 1.66% (2x lime dose) (3.490 kg total)	
4	USMA 0.60% (2x lime dose) (1.260 kg total)			
5	Fort Jackson Control no lime			
6	Fort Jackson 0.5% (1/2x lime dose) (1.238 kg total)			
7	Fort Jackson 1.0% (1x lime dose) (2.476 kg total)			
8	Fort Jackson 2.0% (2x lime dose) (4.951 kg total)			

Note: The USMA Lysimeter Study I and II lime doses differ due to the different soil used to calculate the required lime dose.

Explosives extractions, following SW-846 EPA Method 8330 (1994), were performed on the HGR soils before and after the 16 rain events. Soil core samples were collected from the lysimeter cells 8 and 16 weeks after lime addition and were analyzed for metals, explosives, and soil pH.

Objectives

The objectives of this study were to evaluate and develop a management technology to control active grenade range contaminant mobility and promote contaminant degradation prior to field application.

Column and lysimeter studies were performed using soil from active HGRs in order to demonstrate the potential of the lime application technology potential for reducing migration of RDX and metals from range soils. The following performance objectives for HGR management were monitored and evaluated during the lysimeter studies:

1. **RDX in leachate**: reduce RDX concentrations in waters leaching from the lysimeters by greater than 90 percent;
2. **RDX in surface water**: reduce RDX concentrations in water running from the lysimeter by greater than 90 percent;
3. **Metals migration in pore water**: demonstrate no significant increase in metals concentration leaching from the lysimeter;
4. **Metals migration in surface water**: demonstrate no significant increase in metals migration in water running from the lysimeter;
5. **Effective treatment with minimal side effects:** assess the overall effectiveness and potential side effects of the lime amendment technology by maintaining the pH above 10.5 at the source area and below 9.5 outside the source area.

3 Materials and Methods

This study was undertaken to define protocols necessary to scale-up the lime treatment technology from the laboratory to the field. The Grenade Range Management using lime technology was developed to both reduce metals migration and transform explosives on active HGR soil. The field application will be used to manage munitions constituents on active training ranges.

The treatability study focused on several aspects of the scale-up and used HGR soils with different physical and operational properties. The study focused on the application of lime, under controlled conditions, to soils that were laden with hand grenade explosives constituents in order to:

- Validate the transformation of explosives within limed soil,
- Evaluate metals stability within limed soil,
- Determine engineering parameters, such as application rates and methods for field-scale sites,
- Develop application techniques to be used at operational HGRs.

The HGR soils were subjected to column and lysimeter studies in order to understand and characterize the leachate and runoff waters generated from an equivalent amount of annual rainfall on the lime-treated soils. Bench scale and treatability study results are provided in Appendix A.

Physical and chemical analysis

Several methods and procedures used during this study are listed in Table 2 and summarized below.

The physical characteristics of the HGR soils were determined by standard laboratory procedures. Specific gravity, particle-size distribution, and soil classification were determined according to procedures D-854, D-422, and D-2487, respectively (ASTM 2001).

Table 2. Chemical and physical analytical procedures used during the treatability studies.

Parameter / Procedure	Method	Detection Limit	
		Water (mg/L)	Soil (mg/kg)
Digestion procedures	SW-846-3051 SW-846-3015	0.05	n.a.[1]
TCLP[2]	SW-846-1311	0.05	n.a.
DDI S&S[3]	SW-846-1311 ASTM D-3987-85	0.05	n.a.
Particle-size distribution	SOP[5]	n.a.	n.a.
ICP[4]	Method 200.7	0.05	0.5
RDX/TNT	Method 8330 SPE	0.0005	0.01

[1] n.a. = not applicable.
[2] TCLP = Toxicity Characteristic Leaching Procedure.
[3] DDI S&S = Distilled de-ionized water suspend and settle.
[4] ICP = Inductively coupled plasma.
[5] SOP = standard operating procedure.

Chemical characterization of the HGR soils included explosives concentrations, digested metals content, Toxicity Characteristic Leaching Procedure (TCLP) and distilled de-ionized water suspend and settle (DDI S&S) metals leaching analysis, total organic carbon (TOC), CEC, and pH. The initial metals content of the HGR soil was determined using SW-846 Method 3051 (USEPA 1999). Leachate and runoff samples were analyzed for total metals, dissolved metals, and explosives concentrations. Aqueous leachate and runoff samples were analyzed for dissolved metals after filtering through a 0.45-micron filter following the procedures in Method 3010 (American Public Health Association (APHA) 1998). Explosives were analyzed by high-performance liquid chromatography (HPLC) following filtering of samples to remove large particles, then using a solid phase extraction (SPE) technique on a 500-mL sample.

Total (digested) metals were determined on liquid samples (leachates and runoff) after digestion according to SW-846 Method 3015. All TCLP and DDI S&S leaching was analyzed using to EPA SW-846 Method 6010 Inductively Coupled Plasma (ICP) (USEPA 1999) on a Perkins Elmer Optima 3000 or by SW-846 Method 6020 (USEPA 1999) ICP Mass Spectrometry

(MS) on a Perkins Elmer Sciex 6000. Table 3 lists the estimated ICP detection limits and the reporting limits used in this study. TOC levels were determined using a Zellweger Astro Lab TOC Analyzer Model 2100 following the user's manual and local standing operating procedure (SOP).

Table 3. Estimated ICP Instrumental Detection Limits (IDLs) and Reporting Limit (RL).

Compound	Estimated IDL[1] (mg/L)	Report Limit (mg/L)
Lead	0.0280	0.05
Chromium	0.0047	0.05
Copper	0.0036	0.05
Nickel	0.0100	0.05
Zinc	0.0012	0.05
Iron	0.0041	0.05
Manganese	0.0009	0.05
Molybdenum	0.0053	0.05
Vanadium	0.0050	0.05
Antimony	0.0210	0.05
Calcium	0.0067	0.05

[1] For metals adapted from SW-846 Method 6010B.

Extraction procedures used prior to HPLC explosive analysis varied depending on the sample type. Solid-phase samples were analyzed according to SW-846 Method 8330, but liquid-phase samples were concentrated first using an SPE technique. Pre-packaged cartridges of Propak (Sep-Pak, 6cc, 500 mg) from Waters Corporation were used for the SPE procedure. The cartridges were activated by placing them on a Visiprep solid-phase extraction manifold (Supelco) and passing 15 mL of acetonitrile through each, using gravity flow. The acetonitrile was flushed from the cartridges using 30 mL of reagent grade water. Care was taken to ensure that the cartridges were not allowed to dry after initial activation.

A 60-mL Sep-Pak reservoir was placed on top of the SPE prepacked cartridge. Once the cartridge was cleaned, a 60-mL aliquot of sample was placed in the reservoir. The vacuum was turned on, and the flow rate through each cartridge was set at 10 mL/min. Further sample aliquots were added to the reservoir until the entire 500-mL sample was used. Flow rates were adjusted if they declined significantly due to partial plugging by suspended material. After the sample was extracted, the top plug containing the fitted tubing was removed from each cartridge. Acetonitrile (5 mL) was used to elute the retained analytes from the cartridge under gravity flow at approximately 1 mL/min. The sample was then diluted with reagent grade water (1:1 (v:v) acetonitrile-to-water) and was ready for HPLC analysis.

Soil collection and preparation

Preliminary grab samples were collected from the USMA and Fort Jackson HGRs in order to determine the lime required to elevate the soil pH to greater than 11.5. These grab samples were used to determine preliminary soil characteristics and applicability of the lime addition for range management.

The bulk samples that were used in the treatability studies were transported to the U.S. Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL) (Vicksburg, MS) in 55-gal, polyethylene-lined drums. In addition to the bulk drum samples, several grab and core samples were collected. Grab samples were collected using a small scoop and placed in plastic bags. Core samples were collected using a 5-cm diameter (ID) auger to a depth of 1.8 m below ground surface (bgs) and were placed in plastic bags for transport to ERDC-EL.

A composite sample of the contents of the drums was made using the following procedure. Air-dried soils were homogenized by hand in a large polyethylene-lined box using shovels, rakes, and a small hand tiller. Large rocks and organic debris were removed during the homogenization process. Based on earlier research (Larson et al. 2004), this homogenization process resulted in a 21 percent relative standard deviation for the chemical analysis. Soil subsamples were weighed and stored in 55-gal, polyethylene-lined drums before filling the lysimeters. Nine subsamples of the newly mixed soil were taken for initial explosives and metals analysis. Representative aliquots of the soils were subjected to soil characterization that included soil pH, particle-size distribution, TOC, and CEC. All tests were conducted in conjunction with control samples as the benchmark for comparison.

Concurrent with this preliminary research, the USMA HGR was reworked. A new top layer of crushed rock was put down after the initial soil characterization was conducted (i.e., the bottom soil at the USMA HGR still reflected the initial soil characterization conducted at ERDC-EL, but the top 0.30- to 0.46-m layer of crushed rock did not).

pH column study

A column study was conducted using the USMA crushed rock HGR soil in order to determine the effect passing through limed and then native soil would have on leachate pH. HGR soil (7.62 cm or 300 g) was mixed with 1.66 percent (4× lime dose) hydrated lime (1.66 g lime per 100 g soil) and placed on top of 7.62 cm of native soil inside a 5.08-cm ID column. Two additional 5.08-cm ID columns were packed with 15.24 cm of native soil and were set in series for a total soil depth of 45.72 cm (Figure 1). An equivalent of 3 years of rainfall (average of 119.4 cm per year) was passed through the columns and collected at the 15.24-, 30.48-, and 45.72-cm depths. As the leachate passed through the series of columns, the pH level of the leachate was determined after each 15.24-cm depth.

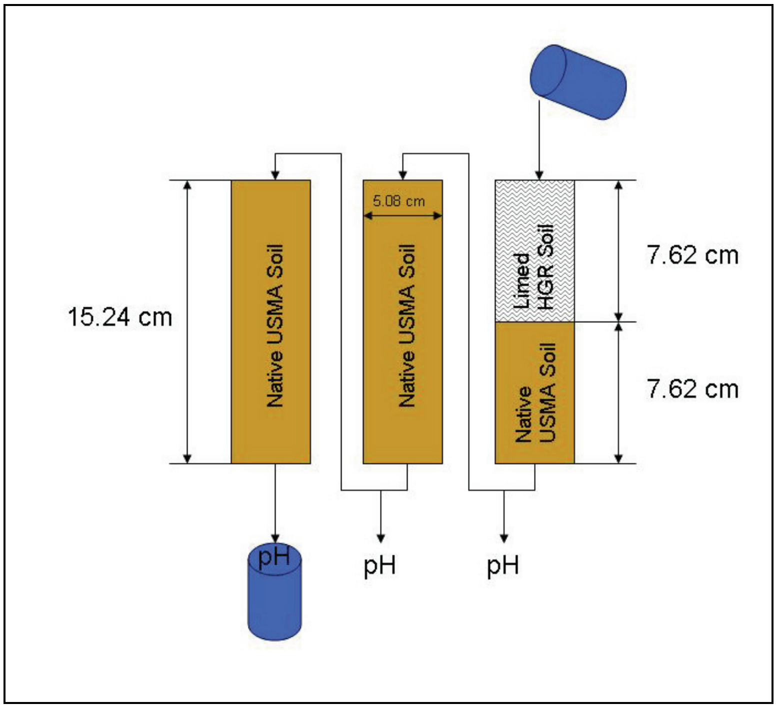

Figure 1. Schematic of pH column study.

Mesoscale lysimeters

The mesocosms were designed to allow for the collection of leachate flowing through the soil as well as runoff from the soil surface (Figures 2-4). The lysimeters were constructed from 1.905-cm-thick, high-density polyethylene that measured 0.7874 m by 0.7874 m by 0.6096 m (inside length

× width × height). The lysimeters were placed on stands constructed from angle iron, with a 1 to 2 degree slope for collection of surface runoff.

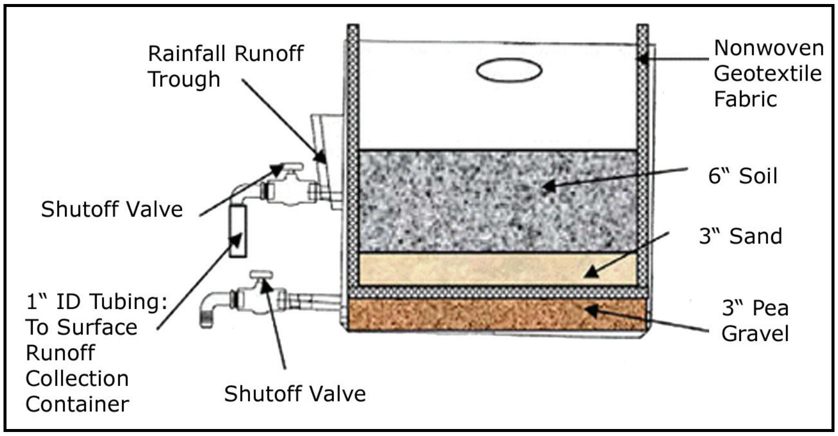

Figure 2. Cross section of lysimeter cell.

Sufficient room remained above the soil mixture for a portion of the simulated rain to puddle and flow through the runoff trough into the runoff collection system (Figures 2 and 3). Leachate and runoff waters were collected in polyethylene pans (Figures 3 and 4). All tubing in the collection system was made from nonreactive silicone or polyethylene.

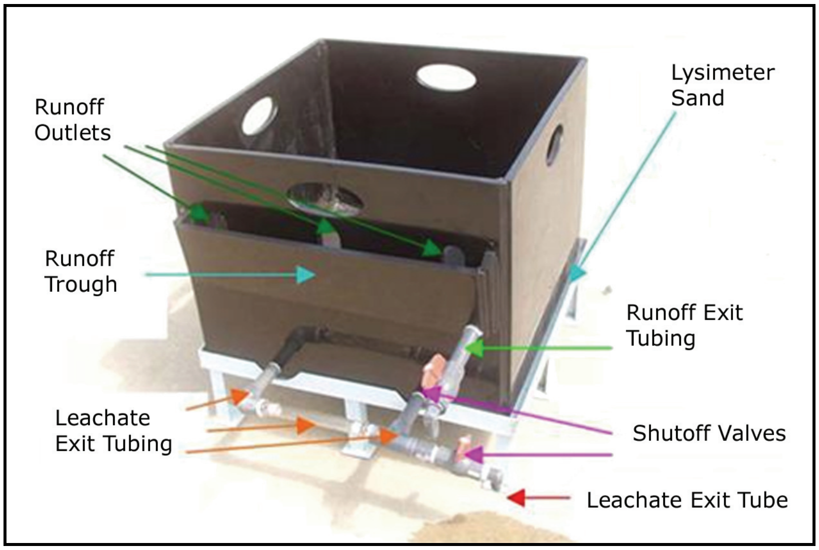

Figure 3. Empty lysimeter cell showing runoff and leachate collection systems.

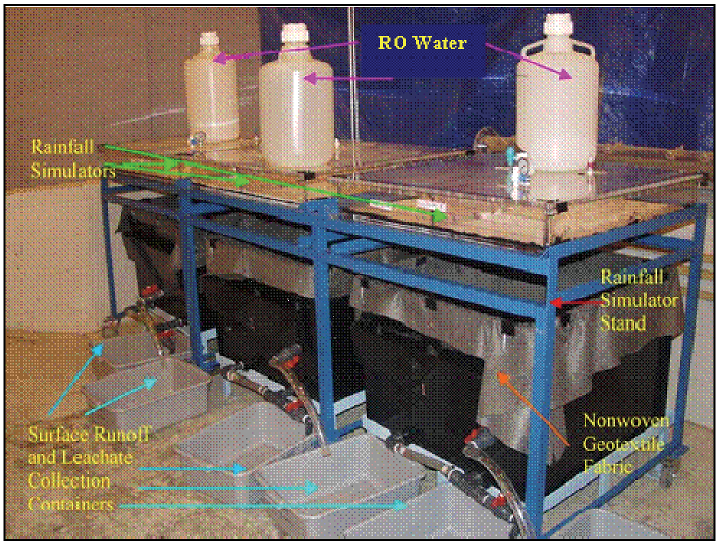

Figure 4. Lysimeters showing rainfall simulators and leachate/runoff collection systems.

Rainfall simulators were constructed from clear Plexiglas boxes and rested on mobile carts directly above the lysimeters (Figure 4). A water reservoir containing RO water was placed above each rain simulator box. Air pressure regulators were fitted into the top of the simulators to control airflow and to apply air pressure to increase rainfall rates. A porous polyethylene material was secured to the bottom of the Plexiglas box using silicone adhesive caulk. This system generated a measured amount of simulated rainfall that flowed through the porous bottom of the rainfall simulator onto the test soil.

In this study, a simulated rainfall amount was used that replicated the total average annual rainfall at Fort Jackson and at the USMA (47 inches per year). In order to simulate this amount of rainfall in 16 weeks, 2.94 inches per week or 46.3 kg of RO water was applied to each lysimeter. Approximately 45 min was required to apply the total amount of rainwater.

