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Topical Lime Treatment for Containment of Source Zone Energetics Contamination

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ABSTRACT: Energetic compounds, such as 2,4,6-trinitrotoluene (TNT) and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and their degradation products can act as a source of contamination for soil on Department of Defense testing and training ranges. Base hydrolysis degrades nitroaromatics and nitramines, and the potential effectiveness of lime to induce this reaction has been demonstrated at the laboratory scale. The objective of this research was to further examine both basic and applied aspects of alkaline application as an inexpensive and effective means of reducing source-zone contamination on military ranges. Bench-scale microcosms were used to examine basic conditions that could affect the alkaline hydrolysis reaction, such as soil organic matter content, lime concentration, soil type, and contamination type. Results from experiments using soil from a variety of ammunition production facilities and training ranges, in general, support the use of explosive contaminant treatment by alkaline material in well-mixed systems. RDX in crystalline form was more resistant to treatment, possibly due to limitations associated with the dissolution of the RDX from the crystal to the aqueous phase. Larger-scale experiments, conducted in vessels packed with approximately 55 kg of soil, were used to investigate topical versus well-mixed applications of three alkaline materials (hydrated lime, quicklime, and Class C fly ash). TNT, RDX, and HMX in the mixed system were removed quickly from both the leachate and soil. However, results from experiments with topical applications of alkali material indicated that the aqueous transport of hydroxide ion was not sufficient to overcome the buffering capacity of the soil. Consequently, the soil pH was not raised to the extent necessary for alkaline treatment of explosive compounds. This result is fundamentally related to the CEC properties of the soil and is consequently considered a soil specific (and therefore site specific) result. Topical application of alkali material may still be a viable treatment technique by taking advantage of circumstances unique to training ranges.

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Preface

The work reported herein was conducted at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. Funding for this project was provided through the Strategic Environmental Research and Development Program (SERDP), project CU-1230.

The work presented in this report was part of an effort to investigate the remediation of soils contaminated with multiple types of explosives from a variety of Department of Defense facilities. Drs. Michael C. Brooks, Jeffrey L. Davis, and Steven L. Larson, Environmental Engineering Branch (EP-E), Environmental Laboratory (EL), ERDC, Vicksburg, MS, and Ms. Deborah Felt and Ms. Catherine Nestler, Applied Research Associates, Inc., Vicksburg, MS, prepared this report. Ms. Anne Weathersby, Environmental Chemistry Branch, EL, ERDC, performed explosives analyses. The Soil Testing Laboratory, Geotechnical and Structures Laboratory, ERDC, performed physical analysis of the soil. Dr. Laura Inouye, EL, ERDC, performed the toxicological analysis of the soil. We gratefully acknowledge the technical assistance provided by Dr. Altaf Wani and Ms Brenda O'Neal, Applied Research Associates, Inc., Dr. Sangchul Hwang, Johns Hopkins University, and Ms. LeAnn Brooks and Mr. Tim Ruff, Mississippi State University students. We also wish to acknowledge the gracious participation of Drs. Tom Jenkins and Tom Ranney, Cold Regions Research Environmental Laboratory (ERDC-CRREL-NH), and Dr. Judy Pennington, ERDC-EL, in sharing soil samples obtained from active military training ranges and for their helpful discussion of the results. Mr. Richard A. Price, ERDC-EL, generously contributed the soil from Nebraska Ordnance Plant.

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COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Explosives-related contamination was believed to primarily reside at production and handling facilities, where contamination resulted from past production operations. However, it has become apparent that explosive contamination extends beyond the boundaries of production facilities and includes 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 contaminants is essential for range management and sustainability (Borthwick and Beshore 2000; Jones et al. 2002).

Jenkins et al. (1997, 2001) and Pennington et al. (2001, 2002) have demonstrated that the explosives contamination on military training ranges is a potential environmental concern. These studies, performed on ranges in both the United States and Canada, have shown that there is a large degree of variability in contamination type, concentration, and spatial distribution, both across a single range and between different ranges. Companion research has found that many of the explosives and energetics occurring on these ranges have slow dissolution rates and low partition coefficients and a high potential for long-term contamination of ground and surface water (Brannon and Pennington 2002). The energetic compounds, such as 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), and their degradation products, lying on and near the surface (less than 1 ft below ground), are the primary source for contamination on Department of Defense training ranges. While the concentration of individual contaminants on live-fire training ranges is generally at low levels, the contaminant dispersion after a detonation is often widespread. Pennington et al. (2002) reported finding soil contamination in areas with no visible impact craters that was as high, or higher, than that in soils on the crater rim. Unexploded ordnances (UXO) and low-order detonations are discrete, point sources of contamination with contaminant concentrations possible in the percent range in the immediate vicinity of the armament.

A treatment technique suitable for successful remediation of distributed energetics contamination on training ranges will have these characteristics:

- a. Inexpensive.
- b. Easily applied in remote locations.

- c. Effective on heterogeneous contaminant distributions.
- d. Effective over wide areas.
- e. Effective on multiple energetic compounds.
- f. Nonintrusive, to the extent possible.
- g. Capable of being able to be incorporated into normal range operations.

Treatment of these areas using current *ex situ* technologies is cost prohibitive, and treatment using current *in situ* biological methods has yet to be effectively demonstrated at field-scale and may inhibit normal range operation. The use of alkaline material has the potential to treat the source zone contamination and prevent transport of the contaminants into the groundwater.

Alkaline hydrolysis has previously been shown to degrade nitroaromatics and nitroamines in solution. Preliminary results for TNT indicated that, in water, the hydroxide ion and the energetic material reacted rapidly to form water soluble polymeric residues and low molecular weight degradation products. Base hydrolysis has been established at bench-scale as a promising technology to eliminate explosive contamination in water systems. It has been studied as an *ex situ* treatment technique for groundwater remediation. The potential effectiveness of lime to induce this reaction has also been demonstrated on soil contaminated with TNT at the laboratory scale. Slower reaction rates were observed in soils, and are likely due to the slow rate of TNT desorption from the soil-solid and TNT-crystalline phase into the hydroxyl laden pore water. The research presented here examines both basic and applied aspects of alkaline application as a means of reducing the explosives and energetics source zone contamination that may be found on live-fire ranges. It is not known how RDX, with its lower soil adsorption, will react with hydroxide in the soil pore water. Transformation of energetics through contact with alkaline pore water prior to migration into groundwater is also expected to prevent the migration of the surface contamination into the groundwater.

Microcosms were used to study the effect of various soil physical and chemical characteristics (such as pH and organic matter content) and explosive characteristics (such as unsorbed particles) on the alkaline hydrolysis reaction. Soil samples from various ammunition plants and training ranges were used to provide a variety of realistic contamination situations and soil types.

Mesocosms were filled with soil from a single contaminated site. It is possible that different sources of alkalinity will have different reaction rates and different interactions with the soil. Therefore, various alkaline materials were evaluated including quicklime, hydrated (slaked) lime and Class C fly ash. The effects of topical application on the removal of the energetic contaminants from soil and the transport of the contaminant through the soil into the leachate were compared to the results obtained when the alkaline material was thoroughly mixed into the soil. In order to evaluate the process effectiveness under differing site scenarios, several additional treatments were evaluated:

- a. Topical application of an aqueous alkali solution.

- b.* Effects of acid rain on the base-induced reaction.
- c.* Low lime application rates.
- d.* High rainfall situations.

2 Literature Review

Contamination by Explosives on Training Ranges

Contamination

Most explosives-contaminated soils found on training ranges contain a mixture of compounds. These include TNT, RDX, and HMX, and their metabolites (Figure 1). Selected physical characteristics of these compounds are summarized in Table 1.

Because of its ubiquitous use as a military explosive in many nations, TNT is a well-characterized explosive; however, RDX is considered to be the most important military explosive in use today (Gorontzy et al. 1994). Funk et al. (1993) and Binks et al. (1995) estimated that, as of their publication dates, at least 28 sites in the United States and 200 areas in Germany, respectively, were contaminated with RDX. Many of these sites also have groundwater contamination or have the potential for groundwater contamination (Adrian and Sutherland 1999).

Jenkins et al. (2001) and Pennington et al. (2001, 2002) have detailed the occurrence of higher-order explosives (TNT, RDX, HMX), and their degradation products, on Department of Defense test and training ranges. They presented evidence that the soil contamination on live-fire ranges:

- a. Is spatially heterogeneous both within and between ranges.
- b. Involves a variety of compounds and their degradation products.

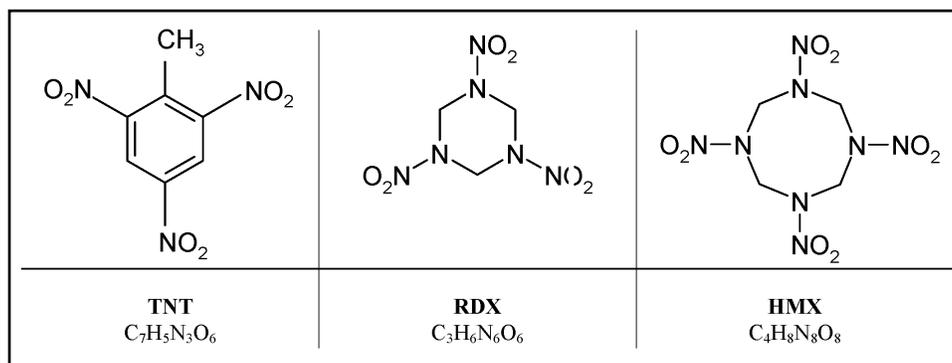


Figure 1. Structures of energetic compounds TNT, RDX, and HMX

Table 1 Selected Physical and Chemical Characteristics of RDX, HMX, and TNT¹			
Parameter	RDX	HMX	TNT
Empirical Formula	C ₃ H ₆ N ₆ O ₆	C ₄ H ₈ N ₈ O ₈	C ₇ H ₅ N ₃ O ₆
Molecular Weight (g/mol)	222.26	296.2	227.13
Aqueous Solubility (mg/L)	28.9 ± 1.0 (10°C) 44.7 (18°C) 42.0 (20°C) 43.2 (23 ± 2°C) 59.9 ± 1.2 (25 ± 0.2°C) 75.7 ± 1.1 (30°C)	1.21 ± 0.04 (10°C) 2.6 ± 0.01 (20°C) 5 (22-25°C) 5.7 ± 0.1 (30°C)	51.3 (6°C) 64.0 (12°C) 88.5 (20°C) 100.5 (25°C) 204.5 (42°C)
Biotransformation/ Biodegradation	Aerobic degradation is limited in water and soils. Significant anaerobic cometabolism. Transformation products include methanol, hydrazine, formaldehyde, dimethylhydrazine (1,1-, 1,2-). Biodegradation occurs under anaerobic conditions.	Aerobic degradation is negligible. Anaerobic degradation slow; but accelerated kinetics in the presence of primary substrate (cometabolism). In waste stream effluent treated with yeast, T _{1/2} = 17 hr and 1.6 hr, for aerobic and anaerobic conditions, respectively. Removal from 22 ppm to <0.05 ppm in 11 days was seen under sulfate-reducing, nitrate-reducing, fermenting, methanogenic, and mixed electron-accepting conditions with enrichment cultures from anaerobic digester sludge.	Major process in surface and groundwaters, significant in soils but slow rates. Successive reduction of nitro to amine groups is most common. A few reports of microbial growth on and mineralization of TNT via elimination reactions. These microorganisms use TNT as the sole nitrogen, and carbon source. Estimates of the half-life in groundwater: 12 mo to 4 weeks. Products: hydroxyamino and azoxytoluene compounds. TNT transformed in soils and other media under both aerobic and anaerobic conditions in 19 to 25 days

¹ Extracted from: McGrath (1995), Brannon and Pennington (2002).

c. Shows concentrations that vary from barely detectable to the percent range.

For example, Pennington et al. (2001, 2002) reported both concentric concentration patterns roughly centered on impact craters and also detectable levels of explosives on soil surfaces at points widely separated from the impact crater. When the explosive was completely detonated, the concentrations on the surface were low, ranging from 0.5 to 1.0 mg/kg. However, incompletely detonated charges (low-order) formed a point source in the soil, some of which had explosive concentrations as high as 1.5 percent.