Pea gravel (7.62 cm) was placed on the bottom of the lysimeter to prevent the sediment from clogging the exit tubes during the weekly rainfall event. A layer of nonwoven geotextile was placed on the pea gravel and draped around the inside of the lysimeter. A 15.24-cm layer of coarse sand was placed on the geotextile, and the sand was compacted to 7.62 cm. The total volume of homogenized soil was divided into four subsamples in order to provide the required soil mass for the lysimeters. The soil subsamples were weighed and mixed in a rotary cement mixer for 15 min with the appropriate amount of hydrated lime. Approximately 200 kg of the HGR soil was then placed in three 5-cm increments over the sand layer.

The test soils were compacted to form a soil layer approximately 15.24 cm deep (Figure 5).

Figure 5. Loaded lysimeter showing soil surface.

Prior to conducting the tests, the lysimeter cells were saturated with RO water supplied from a 60-L polyethylene bottle. One end of a long piece of silicone tubing was attached to the dispensing outlet of the bottle, and the opposite end was connected to the leachate exit tube at the bottom of each lysimeter. Silicone tubing attached to an air pressure pump was fitted with a female quick-connect valve. A male quick-connect valve was placed in a large one-holed silicone stopper, and the stopper was placed in the top of the bottle. The bottle was then placed on a tall mobile stand and positioned over each lysimeter. Approximately 45 L of pressurized water was allowed to drain into each lysimeter in an upward flow through all of the lysimeter cell layers. After complete saturation occurred, as evidenced by a water layer on top of the soil mass, the excess water was drained from each lysimeter.

Statistical analysis

Statistical analysis was performed on data from Lysimeter Study I using SAS, Version 6, Volumes 1 and 2 (SAS Institute Inc. 1988, 1989a, 1989b) to evaluate the analysis of variance (ANOVA) for metals and explosives. The results are detailed in Appendix B.

4 Results and Discussion

Soil characteristics

The soil characteristics of an HGR vary depending on the geographical location of the military installation and the sampling methods used. The USMA and Fort Jackson HGR soil results (Table 4) are from grab samples from the respective range.

Table 4. Preliminary screening properties of USMA and Fort Jackson HGR soils.

Property	USMA[1]	Fort Jackson
Specific gravity	2.75	2.62
Percent gravel	7.1	0.5
Percent fines	16.1	22.3
Percent sand	76.8	77.2
Unified Soil Classification	SM	SM
TOC	0.4	1.24
CEC (meq/100 g)	1.8	6.5
Native soil pH [Crushed rock pH]	4.90 [8.56]	5.48
Calcium (mg/kg)	716	710
Iron (mg/kg)	<8.0	<13.1
Magnesium (mg/kg)	<40	<66
Manganese (mg/kg)	4.9	5.7
Potassium (mg/kg)	<80	<130
Sodium (mg/kg)	<80	<130
Sulfate (mg/kg)	20	30
Total Kjehldahl nitrogen (mg/kg)	<101	<104
Total phosphorus (mg/kg)	<20	<20
Orthophosphate in soil water (mg/kg)	<5.0	<5.2
Nitrogen-ammonia (mg/kg)	<10	<10
Nitrite/nitrate (mg/kg)	<5.0	33.7
Sulfide (mg/kg)	<50	<52
Aluminum (mg/kg)	<40	<66

[1] USMA soil characteristics reflect the bottom native soil at the range. They do not reflect properties of the crushed rock added to the range.

The USMA and Fort Jackson HGR soils were tested using a modified ASTM D6276 (Davis et al. 2006, in press) in order to determine the lime dosage required to bring the study soil above pH 11.5. For the USMA soil, it was determined that 0.415 percent lime application was required or 0.415 g of hydrated lime per 100 g of soil. Fort Jackson HGR soil required 1.00 percent lime application or 1.0 g hydrated lime per 100 g of soil.

A more thorough metals analysis was conducted of the USMA and Fort Jackson HGR soils after mixing the bulk samples to generate more homogeneous samples for use in the treatability studies. Nine subsamples of the newly mixed soil were taken for prelysimeter metals analysis (Table 5).

Table 5. Metals concentrations of homogenized USMA and Fort Jackson HGR soils.

Metal Concentration (mg/kg)	USMA[1]		Fort Jackson	
	Avg (n=9)	Std Dev	Avg (n=9)	Std Dev
Zinc	131	13	934	138
Iron	21,620	1,186	9,761	919
Manganese	974	71	24	4
Calcium	20,130	1,865	75	16
Lead	25	5	33	11
Chromium	30	3	25	1
Copper	34	3	17	1
Nickel	27	2	16	1
Molybdenum	2	<1	1	<1
Vanadium	43	5	24	1
Antimony[2]	<1	<1	<1	<1

[1] USMA soil characteristics reflect the top soil at the range.

[2] Detection limit used in average.

pH column study

A total of 5.67 L, or the equivalent of 119.4 cm of annual rainfall for 3 years, was passed through the columns (45.72 cm of soil). The first 7.62 cm in the column system was USMA HGR topsoil mixed with 1.66 percent hydrated lime (w:w), which registered a soil pH level of 12.4 (Table 6). The rest of the column system was packed with USMA native soil (pH 4.9). The RO water that was added to the test was acidic (pH 5.4), but the leachate pH was significantly higher (pH 11.35 ± 1.02) after it passed through the first column (15.24 cm soil) in a series. The pH level of the leachate steadily decreased to 6.24 as it had passed through the three-column system. This result indicated that the pH level of the leachate had been raised to near treatment levels by the lime addition, but that the leachate was eventually neutralized. The leachate may have been neutralized by contact with the native soil, but other factors may also have had an effect. The column study did not account for hydroxide consumption in such things as explosives degradation, metals immobilization, or natural regeneration of soil buffering capacity in the limed soil over time.

Table 6. pH column study results.

Media	pH [average]	Std
USMA native soil	4.9	n.d.[1]
USMA HGR topsoil	7.7	n.d.
USMA HGR topsoil with 1.66% lime	12.4	n.d.
RO water (n=4)	[5.40]	0.65
Column #1 average leachate (n=12)	[11.35]	1.02
Column #2 average leachate (n=12)	[8.01]	1.72
Column #3 average leachate (n=12)	[6.24]	0.61

[1] n.d. = not determined.

Mesoscale lysimeter studies

Two mesoscale lysimeter studies were performed with HGR soils. One study used HGR soils taken directly from the ranges, while another used HGR soil that had been amended with hand grenade residue containing composition B. The results for both lysimeter studies are presented in relation to the performance objectives in order to highlight the similarities and conclusions drawn from both studies.

1. Reduce explosives concentrations by greater than 90 percent in water leaching from the test cell relative to a baseline defined by the control cell.

The USMA and Fort Jackson HGR soil used in the control and limed cells of Lysimeter Study I were removed systematically from the same bulk homogenized samples and had an initial RDX concentration of 0.87 and 2.38 mg/kg, respectively. By the fifth rain event, the leachate RDX concentrations in all eight cells were reduced by greater than 90 percent compared with the initial RDX concentrations (Figure 6). Since the reduction occurred in all cells, it was hypothesized that the RDX had been flushed out of the soil by the large volume of applied water that had passed through the test cells. To test this hypothesis, a second lysimeter study was conducted (Lysimeter Study II) in which the rainfall amount was reduced by 75 percent. The soil was also amended with additional hand grenade residue containing composition B to increase the initial RDX concentration.

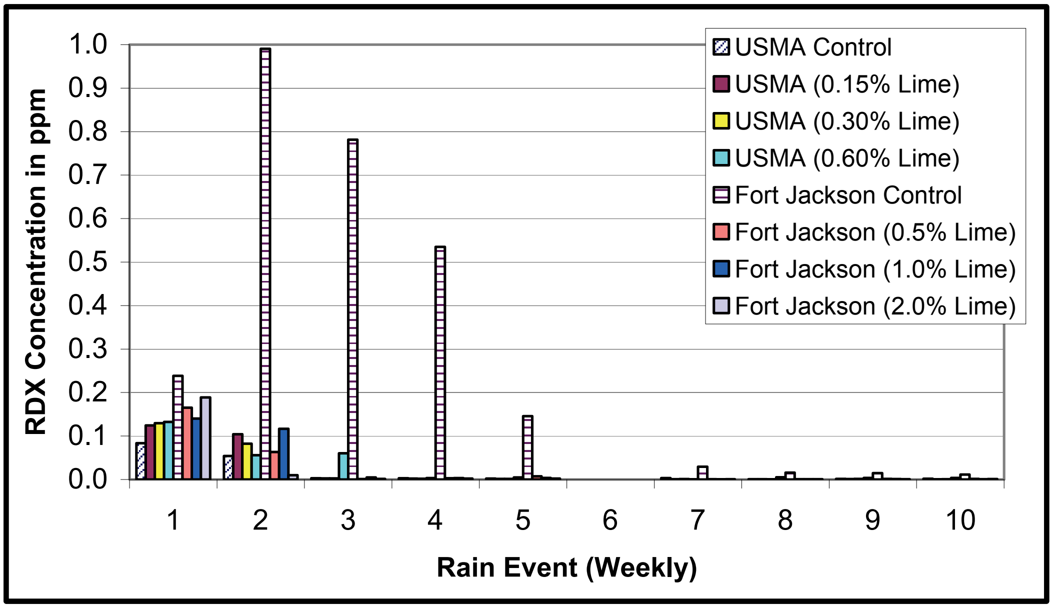

Figure 6. Lysimeter Study I - RDX leachate concentrations per rain event.

In Lysimeter Study II, the initial RDX concentrations for the control, 0.83 percent lime amendment, and 1.66 percent lime amendment were 1.94, 1.96, and 3.46 mg/kg, respectively. During the second lysimeter study, one quarter of the total rainfall was used during each rain event or 11.6 L. The reduced rainfall amount slowed the RDX dissolution rate and increased the retention time of the RDX within the lysimeter cell. This allowed a distinction between the transformation of RDX by alkaline hydrolysis and removal by simple dissolution that was not clearly observed during the first lysimeter study (Figure 6). By week two, the reduction was greater than 90 percent in the RDX concentration in the leachate from the two limed cells compared with the control cell (Figure 7). RDX was noted in the leachate from the limed cells using an SPE procedure, for which the detection limits are lower. The small amount of RDX in the leachate is probably due to the slow dissolution of large composition B particles.

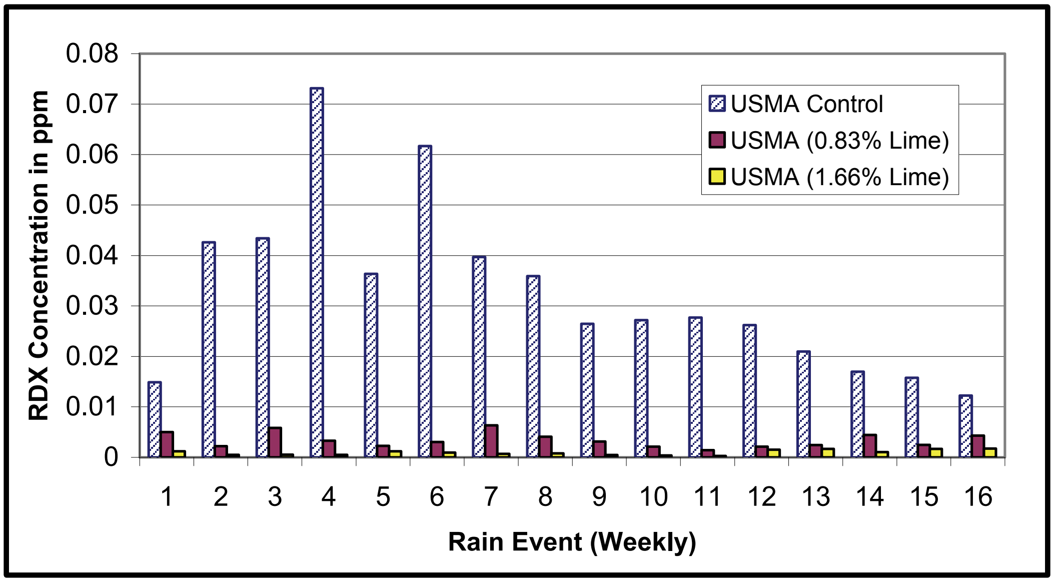

Figure 7. Lysimeter Study II - RDX leachate concentration per rain event.

There was a significant decrease in the amount of RDX leaving the lysimeter cells as leachate from the Fort Jackson limed cells (Table 7). For the Fort Jackson soil, reduction in RDX leaving as leachate from the 1 and 2 percent lime treatment was a greater than 90 percent compared with the untreated cell. The reduced RDX concentration in the leachate from the limed cells indicates that RDX was transformed by alkaline hydrolysis and was no longer available to be leached from the soil as RDX.

For the native USMA soil in Lysimeter Study I, the RDX concentration in the leachate was similar for the untreated and limed cells. This similarity may have been due to the low initial RDX concentration in the native USMA soil, the large volume of water flushing the RDX out of the soil, and/or an insufficient lime dosage level. These possibilities were addressed in Lysimeter Study II, where the USMA soil was amended with hand grenade residue containing composition B, a decreased volume of RO water was applied as artificial rainfall, and an increased lime dosage was used. The USMA soil limed cells using the grenade residue containing composition B showed a greater that 90 percent reduction as compared with the untreated cell under both lime treatments (Table 8).

Table 7. Lysimeter Study I – soluble RDX in leachate (highlighted cells met objective).

Lysimeter Cell Treatment	Mass of Soluble RDX Leaving Cell as Leachate[1] (mg)	% RDX Reduction Compared with Control Cell
USMA control (no lime)	3.70	n.a.[3]
USMA 0.15% lime (1/2x lime dose)	5.43	n.a.
USMA 0.30% lime (1x lime dose)	<5.17[2]	n.a.
USMA 0.60% lime (2x lime dose)	<5.69	n.a.
Fort Jackson control (no lime)	63.14	n.a.
Fort Jackson 0.50% lime (1/2x lime dose)	6.57	89.59
Fort Jackson 1.00% lime (1x lime dose)	6.05	90.42
Fort Jackson 2.00% lime (2x lime dose)	4.79	92.41

[1] Total mass based on concentration of RDX in leachate and the volume of leachate collected per rain event over 10 rain events.

[2] Reporting limit of 0.0005 mg/L used in calculations.

[3] n.a. = not applicable.

Table 8. Lysimeter Study II – soluble RDX in leachate (highlighted cells met objective).

Lysimeter Cell Treatment	Mass of Soluble RDX Leaving Cell as Leachate[1] (mg)	% RDX Reduction Compared with Control Cell
USMA control	2.91	n.a.
USMA 0.83% lime (2x lime dose)	0.28	90.38
USMA 1.66% lime (4x lime dose)	0.08	97.25

[1] Total mass based on concentration of RDX in leachate and the volume of leachate collected per rain event over 16 rain events.

2. Reduce explosives concentrations by greater than 90 percent in the surface water runoff from the lysimeter based on baseline and control concentrations.

By the third rain event of Lysimeter Study I, the RDX concentration was reduced by 90 percent (compared with the initial RDX concentration), leaving as runoff from all eight cells (Figure 8). A slight increase occurred in the runoff RDX concentration for rain event #9 due to the disturbance of the surface soil when soil core samples were collected after rain event #8.

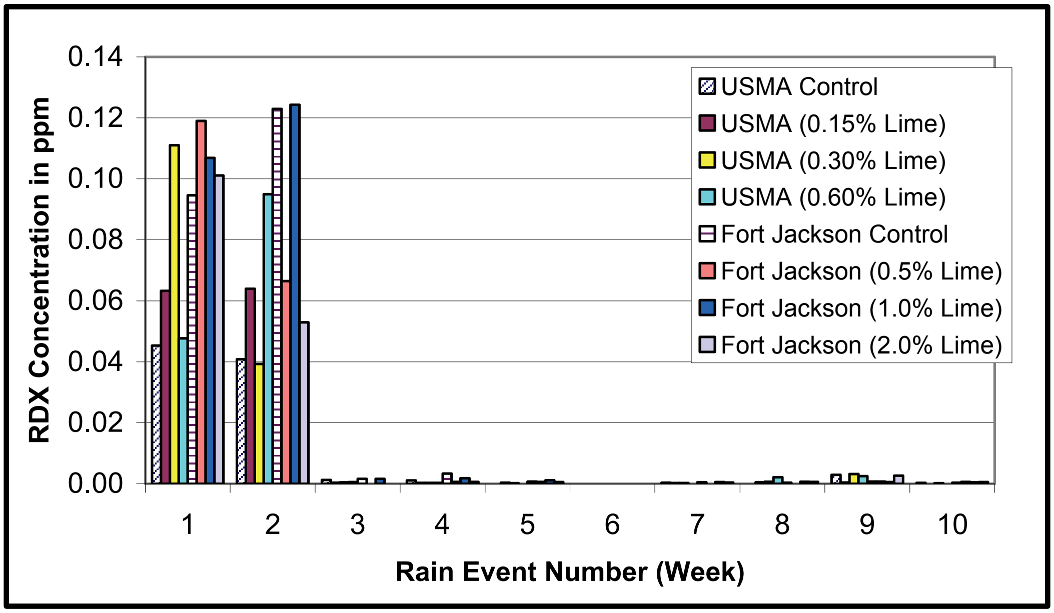

Figure 8. Lysimeter Study I - RDX runoff concentrations per rain event.

The second lysimeter study used a reduced rainfall amount (by 75 percent) and hand grenade residue containing composition B added to the USMA HGR soil in order to clarify results from the first study. The decreased rainfall established conditions that reduced the total RDX dissolution and increased the RDX retention time within the lysimeter cell. The RDX concentration in the runoff was reduced by greater than 90 percent compared with the control cell by week 2 in the 1.66 percent (w:w) lime-treated cell (Figure 9). The RDX concentrations in the runoff fluctuated in all three cells during the test, which could be associated with the decreased rainfall on the cells. Similar to the leachate results, there was a slow release of RDX into the runoff. This extended release likely is due to the increased RDX loading coupled with a lower level of flushing (rain).

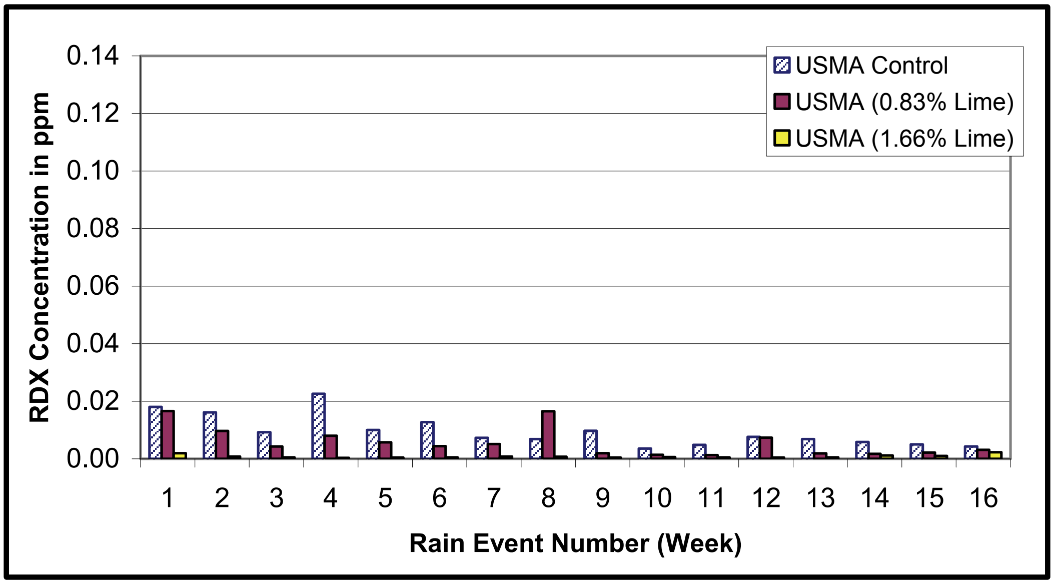

Figure 9. Lysimeter Study II - RDX runoff concentrations per rain event.

In the first lysimeter study, the total mass of RDX in the surface water runoff was less than that in the control for two of the Fort Jackson limed cells (Table 9). During the second lysimeter study, the total mass of RDX was

Table 9. Lysimeter Study I – soluble RDX in runoff.

Lysimeter Cell	Mass of Soluble RDX Leaving Cell as Runoff[1] (mg)	% RDX Reduction Compared with Control Cell
USMA control (no lime)	<1.84[2]	n.a.
USMA 0.15% lime (1/2x lime dose)	<2.80	n.a.
USMA 0.30% lime (1x lime dose)	3.25	n.a.
USMA 0.60% lime (2x lime dose)	<3.32	n.a.
Fort Jackson control (no lime)	4.61	n.a.
Fort Jackson 0.50% lime (1/2x lime dose)	<3.42	>26
Fort Jackson 1.00% lime (1x lime dose)	4.91	n.a.
Fort Jackson 2.00% lime (2x lime dose)	<3.53	>23

[1] Total mass based on concentration of RDX in leachate and the volume of leachate collected per rain event over 10 rain events.

[2] Reporting limit of 0.0005 mg/L used in calculation.

reduced by greater than 90 percent in runoff for the USMA cell with the 1.66 percent (4× lime dose) lime treatment (Table 10). These results indicate that treatment goals (>90 percent reduction) can be realized when sufficient lime is applied.

Table 10. Lysimeter Study II – soluble RDX in runoff (highlighted cells met objective).

Lysimeter Cell	Mass of RDX Leaving Cell as Runoff[1] (mg)	% RDX Reduction Compared with Control Cell
USMA control	0.57	n.a.
USMA 0.83% lime (2x lime dose)	0.30	47.37
USMA 1.66% lime (4x lime dose)	<0.04[2]	>92.98

[1] Total mass based on concentration of RDX in runoff and the volume of runoff collected per rain event over 16 rain events.

[2] Reporting limit of 0.0005 mg/L used in calculations.

3. Demonstrate no significant increase in metals migration in the pore water leaching from the lysimeter based on baseline and control area concentrations.

The hand grenade shell consists primarily of Fe, Zn, and other trace metals. Filtered and total digest leachate samples were analyzed using the ICP for 11 metals (Zn, Fe, Mn, Ca, Pb, Cr, Cu, Ni, Mb, V, and Sn). Four of these metals (Zn, Fe, Mn, and Ca) were consistently above the RL of 0.050 mg/L. Tables 11 and 12 summarize the total mass of metals lost as leachate from the lysimeter cells over the course of Lysimeter Studies I and II, respectively. Lysimeter Study I statistical analysis indicates that Zn and Mn concentrations were significantly greater than the RL (Appendix B). Digested lead concentrations were determined to be significantly greater than the RL during the first few rain events, but then fell below that RL (Appendix B). The tables also include the mass of TSS present in the leachate. TSS was tracked because suspended solids can be indicative of metals loss in particulate form or of metals bound to suspended solids. The TSS data were inconclusive from both lysimeter studies.

Calcium was analyzed to track the presence of the hydrated lime that was added to the lysimeter cells. The total mass of Ca leaving the USMA control cells as leachate was higher than that leaving the limed cells in both studies. This result was in spite of the fact that Ca had been added to the treated cells in the form of hydrated lime (Tables 11 and 12). In contrast, the Fort Jackson cells did not display the same trend because the USMA HGR topsoil has a higher Ca concentration than the Fort Jackson soil (Table 5). The low Ca concentrations in the leachate were attributed to the reaction of the lime with some of the metals in solution. Another Ca sink in the lysimeter cells is the common practice in water softening of adding hydrated lime to water in order to precipitate out carbonate hardness (calcium and magnesium bicarbonate) as calcium carbonate ($CaCO_3$) (Viessman and Hammer 1998).

In general, the total mass of metals leached from the treated cells was not significantly greater than the mass leached from the control cell. As expected, in most cases the control cell actually released more total mass of metals than the treated cells. The filtered metals concentrations were generally low, typically at or below the RL of 0.050 mg/L. Therefore, the overall results demonstrate that metals migration did not significantly increase in the pore water leaching from the lysimeters.

Table 11. TSS and total mass of metals leaving cells in leachate during Lysimeter Study I (highlighted cells met objective).

Cell Leachate	TSS (mg)	Zinc (mg)	Iron (mg)	Manganese (mg)	Calcium (mg)
USMA control (no lime)	538	<41[1]	2227	<91	4776
USMA 0.15% lime (1/2x lime dose)	289	<22	1165	<42	2822
USMA 0.30% lime (1x lime dose)	367	<29	1429	<58	3316
USMA 0.60% lime (2x lime dose)	102	<21	495	<20	3796
Fort Jackson control (no lime)	283	115	539	<27	1899
Fort Jackson 0.50% lime (1/2x lime dose)	215	<30	<498	<27	23,449
Fort Jackson 1.00% lime (1x lime dose)	264	<20	<420	<29	28,410
Fort Jackson 2.00% lime (2x lime dose)	249	<22	<309	<27	52,641

[1] Reporting limit used in calculations.

Table 12. TSS and total mass of metals leaving cells in leachate during Lysimeter Study II (highlighted cells met objective).

Cell Treatment	TSS (mg)	Zinc (mg)	Iron (mg)	Manganese (mg)	Calcium (mg)
USMA control (no lime)	109	<10[1]	<253	<11	4,557
USMA 0.83% lime (2x lime dose)	273	<7	<284	<12	4,000
USMA 1.66% lime (4x lime dose)	148	<6	<262	<8	3,342

[1] Reporting limit used in calculations.

4. Demonstrate no significant increase in metals migration in the surface water running from the lysimeter based on baseline and control area concentrations.

A total digest analysis was performed on the runoff samples to determine the total metals being transported as runoff from the cell. The digested samples were analyzed for 11 metals (Zn, Fe, Mn, Ca, Pb, Cr, Cu, Ni, Mb, V, and Sn) using the ICP. Tables 13 and 14 summarize the total mass of metals lost as runoff from the lysimeter cells during Lysimeter Studies I and II, respectively. Tables 13 and 14 also include the mass of TSS present in the runoff. Of the 11 metals analyzed, only 4 metals (Zn, Fe, MN, and Ca) displayed consistent concentrations above the RL of 0.050 mg/L. Statistical analysis indicated that Zn and Mn concentrations were significantly greater than the RL during Lysimeter Study I (Appendix B). Digested Pb concentrations were determined to be significantly greater than the RL during the first few rain events, but then fell below that RL (Appendix B).

In general, the total mass of metals in the runoff from the treated cells was not significantly greater than from the control cell. In most cases, the control cell released more total metals than the treated cells, with the exception of increased Ca from the treated cells. This result is attributed to the fact that the lime had not reacted with available surface metals to form carbonates as it did in the leachates.

Table 13. TSS and total mass of metals leaving treatment cells as runoff over 16 rain events during Lysimeter Study I (highlighted cells met objective).

Cell Leachate	TSS (mg)	Zinc (mg)	Iron (mg)	Manganese (mg)	Calcium (mg)
USMA control (no lime)	507	<53[1]	2,693	<131	1,594
USMA 0.15% lime (1/2x lime dose)	514	<52	2,680	<128	2,143
USMA 0.30% lime (1x lime dose)	541	<46	2,278	<108	2,788
USMA 0.60% lime (2x lime dose)	653	<52	2,731	<130	4,858
Fort Jackson control (no lime)	945	571	<1,746	<17	<107
Fort Jackson 0.50% lime (1/2x lime dose)	644	376	1,303	<16	789
Fort Jackson 1.00% lime (1x lime dose)	715	393	1,458	<17	2,403
Fort Jackson 2.00% lime (2x lime dose)	373	196	610	<17	2,879

[1] Reporting limit value used in calculations.

Table 14. TSS and total mass of metals leaving the treatment cell as runoff over 16 rain events during Lysimeter Study II (highlighted cells met objective).

Cell Leachate	TSS (mg)	Zinc (mg)	Iron (mg)	Manganese (mg)	Calcium (mg)
USMA[1] control (no lime)	6,515	<1,353[1]	<3,800	<202	2,941
USMA 0.83% lime (2x lime dose)	5,982	<77	<2,351	<126	5,082
USMA 1.66% lime (4x lime dose)	467	<9	<276	<13	1,088

[1] Reporting limit value used in calculations.

5. Assess the overall effectiveness and potential side effects of the lime amendment technology by determining if pH was maintained above 10.5 at the source area and below 9.5 outside the source area.

Soil. During Lysimeter Study II, the initial USMA HGR soil pH was determined to be approximately 8.5 (Table 4). The soil pH in the untreated soil increased slightly after the 8th rain event, then decreased after the 16th rain event during Lysimeter Study II. The soil pH levels of the two treated cells in that study were well above the treatment goal (pH 10.5), as shown in Table 15. This result indicates that this type of lime application could be an effective technique for range management of munitions constituents.

Table 15. Lysimeter Study II soil. The highlighted cells met the elevated pH objective for the treatment zone.

	Soil pH		
Soil / Cell	Initial	8th rain event (n=9)	16th rain event (n=3)
USMA control (no lime)	8.56	9.02	8.26
USMA (0.83% lime)		10.98	10.88
USMA (1.66% lime)		11.98	11.61

Leachate. Leachate pH measurements were recorded during both lysimeter studies. The average leachate pH was below the study goal (9.5) for all cells during Lysimeter Study I except the USMA with 0.60 percent (w:w) lime and the limed Fort Jackson cells (Figure 10). In Lysimeter Study II, the average leachate pH levels for all three cells were also below the study goal of 9.5 (Figure 11). These results imply that lime application sufficient to treat the explosives residue does not result in extremely elevated pH levels in waters leaching from some treated sites, so increased leachate pH is site- and soil-dependent.

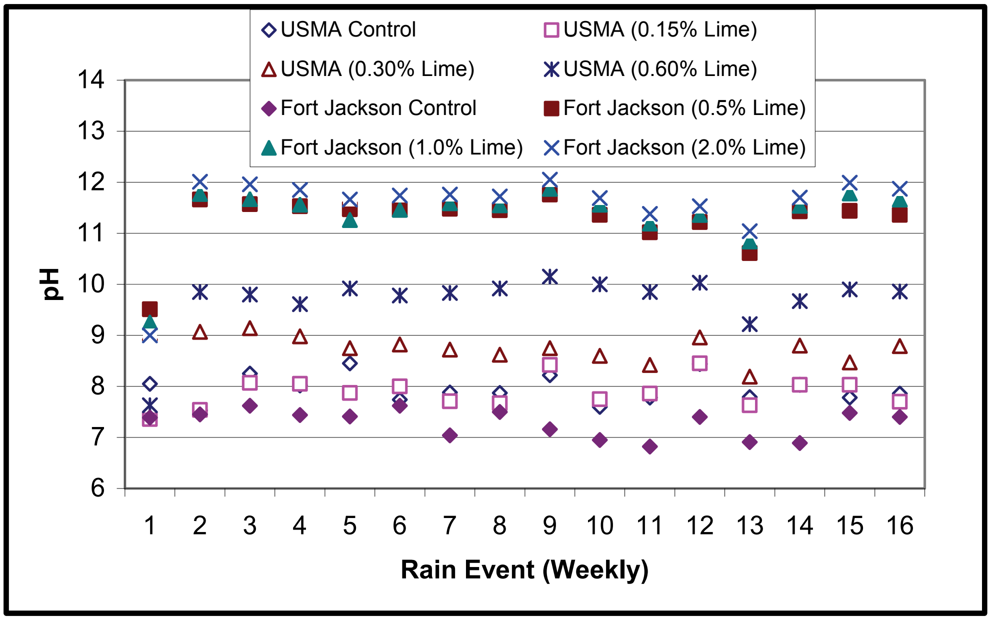

Figure 10. Lysimeter Study I – weekly leachate pH.

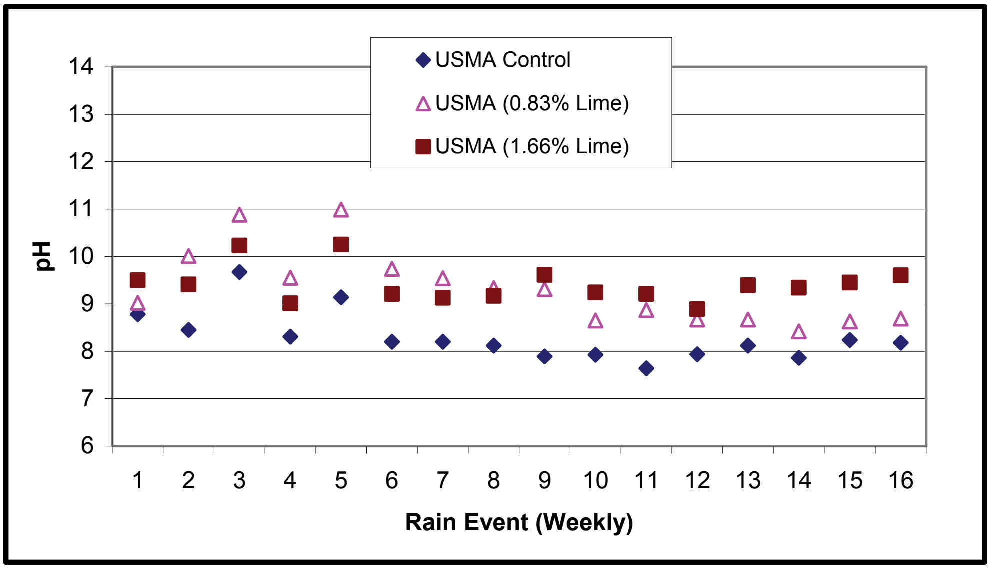

Figure 11. Lysimeter Study II – weekly leachate pH.