In the 1980's, Pennington (1988) first suggested that crystalline TNT is likely present at many sites and acts as a constant source of contamination of soil and groundwater. The combination of a high, but reversible, sorption coefficient, the high water solubility of TNT (Table 1), and the magnitude of contamination at many sites, results in a high potential for continuous percolation of contaminated water from surface and near-surface sources through the unsaturated zone to the groundwater. Although RDX is less water soluble than TNT, it also has a lower soil adsorption potential, which leads to an even greater potential for

migration to, 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.

Toxicological experiments on RDX were begun in the 1940s, studies on HMX even more recently. Only in the past decade have the environmental toxicological effects of explosive mixtures in soil and water been studied (Berthe-Corti et al. 1998). The classification of RDX as a Class C carcinogen (possible human) has been primarily based on research with mice (United States Environmental Protection Agency, Integrated Risk Information System (USEPA-IRIS) 1998a). HMX is classified as a Group D carcinogen (not classifiable), because no cancer bioassays, epidemiological studies, human studies, or chronic animal studies are available (USEPA-IRIS 1998b). TNT is considered to be both mutagenic and carcinogenic, Class C (Agency for Toxic Substances and Disease Registry (ATSDR) 1995) and the USEPA has listed TNT as a priority pollutant (USEPA-IRIS 1997). In summary, TNT is currently considered to be the most environmentally toxic of the energetic compounds studied. RDX is less toxic to human and environmental health than TNT, but more toxic than HMX. HMX environmental and health effects are largely unknown.

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, biotic and abiotic transformation rates, photolysis and volatilization. In general, there is much less published research on fate and transport processes of RDX and HMX than for TNT. Less is known about the sorption characteristics of the RDX transformation metabolites.

It has been recently recognized that abiotic reduction may provide mechanisms to transform not only the parent explosives, but also any toxic intermediates generated by reductive transformation of the parent compound. Hoffsommer et al. (1977), in their studies of alkaline hydrolysis of RDX, proposed a single, initial denitration step that eventually caused ring cleavage. Balakrishnan et al. (2003) have examined the alkaline hydrolysis of RDX, MNX, HMX and the new polycyclic nitramine, 2,4,6,8,10,12-hexanitro-2,4,6,8,10,12-hexaazaisowurtzitane (CL-20) in solution and identified new intermediates in the degradation pathway. They believe their work provides evidence that the initial denitration of the parent nitramine in aqueous solution is sufficient to break open the ring. The ring cleavage products spontaneously decompose to form the known end products, nitrite (NO₂), nitrous oxide (N₂O), N₂, ammonia (NH₃), formaldehyde (HCHO), formic acid (HCOOH), and carbon dioxide (CO₂). In addition, researchers have proposed coupled biotic and abiotic processes (Heijman et al. 1995), such as abiotic reduction coupled to the biological reduction of iron by iron-reducing bacteria. The continuous supply of reducible iron (acting as a reductive equivalent shuttle) enhances the activity and growth of the iron reducing bacteria (Dunnivant and Schwarzenbach 1992).

Current Remediation Strategies

Rodgers and Bunce (2001) and the Federal Remediation Technologies Roundtable (FRTR 2003) have summarized current technologies available for the remediation of explosives-contaminated soil. Most of these processes were developed and tested only with TNT. The performance of the technology with other explosives, metabolites, and/or mixed explosive compositions is unknown. One *in situ* process that was reviewed favorably is enhanced bioremediation. The length of time required for cleanup was considered a drawback. *Ex situ* technologies received better reviews, including the biological processes, composting and slurry phase treatment, and the thermal treatments, incineration, open burn/open detonation, and thermal desorption. All of these are fully developed and commercially available technologies. Inherent in all *ex situ* processes is the required excavation and transport of the contaminated soil with the associated health and safety risks. These systems are often part of a treatment train and, as such, are expensive to initiate and often produce residuals that must be treated in turn.

As in soil remediation, current technologies to treat explosives-contaminated water (groundwater, surface water, and leachate) have focused on TNT, with little consideration of other explosive compounds or mixed waste streams. Passive/reactive treatment walls, of the *in situ* treatment processes, received a favorable review. The stand-alone technology is widely available from several commercial vendors and has a good reliability rating. The length of time required for effective treatment is considered a drawback. *Ex situ* biological processes for treating groundwater include bioreactors and constructed wetlands, both of which produce residual metabolites. Bioreactors are widely available, have good reliability, but are expensive. Constructed wetlands are not as widely available and cleanup times and effectiveness are determined by site-specific constraints. One physical/chemical *ex situ* process, advanced oxidation, received promising reviews and is widely available. The use of granular activated carbon (GAC) cartridges coupled with a pump-and-treat system is also widely used for treatment of explosives-contaminated liquid. An innovative cartridge regeneration method using alkali treatment has been reported by Heilmann et al. (1996).

In summary, there are no available technologies that can effectively remediate or prevent the wide range of type, concentration, and distribution of energetic contamination currently found on active training ranges. There is also no available technology to prevent transport of the explosives into the groundwater.

Alkaline Hydrolysis of Explosives

Aqueous treatment

Janowsky (1891) first established the transformation of TNT in basic solutions. The need for a simple and economical treatment technology for application to ranges and explosives/energetics production facilities was the impetus for more recent studies in alkaline destruction of explosives and energetics. Saupe and Wiesmann (1996) conducted flask experiments under high alkaline

conditions (pH 14) that resulted in complete TNT transformation and partial mineralization. Saupe et al. (1997) studied the alkaline hydrolysis of TNT at elevated temperatures. A dark-brown hydrolysate was noted after adding sodium hydroxide to TNT solutions. Polymerization above 60 °C was noted by increased molecular size in the organic fraction, and solids precipitated out of solution at, and above, 200 °C with this method. A Meisenheimer or charge transfer complex was postulated.

In work using hydrated lime, (calcium hydroxide, $\text{Ca}(\text{OH})_2$), Arienzo (1999) reported complete removal of TNT from soil in 10 min with the application of 1 percent $\text{Ca}(\text{OH})_2$. In recent studies, Emmrich (1999, 2001) also treated TNT and RDX in solution and soils with calcium hydroxide at 20 °C. Nitrite and nitrate formation were reported as end products.

Felt et al. (2001a and b, 2002) and Hansen et al. (2001) studied the alkaline hydrolysis of explosives in solution as a first step in establishing the feasibility of chemical remediation of firing ranges as well as former munitions plants. They found that using a TNT concentration of 25 ppm, and a pH of 10, one-half of the TNT was removed in 24 hr. Nearly instantaneous removal of TNT was achieved when the pH of the solution was increased above 11. The addition of NaOH resulted in a 4- to 7-fold reduction in the acute toxicity of TNT solutions, based on Microtox® tests with *Vibrio fischeri*.

Felt et al. (2001b) also established that several unidentified product compounds were formed in a sequential manner during alkaline hydrolysis of TNT. The authors employed universally labeled TNT in a reaction that was run to completion and then characterized the final products of the reaction by both chemical reactivity and molecular size. They found that 98 percent of the products were polar compounds. The majority of the nonpolar compounds were smaller than TNT. Mass balance calculations appeared to indicate that, as well as cleavage of the methyl groups from the nitroaromatic ring, there was cleavage of the ring itself during the reaction of TNT with the hydroxide. Significant amounts of the final products of the TNT-hydroxide reaction were large molecular weight molecules possibly formed by TNT polymerization. While TNT polymerization has been established under alkaline conditions at high temperature (Saupe et al. 1997), results from Felt et al. (2001b) may indicate that polymerization also occurs at ambient temperature. Large molecules, such as those reported, may be less likely to transport into groundwater, effectively stabilizing the contamination. Hansen et al. (2001) found the final products of the alkaline hydrolysis of TNT to be less toxic than the parent compound, which could be a result of larger molecular size, leading to a potentially lower bioavailability.

Compared to the abundance of research examining the alkaline hydrolysis of TNT, much less work has examined the reactions of RDX and HMX. Hoffsommer et al. (1977) reported the kinetics of the aqueous alkaline hydrolysis of RDX at temperatures between 25 and 45 °C, normal pressure, and hydroxide ion concentrations between 0.02 and 0.2 molar (M). They found that intermediates formed by ring cleavage of the nitramine continued to react with the hydroxide ion. One reaction end product formed was nitrite. They also stated that reaction products were formed based on the hydroxide ion concentration.

Heilmann et al. (1996) demonstrated alkaline hydrolysis of RDX and HMX across a pH range of 10 to 12 as a potential treatment technology for disposal of surplus munitions. Results indicated that both HMX and RDX are susceptible to degradation by alkaline attack. Balakrishnan et al. (2003) examined the degradation intermediates and end products produced by alkaline hydrolysis of RDX and HMX in solution at $\text{pH} \geq 10$. They present evidence that the initial step in alkaline hydrolysis is denitration of the ring, which causes ring cleavage and is followed by spontaneous decomposition. RDX, HMX, and MNX all formed nitrite (NO_2), nitrous oxide (N_2O), nitrogen (N_2), ammonia (NH_3), formaldehyde (HCHO), formic acid (HCOOH), and carbon dioxide (CO_2), nontoxic compounds typical of microbial degradation processes. Balakrishnan et al. (2003) confirmed that HMX is degraded at a slower rate than RDX, but this rate increases as the pH is raised. End products were confirmed at pH 12.3. In contrast to research using aqueous systems, Garg et al. (1991) discussed the use of alkaline hydrolysis for destruction of explosives found in lagoon sludge.

Soil treatment

Soil slurry microcosms (5 g soil in a 40-mL vial) confirmed the explosives loss by alkaline hydrolysis first observed during aqueous studies (Hansen et al. (in preparation)). TNT was removed rapidly from soil (<24 hr) when challenged with base exceeding pH 10.5. RDX was removed less rapidly, but still in less than 24 hr. The reaction is relatively insensitive to temperature in that it proceeds at temperatures as low as 0 °C, although at a slightly slower rate, and soil moisture can be as low as 33 percent (mass:mass). These microcosm results were validated by using a larger mass of soil (2,000 g) mixed with 5 percent hydrated lime. The base-induced transformation reaction did not proceed as rapidly in these bench-scale experiments as in the microcosms. The TNT was removed in a reaction with a calculated half-life of approximately 7 days.

Alkaline Amendments

Formulations and use

Amendments used to raise the pH in liquid and soil systems conventionally include metal oxides, hydroxides, and carbonates. These materials have been used in a variety of applications, including domestic water treatment, industrial wastewater treatment, acid mine drainage treatment, and agricultural soil treatment. Table 2 presents a survey of the various amendments that have been historically used. In general, metal carbonates do not raise the pH as high as the metal oxides and hydroxides as a result of carbonate chemistry limitations. Furthermore, upon dissociation in the aqueous phase, the oxides in metal oxides are converted to hydroxides, in some cases by very exothermic reactions.

Amendment	Common Name	Solubility	pH	Application(s)
CaCO ₃	Calcium carbonate, chalk	<0.1%	8	Manufacturing of paint, rubber, plastics, pharmaceuticals, and others; agricultural soil amendment
CaO/Ca(OH) ₂	Calcium oxide, quicklime, calcium (di)hydroxide, hydrated lime	0.18 g/100 mL	12.5	Wastewater treatment, fertilizers, manufacturing of paint, rubber, construction industry
MgO/Mg(OH) ₂	Magnesium oxide/hydroxide, milk of magnesia	0.076 g/L	10.3	Manufacture of medications, refractory crucibles, fine bricks, and water treatment
NaOH	Sodium hydroxide, lye	111g/100g water	14	Chemical, industrial, construction, and agricultural applications
KOH	Potassium hydroxide, caustic potash,	110g/100 mL water @25 °C	13.5	Used in soaps, fertilizers, electroplating, and chemical manufacturing
Fly ash	Boiler ash	<2%	9-12	Used in many construction capacities, an additive in concrete and pavements
K ₂ CO ₃	Potassium carbonate, carbonic acid, Potash	112g/100 mL water @ 20 °C	11.6	Glass, ceramic explosives, fertilizer production, dyeing, and wool industry

There are different formulations of lime, derived from calcination of limestone, available for agricultural and engineering use, each having different chemical and physical properties (Jones 1979). The two major classifications are the dolomitic (35 to 46 percent magnesium content) and calcitic (primarily calcium-based) lime. The calcitic limes, hydrated lime (Ca(OH)₂) and quicklime (CaO), are used primarily in engineering applications. Quicklime is typically used in construction and geochemical applications. Fly ash, a by-product of coal combustion, contains a number of metals and metal oxides. It also has been used in construction and geotechnical applications. As designated in American Society of Testing and Materials (ASTM) Method C 618 (2003), Class C fly ash contains at least 30 percent calcium oxide as well as silica, aluminum, and iron oxides up to 50 percent. Because it contains these metal oxides, fly ash may potentially be an inexpensive source of alkaline material. It has been demonstrated that fly ash can immobilize internal and added metals and prevent leaching into the environment (Mehta 1998). Hydrated limes, used in water and wastewater treatment situations, often demonstrate slightly different dissolution rates depending on the manufacturing formulation (Robinson and Burnham 2001). Agricultural lime is composed from either limestone, chalk, burnt lime, hydrated lime, or a mix of these materials, which are either calcium or magnesium based and have a hydroxide content sufficient to neutralize soil acidity. In addition, each of these compounds is available in particle sizes ranging from pulverized to granular. In general, the greater the surface area, the more effective at raising the pH, therefore, dust formulations are more effective than granular formulations. Granules are, however, longer lasting in the soil and easier to handle. Because of the tendency for dusts to spread out from the point of application, the preferred application method is land spreading. Granular formulations perform well under aerial application, with a minimum of over-spreading. In choosing a particular alkaline material, the factors that need to be considered are

the desired pH, chemistry of the particular lime species, the type of application process being used, the efficiency and effectiveness required in raising the pH, and the cost.

The changes that occur in soil chemistry as a result of liming are because of the decrease in the hydrogen ion (H^+) saturation, which increases the effective cation exchange capacity of the soil (Kamprath and Foy 1985). Aluminum is typically grouped with the hydrogen ion as a source of soil acidity (Skousen et al. 1990) because its solubility depends on pH. At high pH, aluminum precipitates from solution as hydroxide-aluminum polymer complexes. The aluminum concentration in the soil potentially affects the rate of the alkaline hydrolysis reaction and, therefore, the treatment of the explosives contamination.

Fate and transport

Under topical applications of lime, the fate of OH^- ions during transport through the soil will presumably be an important aspect of this proposed remediation technology. The alkaline hydrolysis reaction occurs in the aqueous phase. Therefore, in an environmental remediation situation, the amendment placed on top of or mixed into the soil, must first dissolve into the soil pore water before the reaction can take place. Once dissolved, OH^- ions can then interact with the explosive contaminants, also in the aqueous phase. Advective and dispersive processes will transport the metal (i.e., Ca^{2+}) and alkaline ionic (i.e., OH^-) species. Metal cations will undergo ion exchange with other cations sorbed at exchange sites in the soil, including hydrogen (low pH soils) and aluminum (high clay soils). It is only once they have been displaced from the exchange sites by the amendment metal ions (Ca^{2+}), that they may interact with the OH^- ions. This inhibits the alkaline hydrolysis of the explosive contaminants by neutralizing the OH^- ions, effectively buffering the system. Base cations can also interact with the OH^- ion to form insoluble hydroxides, again removing them from potential contaminant 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 contaminants. Soil chemistry will therefore play an important role in energetics remediation through alkaline hydrolysis.

The addition of lime to soil by either surface application (top dressing) or mixing (plow) is a well-established agricultural practice for increasing the pH of acidic surface and subsurface soils. In an assessment of the relative efficacy of various alkaline sources, Smith et al. (1994) reported limited leaching of topically applied lime through the soil profile. The effects on the exchangeable soil cations were seen in the top 5 cm of the soil within the 18-month study period. The Agricultural Lime Association (ALA) surface liming recommendations are based on a soil depth of 15 to 20 cm.

The effect of hydroxide consumption by soil cations has also been studied in the oil industry for years, where it is a factor in caustic flooding during oil recovery operations (Breit et al. 1979; Somerton and Radke 1980). The hydroxide ions were bound by the cations (Ca^{2+} and Mg^{2+}) in the sediment. The use of softened, preflush water improved the performance of the caustic flood by

displacing these divalent ions and minimizing the reactions between the hydroxide and the cations. In other work, DeZabala et al. (1980) reported that a cation exchange capacity (CEC) of as little as 1-mequiv/100 g porous media could retard alkali migration in alkaline flooding operations. For this reason, the authors concluded that alkaline flooding should be conducted at elevated pH values to prevent significant OH^- retardation by ion exchange processes.

Collectively, these studies provide evidence of potential transport limitations of hydroxide ions in soils, particularly those with significant clay content. In the case of well-mixed lime applications for remediation of explosive-contaminated soil, transport of the hydroxide ion is over a comparatively small range and should not be a significant factor in the alkaline hydrolysis reaction. Topical and well-mixed lime applications can each have a useful remediation role, especially in light of the widely dispersed, heterogeneous distribution of expended munitions on training ranges.

3 Materials and Methods

While TNT destruction by alkaline hydrolysis has been established in both aqueous and soil systems, the same cannot be said for the destruction of RDX and HMX. This indicates a need for further basic and applied research before the technology is introduced into the field. We performed basic research at microcosm scale, first examining the effect of lime dose (treatment pH), soil organic matter, and the presence of explosive particles on alkaline hydrolysis in a soil contaminated naturally with a mixture of explosive compounds. Secondly, to confirm the efficacy of alkaline hydrolysis in field contaminated soils having a range of soil chemistry, we treated a variety of munitions plant and range soils at microcosm scale. Follow-on applied research was performed in mesocosms using contaminated soil from one site and evaluating the effectiveness of various hydroxide sources and application methods.

Microcosm Study

Objectives

The first objective of the microcosm experiments was to study the effect on the alkaline hydrolysis reaction of:

- a.* Lime dose (treatment pH).
- b.* Soil organic matter content.
- c.* Presence of particles of explosive material.

The second objective of the microcosm experiments was to evaluate the efficiency of the alkaline hydrolysis reaction under a variety of soil chemistries, each contaminated with mixtures of different energetic materials.

Experimental design

The experimental design for the microcosm portion of the study is outlined in Table 3. Three parameters were examined for their effect on the alkaline hydrolysis of explosives: lime dosage (treatment pH), organic matter concentration, and particulate contamination. Unless stated otherwise, the initial microcosm tests were performed using Nebraska Ordnance Plant (NOP) soil as the

Test	Variable¹	Total Sacrificial Samples	Contaminant Source	Soil
Treatment pH	0%, 1%, 3%, and 5% lime	48	NOP soil	NOP
Soil organic matter	0%, 1%, 5%, 10%, and 100% organic matter	72	Radiolabeled RDX	Clean sand and peat moss
Explosive crystals	RDX crystal, whole TNT grain, broken TNT grain	36	Explosives crystals	NOP
Site soils	Soil geochemistry and contamination	306	Site soil	17 different sites

¹ Percentages listed are expressed as the ratio of alkaline material mass or organic matter mass to the soil mass.

reference soil and hydrated lime (application dosage of 5 percent) as the alkaline source. The tests were run at a soil moisture content of 50 percent (water:soil). All energetic compounds identified under SW 846, Method 8330 (1994) were evaluated.

Additional microcosm tests treated 17 soils from ammunition plants and firing ranges. These soils provided a wide range of explosives contamination and soil chemistry to evaluate the efficiency of the reaction. The alkaline source and moisture conditions were also 5 percent hydrated lime and 50 percent moisture, respectively, based on the results of previous soil work (Hansen et al. 2003). Future work will refine these parameters.

Microcosm materials

Microcosm experiments were performed in 40-mL amber vials (VWR Scientific Products, Inc.). Chemicals used in the explosives extraction and analyses were HPLC/GC grade, purchased from Burdick & Jackson or J. T. Baker. Deionized water was produced by filtration through a Millipore “MilliQ” or a Barnstead-Thermolyne system.

The RDX tracer used in the evaluation of organic matter effects portion of this study was universally labeled ¹⁴C-RDX with a specific activity of 0.98 µCi/µmol RDX (New England Nuclear, MA). The samples were counted in Ultima Gold scintillation cocktail (Packard Instruments Company, Meridian, CT) on a liquid scintillation counter (Packard Instruments model 2500 TR). The counter was equipped with a barium external source to enable correction for machine efficiency. Vials were counted twice for 2 min. Unlabelled RDX and TNT were obtained from Hallston Army Ammunition Plant (Kingston, TN).

A list of the range and ammunition plant soils, the abbreviations used in this report, a site description, and the major contaminant(s) is summarized in Table 4. Several pertinent soil chemistry parameters are listed for the site soils in Table 5. Soil from the NOP was used in the site survey, serving as the base soil for the contaminant type and the lime dosage study. The NOP soil was also used

Table 4 Summary of Microcosm Site Soils			
Site	Abbr	Contaminant(s)	Site Description /Primary Contaminant(s)
Nebraska Ordnance Plant	NOP	RDX	A former load & pack facility, the composite sample was collected from the wash area.
Lake Ontario Ordnance Works	LOOW	TNT	A former manufacturing plant. A composite sample was removed from the upper waste pipeline.
Crane Firing Range	Crane	RDX	An open-detonation disposal facility.
Volunteer Army Ammunition Plant	VAAP	RDX	Former RDX and TNT manufacturing plant.
Iowa Army Ammunition Plant	IAAP	TNT/TNB	Former TNT munitions load and pack facility.
Fort Lewis – firing origin point	FLFP	DNT	Approximately 575 rounds/gun of 105-mm howitzer fired from this point.
Fort Lewis – impact area	FLI	RDX	Impact area with scattered, spent howitzer rounds. The contamination is low concentration.
Fort Lewis – grenade surface soil	FLGS	RDX	Soil collected from the surface around an M67 hand grenade.
Fort Bliss	FB	TNT	A composite sample collected around a low order 155-mm howitzer round that showed explosive particles present.
Fort Wainwright	FW	RDX	A composite sample taken at an M67 hand grenade range, approximately 20 m from the throwing point.
Camp Guernsey, site 32	GC32	TNT	A composite sample taken in a 3-m-radius circle around an unexploded 500-lb bomb before clearing detonation.
Camp Guernsey, site 48	GC48	RDX	A composite sample taken in a 5-m-radius circle around an unexploded 155-mm howitzer round following detonation using C4.
Camp Guernsey, site 51	GC51	TNT	A composite sample taken after detonation using C4 of the bomb fragment from sample site 48.
Camp Guernsey, site 52	GC52	TNT	A duplicate of GC51
Yakima Training Center, Site 1	YC1	RDX	A composite sample taken from an anti-tank range around an APC target. The ordinance was LAW and AT-4 rockets and 40-mm rifle grenades. Site 1 was collected within 2 m of the target.
Yakima Training Center, Site 2	YC2	RDX	A duplicate of YC1.
Yakima Training Center, Site 4	YC4	HMX	A composite sample taken from 2 to 5 m of the target.

in the mesocosm study. Because of its wide use in this study, a detailed summary of the NOP soil characteristics are shown in Tables 6, 7, and 8. Range and ammunition plant soils were obtained through Dr. Judy Pennington, Dr. Steve Larson, and Mr. Richard A. Price (ERDC-EL, Vicksburg) and Dr. Tom Jenkins (ERDC-CRREL, Hanover).