Runoff. The pH of lysimeter cell runoff was recorded weekly. The runoff pH during Lysimeter Study I averaged 9.5 or less for all cells except for the 0.60 percent lime (w:w) USMA cell, and the 1 and 2 percent lime (w:w) Fort Jackson cells, as shown in Figure 12. Runoff from USMA soil treated with 0.60 percent lime averaged a pH of 9.51 while the runoff for the Fort Jackson 1 and 2 percent (w:w) lime averaged a pH of 9.60 and 9.69 respectively. In Lysimeter Study II, all three average runoff pH levels were below 9.5 (Figure 13). Under natural conditions, runoff water chemistry is

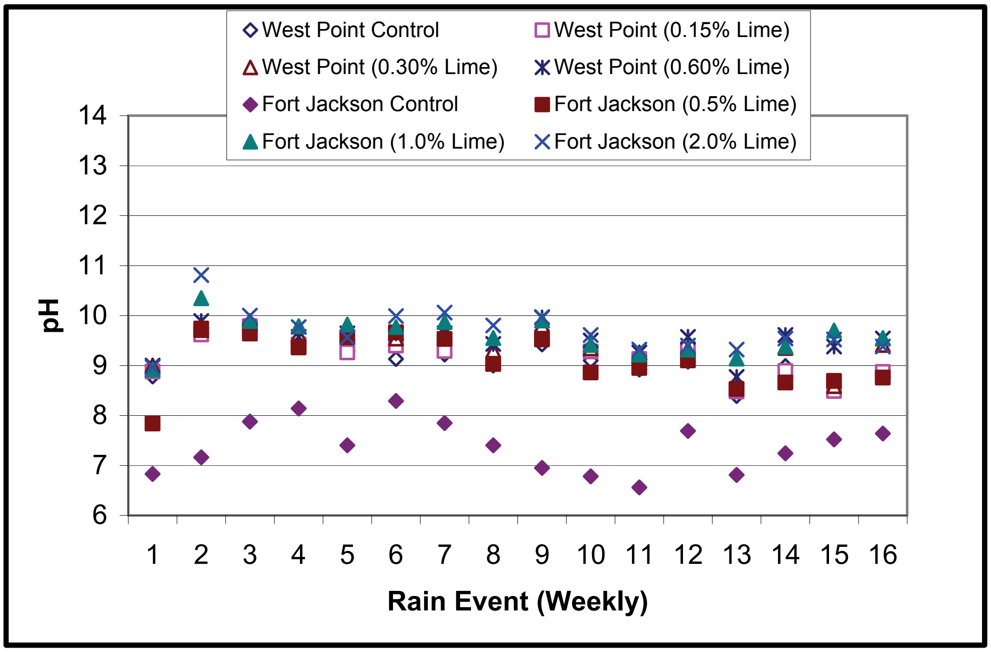

Figure 12. Lysimeter Study I – weekly runoff pH.

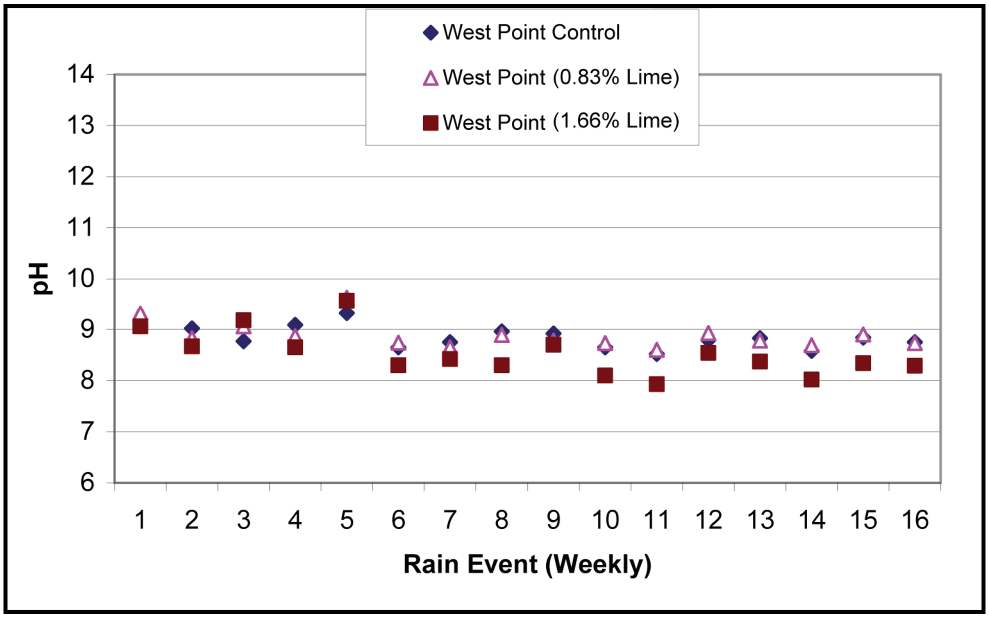

Figure 13. Lysimeter Study II – weekly runoff pH.

modified by the soil as it passes over it, thus typically allowing the runoff to take on the soil's near-surface pH characteristics. These results indicate that, for the experimental conditions considered (e.g., rainfall rate, slope, soil condition), lime application would not result in elevated pH levels in runoff water from treated areas, which otherwise might affect surface waters offsite.

The results from these studies indicate that the source zone soil pH can achieve the desired treatment pH level of 10.5. The pH levels of the leachate and runoff water can be held below 9.5 if lime is not applied in excessive amounts. This represents the water that could potentially enter a surrounding watershed from a treated site. The leachate and runoff from this study were collected directly from the source, so no natural buffering of the solution occurred that would occur in a watershed with the surrounding soils and atmospheric conditions. As previously stated, the water leaving the amended areas on the range will also move through or over unamended soils and further ameliorate the pH. The pH of the water leaving the amended areas will also be decreased when it is mixed with surface and subsurface water from un-amended areas. All of these factors work together to suggest that lime addition is an effective treatment for munitions constituents on grenade ranges and that it may not pose adverse side effects.

Site-specific conditions will influence the buffering capacity at each treatment area. The rainfall at USMA typically is acidic, with a pH range of 3.87 to 5.85 based on 2001 precipitation data (Munson 2001). This acidic rain will tend to buffer the pH of the surface and subsurface drainage from treated sites. Field measurements of surface and subsurface water pH taken in September and October 2005 at the USMA grenade range showed modest variation. Surface water pH levels varied from 6.84 to 8.75 and subsurface water pH levels ranged from 5.71 to 7.70. These pH levels are less than the pH measurements of the control cell observed in this study and support the potential buffering characteristics of the natural precipitation at that site.

The soil conditions, range maintenance, and range usage conditions will dictate the lime application amount and rate at each potential site. No environmentally adverse effects are expected to occur as a result of lime application to grenade range impact areas based on the criteria stated above (<pH 9.5).

5 Summary and Conclusions

Summary

Effective management of metals and explosives on HGRs requires an understanding of the natural and engineered processes controlling their fate and transport at these sites. Metals and explosives releases from these impact areas occur through a variety of mechanisms, such as transport following soil erosion caused by rain events. Explosives and metals can also be transported through leaching and surface water runoff. The surface water runoff may contain soluble explosives and metals associated with the suspended and/or colloidal fractions. These mechanisms can result in soluble and particulate contaminant releases from impact areas.

The objectives of this study were to evaluate and develop a management technology to control active HGR contaminant mobility and promote on-site contaminant degradation. Hydrated lime was tested for its ability to transform explosives and stabilize metals in HGR soils collected from USMA (West Point, NY) and Fort Jackson, SC. Two lysimeter studies were conducted using the HGR soils with different lime applications. Lysimeter Study I used native HGR soils with an annual rainfall equivalent of 119.4 cm per year. Lysimeter Study II used HGR soil amended with additional hand grenade residue containing composition B, an annual rainfall equivalent of 29.8 cm per year, and increased lime addition to the treated cells. The decreased rainfall amount in Lysimeter Study II was used primarily to reduce the washout effects associated with the larger rainfall volume of Lysimeter Study I.

One goal of this research was to evaluate and develop a technology that could be used to manage munitions constituents on ranges by transforming or degrading explosives. Another goal was to use this same technology to permanently reduce the amount of total metals (dissolved and particulate) leaving the impact area. The results of this study indicate that hydrated lime amendment to HGR soils was effective in achieving these goals, specifically:

1. *Reduced RDX leaving as leachate.* The leachate RDX concentrations leaving the source area were reduced more than 90 percent when the appropriate amount of lime was added.

2. *Reduced RDX leaving as runoff.* The runoff RDX concentration leaving was reduced by more than 90 percent when the appropriate amount of lime was added.
3. *Stabilized metals in soil.* The total metals concentrations in the leachate were generally less than or not significantly greater than the metals in the control cell.
4. *Stabilized metals on soil surface.* The total metals in the runoff of the lime-treated cells was generally less than or not significantly greater than the metals leaving the control cell.
5. *Effective treatment with minimal side effects.* The soil pH was maintained within the treatment zone at greater than the desired 10.5, while surface and subsurface water pH leaving the source zone were controlled below the desired maximum pH of 9.5.

All of the treatment goals for this study were met. Together, these results indicate that lime addition can be an effective treatment for munitions constituents on ranges, and this method does not appear to pose adverse side effects to the surrounding area if properly applied and monitored.

Conclusions

The application of hydrated lime appears to be a useful technology to manage explosives on HGRs. Under experimental conditions, the alkaline hydrolysis degraded the explosives before they left the top 15.24 cm of treated HGR soils. Lime application as a range management technology is currently being demonstrated at the Fort Jackson HGR and is scheduled to be conducted at the USMA HGR. Fort Jackson provides a high optempo or high usage training range to evaluate the technology, while USMA will provide a low optempo training range.

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Appendix A: Bench Scale and Treatability Study Results

pH column study

Table A1. Leachate pH from column study.

480 mL per Wetting Event (equivalent to 1/4 annual rain fall per wetting event)	pH		
	Column #1	Column #2	Column #3
	Top 15.24 cm	Middle 15.24 cm [equilibrated pH[1]]	Bottom 15.24 cm
1	8.45	5.03	5.75
2	12.24	4.84	6.00
3	12.33	6.15	5.78
4	12.26	7.51	5.94
5	11.69	8.84	5.53
6	11.58	8.92	5.63
7	11.27	9.39	6.10
8	11.58	8.64	6.64
9	11.38	8.67	6.34
10	11.18	9.06	6.59
11	11.03	9.6 [8.17][1]	7.45[3]
12	11.2	9.42 [8.52][1]	7.15[3]
Average (n=12) [n=2]	11.35	8.01 [8.35][2]	6.24
std dev	1.02	1.72 [0.25]	0.61

[1] Allowed to equilibrate with the atmosphere for 3 days after collected from column #2.

[2] Average of equilibrated leachate.

[3] After equilibrating with atmosphere poured into column #3.

Mesoscale Lysimeter Studies I and II

RDX in leachate and runoff

Table A2. RDX leaving as filtered leachate and runoff in Lysimeter Study I.

HGR Soil in Lysimeter Cell	Water Type	Weekly Reported Concentration of RDX in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	std
USMA Control	Leachate	0.0835	0.0542	0.0030	0.0029	0.0021	n.d.[2].	0.0033	0.0007	0.0014	0.0017	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0153	0.0291
USMA (0.15%)		0.1243	0.1043	0.0026	0.0022	0.0016	n.d.	0.0007	0.0006	0.0010	0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0238	0.0479
USMA (0.30%)		0.1294	0.0823	0.0024	0.0019	0.0015	n.d.	0.0010	<0.0005	0.0014	0.0009	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0221	0.0455
USMA (0.60%)		0.1326	0.0561	0.0604	0.0032	0.0046	n.d.	<0.0005	0.0050	0.0037	0.0038	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0270	0.0437
Fort Jackson Control		0.2384	0.9905	0.7814	0.5351	0.1458	n.d.	0.0295	0.0160	0.0149	0.0116	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.2763	0.3642
Fort Jackson (0.5%)		0.1652	0.0632	0.0012	0.0029	0.0074	n.d.	0.0006	0.0009	0.0016	0.0016	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0245	0.0531
Fort Jackson (1.0%)		0.1401	0.1167	0.0047	0.0032	0.0036	n.d.	<0.0005	0.0008	0.0010	0.0007	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0271	0.0537
Fort Jackson (2.0%)		0.1889	0.0100	0.0013	0.0024	0.0023	n.d.	0.0006	0.0008	0.0008	0.0009	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0208	0.0591
USMA Control	Runoff	0.0453	0.0408	0.0013	0.0011	<0.0005	n.d.	<0.0005	<0.0005	0.0030	<0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0093	0.0178
USMA (0.15%)		0.0633	0.0640	0.0003	<0.0005	<0.0005	n.d.	<0.0005	0.0005	<0.0005	<0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0131	0.0267
USMA (0.30%)		0.1110	0.0393	0.0005	<0.0005	<0.0005	n.d.	<0.0005	0.0007	0.0032	<0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0157	0.0356
USMA (0.60%)		0.0477	0.0950	0.0006	<0.0005	<0.0005	n.d.	<0.0005	0.0021	0.0025	<0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0150	0.0317
Fort Jackson Control		0.0946	0.1229	0.0016	0.0034	0.0008	n.d.	0.0005	<0.0005	0.0007	<0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0225	0.0459
Fort Jackson (0.5%)		0.1190	0.0665	<0.0005[1]	0.0006	0.0006	n.d.	<0.0005	<0.0005	0.0007	0.0006	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0190	0.0408
Fort Jackson (1.0%)		0.1069	0.1243	0.0016	0.0018	0.0012	n.d.	0.0006	0.0007	0.0006	0.0005	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0238	0.0486
Fort Jackson (2.0%)		0.1011	0.0529	<0.0005	0.0006	0.0006	n.d.	<0.0005	0.0006	0.0026	0.0006	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.0160	0.0341

1 IDL for RDX.

2 n.d. = not determined.

Table A3. RDX leaving as extracted (8330) leachate and runoff in Lysimeter Study I.

HGR Soil in Lysimeter Cell	Water Type	Weekly Reported Concentration of RDX in mg/L			
		1	2	Avg	Std
USMA Control	Leachate	0.0939	0.1220	0.1080	0.0199
USMA (0.15% Lime)		0.1361	0.0881	0.1121	0.0339
USMA (0.30% Lime)		0.1579	0.0641	0.1110	0.0663
USMA (0.60% Lime)		0.2268	0.0939	0.1604	0.0940
Fort Jackson Control		0.3154	1.0493	0.6824	0.5189
Fort Jackson (0.5% Lime)		0.1201	0.0100	0.0651	0.0779
Fort Jackson (1.0% Lime)		0.2390	0.0389	0.1390	0.1415
Fort Jackson (2.0% Lime)		0.1309	0.0100	0.0705	0.0855
USMA Control	Runoff	0.1129	0.0426	0.0778	0.0497
USMA (0.15% Lime)		0.0568	0.0269	0.0419	0.0211
USMA (0.30% Lime)		0.0575	0.0582	0.0579	0.0005
USMA (0.60% Lime)		0.0919	0.0400	0.0660	0.0367
Fort Jackson Control		0.0762	0.0577	0.0670	0.0131
Fort Jackson (0.5% Lime)		0.0781	0.0455	0.0618	0.0231
Fort Jackson (1.0% Lime)		0.1466	0.0375	0.0921	0.0771
Fort Jackson (2.0% Lime)		0.0725	0.0141	0.0433	0.0413

Table A4. RDX leaving as filtered leachate and runoff in Lysimeter Study II.

HGR Soil in Lysimeter Cell	Water Type	Weekly Reported Concentration of RDX in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.0149	0.0426	0.0434	0.0732	0.0364	0.0617	0.0397	0.0359	0.0265	0.0272	0.0277	0.0262	0.0210	0.0170	0.0158	0.0122	0.0326	0.0169
USMA (0.83%)		0.0050	0.0022	0.0058	0.0033	0.0023	0.0030	0.0063	0.0041	0.0031	0.0021	0.0014	0.0021	0.0024	0.0044	0.0025	0.0043	0.0034	0.0014
USMA (1.66%)		0.0012	0.0005	0.0006	0.0005	0.0012	0.0010	0.0007	0.0008	0.0005	0.0004	0.0003	0.0015	0.0017	0.0010	0.0017	0.0017	0.0010	0.0005
USMA Control	Runoff	0.0181	0.0161	0.0092	0.0226	0.0100	0.0127	0.0073	0.0068	0.0097	0.0036	0.0048	0.0076	0.0068	0.0059	0.0050	0.0043	0.0094	0.0054
USMA (0.83%)		0.0165	0.0097	0.0043	0.0080	0.0057	0.0044	0.0051	0.0165	0.0019	0.0014	0.0013	0.0073	0.0019	0.0017	0.0022	0.0031	0.0057	0.0049
USMA (1.66%)		0.0019	0.0008	<0.0005[1]	<0.0005	0.0005	<0.0005	0.0008	0.0007	<0.0005	0.0006	<0.0005	0.0005	<0.0005	0.0012	0.0010	0.0023	0.0008	0.0005

[1] IDL for RDX.