Table 5 Microcosm Study - Selected Soil Chemistry Parameters				
Soil	Initial pH	Treatment pH 5% lime	CEC	Organic Matter¹ %
NOP	4.54	11.33	42	6.4
VAAP	5.90	11.39	20	7.4
IAAP	6.09	11.28	10	1.2
LOOW	6.21	10.95	15	11.3
Crane	6.03	10.76	8	14.1
FB	7.99	12.49	14	nd
FLI	7.02	12.52	38	7.4
FLFP	4.98	10.96	47	11.3
FLGS	7.56	12.48	7	0.3
FW	8.10	12.80	4	nd
YC1	6.65	12.65	23	2.3
YC2	7.16	12.67	22	2.3
YC4	6.91	12.68	24	2.3
GC32	7.96	12.48	26	nd
GC48	7.26	12.69	24	nd
GC51	7.43	12.68	26	nd
GC52	7.83	12.42	26	nd

¹ nd = not determined, due to insufficient soil.

Table 6 Initial Explosives Concentration of NOP Soil	
Explosive	Concentration, mg/kg
RDX	38.35 ± 3.82
HMX	4.40 ± 0.30
TNT	10.79 ± 6.99
TNB	2.71 ± 0.56
4A/2A-DNT	0.11 ± 0.02

Table 7 Selected Nutrient and Metal Concentrations in NOP Soil			
Sample	Concentration mg/kg	Sample	Concentration mg/kg
<i>ortho</i> -phosphate	25	Aluminum	24,500
Ammonia	7	Calcium	2,900
Sulfate	20	Iron	21,600
Nitrate/nitrite	4	Magnesium	4,500
Chlorine	30	Potassium	4,900
Bicarbonate	<20	Sodium	90

Test	Result		
Liquid limit	47	% gravel	0.0
Plastic limit	23	% sand	4.7
Plasticity index	24	% fines	95.3
Soil classification	108: clay (CL), gray; trace of sand		
pH	4.54	% FOM	6.4
CEC	42	Specific gravity	2.64

Microcosm methods

For each test, 5 g of dry soil was placed in a 40-mL amber vial. The alkaline source was added, if required, and the contents mixed manually until visual inspection showed a homogeneous distribution of the lime throughout the dry soil. Tap water was used as the water in this study and in the later mesocosm study because, when the treatment is taken to the field, each site will use the local water source. The tap water was tested for pH and hardness to evaluate its effects on the alkaline hydrolysis reaction. It was added to bring the moisture content of the soil to 50 percent. The vials were mixed at this point, and daily thereafter, for 1 min with a Vortex mixer. Triplicate sacrificial samples were taken at $t = 0, 1, 3, 7, 14,$ and 21 days and extracted in acetonitrile, according to methods specified in SW 846, EPA Method 8330 (1994).

Effect of lime dose/treatment pH

The influence of treatment pH on the alkaline hydrolysis of energetic contaminants was examined. To achieve a gradient of pH, hydrated lime dosages of 0, 1, 3, and 5 percent (w:w, lime:dry soil) were used. These dosages equate to topical applications of approximately 44 to 220 metric tons per hectare, assuming a treatment depth of 30 cm. The normal range of application rates, as published by the ALA, is 2 to 29 metric tons per hectare depending on the organic matter content of the soil, the target pH, and the application method (mixed by plow or field surface dressing).

Effect of soil organic matter

The influence of organic matter concentration was examined using clean Ottawa sand amended with peat moss to yield organic matter concentrations of 1, 5, and 10 percent. The solids in each vial (5 g) were amended with hydrated lime (5 percent), except the controls. The sand, sand/peat moss, and peat moss mixtures were spiked with ^{14}C -RDX (0.016 $\mu\text{Ci}/\text{test}$). Tap water (8 mL) was added to each vial. The contents were mixed at this point for 1 min on a Vortex mixer and once daily thereafter. Triplicate sacrificial replicates were taken at 0, 1, 3, 7, 14, and 21 days. The vials were centrifuged for 10 min at 2,000 rpm. The supernatant was decanted and measured, and 1 mL was removed to a scintillation vial for beta emission analysis.

Effect of particulate explosive contamination

The influence of energetic particulates on alkaline hydrolysis was studied using crystalline RDX and grains of TNT added to NOP soil. The TNT grain was covered with a plasticizer (phthalate ester). Both whole and broken grains of TNT were examined separately and added to the NOP soil in the microcosms at a concentration of 0.5 percent (particle: soil). The mass of energetic particles added to each vial was equal to 5 percent of the soil mass (NOP soil) and was treated with 5 percent hydrated lime.

Effect of different soil chemistry and explosives mixtures

The influence of various soil characteristics and explosives contaminant mixtures on alkaline hydrolysis was examined using soils collected from training ranges and ammunition plants with a variety of characteristics. The experimental soil was mixed with 5 percent hydrated lime and sampled as above. The soils were also tested for pH, CEC, and flammable organic matter (FOM). Analysis methods are detailed in text under subheading entitled Analysis Methods. Appendix A presents Microcosm Data.

Mesocosm Study

Objective

The objectives of the mesocosm study were to:

- a. Evaluate several alkaline sources for their efficiency in achieving and maintaining the desired soil pH for the time required for transformation of the explosives.
- b. Evaluate application methods, topical, mixed, and liquid on the efficiency of the alkaline hydrolysis reaction.
- c. Study the effect of alkaline source and mode of application on contaminant transport into the leachate.
- d. Determine the extent to which selected environmental parameters such as amount of precipitation and pH (acid rain), would affect the alkaline hydrolysis reaction.
- e. Determine the existence of any scale-up factors that would need to be considered before taking the technology to the field.

Experimental design

The mesocosm studies were designed to provide information critical to field applications of the technology and provide an early indication of any scale-up problems. The experimental design of the larger-scale mesocosms is shown in Table 9. The lime dose used in the mesocosm-scale study was set at 5 percent based on results of the lime dosing study from the microcosms. A total of

**Table 9
Experimental Design for Mesocosm Remediation of Energetic-Contaminated Soil by Alkaline Treatment**

Mesocosm	Treatment	Alkalinity Type	Application Method	Application Amount, alkaline mass/soil mass	Applied Water cm/week
1	Control	None	None	0	1.3
2	Full test	Hydrated lime	Topical	0.2%	1.3
3	Full test	Hydrated lime	Topical	5%	1.3
4	Full test	Hydrated lime	Topical	5%	2.5
5	Full test	Quicklime	Topical	5%	1.3
6	Full test	Hydrated lime	Topical	5%	1.3 Acid, pH 4
7	Full test	Class C fly ash	Topical	5%	1.3
8	Full test	Aqueous hydrated lime	Topical	Aqueous pH = 10 ¹	1.3
9	Full test	Quicklime	Mixed	5%	1.3
10	Full test	Hydrated lime	Mixed	5%	1.3
11	Full test	Class C fly ash	Mixed	5%	1.3

¹ The pH of the applied water was adjusted to 10 using hydrated lime prior to topical application on the mesocosm.

11 mesocosms were employed to study the effect of mode of application and different alkaline sources on alkaline hydrolysis of explosive contaminants in soil and contaminant transport into leachate. Six mesocosms were used to evaluate three alkaline sources and the effects of topical versus mixed application of the alkaline sources. The efficiency of topical application of a liquid alkaline source was also examined. Liquid alkali sprayed onto the munition impact areas would provide the hydroxide source and the moisture in one step while keeping personnel away from UXO hazard and was considered worth investigating before the technology was taken to the field. A low lime dose (0.2 percent) in a topical application was studied to contrast with the high lime dose (5 percent) topical application. Other mesocosms were used to investigate alkaline hydrolysis under higher flowrate (to simulate sites with high rainfall conditions) and with possible interference from acid rain which could affect some site soils.

The sampling and analysis schedule for the chemical, physical, microbiological, and toxicological assessment of the alkaline treatment of the explosives-contaminated NOP soil is shown in Table 10.

Mesocosm materials

Three types of alkaline material were evaluated in the mesocosm portion of this project. Hydrated lime and quicklime were donated from Falco Lime, Vicksburg, MS; and Class C fly ash was donated from Phoenix Cement

Soil Test	Week						
	Initial	1	2	4	10	18	26
pH	X	X	X	X	X	X	X
Explosives (8330 compounds)	X	X	X	X	X	X	X
Explosives (MNX, DNX, and TNX)		X	X			X	X
Toxicity	X						X
Aerobic heterotrophic cell count	X						X
Anaerobic cell count				X			X
Flammable organic matter (FOM)	X						X
Cation exchange capacity (CEC)	X						X
Atterberg limits/particle size distribution	X						

Company, Scottsdale, AZ. Class C fly ash was selected because it contains a higher content of calcium oxide than the other classes of fly ash. A total of 11 stainless steel pots purchased from McMaster-Carr Supply Company (57-L; 41-cm diam by 46-cm height, nominal capacity) were used to contain the contaminated soil and the various amendments. Porous polyvinyl chloride (PVC) and high-density polyester liners were purchased from Porex (Fairburn, GA). Standard 24-in. soil core liners (Forestry Suppliers, Inc., Jackson, MS) were used to sample the soil.

Mesocosm methods

Construction and assembly. The mesocosms were constructed by first drilling a hole in the bottom of each pot. In order to collect leachate draining from the soil, a bulkhead fitting (1.3-cm, nominal size) and Teflon tubing were installed as shown in Figure 2. A high-density polyethylene liner (black) was installed in the bottom of the pot, on top of which was placed a porous PVC liner (Figure 3). The liners were attached to the sides of the mesocosm with a clear



Figure 2. Assembly of the mesocosm leachate drainage system



Figure 3. Mesocosm assembly: Pot, plug, porous plastic (white), and plastic liner (black)

silicone sealant to prevent water flow around the liners. A wooden bench provided a lower level for leachate collection and secondary containment systems (Figure 4). All leachate was collected in 1-L, glass Erlenmeyer flasks sealed from the open air with Parafilm™ to reduce evaporation and carbonation from atmospheric carbon dioxide.

Contaminated soil from the NOP was mixed manually to promote homogeneous conditions and sampled to verify a homogeneous distribution of explosives prior to emplacement in the mesocosms. The initial explosives concentrations, nutrient and metal composition, cation exchange capacity, and geochemistry are reported in Tables 6, 7, and 8, respectively. The initial soil moisture content was 0 percent, having been dried and stored for several years prior to this investigation.

Before the mesocosms were filled, the porous PVC insert was saturated with water to minimize capillary effects and promote rapid drainage of leachate. Mesocosms were filled with a measured mass of the soil, which was emplaced in approximately 5- to 10-cm layers, and gently tamped to promote dense packing. When the experimental design called for mixed lime, the soil was first weighed, then a lime mass equal to 5 percent of the soil mass was thoroughly mixed, manually, with the soil prior to filling the mesocosm. When the experimental design called for topical addition, the soil was weighed and added to the mesocosm and lime applied to the surface in a final step. The soil and lime masses for the individual mesocosms are listed in Appendix B, Mesocosm Data.

Measured amounts of tap water were added to the mesocosms until an initial breakthrough leachate was achieved for each treatment. To simulate multiple rainfall events, 0.8 L of water was added twice weekly to each mesocosm using a random distribution water delivery vessel. Mesocosm 8 received water raised to pH 10 with hydrated lime. Mesocosm 6 received tap water lowered to pH 4 with hydrochloric acid to simulate the pH of acid rainfall. Mesocosm 4 received twice the amount of water added to the others (0.8 L added four times each week).

Sampling. All leachate was collected and total leachate volume was measured, first daily, and then twice weekly. The pH was measured and an explosives chemical analysis was conducted weekly. Metal analysis was performed for calcium and magnesium as indicated in the sampling schedule. The remainder of the leachate sample was archived at 0 to 4 °C. The mesocosm water budget is presented in Appendix B.



Figure 4. Final assembly of mesocosms: Benches holding soil-filled mesocosms (upper level), leachate collection, and secondary containment system (lower level)

Soil was sampled as outlined in the experimental design (Table 9). Three cores were collected from the top, middle, and bottom thirds of each mesocosm. The three cores collected from the same depth of each mesocosm were combined in 1-L amber glass jars and homogenized before subsampling for chemical, physical, toxicological, or microbiological analysis. The remaining soil was archived in the original amber jar at 0 to 4 °C. After sampling was complete, the holes left by the cores were filled with bentonite added in small increments with sufficient water for activation. The core positions were marked by closed sample tubes (approximately 3-in. long) inserted into the bentonite. Leggett (1985) examined the adsorption of TNT, DNT, RDX, and HMX onto bentonite drilling mud in slurry form. The results confirmed bentonite adsorption of these explosive compounds. However, 250 mg/L of bentonite drilling mud was required to produce a 5-percent error in analysis when the explosive was present at 0.05 mg/L concentration. At higher concentrations more bentonite was required to produce the 5-percent error. For example, explosives present at 1.0 mg/L, require 820 mg/L of drilling mud to cause a 5-percent error. Considering the high concentration of RDX in our study (38.35 ± 3.82 mg/kg), this was an acceptable value. Also, many of Leggett's experiments were run between pH 8 and 9. These pH's also contribute to removal of the explosive and appear to indicate that higher concentrations of bentonite would be required to have an effect on analysis error than those he proposed.

Analysis Methods

Soil and leachate analysis

The Geotechnical and Structures Laboratory (GSL) at the ERDC-Vicksburg performed the Atterberg limit and particle size distribution (PSD) tests used to evaluate the physical structure of NOP soil and provide the USGS soil classification (U.S. Army Corps of Engineers (USACE) 1986). Soil moisture was determined by oven-drying at 105 °C for 24 hr. FOM was calculated by burning soil samples at 500 °C for 1 hr after moisture analysis. Soil pH was determined both directly and by using a soil:distilled water slurry (1:1, wt/vol) using a Denver Instruments® pH meter.

Calcium and magnesium concentrations, cation exchange capacity, and cation and anion concentrations were analyzed by the Environmental Chemistry Branch of the ERDC, Vicksburg, on both treated and untreated soil. The nitrogen and phosphate analysis was performed using a Lachat 8000 Flow Injection Analyzer. Soil CEC was determined using USEPA-SW 846, Method 9081 (1986) and atomic absorption emission spectroscopy. Calcium and magnesium concentrations were determined using USEPA-SW 846, Method 6010B for inductively coupled plasma-atomic emission spectrometry (1996). Leachate hardness was calculated from these concentrations and reported as mg equivalent CaCO₃/L.

Explosives analysis

Explosives contaminants were analyzed for both treated and untreated soil and leachate using USEPA-SW846, Method 8330. All analyses were performed on a Waters high performance liquid chromatograph (HPLC) system with a Waters tunable ultraviolet absorbance detector set at 245 nm. Separation of analytes was achieved using a Supelco LC-18 reverse phase column (25 cm × 4.6 mm) with a pore size of 5 μm, and a Supelco CN column (25 cm × 4.6 mm) with a pore size of 5 μm. A comparison of analysis from the two columns was performed. The eluent was a filtered 1:1 mixture of methanol and water. A standard curve based on uv absorbance at 245 nm was developed based on multicomponent explosives standards obtained from Ultrascientific, Inc. Retention times and machine detection limits for explosive compounds under these conditions are listed in Appendix A, Microcosm Data. The soil explosives concentrations were reported as the mass of analyte per mass of dry soil.

Microbiology

Microbiological analysis of both soil and leachate were periodically completed to assess the relative number of aerobic and anaerobic colony-forming units (CFU) in both treated and untreated soil and leachate over time. Soil from each mesocosm (100 g, dry weight) was mixed 1:1 with tap water. Viable bacteria were released from the soil by rotary shaking for 24 hr at 200 rpm. Serial dilutions (to 10⁻⁶) were prepared in peptone broth from either the soil slurries or the leachate. Five replicates for each dilution of each soil or leachate were plated on R2A agar. Plate counting followed 3- or 7-day room temperature incubation for aerobes and anaerobes, respectively. Anaerobic incubation took place in a Coy® glove bag under an N₂:H₂ (96 percent:4 percent) atmosphere.

Toxicology

Both MicroTox and MutaTox tests were used to characterize the toxicity of the NOP soil. The MicroTox assay, based upon the luminescent bacteria, *Vibrio fischeri* NRRL B-11177, was conducted using a modified version of method ASTM D5660 (1996). Light output was measured on a MicroTox reader at 0, 5, 15, and 30 min after addition of the bacteria. These data were graphically analyzed and the concentration required to reduce light output by 50 percent was calculated (IC₅₀). Samples that had >95 percent inhibition at this concentration were listed as “toxic, nonquantifiable” (TNQ) and the maximal inhibition listed. Samples that didn’t inhibit light output by at least 95 percent were declared nontoxic.

The MutaTox assay is based upon the *V. fischeri* strain M16, which possesses a mutation in the gene responsible for the production of luminescence. Exposure to genotoxic agents restores the luminescence by reversing the mutation. Samples were tested using both the direct assay, which detects compounds that do not require metabolic activation, and the S-9 assay to detect compounds that do require oxidative metabolism to form the reactive metabolite(s) responsible for genotoxicity.

Standard MutaTox methods were modified to a 96-well format and light output was measured in a Dynes MLX 1000 luminometer rather than the MicroTox/MutaTox reader. For the S-9 assay, samples were diluted with MutaTox S-9 Media. Four (4) μ l of MutaTox S-9 Reagent (bacteria) was added after serial dilutions were complete. Readings were taken at 16, 20, and 24 hr. Positive controls for the assays were phenol for the direct assay and benzo[a]pyrene for the S-9 assay. Samples were declared mutagenic if 2 or more sequential dilutions had light outputs at least double that of the solvent control. Samples were declared toxic if light output was less than half of the solvent control. If three or more dilutions were toxic, the sample was retested at lower dilutions.

4 Microcosm Study: Results and Discussion

Effect of Lime Dosage/Treatment pH

The initial pH of the NOP soil used in the lime-dosing test was 4.54 ± 0.39 . The addition of 1, 3, and 5 percent lime raised the soil pH to a 21-day average of 8.41 ± 0.80 , 10.54 ± 0.47 , and 11.33 ± 0.29 , respectively, for the treatment pH. RDX and HMX in soil treated with 5 percent hydrated lime were removed rapidly, demonstrating first-order removal rate coefficients of $k = 0.21 \text{ day}^{-1}$ (RDX) and $k = 0.065 \text{ day}^{-1}$ (HMX) (Figure 5). The large standard deviation in the data at day 7 is the result of two of the three samples having achieved “non-detectable” (ND) concentrations (below machine detection limits, $<0.02 \text{ mg/kg}$ for RDX and TNT). Results less than machine detection limits were treated as zero for the average and standard deviation calculations. Soil treatment with 3 percent lime yielded RDX concentrations statistically similar to 5 percent lime. However, at 1 percent lime (pH 8.47) RDX removal leveled off at day 7. While the concentration of RDX appears to be increasing from day 7 to day 21, when the standard deviation is considered, statistically these are the same concentration ($p = 0.05$). RDX was more susceptible to lime treatment than HMX. At 1 percent lime, no significant removal of HMX was observed, suggesting a pH-dependent mechanism (also noted with 4A-DNT). The experimental data are available in Appendix A.

The TNT concentration in the soil was below detection limit within 3 days when treated with 3 and 5 percent hydrated lime. In soil mixed with 1 percent hydrated lime, the removal rate was slower. The large standard deviation apparent at day 7 is again the result of two out of three samples having achieved ND levels (Figure 6). Trinitrobenzene (TNB) and dinitrobenzene (DNB) responded rapidly to 3 and 5 percent lime treatments, showing complete removal within 24 hr. As seen with TNT, removal with 1 percent lime was slower. A different response to lime treatment was demonstrated by 4-amino-dinitrotoluene (4A-DNT) (Figure 7). There was no significant removal of this compound after treatment with 1 percent lime (pH 8.4) and only slight removal at 3 percent lime (pH 10.5). Only treatment at a 5 percent dosing level achieved removal of 4A-DNT from the soil, suggesting that the minimum pH for removal of 4A-DNT by alkaline hydrolysis is 11, or higher.