Table A5. RDX leaving as extracted (8330) leachate and runoff in Lysimeter Study II.

HGR Soil in Lysimeter Cell	Water Type	Weekly Reported Concentration of RDX in mg/L				
		1	2	3	Avg	std
USMA Control	Leachate	0.78	0.09	<0.01	0.29	0.42
USMA (0.83%)		0.67	<0.01[1]	<0.01	0.23	0.38
USMA (1.66%)		0.55	<0.01	0.05	0.20	0.30
USMA Control	Runoff	0.68	0.05	<0.01	0.24	0.37
USMA (0.83%)		0.83	<0.01	<0.01	0.28	0.47
USMA (1.66%)		0.74	<0.01	<0.01	0.25	0.42

[1] IDL for RDX (8330)

RDX concentration in homogenized soil

Table A6. Lysimeter Study I RDX concentration in USMA HGR soil after homogenization.

Sample ID		UV_VIS_1 (Retention Time)	UV_VIS_1 (mg/L)	Conversion Factor	RDX (mg/kg)	Avg RDX (mg/kg)	Std
USMA West Point 1A	REP 1	5.20	0.2023	5	1.010	0.869	0.412
	REP 2	5.23	0.1678		0.838		
	REP 3	5.28	0.2543		1.270		
USMA West Point 1B	REP 1	5.22	0.1847	5	0.922		
	REP 2	5.34	0.1923		0.961		
	REP 3	5.30	0.2382		1.191		
USMA West Point 1C	REP 1	5.33	0.1499	5	0.748		
	REP 2	5.26	0.2723		1.361		
	REP 3	5.26	0.3832		1.915		
USMA West Point 2A	REP 1	5.17	0.1448	5	0.723		
	REP 2	5.29	0.1862		0.931		
	REP 3	5.23	0.0887		0.443		
USMA West Point 2B	REP 1	5.19	0.1242	5	0.620		
	REP 2	5.21	0.1479		0.739		
	REP 3	5.20	0.1917		0.957		
USMA West Point 2C	REP 1	5.26	0.0835	5	0.417		
	REP 2	5.26	0.0601		0.300		
	REP 3	5.26	0.1280		0.639		
USMA West Point 3A	REP 1	5.26	0.3810	5	1.903		
	REP 2	5.26	0.1008		0.504		
	REP 3	5.24	0.0587		0.293		
USMA West Point 3B	REP 1	5.25	0.1137	5	0.568		
	REP 2	5.21	0.1151		0.575		
	REP 3	5.20	0.2432		1.215		
USMA West Point 3C	REP 1	5.21	0.1691	5	0.845		
	REP 2	5.19	0.1911		0.954		
	REP 3	5.26	0.1267		0.633		

Table A7. Lysimeter Study I RDX concentration in Fort Jackson HGR soil after homogenization.

Sample ID		UV_VIS_1 (Retention Time)	UV_VIS_1 (mg/L)	Conversion Factor	RDX (mg/kg)	Avg RDX (mg/kg)	Std
Fort Jackson 1A	REP 1	5.22	0.3271	5	1.633	2.375	0.975
	REP 2	5.21	0.3114		1.556		
	REP 3	5.22	0.3944		1.972		
Fort Jackson 1B	REP 1	5.23	0.5191	5	2.592		
	REP 2	5.22	0.5872		2.935		
	REP 3	5.21	0.7951		3.971		
Fort Jackson 1C	REP 1	5.22	0.2462	5	1.230		
	REP 2	5.22	0.8012		4.001		
	REP 3	5.22	0.7073		3.535		
Fort Jackson 2A	REP 1	5.23	0.4101	5	2.050		
	REP 2	5.21	0.4081		2.040		
	REP 3	5.21	0.3363		1.681		
Fort Jackson 2B	REP 1	5.21	0.7236	5	3.617		
	REP 2	5.21	0.6279		3.135		
	REP 3	5.22	0.4842		2.417		
Fort Jackson 2C	REP 1	5.22	0.4221	5	2.107		
	REP 2	5.22	0.3669		1.831		
	REP 3	5.21	0.4340		2.169		
Fort Jackson 3A	REP 1	5.22	0.2160	5	1.080		
	REP 2	5.21	0.4442		2.217		
	REP 3	5.21	0.5162		2.581		
Fort Jackson 3B	REP 1	5.21	0.5084	5	2.539		
	REP 2	5.19	0.4812		2.401		
	REP 3	5.20	0.2779		1.389		
Fort Jackson 3C	REP 1	5.20	0.2182	5	1.090		
	REP 2	5.22	0.2828		1.412		
	REP 3	5.20	0.9886		4.938		

Table A8. Lysimeter Study II RDX conc. in USMA HGR soil plus residue after homogenization.

Sample ID		UV_VIS_1 (mg/L)	Conversion Factor	RDX (mg/kg)	Cell Avg (mg/kg)	Std
USMA Control A	Rep 1	0.8990	5	4.495	1.944	1.368
	Rep 2	0.2849		1.425		
	Rep 3	0.4243		2.122		
USMA Control B	Rep 1	0.1871	5	0.936		
	Rep 2	0.3476		1.738		
	Rep 3	0.2189		1.095		
USMA Control C	Rep 1	0.5222	5	2.611		
	Rep 2	0.8867		4.434		
	Rep 3	0.1585		0.793		
USMA Control D	Rep 1	0.1979	5	0.990		
	Rep 2	0.4883		2.442		
	Rep 3	0.0500		0.250		
USMA (0.83%) A	Rep 1	0.2493	5	1.247	1.959	2.687
	Rep 2	1.4629		7.315		
	Rep 3	0.3199		1.600		
USMA (0.83%) B	Rep 1	0.1691	5	0.846		
	Rep 2	0.1706		0.853		
	Rep 3	1.5573		7.787		
USMA (0.83%) C[1]	Rep 1	0.0870	5	0.435		
	Rep 2	0.0047		0.023		
	Rep 3	<0.0100[2]		0.050		
USMA (0.83%) D[1]	Rep 1	0.0641	5	0.321		
	Rep 2	0.4367		2.184		
	Rep 3	0.1690		0.845		
USMA (1.66%) A	Rep 1	0.4402	5	2.201	3.456	1.123
	Rep 2	0.5349		2.675		
	Rep 3	0.2959		1.480		
USMA (1.66%) B	Rep 1	0.4168	5	2.084		
	Rep 2	0.6812		3.406		
	Rep 3	0.9143		4.572		
USMA (1.66%) C	Rep 1	0.8520	5	4.260		
	Rep 2	0.6518		3.259		
	Rep 3	0.8968		4.484		
USMA (1.66%) D	Rep 1	0.7928	5	3.964		
	Rep 2	0.8322		4.161		
	Rep 3	0.9846		4.923		

[1] 8330 conducted after lime addition.

[2] IDL for RDX used.

Table A9. Lysimeter Study II RDX concentration comparisons.

HGR Soil	RDX Concentration (mg/kg)					
	Initial		Mid Core Samples (8th rain event)		Final (16th Rain Event)	
	Avg (n=12)	Std	Avg (n-9)	Std	Avg (n=3)	Std
USMA Control	1.944	1.368	2.245	1.764	1.965	0.593
USMA (2x lime dose[1])	1.959	2.687	1.256	0.549	2.388	0.331
USMA (4x lime dose)	3.456	1.123	0.982	0.374	2.469	0.949

[1] 8330 conducted after lime addition.

Significant metals in leachate and runoff from Lysimeter Study I

Table A10. Lysimeter Study I soluble (0.45 micron filtered) Zn in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Soluble Zn Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.050[1]	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.[2]	0.050	0.000
USMA (0.15%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.070	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.051	0.005
Fort Jackson Control		0.050	0.282	0.050	0.379	0.126	0.086	0.127	0.133	0.224	0.119	0.272	0.333	0.242	0.310	0.377	n.d.	0.207	0.115
Fort Jackson (0.5%)		0.050	0.050	0.050	0.050	0.055	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.001
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA Control	Runoff	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.15%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson Control		0.638	0.749	0.673	0.418	0.568	0.527	0.349	0.292	0.440	0.050	0.449	0.371	0.343	0.270	0.110	n.d.	0.416	0.196
Fort Jackson (0.5%)		0.224	0.114	0.114	0.120	0.063	0.057	0.116	0.096	0.068	0.055	0.107	0.050	0.107	0.113	0.110	n.d.	0.101	0.043
Fort Jackson (1.0%)		0.050	0.050	0.050	0.070	0.050	0.050	0.098	0073	0.050	0.050	0.050	0.050	0.050	0.050	0.115	n.d.	0.060	0.020
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.052	0.053	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.001

[1] RL for metal.

[2] n.d. = not determined.

Table A11. Lysimeter Study I total (digested) Zn in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Total Zn Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.414	0.152	0.206	0.177	0.084	0.071	0.076	0.050	0.088	0.102	0.050	0.050	0.050	0.050	0.050	0.050	0.108	0.096
USMA (0.15%)		0.161	0.074	0.070	0.055	0.050	0.051	0.050	0.050	0.058	0.072	0.050	0.050	0.050	0.050	0.050	0.050	0.062	0.028
USMA (0.30%)		0.180	0.121	0.119	0.103	0.092	0.083	0.076	0.050	0.050	0.080	0.050	0.050	0.050	0.050	0.050	0.050	0.078	0.037
USMA (0.60%)		0.050[1]	0.245	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.062	0.049
Fort Jackson Control		0.164	0.386	0.407	0.446	0.226	0.211	0.305	0.109	0.111	0.271	0.346	0.396	0.348	0.416	0.626	0.453	0.326	0.139
Fort Jackson (0.5%)		0.116	0.098	0.060	0.063	0.163	0.118	0.053	0.050	0.050	0.099	0.050	0.050	0.092	0.050	0.050	0.059	0.076	0.034
Fort Jackson (1.0%)		0.165	0.060	0.050	0.050	0.050	0.052	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.057	0.029
Fort Jackson (2.0%)		0.101	0.095	0.062	0.050	0.050	0.085	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.059	0.018
USMA Control	Runoff	0.777	0.394	0.287	0.249	0.224	0.092	0.093	0.051	0.057	0.149	0.050	0.080	0.050	0.050	0.050	0.050	0.169	0.194
USMA (0.15%)		0.760	0.260	0.289	0.195	0.116	0.124	0.072	0.053	0.082	0.177	0.050	0.068	0.050	0.050	0.050	0.050	0.153	0.180
USMA (0.30%)		0.619	0.135	0.189	0.181	0.192	0.124	0.134	0.050	0.081	0.126	0.103	0.050	0.050	0.050	0.050	0.050	0.136	0.139
USMA (0.60%)		0.569	0.407	0.118	0.172	0.162	0.134	0.106	0.050	0.119	0.130	0.050	0.080	0.050	0.052	0.050	0.050	0.144	0.144
Fort Jackson Control		2.442	4.132	3.849	2.151	1.466	1.103	1.028	0.433	2.242	1.090	1.857	0.403	1.216	2.091	0.861	0.878	1.703	1.092
Fort Jackson (0.5%)		1.028	1.879	2.314	1.098	1.945	1.935	1.240	0.610	0.850	1.559	0.770	0.904	0.643	0.835	0.665	0.511	1.174	0.572
Fort Jackson (1.0%)		0.947	1.042	1.526	1.313	2.782	1.584	1.183	0.605	1.034	1.562	0.695	0.826	0.958	0.800	0.613	1.050	1.158	0.537
Fort Jackson (2.0%)		0.386	0.611	0.686	0.631	0.690	0.784	0.737	0.354	0.401	1.123	0.589	0.427	0.483	0.675	0.274	0.267	0.570	0.222

[1] RL for metal.

Table A12. Lysimeter Study I soluble (0.45 micron filtered) Fe in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Soluble Fe Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.224	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.[2]	0.062	0.045
USMA (0.15%)		0.795	0.195	0.060	0.077	0.062	0.053	0.052	0.065	0.050	0.050	0.050	0.050	0.050	0.091	0.098	n.d.	0.120	0.190
USMA (0.30%)		0.744	0.070	0.050	0.050	0.051	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.086	0.095	n.d.	0.103	0.178
USMA (0.60%)		0.632	0.050	0.050	0.050	0.050	0.050	0.050	0.092	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.092	0.150
Fort Jackson Control		1.066	0.050	0.050	0.058	0.142	0.144	0.157	0.167	0.190	0.171	0.050	0.103	0.183	0.139	0.141	n.d.	0.187	0.248
Fort Jackson (0.5%)		0.050[1]	0.050	0.050	0.050	0.051	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.204	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.060	0.040
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA Control	Runoff	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.058	0.050	0.050	0.050	n.d.	0.051	0.002
USMA (0.15%)		0.050	0.050	0.050	0.054	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.001
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson Control		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (0.5%)		0.050	0.050	0.050	0.187	0.063	0.432	0.050	0.171	0.050	0.050	0.085	0.073	0.136	0.085	0.050	n.d.	0.106	0.101
Fort Jackson (1.0%)		0.050	0.050	0.050	0.488	0.385	0.411	0.709	0.588	0.050	0.050	0.050	0.050	0.050	0.068	0.852	n.d.	0.260	0.285
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.263	0.343	0.050	0.368	0.050	0.050	0.050	0.050	0.050	0.056	0.356	n.d.	0.126	0.131

[1] RL for metal.

[2] n.d. = not determined.

Table A13. Lysimeter Study I total (digested) Fe in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Total Fe Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	34.700	7.442	12.540	9.388	3.907	2.578	2.458	1.862	4.765	3.730	1.216	1.777	2.370	1.657	1.277	1.231	5.806	8.365
USMA (0.15%)		22.960	4.535	4.053	3.005	1.512	1.938	0.657	0.552	2.711	2.367	0.993	2.202	0.628	1.012	1.163	0.983	3.204	5.405
USMA (0.30%)		18.210	6.538	7.208	5.324	4.038	4.207	2.824	1.489	2.534	3.123	0.205	1.868	1.242	1.644	0.763	1.224	3.903	4.330
USMA (0.60%)		4.775	10.600	1.417	0.788	1.004	0.688	0.480	0.106	0.798	0.435	0.240	0.330	0.395	0.282	0.445	0.302	1.443	2.680
Fort Jackson Control		16.970	1.152	0.348	0.723	1.180	1.708	0.427	0.380	0.547	0.390	0.116	0.184	0.190	0.383	0.850	0.382	1.621	4.116
Fort Jackson (0.5%)		14.320	1.422	0.213	0.118	0.950	0.354	0.059	0.067	0.206	0.133	0.050	0.086	0.109	0.101	0.166	0.230	1.161	3.529
Fort Jackson (1.0%)		12.600	5.216	0.397	0.166	0.135	0.124	0.050[1]	0.050	0.064	0.050	0.050	0.050	0.050	0.051	0.087	0.050	1.199	3.299
Fort Jackson (2.0%)		5.276	6.315	0.370	0.195	0.119	0.243	0.050	0.050	0.050	0.050	0.088	0.085	0.050	0.055	0.137	0.050	0.824	1.952
USMA Control	Runoff	44.280	20.630	17.380	14.180	11.400	4.391	4.699	2.879	3.154	5.432	1.365	2.691	1.978	0.817	0.857	1.417	8.597	11.380
USMA (0.15%)		42.500	13.230	16.640	11.840	5.352	5.654	3.981	3.091	4.773	6.845	2.288	4.041	0.963	1.190	1.123	1.818	7.833	10.330
USMA (0.30%)		36.180	6.207	11.480	9.937	9.677	5.821	7.092	2.387	4.890	6.002	1.455	1.780	2.613	1.321	0.511	1.045	6.775	8.573
USMA (0.60%)		33.040	23.530	7.165	10.510	7.738	5.722	5.506	3.146	7.055	5.789	2.406	4.420	1.326	1.754	1.799	1.070	7.624	8.671
Fort Jackson Control		8.380	14.450	23.270	9.791	4.473	2.782	1.346	0.770	6.325	1.304	1.988	0.050	1.518	3.034	2.730	1.450	5.229	6.196
Fort Jackson (0.5%)		4.963	9.358	11.920	5.672	6.370	7.415	2.427	2.347	3.541	2.795	1.209	1.767	1.329	1.462	2.231	1.227	4.127	3.227
Fort Jackson (1.0%)		3.769	4.066	9.506	6.927	14.440	9.470	2.381	1.917	4.236	2.692	1.248	1.686	1.672	1.280	2.141	2.229	4.354	3.803
Fort Jackson (2.0%)		0.901	1.553	4.090	3.348	3.062	4.215	1.341	1.237	1.490	1.978	0.938	0.794	0.844	1.078	0.962	0.646	1.780	1.206

[1] RL for metal.

Table A14. Lysimeter Study I soluble (0.45 micron filtered) Mn in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Soluble Mn Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.050[1]	0.050	0.050	0.050	0.085	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.[2]	0.052	0.009
USMA (0.15%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson Control		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (0.5%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA Control	Runoff	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.15%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson Control		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (0.5%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000

[1] RL for metal.

[2] n.d. = not determined.

Table A15. Lysimeter Study I total (digested) Mn in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Total Mn Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	std
USMA Control	Leachate	1.279	0.314	0.489	0.372	0.196	0.099	0.134	0.079	0.183	0.199	0.071	0.083	0.140	0.063	0.050	0.057	0.238	0.305
USMA (0.15%)		0.629	0.170	0.149	0.109	0.066	0.064	0.050	0.050	0.111	0.115	0.050	0.114	0.050	0.050	0.050	0.050	0.117	0.142
USMA (0.30%)		0.675	0.256	0.282	0.206	0.149	0.146	0.130	0.063	0.096	0.157	0.050	0.092	0.062	0.067	0.050	0.050	0.158	0.156
USMA (0.60%)		0.156	0.132	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.060	0.033
Fort Jackson Control		0.518	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.079	0.117
Fort Jackson (0.5%)		0.327	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.067	0.069
Fort Jackson (1.0%)		0.572	0.072	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.084	0.130
Fort Jackson (2.0%)		0.381	0.085	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.073	0.083
USMA Control	Runoff	2.332	1.066	0.740	0.575	0.478	0.179	0.244	0.134	0.141	0.296	0.076	0.176	0.108	0.051	0.050	0.071	0.420	0.585
USMA (0.15%)		2.238	0.612	0.712	0.479	0.224	0.220	0.211	0.134	0.215	0.364	0.126	0.230	0.050	0.052	0.050	0.082	0.375	0.535
USMA (0.30%)		1.905	0.265	0.517	0.403	0.397	0.224	0.348	0.103	0.209	0.304	0.069	0.093	0.148	0.070	0.050	0.050	0.322	0.446
USMA (0.60%)		1.735	1.143	0.276	0.426	0.321	0.221	0.320	0.143	0.294	0.320	0.164	0.261	0.053	0.050	0.068	0.050	0.365	0.448
Fort Jackson Control		0.050[1]	0.055	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.001
Fort Jackson (0.5%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.000
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.000
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.000

[1] RL for metal.

Table A16. Lysimeter Study I soluble (0.45 micron filtered) Ca in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Soluble Ca Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	8.867	10.820	12.010	14.080	12.350	12.760	14.410	14.660	24.580	19.870	0.629	10.450	14.540	10.800	10.240	n.d.[2]	12.738	5.236
USMA (0.15%)		3.171	6.798	7.402	8.348	7.138	7.619	9.227	8.581	16.520	12.430	11.800	10.230	8.425	6.147	6.158	n.d.	8.666	3.162
USMA (0.30%)		6.845	8.146	9.010	10.080	9.654	8.153	9.809	8.520	14.500	9.862	8.058	6.191	7.737	6.355	7.164	n.d.	8.672	2.048
USMA (0.60%)		4.155	11.970	16.490	12.460	11.270	10.120	10.540	7.883	17.300	14.680	11.000	9.829	11.540	8.518	9.632	n.d.	11.159	3.310
Fort Jackson Control		3.253	17.280	26.250	12.820	5.522	3.261	3.257	2.880	4.336	2.964	2.421	2.236	2.089	1.959	1.764	n.d.	6.153	7.094
Fort Jackson (0.5%)		20.010	24.870	32.780	32.860	48.270	18.220	17.880	16.160	25.630	23.300	16.640	14.270	16.310	15.600	34.070	n.d.	23.791	9.547
Fort Jackson (1.0%)		21.940	26.720	37.810	30.330	18.030	17.160	21.810	8.810	28.950	24.410	17.850	24.830	17.230	16.000	67.260	n.d.	25.276	13.576
Fort Jackson (2.0%)		23.960	32.660	25.210	36.930	77.980	84.490	69.760	45.340	26.730	25.340	16.860	55.960	11.780	64.630	114.300	n.d.	47.462	29.453
USMA Control	Runoff	8.008	5.319	4.215	5.150	3.989	3.006	2.986	3.472	4.126	4.177	2.689	2.827	2.523	1.476	1.310	n.d.	3.685	1.667
USMA (0.15%)		9.474	5.817	4.701	4.816	3.341	3.831	3.223	4.176	5.075	0.429	3.352	3.219	2.830	1.977	1.456	n.d.	3.848	2.105
USMA (0.30%)		10.480	5.590	6.102	5.073	4.559	4.042	4.657	4.356	5.456	0.355	3.276	3.580	4.458	2.875	3.468	n.d.	4.555	2.142
USMA (0.60%)		10.270	5.462	5.888	5.575	4.691	4.501	4.773	4.536	5.853	0.430	3.929	4.001	5.009	3.679	3.243	n.d.	4.789	2.029
Fort Jackson Control		0.268	0.240	0.222	0.218	0.050[1]	0.050	0.197	0.150	0.440	0.435	0.089	0.050	0.189	0.181	0.345	n.d.	0.208	0.126
Fort Jackson (0.5%)		2.728	4.229	4.208	2.736	2.814	2.401	2.127	2.214	2.615	0.083	1.727	1.649	1.790	1.137	1.010	n.d.	2.231	1.103
Fort Jackson (1.0%)		12.020	8.665	6.650	5.684	5.189	4.783	4.884	9.159	3.978	0.735	3.139	3.485	3.657	2.993	2.485	n.d.	5.167	2.928
Fort Jackson (2.0%)		11.410	9.187	6.600	5.821	5.071	4.255	19.170	4.639	5.948	0.348	3.815	3.789	3.864	3.136	2.195	n.d.	5.950	4.534

[1] RL for metal.

[2] n.d. = not determined.

Table A17. Lysimeter Study I total (digested) Ca in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Total Ca Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	13.830	10.650	10.580	11.960	10.060	10.910	11.570	7.935	9.536	13.100	14.750	13.400	16.830	16.670	14.220	13.180	12.449	2.502
USMA (0.15%)		6.778	7.271	5.895	6.531	5.892	6.622	7.648	4.335	5.239	9.102	11.840	12.510	10.060	9.769	9.775	9.154	8.026	2.370
USMA (0.30%)		12.230	10.340	9.320	8.916	7.922	7.528	8.124	4.634	5.967	7.955	9.786	9.805	9.709	10.390	11.620	9.285	8.971	1.939
USMA (0.60%)		5.461	12.490	12.880	9.800	9.643	8.855	9.149	6.453	6.574	10.480	14.730	13.970	14.980	12.830	17.420	15.650	11.335	3.571
Fort Jackson Control		6.424	16.120	19.340	10.260	4.606	2.980	2.825	1.634	1.501	2.326	2.682	2.598	3.557	2.283	3.265	2.166	5.285	5.348
Fort Jackson (0.5%)		22.570	83.130	45.810	45.820	58.440	75.280	66.070	46.290	44.400	68.220	78.070	73.340	72.120	73.460	72.000	66.210	61.952	16.461
Fort Jackson (1.0%)		24.940	90.390	70.710	55.650	34.640	64.510	78.340	53.100	53.840	102.400	124.100	41.350	120.500	85.760	158.900	129.700	80.552	38.150
Fort Jackson (2.0%)		29.910	119.600	94.530	76.380	89.160	139.100	134.400	86.650	81.620	148.000	211.700	336.500	184.800	132.400	241.300	208.200	144.641	76.582
USMA Control	Runoff	23.710	10.580	7.031	6.094	5.462	2.756	2.832	1.921	1.775	3.631	3.113	4.445	3.093	1.973	1.398	1.846	5.104	5.524
USMA (0.15%)		32.370	10.090	8.666	6.655	3.981	3.729	3.318	2.624	3.111	5.227	4.488	5.316	2.997	2.967	1.817	2.764	6.258	7.323
USMA (0.30%)		38.210	8.603	10.750	8.686	8.249	5.439	7.530	3.404	5.172	6.509	6.696	5.664	6.762	4.541	4.718	3.319	8.391	8.206
USMA (0.60%)		53.990	37.890	9.498	12.760	10.270	8.054	10.150	6.194	11.550	9.958	10.020	12.780	6.048	7.088	5.996	4.692	13.559	13.204
Fort Jackson Control		1.157	0.620	0.511	0.348	0.367	0.358	0.299	0.201	0.183	0.761	0.050[1]	0.050	0.050	0.050	0.050	0.050	0.319	0.316
Fort Jackson (0.5%)		3.149	4.994	3.854	2.681	3.019	2.736	1.964	1.497	1.678	2.492	2.570	2.275	2.346	2.081	1.258	0.952	2.472	0.999
Fort Jackson (1.0%)		22.860	14.180	9.086	6.281	9.659	4.797	4.523	2.727	3.931	4.983	4.755	4.655	6.397	4.834	4.181	5.230	7.067	5.062
Fort Jackson (2.0%)		36.310	23.810	9.698	6.265	5.375	4.350	4.636	3.051	3.750	5.572	6.104	4.264	5.892	7.278	3.211	3.538	8.319	8.948

[1] RL for metal.

Table A18. Lysimeter Study I soluble (0.45 micron filtered) Pb in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Soluble Pb Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	<0.050[1]	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.[2]	0.050	0.000
USMA (0.15%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson Control		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (0.5%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA Control	Runoff	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.15%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.30%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
USMA (0.60%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson Control		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (0.5%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (1.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000
Fort Jackson (2.0%)		0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	n.d.	0.050	0.000

[1] RL for metal.

[2] n.d. = not determined.

Table A19. Lysimeter Study I total (digested) Pb in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Total Pb Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.178	0.050	0.067	0.051	0.050	0.063	0.056	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.060	0.032
USMA (0.15%)		0.251	0.060	0.050	0.050	0.050	0.066	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.064	0.050
USMA (0.30%)		0.098	0.050	0.050	0.051	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.053	0.012
USMA (0.60%)		0.076	0.061	0.055	0.050	0.050	0.067	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.054	0.008
Fort Jackson Control		0.091	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.053	0.010
Fort Jackson (0.5%)		0.081	0.050	0.050	0.061	0.050	0.056	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.053	0.008
Fort Jackson (1.0%)		0.095	0.050	0.055	0.050	0.050	0.061	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.054	0.011
Fort Jackson (2.0%)		0.090	0.050	0.056	0.061	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.054	0.010
USMA Control	Runoff	0.084	0.050	0.087	0.050	0.053	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.055	0.012
USMA (0.15%)		0.109	0.050	0.069	0.050	0.051	0.055	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.055	0.015
USMA (0.30%)		0.074	0.050	0.050	0.060	0.056	0.066	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.053	0.007
USMA (0.60%)		0.086	0.050	0.055	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.053	0.009
Fort Jackson Control		0.072	0.127	0.153	0.089	0.063	0.061	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.067	0.031
Fort Jackson (0.5%)		0.063	0.063	0.099	0.055	0.078	0.079	0.050	0.050	0.050	0.051	0.050	0.050	0.050	0.050	0.050	0.050	0.059	0.015
Fort Jackson (1.0%)		0.050[1]	0.050	0.073	0.076	0.111	0.077	0.050	0.050	0.050	0.057	0.050	0.050	0.050	0.050	0.050	0.050	0.059	0.017
Fort Jackson (2.0%)		0.050	0.050	0.054	0.050	0.050	0.052	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.001

[1] RL for metal.

Significant metals in leachate and runoff from Lysimeter Study II.

Table A20. Lysimeter Study II digested (total) Zn in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Digested Zn Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.094	0.478	0.147	0.050[1]	0.050	0.151	0.112	0.077	0.086	0.050	0.050	0.050	0.050	0.231	0.050	0.050	0.111	0.111
USMA (0.83%)		0.087	0.082	0.131	0.050	0.050	0.067	0.068	0.208	0.050	0.055	0.050	0.050	0.050	0.248	0.050	0.050	0.084	0.061
USMA (1.66%)		0.081	0.061	0.082	0.050	0.050	0.103	0.058	0.077	0.050	0.050	0.050	0.050	0.050	0.150	0.050	0.050	0.066	0.028
USMA Control	Runoff	5.500	5.410	5.337	0.050	0.050	3.475	1.335	1.953	3.163	2.128	0.191	1.654	0.050	1.794	1.905	1.216	2.201	1.894
USMA (0.83%)		2.211	3.312	1.794	0.050	0.050	1.851	0.983	2.918	2.699	1.729	0.156	2.104	0.050	1.923	0.960	1.050	1.490	1.062
USMA (1.66%)		0.714	0.172	0.192	0.050	0.050	0.204	0.111	0.235	0.341	0.130	0.050	0.136	0.050	0.274	0.055	0.050	0.176	0.170

[1] RL for metal.

Table A21. Lysimeter Study II digested (total) Fe in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Digested Fe Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	7.344	16.830	5.275	0.050[1]	0.050	3.115	2.293	1.060	1.121	0.154	0.313	0.242	0.050	0.309	0.050	0.050	2.394	4.404
USMA (0.83%)		25.660	7.076	6.912	0.050	0.050	0.799	0.636	5.642	0.387	1.030	0.437	0.509	0.050	1.337	0.166	0.531	3.204	6.474
USMA (1.66%)		21.070	4.348	5.951	0.050	0.050	1.506	1.221	1.403	0.336	0.594	0.232	0.451	0.050	0.386	0.081	0.057	2.362	5.264
USMA Control	Runoff	194.900	167.300	178.200	0.152	0.138	90.530	35.970	54.630	80.260	52.750	2.614	41.860	0.050	23.880	27.820	20.870	60.745	65.283
USMA (0.83%)		93.590	105.900	70.380	0.050	0.084	61.340	33.110	100.500	90.650	53.160	1.671	55.890	0.050	28.960	18.190	21.110	45.915	38.246
USMA (1.66%)		33.870	5.693	8.456	0.050	0.050	7.257	4.153	7.667	11.780	3.751	0.176	2.790	0.050	3.970	0.881	0.521	5.695	8.320

[1] RL for metal.

Table A22. Lysimeter Study II Digested (Total) Mn in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Digested Mn Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	0.199	0.702	0.186	0.050[1]	0.050	0.124	0.086	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.116	0.164
USMA (0.83%)		0.907	0.261	0.202	0.050	0.050	0.050	0.050	0.212	0.050	0.050	0.050	0.050	0.050	0.067	0.050	0.050	0.137	0.217
USMA (1.66%)		0.365	0.148	0.118	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.080	0.081
USMA Control	Runoff	10.270	8.535	8.933	0.050	0.050	5.232	1.590	2.594	3.475	2.775	0.093	2.181	0.050	2.097	2.354	1.565	3.240	3.303
USMA (0.83%)		4.558	6.194	3.266	0.050	0.050	3.040	1.438	4.696	4.118	2.729	0.065	3.147	0.050	2.692	1.400	1.546	2.440	1.894
USMA (1.66%)		1.529	0.264	0.364	0.050	0.050	0.337	0.185	0.315	0.507	0.171	0.050	0.124	0.050	0.179	0.070	0.050	0.268	0.364

[1] RL for metal.

Table A23. Lysimeter Study II digested (total) Ca in leachate and runoff (highlighted greater than RL).

HGR Soil In Lysimeter Cell	Water Type	Weekly Digested Ca Concentration in mg/L																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	21.780	59.520	38.060	73.420	65.540	85.020	74.440	50.170	79.570	37.600	37.360	38.290	81.120	42.150	38.440	39.530	53.876	20.002
USMA (0.83%)		26.020	69.810	67.770	66.430	57.890	47.900	49.260	71.740	62.840	32.190	26.980	28.710	69.770	37.920	23.550	27.580	47.898	18.667
USMA (1.66%)		29.680	27.930	36.510	37.850	38.690	43.200	50.400	55.860	33.320	29.330	33.630	26.860	65.520	32.780	27.480	25.300	37.146	11.426
USMA Control	Runoff	99.160	73.960	101.400	32.620	31.580	61.360	74.440	30.980	34.970	30.960	7.182	25.760	82.490	30.550	33.600	21.740	48.297	29.242
USMA (0.83%)		168.300	234.700	122.400	49.110	25.030	113.900	49.260	167.300	148.200	99.300	11.380	114.200	51.700	101.700	53.810	56.980	97.954	60.800
USMA (1.66%)		81.860	17.270	21.770	28.300	15.060	19.800	50.400	22.590	21.940	10.870	5.064	8.105	16.210	10.010	8.175	7.561	21.562	19.464

Leachate, runoff, and HGR soil pH

Table A24. Lysimeter Study I leachate and runoff pH.