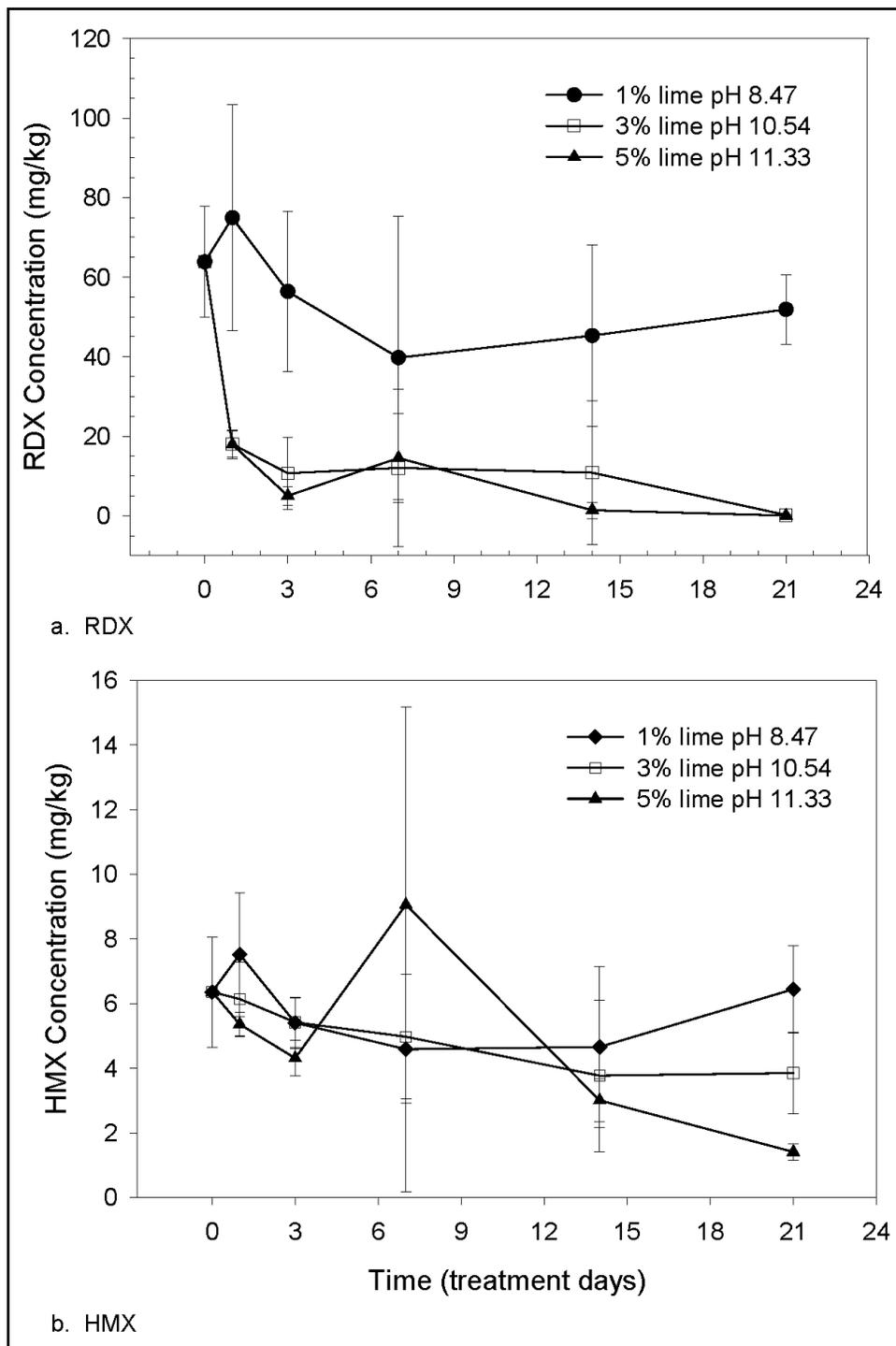


Figure 5. Removal of RDX and HMX from soil treated with hydrated lime

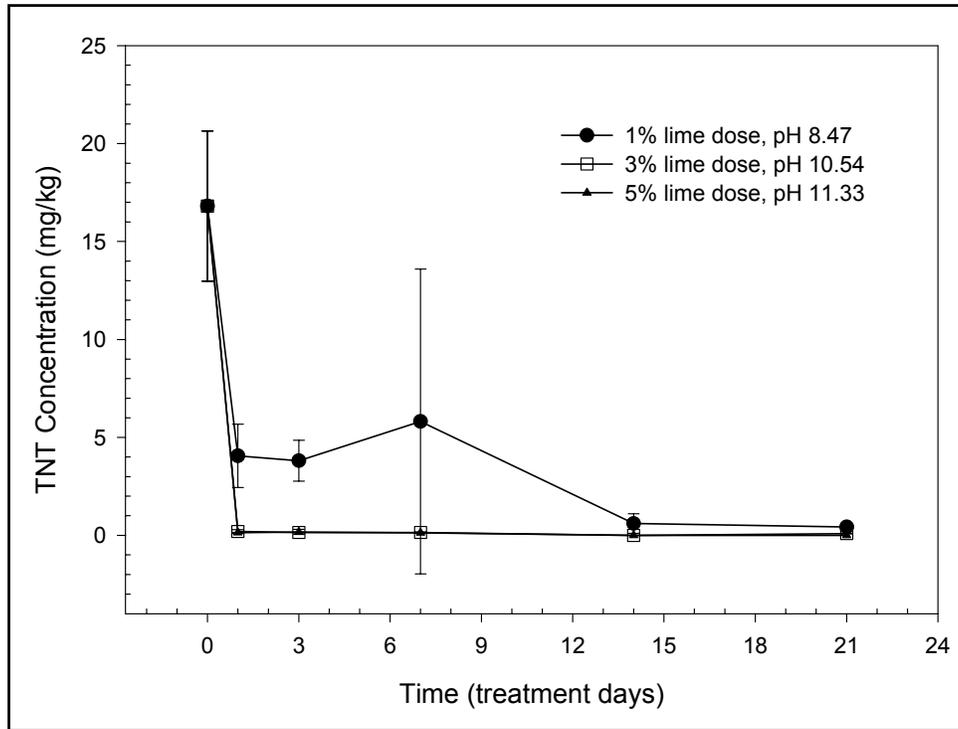


Figure 6. Removal of TNT from soil treated with hydrated lime

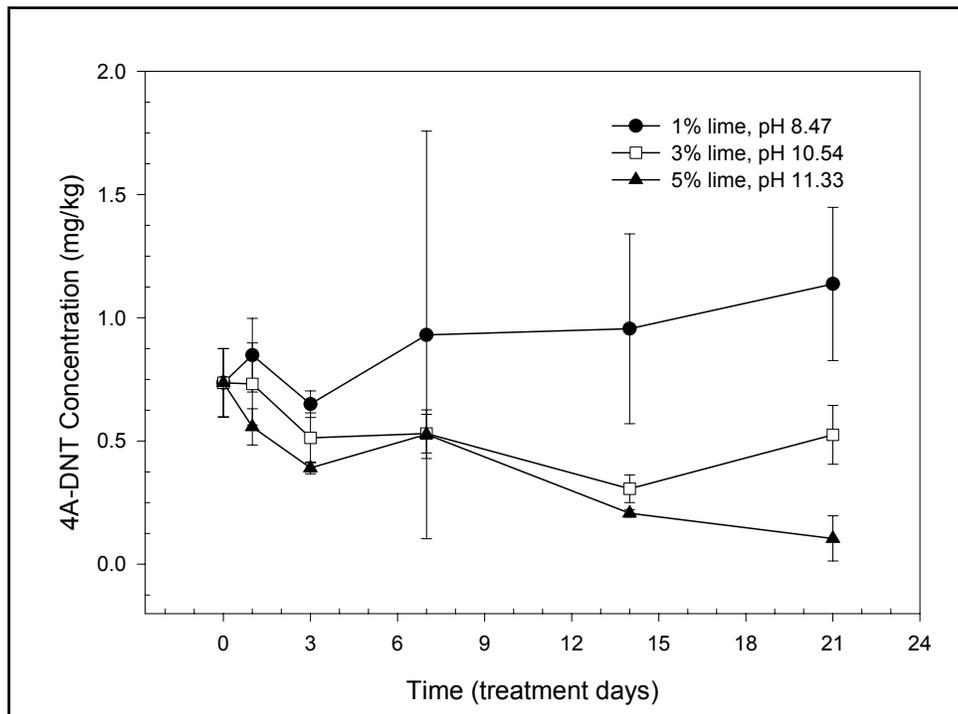


Figure 7. Removal of 4A-DNT from soil treated with hydrated lime

In summary, these results suggest that the 3-percent lime addition, raising the soil pH over 10, would be sufficient to drive the alkaline hydrolysis of most explosive compounds. Other compounds, such as the amino-dinitrotoluenes and HMX, apparently require a higher pH level. The 5 percent lime addition, raising the soil pH over 11:

- a. Decreases the time required for complete removal of the explosive
- b. Initiates removal of recalcitrant explosives and metabolites.

However, raising the soil pH to 11, or higher, involves issues of soil recovery time, plant growth survival, and possible surface water pH changes.

Effect of Organic Matter

The effect of soil organic matter on the alkaline hydrolysis of RDX is shown using peat moss as the source of organic matter (OM), ^{14}C -RDX, and 5 percent hydrated lime (Figure 8). For the sand (0 percent OM), only 17 to 30 percent of the ^{14}C labeled isotope was retained in the solid phase both before and after alkaline treatment. The amount of ^{14}C isotope retained in the solid phase increased as the percentage of OM was increased. At 100 percent OM, 90 percent or greater of the ^{14}C isotope was retained in the solid phase before and after alkaline treatment. A multiple comparison against the control (the 0 percent OM) using Dunn's Method showed that just the 10 and the 100 percent OM were significantly different from the control ($p = 0.05$). Several conclusions appear possible from these data. RDX sorption increases with an increase in soil OM. Below 5 percent OM, there are no differences in RDX sorption. Lime treatment produced no significant changes in the adsorption of RDX or its degradation products. Further data are presented in Appendix A.

Effect of Particulate Explosive Contamination

Jenkins et al. (1997), in initial studies concerning environmental sampling problems on training ranges, established that explosives contamination was present on the ranges in three forms: bound to the soil matrix, as micro-crystals, and as particulates in the soil. This results in considerable spatial heterogeneity of contamination. As pointed out by Pennington et al. (2002), point sources of contamination on training ranges are formed by low-order detonations that release particles of the explosive onto the soil surface. Radke et al. (2002) established the importance of particulate explosives in soil in site contamination characterization and remediation. In this study, we examined solid forms of RDX and TNT to investigate alkaline hydrolysis of nonsorbed energetic contaminants in soil, simulating the occurrence of energetic particles from low-order detonation of munitions. The effect on RDX crystals is shown in Figure 9. HMX, found as a contaminant of NOP soil and as a manufacturing by-product of the RDX crystal, was removed more slowly. Neither RDX nor HMX achieved concentrations below machine detection levels in the 21 days of treatment, suggesting a limiting factor associated with the crystalline explosive contaminant which may be rate-limited dissolution.

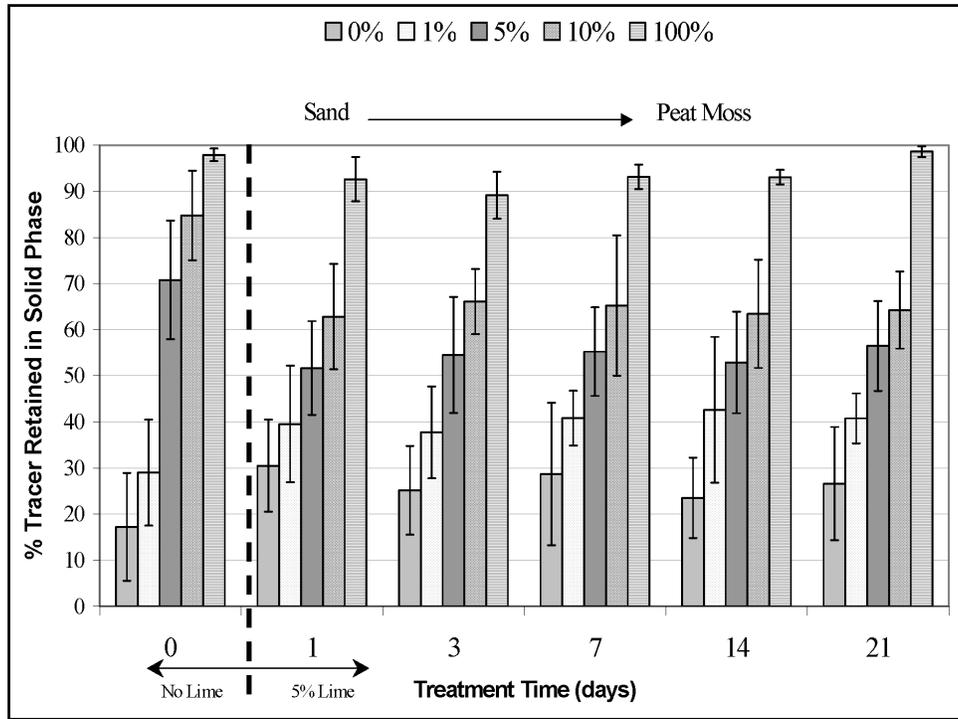


Figure 8. The effect of soil OM on alkaline hydrolysis of RDX

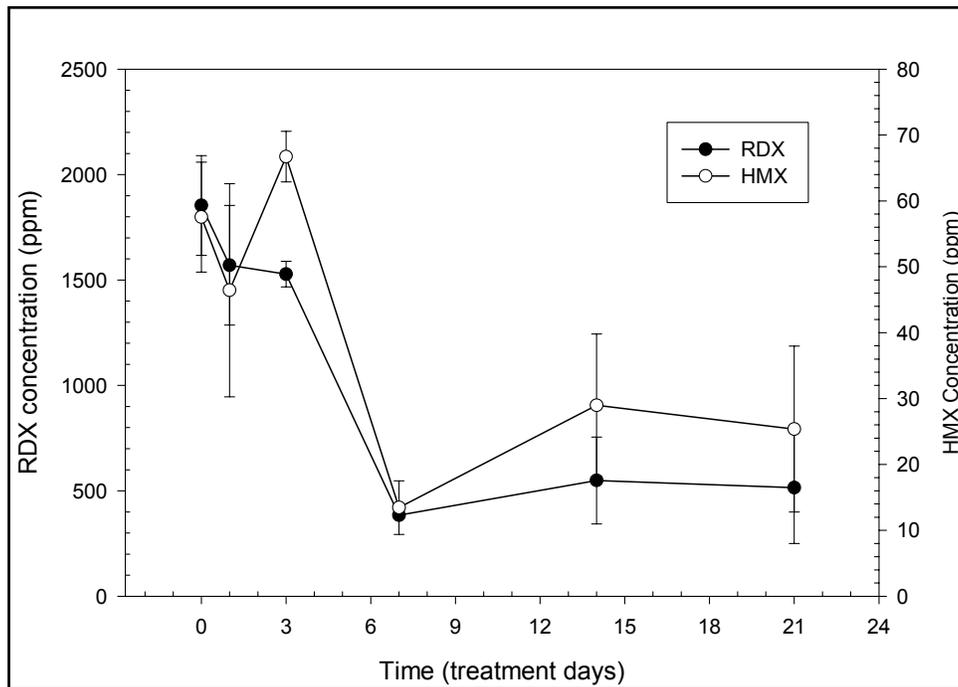


Figure 9. Removal of RDX and HMX from RDX crystal in soil treated with 5-percent hydrated lime

The crystalline TNT was coated with a plasticizer, and microcosm experiments were conducted using both whole and broken grains of coated crystalline TNT. TNT grains surrounded by plasticizer are more resistant to degradation by the hydroxide ions in the soil pore water than unprotected TNT. However, as shown in Figure 10, in 21 treatment days, both the whole and the broken grains had achieved the same soil concentration.

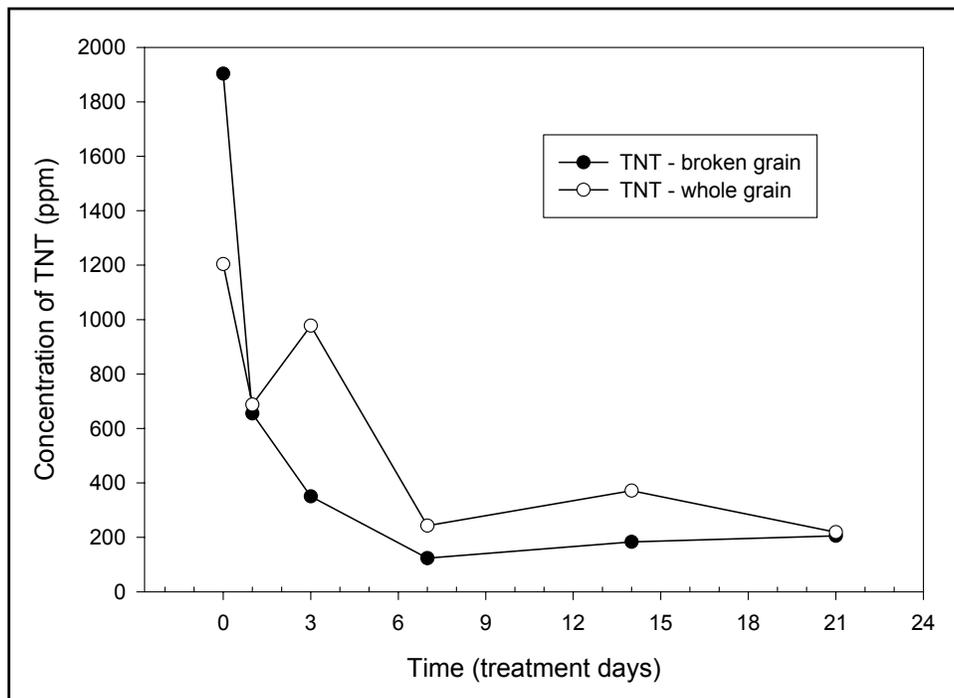


Figure 10. Comparison of TNT removal from whole and broken grains of TNT

Effect of Explosive Mixtures in Soil from Training Ranges and Ammunition Plants

Soil chemistry

The ammunition plant and range soils, including NOP soil, had a wide range of soil pH, CEC, and organic carbon content characteristics (Figure 11). The organic carbon content of the soil is inferred by the total organic carbon (TOC) or the FOM, expressed as a percentage of the dry weight of the soil. The organic carbon varied from less than 1 to 14 percent. The CEC of these soils ranged from 4 to 50 mequiv/100 g soil. The untreated soil pH varied from 5 to 8.

Contaminant removal

In the 17 site soils studied, RDX and TNT were rapidly removed following treatment with 5 percent hydrated lime (Tables 11 and 12). The half-life of RDX in two representative samples of these soils was calculated to be 0.28 days

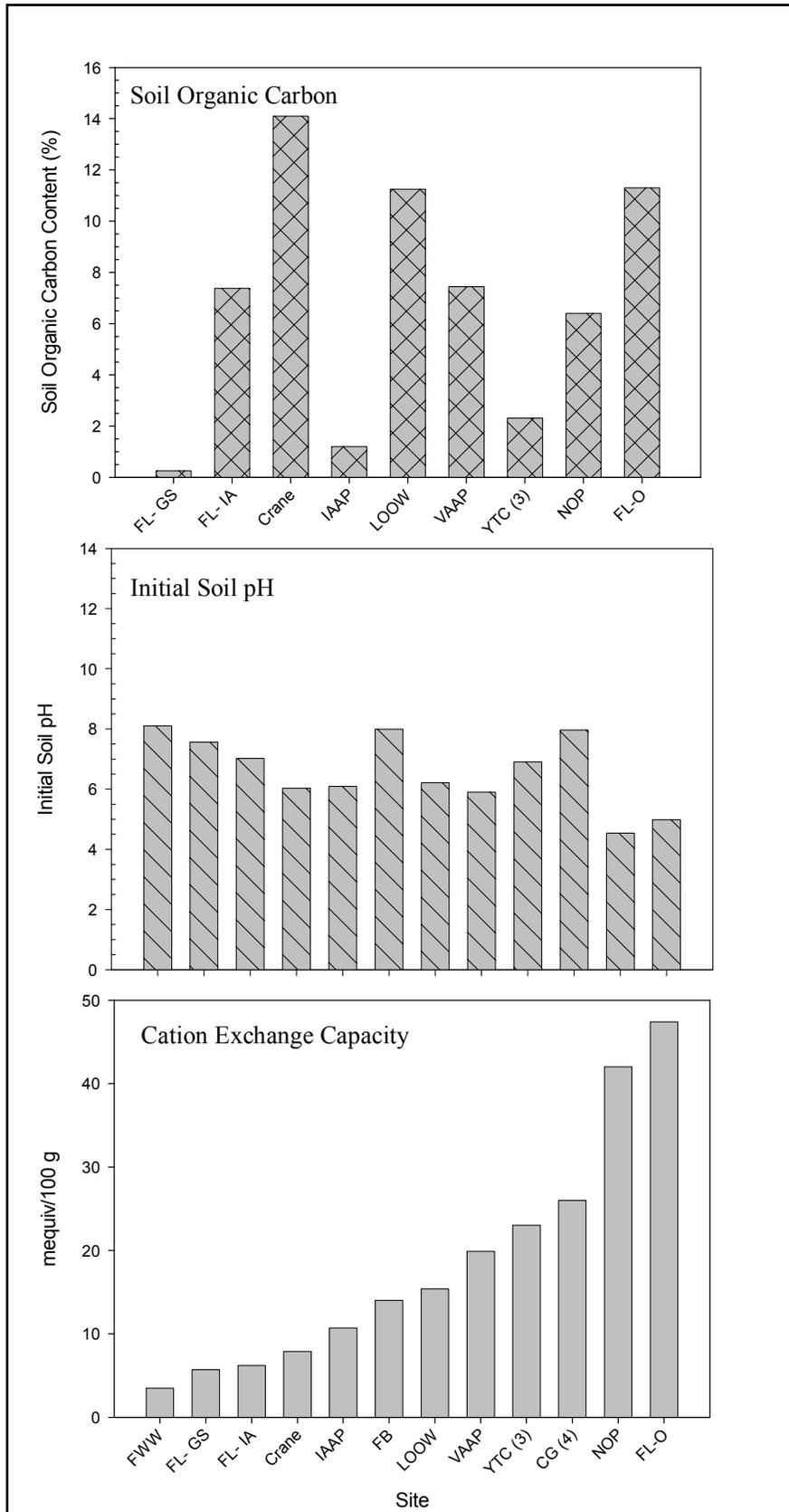


Figure 11. Microcosm soil diversity

Site	CEC meq/100 g	pH initial	pH Treated 5% lime	C _i /C _o mg/kg	Time to Completion days	k _{RDX} day ⁻¹	r ²
NOP	42	4.54	11.33	0/63.84	21	0.210	0.6889
Crane	8	6.03	10.76	0.62/49.94	21	0.232	0.7976
VAAP	20	5.90	11.39	24.7/1360.7	21	0.194	0.9262
FLGS	8	7.56	12.48	0/11.96	14	0.379	0.7256
FW	4	8.10	12.80	0.03/32.47	21	0.268	0.8140
GC48	24	7.26	12.69	42.34/112.61	21	0.027	0.2361
YC1	23	6.65	12.65	0.29/4.13	21	0.125	0.9341

Site	CEC meq/100 g	pH initial	pH Treated 5% lime	C/Co mg/kg	Time to Completion days	k _{TNT} day ⁻¹	r ²
NOP	42	4.54	11.33	0/16.81	14	0.466	0.3706
LOOW	15	6.21	10.95	29.89/12,905.47	21	0.232	0.8730
GC32	26	7.96	12.48	0/27.68	21	0.458	0.5816
GC48	24	7.26	12.69	0/25.88	7	1.102	0.6058
GC51	26	7.43	12.68	0/182.46	21	0.428	0.3549
GC52	26	7.83	12.42	0.06/32.84	21	0.135	0.2478

(Figure 12). TNT removal from the microcosm soils was almost twice as rapid, with a half-life of 0.15 days. The contaminant HMX followed a similar pattern of removal to that of RDX (Figure 13), but at a slower rate, confirming results of the lime dosing (treatment pH) study and the results of Balakrishnan et al. (2003). Two soils with high concentrations of HMX were those from the Yakima Training Center (YC) and the Volunteer Army Ammunition Plant (VAAP). While the CEC of these soils are comparable (low 20s), the organic carbon content is different, 2 percent for the Yakima soils as compared to 7 percent for the Volunteer soil. VAAP, with a lower initial soil pH and higher organic carbon concentration, did not achieve the high treatment pH seen in the Yakima soils (11.4 versus >12). HMX contamination in the VAAP soil only decreased to about half the original contamination. The three Yakima soils achieved 86 to 99 percent reduction ($p = 0.05$). Complete data on removal of all contaminants from all the microcosm soils is available in Appendix A.

Several of the site soils contained, along with TNT, measurable concentrations of the amino-dinitrotoluenes, 2A- and 4A-DNT. As seen in Figure 7, lime dosing of NOP soil demonstrated differences in the removal of 4A-DNT by pH. A one-way ANOVA, Holm-Sidak pairwise, multiple comparison test, found that removal with 1 percent lime was significantly different from 3 or 5 percent lime. However, the 3-percent treatment was not significantly different from the 5-percent treatment ($p = 0.003$). Other sites with TNT and ADNT as co-contaminants include Fort Bliss, Fort Wainwright, Camp Guernsey, and the Lake Ontario Ordnance Works. Treatment pH for these soils was 12.54, 12.86, 12.50, and 10.95, respectively. Removal of the ADNTs from these soils also

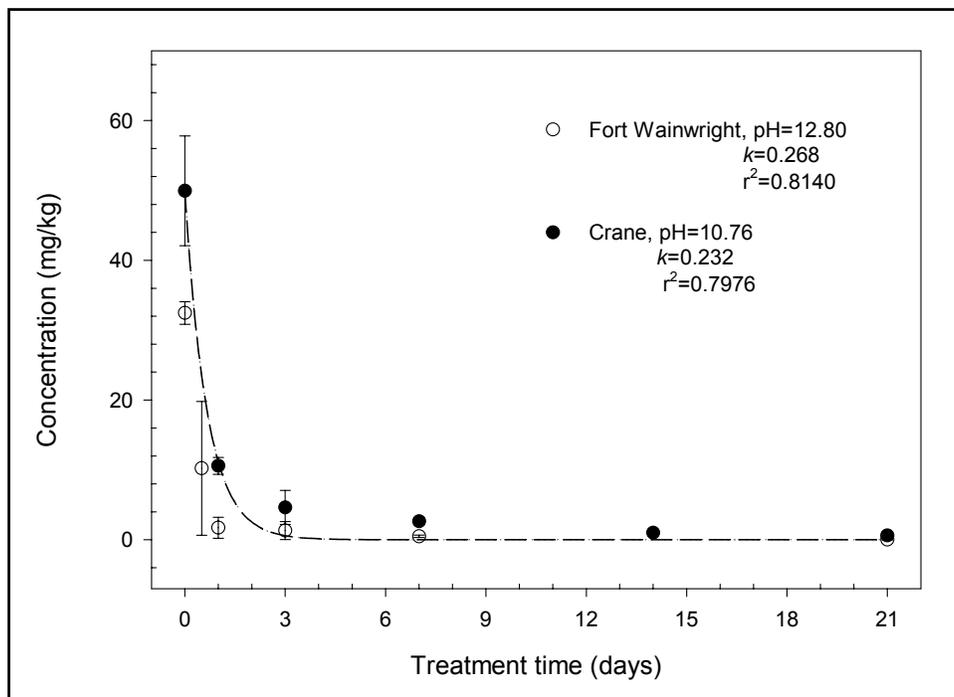


Figure 12. RDX removal from microcosm soils (Note: Regression lines are overlaid, error bars are beneath symbols)

Site	CEC meq/100 g	pH Initial	pH Treated 5% lime	C/Co mg/kg	Time to Completion days	k_{HMX} day ⁻¹	r^2
NOP	42	4.54	11.33	1.41/6.36	21	0.065	0.6701
VAAP	20	5.90	11.39	77.26/141.79	21	0.036	0.3163
FLI	6	7.02	12.52	0/0.32	7	0.384	0.5521
FLGS	6	7.56	12.48	0/2.50	14	0.159	0.7243
FW	4	8.10	12.80	0/4.03	21	0.246	0.8879
YC1	23	6.65	12.65	0.65/53.43	21	0.195	0.8935
YC2	22	7.16	12.67	8.98/62.26	21	0.097	0.9176
YC4	24	6.91	12.68	0.35/30.33	21	0.182	0.7789

appears to vary by treatment pH. In addition, the amino-dinitrotoluenes are found as co-contaminant with the dinitrotoluenes, 2,4- and 2,6-DNT. While the amino compounds were removed from the soil by the alkaline treatment, the dinitrotoluene compounds (treatment pH 10.96) were not removed (Figure 13).