HGR Soil In Lysimeter Cell	Water Type	Weekly pH																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	8.05	7.53	8.25	8.02	8.45	7.74	7.88	7.87	8.22	7.60	7.78	8.44	7.79	8.03	7.78	7.86	7.96	0.27
USMA (0.15%)		7.36	7.54	8.07	8.05	7.87	8.00	7.71	7.67	8.42	7.75	7.86	8.45	7.63	8.03	8.03	7.70	7.88	0.30
USMA (0.30%)		9.04	9.07	9.14	8.98	8.75	8.82	8.72	8.62	8.75	8.60	8.42	8.96	8.19	8.80	8.47	8.79	8.76	0.26
USMA (0.60%)		7.63	9.85	9.80	9.61	9.92	9.78	9.83	9.92	10.15	10.00	9.85	10.03	9.22	9.67	9.90	9.86	9.69	0.59
Fort Jackson Control		7.39	7.45	7.62	7.44	7.41	7.62	7.04	7.50	7.16	6.95	6.82	7.40	6.91	6.89	7.48	7.40	7.28	0.27
Fort Jackson (0.5%)		9.51	11.66	11.57	11.53	11.47	11.46	11.48	11.45	11.76	11.36	11.02	11.22	10.61	11.43	11.44	11.36	11.27	0.54
Fort Jackson (1.0%)		9.25	11.77	11.67	11.56	11.26	11.46	11.59	11.55	11.87	11.56	11.19	11.36	10.84	11.54	11.78	11.66	11.37	0.62
Fort Jackson (2.0%)		9.00	12.01	11.96	11.85	11.66	11.74	11.76	11.72	12.05	11.69	11.38	11.53	11.04	11.70	11.99	11.87	11.56	0.73
USMA Control	Runoff	8.78	9.64	9.72	9.51	9.29	9.13	9.22	9.00	9.42	9.10	8.92	9.08	8.39	8.99	8.56	8.76	9.09	0.37
USMA (0.15%)		8.88	9.62	9.79	9.42	9.26	9.40	9.29	9.03	9.57	9.28	9.13	9.33	8.48	8.89	8.49	8.87	9.17	0.38
USMA (0.30%)		9.00	9.71	9.64	9.62	9.58	9.54	9.59	9.30	9.80	9.34	9.25	9.33	8.68	9.35	8.59	9.41	9.36	0.35
USMA (0.60%)		9.00	9.89	9.69	9.57	9.64	9.64	9.64	9.43	9.96	9.50	9.26	9.57	8.77	9.61	9.38	9.54	9.51	0.30
Fort Jackson Control		6.83	7.16	7.88	8.14	7.40	8.29	7.85	7.40	6.95	6.78	6.56	7.69	6.81	7.24	7.52	7.64	7.38	0.51
Fort Jackson (0.5%)		7.84	9.74	9.68	9.36	9.56	9.66	9.53	9.03	9.52	8.86	8.95	9.10	8.53	8.66	8.69	8.76	9.09	0.53
Fort Jackson (1.0%)		8.92	10.35	9.89	9.79	9.82	9.77	9.87	9.55	9.90	9.41	9.22	9.32	9.14	9.38	9.70	9.55	9.60	0.36
Fort Jackson (2.0%)		8.97	10.81	10.00	9.77	9.56	9.99	10.06	9.80	9.97	9.61	9.32	9.40	9.32	9.54	9.52	9.38	9.69	0.43

Table A25. Lysimeter Study II leachate and runoff pH.

HGR Soil In Lysimeter Cell	Water Type	Weekly pH																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	Std
USMA Control	Leachate	8.78	8.45	9.67	8.31	9.14	8.20	8.20	8.12	7.89	7.93	7.64	7.94	8.12	7.86	8.24	8.18	8.29	0.52
USMA (0.83%)		9.02	10.01	10.88	9.55	10.99	9.74	9.54	9.33	9.31	8.65	8.87	8.67	8.67	8.42	8.63	8.69	9.31	0.79
USMA (1.66%)		9.50	9.41	10.23	9.01	10.25	9.21	9.13	9.17	9.61	9.24	9.21	8.89	9.39	9.34	9.45	9.60	9.42	0.38
USMA Control	Runoff	9.06	9.02	8.77	9.09	9.32	8.65	8.75	8.96	8.92	8.65	8.52	8.79	8.83	8.58	8.84	8.75	8.84	0.21
USMA (0.83%)		9.32	8.83	9.06	8.87	9.63	8.74	8.65	8.89	8.78	8.73	8.60	8.93	8.78	8.69	8.90	8.73	8.88	0.26
USMA (1.66%)		9.06	8.67	9.18	8.65	9.57	8.30	8.42	8.30	8.70	8.10	7.93	8.54	8.37	8.02	8.34	8.29	8.53	0.44

Table A26. Lysimeter Study I final (16th rain event) soil pH.

Sample ID		Soil pH	Avg Soil pH	Std
USMA Control	Rep 1	8.68	8.63	0.07
	Rep 2	8.67		
	Rep 3	8.55		
USMA (0.15% Lime)	Rep 1	8.71	8.75	0.04
	Rep 2	8.76		
	Rep 3	8.78		
USMA (0.30% Lime)	Rep 1	8.89	8.92	0.03
	Rep 2	8.91		
	Rep 3	8.95		
USMA (0.60% Lime)	Rep 1	9.28	9.29	0.01
	Rep 2	9.30		
	Rep 3	9.29		
Ft. Jackson Control	Rep 1	6.51	6.62	0.12
	Rep 2	6.60		
	Rep 3	6.74		
Ft. Jackson (0.5% Lime)	Rep 1	8.79	8.86	0.07
	Rep 2	8.88		
	Rep 3	8.92		
Ft. Jackson (1.0% Lime)	Rep 1	9.99	10.04	0.05
	Rep 2	10.06		
	Rep 3	10.08		
Ft. Jackson (2.0% Lime)	Rep 1	10.49	10.45	0.05
	Rep 2	10.40		
	Rep 3	10.46		

Table A27. Lysimeter Study II mid (8th rain event) soil pH (highlighted cell achieved pH objective).

Sample ID		Soil pH	Avg Soil pH	Std
USMA Control	Cell 1-1A	9.19	9.02	0.19
	Cell 1-1B	9.03		
	Cell 1-1C	9.21		
	Cell 1-2A	9.01		
	Cell 1-2B	8.98		
	Cell 1-2C	9.11		
	Cell 1-3A	9.17		
	Cell 1-3B	8.89		
	Cell 1-3C	8.60		
USMA (0.83% Lime)	Cell 2-1A	10.42	10.98	0.29
	Cell 2-1B	11.14		
	Cell 2-1C	11.38		
	Cell 2-2A	10.81		
	Cell 2-2B	11.05		
	Cell 2-2C	10.77		
	Cell 2-3A	11.02		
	Cell 2-3B	10.98		
	Cell 2-3C	11.25		
USMA (1.66% Lime)	Cell 3-1A	12.13	11.98	0.30
	Cell 3-1B	12.20		
	Cell 3-1C	12.08		
	Cell 3-2A	11.53		
	Cell 3-2B	12.11		
	Cell 3-2C	11.94		
	Cell 3-3A	12.33		
	Cell 3-3B	12.08		
	Cell 3-3C	11.46		

Table A28. Lysimeter Study II final (16th rain event) soil pH (highlighted cell achieved pH objective).

Sample ID		Soil pH	Avg Soil pH	Std
USMA Control	Rep 1	8.19	8.26	0.065574
	Rep 2	8.27		
	Rep 3	8.32		
USMA (0.83% Lime)	Rep 1	10.83	10.88	0.045826
	Rep 2	10.89		
	Rep 3	10.92		
USMA (1.66% Lime)	Rep 1	11.58	11.61	0.03
	Rep 2	11.61		
	Rep 3	11.64		

Total suspended solids in leachate and runoff

Table A29. Lysimeter Study I TSS in leachate and runoff.

HGR Soil In Lysimeter Cell	Water Type	Weekly TSS (mg) in 200 mL of solution																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
USMA Control	Leachate	250.4	31.3	38.2	44.8	21.0	9.4	25.6	16.8	25.2	21.5	9.5	15.5	15.6	5.8	5.3	2.2	538.1
USMA (0.15%)		142.5	21.4	16.0	14.4	8.9	3.8	5.2	9.3	20.7	11.9	7.4	12.8	3.7	4.6	4.6	2.1	289.3
USMA (0.30%)		153.1	28.9	23.8	23.7	17.7	11.3	14.9	17.1	20.1	16.6	6.5	13.5	8.1	7.0	3.1	1.5	366.9
USMA (0.60%)		28.3	39.0	6.5	5.2	3.1	1.4	2.9	2.2	3.9	2.1	0.8	2.1	1.8	1.5	0.7	0.7	102.2
Fort Jackson Control		150.3	1.2	5.7	4.0	6.5	4.5	3.2	10.6	6.8	70.3	2.1	4.4	2.3	4.4	3.6	3.1	283.0
Fort Jackson (0.5%)		132.8	8.7	24.1	6.3	5.4	6.2	3.9	3.2	1.7	2.7	6.6	5.3	2.0	3.8	2.4	0.3	215.4
Fort Jackson (1.0%)		137.1	26.2	28.2	16.6	9.1	3.9	4.8	2.0	1.1	0.2	10.7	5.6	8.8	6.2	3.3	0.4	264.2
Fort Jackson (2.0%)		137.3	29.5	18.5	14.1	12.2	5.2	1.5	2.3	1.4	0.9	0.7	11.3	6.6	3.7	2.3	1.4	248.9
USMA Control	Runoff	122.0	53.0	37.9	54.7	43.3	15.8	19.9	34.6	27.7	32.5	18.3	25.8	13.7	0.5	1.7	5.9	507.3
USMA (0.15%)		167.4	27.1	56.0	44.6	25.7	18.7	15.4	34.8	36.8	37.2	14.8	26.0	3.2	2.6	1.0	2.2	513.5
USMA (0.30%)		173.4	20.2	54.9	34.7	46.0	22.0	37.5	28.5	39.2	31.6	13.3	12.3	20.5	4.1	0.4	2.5	541.1
USMA (0.60%)		174.8	75.4	29.8	35.8	39.3	26.9	36.5	33.2	76.8	38.6	24.7	38.0	7.0	6.7	7.1	2.0	652.6
Fort Jackson Control		87.8	135.5	118.3	58.0	72.4	20.3	51.3	29.3	46.1	3.9	95.9	9.3	53.1	99.6	31.4	32.8	945.0
Fort Jackson (0.5%)		32.7	61.2	78.8	28.2	46.3	71.9	46.3	46.8	53.0	51.1	23.0	26.9	18.7	26.0	18.1	14.6	643.6
Fort Jackson (1.0%)		41.4	38.4	32.8	46.8	98.9	39.1	54.0	49.6	75.2	56.3	13.3	22.6	47.5	29.5	25.6	44.4	715.4
Fort Jackson (2.0%)		32.7	26.5	32.8	22.3	21.9	22.2	29.4	27.8	24.4	32.6	21.8	13.7	16.1	25.1	9.3	14.1	372.7

Table A30. Lysimeter Study II TSS in leachate and runoff.

HGR Soil In Lysimeter Cell	Water Type	Weekly TSS (mg) in 200 mL of solution																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total
USMA Control	Leachate	27.0	32.7	11.1	4.9	18.1	3.5	3.8	0.5	0.3	1.4	2.1	0.4	1.2	0.4	0.9	0.3	108.6
USMA (0.83%)		115.9	34.3	32.3	10.4	8.5	2.9	7.2	13.2	0.8	5.4	7.4	9.5	3.0	5.5	8.0	8.9	273.2
USMA (1.66%)		57.9	25.6	14.2	12.0	7.7	2.1	1.8	0.6	0.8	1.8	0.6	2.3	0.5	0.5	7.0	12.8	148.2
USMA Control	Runoff	436.2	1,011.6	696.6	675.4	214.0	144.2	286.2	478.0	520.1	349.4	390.9	318.9	300.8	272.0	265.4	155.7	6,515.4
USMA (0.83%)		528.3	540.0	530.8	386.6	325.2	261.4	328.1	562.5	513.3	171.7	373.4	343.4	295.0	318.4	242.5	261.0	5,981.6
USMA (1.66%)		122.4	30.6	24.5	30.4	17.7	13.7	13.6	7.0	102.9	29.0	14.5	15.6	12.9	17.4	12.2	2.4	466.8

Volume leachate and runoff collected

Table A31. Lysimeter Study II volume leachate and runoff collected.

HGR Soil In Lysimeter Cell	Water Type	Weekly Volume (L)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	std
USMA Control	Leachate	6.30	7.60	5.35	6.65	5.85	6.55	5.50	5.70	5.15	3.90	4.90	4.50	3.65	4.05	3.40	3.30	6.02	3.81
USMA (0.83%)		5.15	7.45	5.85	5.20	5.50	6.45	6.80	5.50	4.85	3.85	4.50	3.85	3.35	3.40	4.05	4.65	5.91	3.82
USMA (1.66%)		7.60	7.55	5.85	5.30	5.70	5.80	4.70	5.65	5.65	5.25	5.15	4.85	5.35	5.45	4.90	6.25	6.53	3.57
USMA Control	Runoff	5.60	2.80	3.95	4.00	2.95	2.80	4.00	4.50	3.80	3.05	3.30	3.10	3.35	3.55	3.85	4.60	3.48	1.16
USMA (0.83%)		3.35	2.60	3.45	3.10	3.80	3.00	2.75	3.15	3.30	2.90	3.70	4.00	3.70	3.90	3.55	3.15	3.14	0.90
USMA (1.66%)		2.60	2.50	3.50	2.95	3.45	3.75	3.80	3.30	3.25	2.60	3.40	3.40	3.45	3.20	3.30	2.75	3.01	0.87

Table A32. Lysimeter Study I volume leachate and runoff collected.

HGR Soil In Lysimeter Cell	Water Type	Weekly Volume (L)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Avg	std
USMA Control	Leachate	23.95	24.80	24.35	22.90	24.50	23.60	24.95	22.60	24.00	22.45	23.70	31.50	22.15	22.40	22.75	23.75	24.02	2.18
USMA (0.15%)		23.60	21.95	22.40	21.05	22.50	23.40	21.90	22.60	23.70	20.85	21.30	21.25	23.50	23.95	20.00	19.85	22.11	1.32
USMA (0.30%)		23.00	24.05	24.80	20.45	21.50	21.95	22.40	22.50	19.25	21.75	24.60	29.10	25.25	23.10	20.25	23.25	22.95	2.35
USMA (0.60%)		21.50	22.05	19.50	19.15	21.70	20.10	22.55	18.60	19.65	23.10	23.70	23.05	20.65	19.00	19.20	20.50	20.88	1.66
Fort Jackson Control		20.10	23.70	23.05	22.50	22.45	21.90	21.05	20.55	22.80	22.90	23.25	22.10	22.80	21.70	19.90	21.55	22.02	1.14
Fort Jackson (0.5%)		27.45	25.95	25.50	25.05	25.45	24.75	22.65	20.00	22.95	23.50	23.10	23.95	24.20	23.10	22.25	20.50	23.77	1.95
Fort Jackson (1.0%)		21.10	23.75	23.25	20.30	23.65	22.85	21.00	20.25	21.45	22.35	22.10	20.85	22.80	22.70	21.15	21.95	21.97	1.14
Fort Jackson (2.0%)		23.00	23.95	24.05	22.40	20.15	22.65	23.30	23.35	24.00	21.70	23.50	22.90	24.95	21.25	21.20	22.15	22.78	1.26
USMA Control	Runoff	18.95	20.50	19.00	19.95	19.35	20.35	19.70	20.20	20.55	22.30	20.50	12.30	21.90	22.15	21.60	21.10	20.03	2.31
USMA (0.15%)		20.25	22.85	21.50	22.30	21.55	21.00	22.40	22.20	20.15	22.95	22.80	21.50	20.85	20.10	23.70	22.15	21.77	1.09
USMA (0.30%)		21.05	20.05	18.75	21.10	21.70	21.85	22.10	19.65	25.05	22.55	19.25	14.45	20.60	20.95	22.20	20.90	20.76	2.25
USMA (0.60%)		21.50	22.40	24.75	21.55	21.90	24.15	22.95	23.55	23.35	22.90	19.35	21.05	24.10	24.80	24.60	23.45	22.90	1.53
Fort Jackson Control		21.25	19.80	20.85	21.50	20.60	21.70	22.70	22.45	19.65	20.80	20.05	19.60	21.65	21.60	22.30	23.55	21.25	1.16
Fort Jackson (0.5%)		18.00	17.95	19.50	19.60	17.20	21.70	22.30	23.10	20.25	19.65	20.10	20.50	20.95	21.90	21.10	23.55	20.46	1.82
Fort Jackson (1.0%)		19.30	21.70	20.25	23.20	18.95	21.20	24.25	20.75	20.60	20.90	21.10	21.90	20.75	22.65	22.30	23.95	21.48	1.51
Fort Jackson (2.0%)		22.95	20.40	21.40	20.45	22.65	21.45	21.50	19.50	21.00	22.70	19.10	21.35	19.15	23.60	23.02	22.25	21.40	1.41

Appendix B: Statistical Analysis of Lysimeter Study I

Description

USMA HGR soil and Fort Jackson HGR soil with four treatments (i.e., control and three lime levels). Evaluate the soils independently.

Data

Leachate and surface runoff concentrations of RDX and metals (Zn, Mn, and Pb) collected over a 16-week period. Each sampling period has one value only.

Soil core concentrations of RDX and metals (Zn, Mn, and Pb) collected at weeks 0, 8, and 16. Each sampling period has one value only.

Software

Statistical Analysis System (SAS) Release 8.2.

Leachate and surface runoff analysis

1. Evaluate analysis of variance (ANOVA) normality and equality of variances assumptions.
    a. If either assumption is rejected, use log transformation and reevaluate.
    b. If either assumption is rejected with transformed data, use non-parametric method.
2. If ANOVA assumptions are not rejected, test H_o: $\mu_C=\mu_{L1}=\mu_{L2}=\mu_{L3}$.
    a. If the null hypothesis is rejected, use Dunnett's one tailed t-test to identify means significantly greater than the control.
    b. Alternately, use Dunnett's two-tailed t-test to identify means significantly different from the control.
3. (Nonparametric method) If ANOVA assumptions are rejected use Kruskal-Wallis to determine if at least one treatment is significantly different from the others.
    a. If the null hypothesis is rejected, use a multiple comparison with ranks to identify populations which are significantly different (Conover 1980).

   b. Alternatively, use normal scores computed from ranks.
4. Linear or nonlinear regression could be used to predict metal concentrations over time.

Data analysis

This study evaluated HGR soil from USMA and Fort Jackson. The data consist of leachate and surface runoff concentrations of RDX and metals (Zn, Mn, and Pb) collected over a 16-week period. Each sampling period had one replicate. There were four treatments (i.e., control and three lime levels). The RL of 50 ppb (μg/L) was used for metals contaminant concentrations less than the RL. SAS release 8.2 was used to perform the data analysis (SAS Institute Inc. 1989a; 1989b).

Step (1): (A) Evaluate the normality and equality of variances assumptions. PROC UNIVARIATE with the NORMAL option was used to test normality of residuals using the Shapiro-Wilk's Test (Conover 1980). This test provides a test statistic W, which is compared to values of W expected from a normal distribution. Because normality is desired, one looks for a high value of W with an associated probability greater than corresponding alpha level. The alpha level used was 0.05. An associated probability less than the alpha level indicates the inappropriateness of the normality assumption.

(B) Cochran's Test was used to evaluate the equality of variances assumption (Winer 1971). Cochran's Test was accomplished using PROC MEANS twice, and a subsequent data step. The calculated C statistic was compared to a critical value from Table C.8 of Winer (1971). Equality of variances was rejected if the C statistic was greater than or equal to the critical value at alpha = 0.05.

(C) If the normality hypothesis in (A) or the equality of variances hypothesis in (B) was rejected, Step (2) was utilized. If the normality and equality of variances null hypotheses were not rejected, the ANOVA was used to evaluate H_0: $\mu_C=\mu_{L1}=\mu_{L2}=\mu_{L3}$.

If the null hypothesis was rejected, Dunnett's one tailed t-test to identify lime treatment means significantly less than the control mean (SAS Institute Inc. 1989a). The alpha level used was 0.05. Test results are shown on

Tables B1-B4. The # symbol identifies instances where these procedures were used to evaluate data.

Step (2): Transform leachate and runoff concentrations by taking the common logarithm of each concentration. Evaluate the transformed data with the Shapiro-Wilk and Cochran Tests as described in (A) and (B) of Step (1) above. If the normality hypothesis or the equality of variances hypothesis was rejected, Step (3) was utilized. If the normality and equality of variances null hypotheses were not rejected, data analysis was performed as described in section C of Step (1). Test results are shown on Tables B1-B4. The & symbol identifies instances where these procedures were used to evaluate data.

Step (3): The rankit transformation was used to calculate normal scores from concentration ranks. This was accomplished using PROC RANK with the NORMAL= BLOM option (SAS Institute Inc. 1988).

Evaluate the transformed data with the Shapiro-Wilk and Cochran Tests as described in (A) and (B) of Step (1) above. If the normality hypothesis or the equality of variances hypothesis was rejected, Step (4) was utilized.

If the normality and equality of variances null hypotheses were not rejected, data analysis was performed as described in section C of Step (1). Test results are shown in tables below. The @ symbol identifies instances where these procedures were used to evaluate data.

Step (4): The one-way ANOVA applied to ranks is equivalent to the Kruskal-Wallis k-sample test. This was accomplished using PROC RANK (SAS Institute Inc. 1988). Evaluate the ranks data with the Cochran's Test as described in (B) of Step (1) above. If the equality of variances null hypotheses were not rejected, data analysis was performed as described in section C of Step (1). Multiple comparison tests can be used with ranks to identify populations which are significantly different (Conover 1980). This step was not needed for the data presented in Tables B1-B4.

Many of the dissolved and total metal concentrations were less than the method detection limit. The method detection limit of 50 ppb was used as the contaminant concentration. Hence, the data analysis sequence described in Steps (1) through (4) could not be utilized. For each soil and treatment, the one sample t-test was used to evaluate H_o: $\mu=50$ and H_o:

μ>50 (Steel and Torrie 1980). This was accomplished by subtracting 50 from each concentration and using PROC TTEST to evaluate the resulting data (SAS Institute Inc. 1989b). Reject H_0 if the calculated test statistic greater than $t_{(0.05, n-1)}$ (Steel and Torrie 1980; Table A.3). This is a one tailed test. Test results are shown on Tables B2-B5.

Statistical Analysis Results

Explosives

The RDX analysis shown in Table B1 indicates that the lime-treated Fort Jackson leachate mean concentrations were significantly lower than the control mean concentration.

Table B1. Lysimeter Study I statistics: RDX

Type	Treatment	USMA	Fort Jackson
Leachate	Control (no lime)	1.70E-02@	3.07E-01@
	½x lime dose	2.64E-02	2.72E-02***
	1x lime dose	2.46E-02	3.01E-02***
	2x lime dose	3.00E-02	2.31E-02***
Runoff	Control (no lime)	1.02E-02@	2.50E-02@
	½x lime dose	1.44E-02	1.19E-03
	1x lime dose	1.73E-02	1.01E-03
	2x lime dose	1.65E-02	1.31E-03

@ Rankit Transformation
$ Kruskal-Wallis using Rank Data
# Untransformed Data
& Log_{10} Transformed Data
*** Mean Statistically Less than the Control Mean

Metals

The soluble Zn analysis results are shown in Table B2. Table B2 indicates that the control Fort Jackson leachate and the ½× and 1× lime dose treated Fort Jackson runoff mean concentrations were significantly greater than the report limit of 50 ppb. The total Zn analysis shown in Table B3 indicates that the control, ½×, and 1× lime dose treated USMA leachate and the control, ½×, 1×, and 2× lime dose treated USMA and Fort Jackson runoff mean concentrations were significantly greater than the report limit of 50 ppb.

Table B2. Lysimeter Study I statistics: soluble zinc.

Type	Treatment	USMA	Fort Jackson
Leachate	Control (no lime)	5.00E+01	2.07E+02***
	½x lime dose	5.00E+01	5.03E+01
	1x lime dose	5.00E+01	5.00E+01
	2x lime dose	5.13E+01	5.00E+01
Runoff	Control (no lime)	5.00E+02	4.16E+02
	½x lime dose	5.00E+02	1.01E+02***
	1x lime dose	5.00E+02	6.04E+01***
	2x lime dose	5.00E+02	5.04E+01
*** Mean Statistically Less than the Control Mean.			

Table B3. Lysimeter Study I statistics: total zinc.

Type	Treatment	USMA	Fort Jackson
Leachate	Control (no lime)	1.48E+02***	7.15E+02
	½x lime dose	8.09E+01***	2.50E+02
	1x lime dose	1.09E+02***	2.61E+02
	2x lime dose	8.65E+01	1.39E+02
Runoff	Control (no lime)	2.55E+02***	1.76E+03***
	½x lime dose	2.22E+02***	1.43E+03***
	1x lime dose	1.89E+02***	1.33E+03***
	2x lime dose	2.73E+02***	6.43E+02***
*** Mean Statistically Less than the Control Mean.			

The total Pb analysis (Table B4) indicates that the 2× lime dose treated USMA leachate mean concentration was significantly greater than the report limit of 50 ppb. The control, ½×, and lime dose treated Fort Jackson and 1× lime dose treated USMA runoff mean concentrations were significantly greater than the report limit of 50 ppb.

Table B4. Lysimeter Study I statistics: total lead.

Type	Treatment	USMA	Fort Jackson
Leachate	Control (no lime)	6.66E+01	6.31E+01
	½x lime dose	7.27E+01	5.48E+01
	1x lime dose	5.48E+01	5.61E+01
	2x lime dose	5.59E+01***	5.57E+01
Runoff	Control (no lime)	5.75E+01	7.65E+01***
	½x lime dose	5.85E+01	6.37E+01***
	1x lime dose	5.56E+01***	6.45E+01***
	2x lime dose	5.40E+01	5.06E+01

*** Mean Statistically Less than the Control Mean.

The total Mn analysis shown in Table B5 indicates that the control, ½× and 1× lime dose treated USMA leachate mean concentration was significantly greater than the report limit of 50 ppb. The control, ½×, 1×, and 2× lime dose treated USMA runoff mean concentrations were significantly greater than the report limit of 50 ppb.

Table B5. Lysimeter Study I statistics: total manganese.

Type	Treatment	USMA	Fort Jackson
Leachate	Control (no lime)	3.52E+02***	9.68E+01
	½x lime dose	1.82E+02***	7.77E+01
	1x lime dose	2.55E+02***	1.04E+02
	2x lime dose	1.19E+02	86.6E+01
Runoff	Control (no lime)	6.54E+02***	7.34E+01
	½x lime dose	5.55E+02***	5.00E+01
	1x lime dose	4.76E+02***	5.00E+01
	2x lime dose	4.88E+02***	5.00E+01
*** Mean Statistically Less than the Control Mean.			

Appendix C: Standard Procedure for Determination of Lime Requirement of Different Soils for Alkaline Hydrolysis of Ordnance Related Compounds and Metals

If sufficient laboratory facilities and supplies are available and/or there is a need to determine the lime dose required for range soil other than the use or complementing Test Kit #1, the following procedure can be used (Davis et al. 2006).

Materials

- Stir plates – 8
- Stir bars to fit a 50-mL beaker – 8
- Weighing paper and spatula
- pH buffers, 4 and 10
- Soil to be tested (approximately 200 g)
- 50-mL glass beakers – 8
- Balance with an accuracy to three decimal places
- pH meter and electrode
- 20-mL pipettes and pipettor

Chemicals

- Water (tap or rainwater)
- Powdered hydrated lime ($Ca(OH)_2$)

Method

1. Add stir bars to the beakers and label the beakers according to the lime content to be added, listed in Table C1. One beaker will have no lime added - the pH control.
2. Calibrate the pH meter using a two-point calibration of pH 4 and 10.
3. Weigh out 20 g of the test soil for each beaker.
4. Weigh out the appropriate lime dose for each beaker (Table C1) and add it to the soil.
5. Add 20 mL water to each beaker and start the slurry gently mixing.
6. Mix the slurry for 30 min.

7. Take the pH of each slurry, beginning with the lime control, which will establish the initial soil pH.
8. Repeat the test twice more and average the pH achieved at each level of lime addition. Create a table of lime dose and pH (using the template shown in Table C2).
9. Plot the data on a graph with the amount of lime addition to the soil slurry on the X-axis and the resulting average pH on the Y-axis (Figure C1).
10. A line drawn horizontally from the desired pH to the line formed from the experimental data and then dropped to the X-axis will provide an estimate of the amount of lime (per 20 g of soil) that is needed to bring the soil to the desired pH.
11. This value is used in the calculation to determine tons of lime to be added to the soil for either a plowed-in treatment or a top-dressing treatment.

Table C1. Procedure for lime addition to each experimental beaker.

Beaker	Lime (% soil weight)	Lime (g)
1	0.00	0.00
2	0.05	0.01
3	0.1	0.02
4	0.5	0.1
5	1.0	0.2
6	2.0	0.4
7	3.0	0.6
8	5.0	1.0

Table C2.Template for soil slurry pH determined from each lime addition after mixing for 30 min.

Beaker	Lime (% soil weight)	Lime (g)	Soil pH			Avg pH
			Rep 1	Rep 2	Rep 3	
1	0.00	0.00				
2	0.05	0.01				
3	0.1	0.02				
4	0.5	0.1				
5	1.0	0.2				
6	2.0	0.4				
7	3.0	0.6				
8	5.0	1.0				

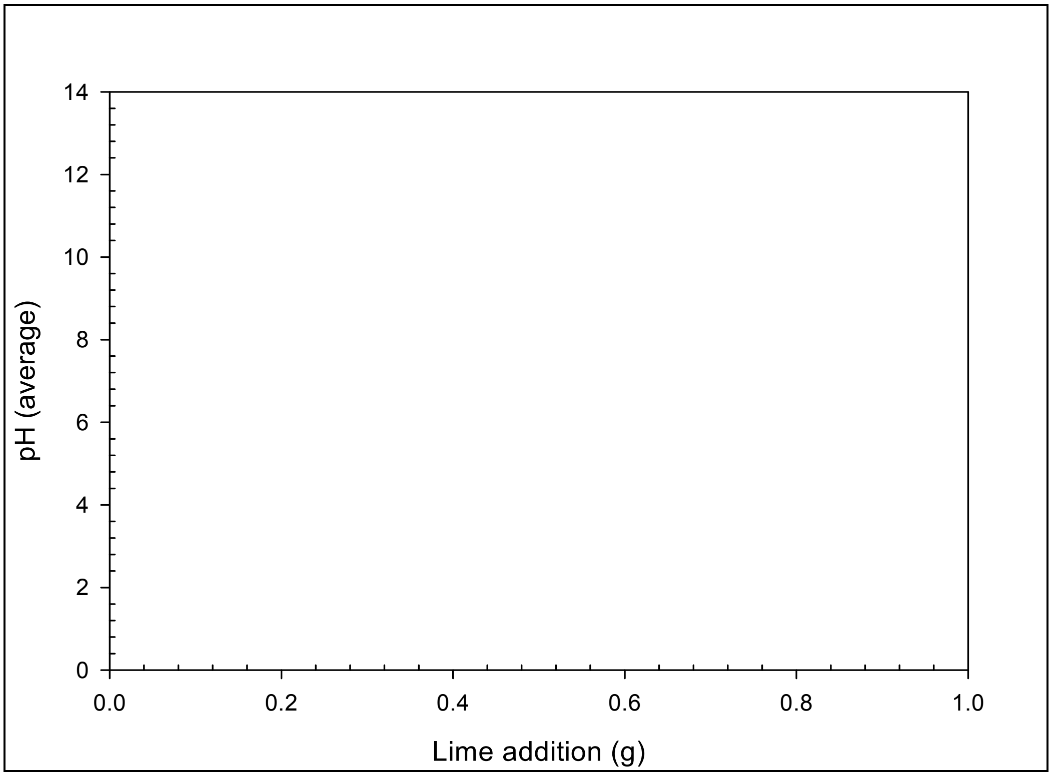

Figure C1. Graph for plotting lime addition vs. average pH.

Calculation of lime dosage 6-in. application depth

- Uses – land in use
- Mode of application – mix into HGR soil
- Convert from grams of lime per 20 g of soil to tons of lime per acre-6-in.

(X g lime/20 g soil) x (153.8508) x 6 = Y tons lime/acre-3-in.

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14. ABSTRACT

The Department of Defense operates hundreds of hand grenade ranges (HGRs) for training purposes. Live fire training is a necessary function to maintain mission readiness for our Nation’s warfighters, but it creates a potential source zone for munitions constituents such as metals and explosives. Fragmentation grenades — typically containing composition B within a steel shell casing — constitute the majority of hand grenades used at fixed position ranges. Explosives have been detected in HGR soils at levels in the low parts per billion (µg/kg) up to percent levels. Two mechanisms with potential for offsite migration of metals and explosives from HGR soil are transport in surface water and subsurface transport in leachate or pore water. Simple, innovative, and cost-effective technologies are being developed that can break down munitions constituents quickly at the training sites and prevent residues from migrating to local surface water or groundwater supplies. The application of hydrated lime to HGRs provides both a mechanism for metals immobilization and explosives transformation. The results from this treatability study indicate that the application of lime can be incorporated into range sustainability operations and the management practices for active HGRs.

15. SUBJECT TERMS

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