The ADNT and DNT microcosm results prompted further investigation of the pH levels required for alkaline hydrolysis of these compounds. An aqueous titration was performed using standards of 2A- and 4A-DNT, combined with 2,4- and 2,6-DNT each at a concentration of 10 ppm. The solution was raised and held at a constant pH 12 with KOH. No significant transformation of any of these contaminants was observed in 14 days, although the contaminant concentration in solution was higher than seen normally in firing range soils

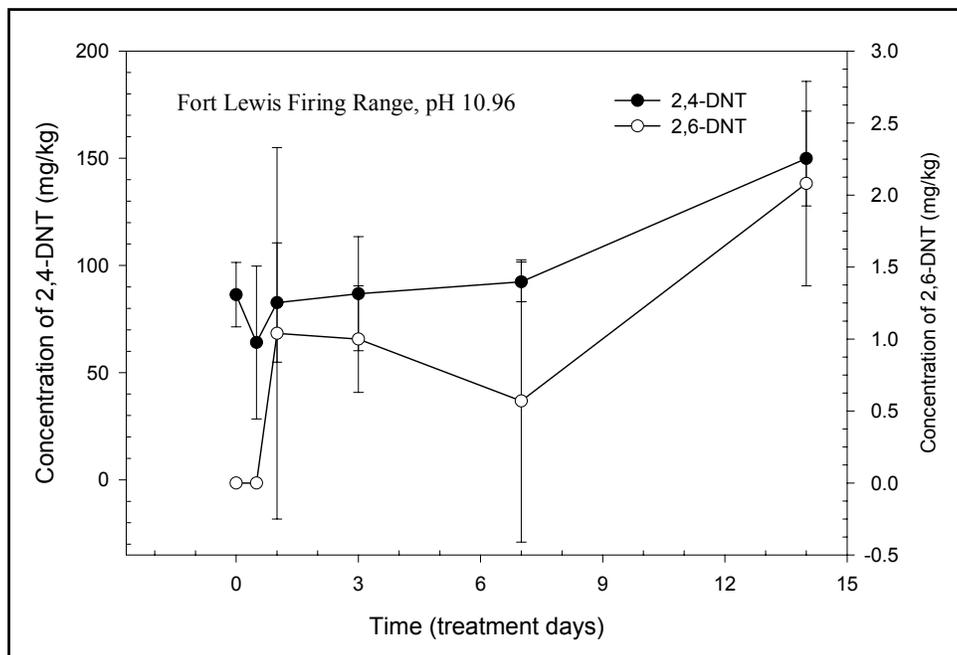


Figure 13. Removal of dinitrotoluenes from microcosm soils

(Figure 14) and in contrast to the microcosm soils (treatment pH 12.6 and higher) which demonstrated significant removal of the amino-dinitrotoluenes. This is an area that clearly needs further investigation. Because lime in solution can only achieve pH of 12.2, lime treatment of soil may not effectively treat the DNTs.

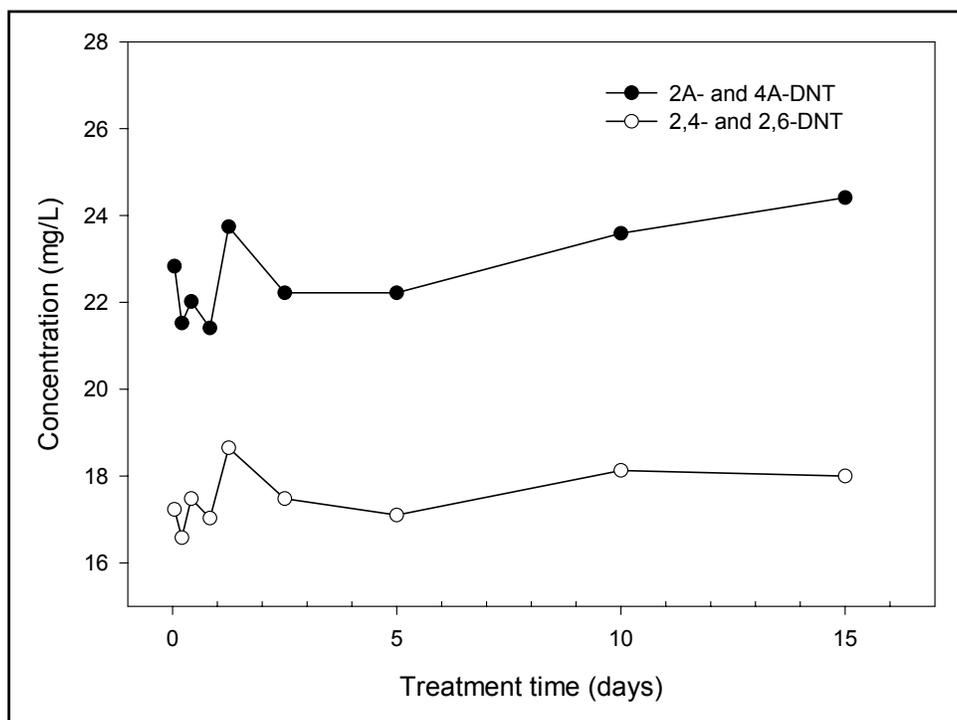


Figure 14. Titration of amino-dinitrotoluenes and dinitrotoluenes, pH 12

5 Mesocosm Study: Results and Discussion

Soil

Soil pH and CEC

Figure 15 summarizes the soil pH measurements collected over the duration of the mesocosm experiment. Due to the limited pH changes with depth, all pH measurements collected over the duration of the experiment within a mesocosm, have been averaged, the value of which is shown in the figure, and the error bars denote the standard deviation of the measurements. A complete listing of soil pH measurements is given in Appendix B. Mesocosms well-mixed with the quick-lime (mesocosm 9) or the hydrated lime (mesocosm 10) showed soil pH that increased dramatically and was maintained for the entire 26-week study. The average pH (8.7) in the well-mixed fly ash mesocosm was higher than the pH levels in the control (average of 6.1) but less than the pH of the well-mixed lime mesocosms (pH 11 and 12). Average soil pH values of 6.2 to 6.6 were measured in the mesocosms with the topical applications (mesocosms 2 through 8), slightly higher than the average pH measured in the control (6.1), but not significantly different. An ANOVA test of the mesocosms ($p = 0.05$) reported no significant differences between mesocosms 1 through 8. Mesocosms 9 through 11 were similar to each other but significantly different than mesocosms 1 through 8.

In order to confirm the apparent limitations in raising soil pH by aqueous transport of topically applied hydroxide, lime was removed from the surface of mesocosm 3, along with the surficial soil, until no lime was visible. The pH was measured at this point, and at 0.6-cm increments down to a depth of 3 cm. The surface soil pH, and readings down to 3 cm, were 12.0. At 3 cm, soil pH returned to 6.6. The conclusion was that the hydroxide ions had only been transported 3 cm through the soil in approximately 26 weeks. An additional experiment was run to investigate possible mass limitations between the lime and the water. This experiment is discussed under the leachate pH results.

The original CEC of the NOP soil was 42 mequiv/100 gm soil. The final CEC of the control mesocosm was 38 mequiv/100 gm soil. Mesocosms 2 through 8 and 11 all measured 37 and 38 mequiv. The mixed mesocosms, 9 and 10, measured 40 and 41 mequiv, respectively. Statistical analysis ($p = 0.05$) confirmed that there were no significant changes in the CEC of the NOP soil from its original condition by any of the alkali treatments over this time period.

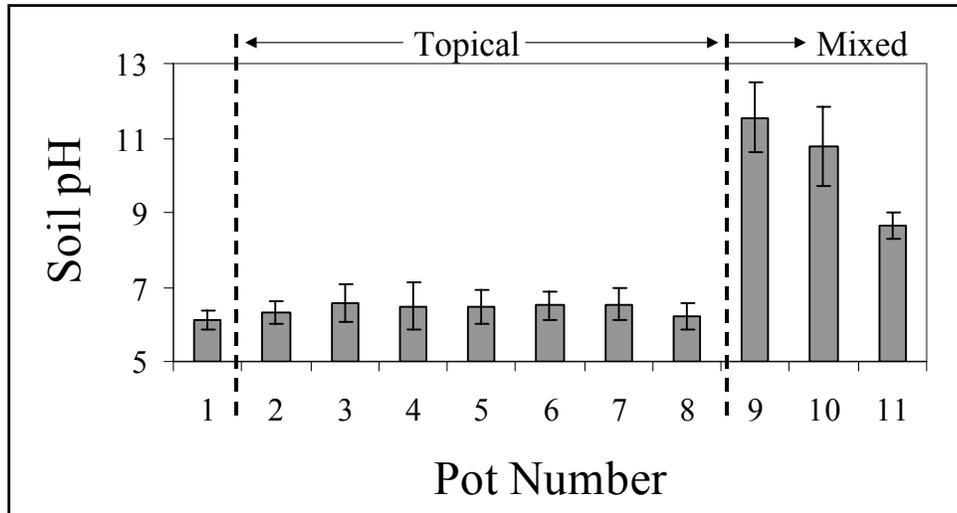


Figure 15. Soil pH of mesocosms

Explosives contamination removal

Figure 16 shows the RDX concentration in mesocosm soil collected at 1, 2, 4, 10, 18, and 26 weeks compared by alkaline source and application method. In the well-mixed quicklime and hydrated lime systems RDX was removed rapidly from the soil relative to the control (mesocosm 1), with significant reductions (82- and 83-percent removal, respectively) in RDX concentration noted in the first week's sampling event. RDX removal in the well-mixed quicklime and hydrated lime mesocosms was more rapid than RDX removal in the corresponding topical application mesocosms. In contrast, the well-mixed fly ash did not show significant differences from either the control or the topically applied fly ash. After 4 weeks of treatment, the mixed fly ash had 67 percent removal, the topical fly ash had 68 percent removal. The reason why RDX concentrations were more persistent in the topical quicklime treatment are unclear (Section on "Leachate"). Figure 16 shows a comparison of RDX removal from mesocosms treated with hydrated lime in other application scenarios. The results for all systems were similar to the control except for the high water flow, mesocosm 4, in which RDX was more persistent than in the control mesocosm. Additional data are presented in Appendix B.

TNT and HMX removal trends, between treatments and over time, were similar to those noted for RDX except for mesocosm 4 where TNT removal was faster than RDX and HMX removal was slower than RDX. Also, there was little difference in contaminant removal between the control and the topical application of hydrated lime and fly ash. After 26 weeks of treatment, TNT removal was 99 percent in the mixed quicklime and hydrated lime mesocosms. The fly ash showed 65- and 79-percent removal in topical and mixed systems, respectively. However, in mesocosm 4 the removal trend was reversed, with RDX being removed faster than TNT, only 10 percent of the TNT being removed at week 1. This is probably due to the stronger soil adsorption of TNT. Four treatment scenarios achieved 90-percent removal of HMX by 10 weeks. These were the three mixed application systems and the high water flow system.

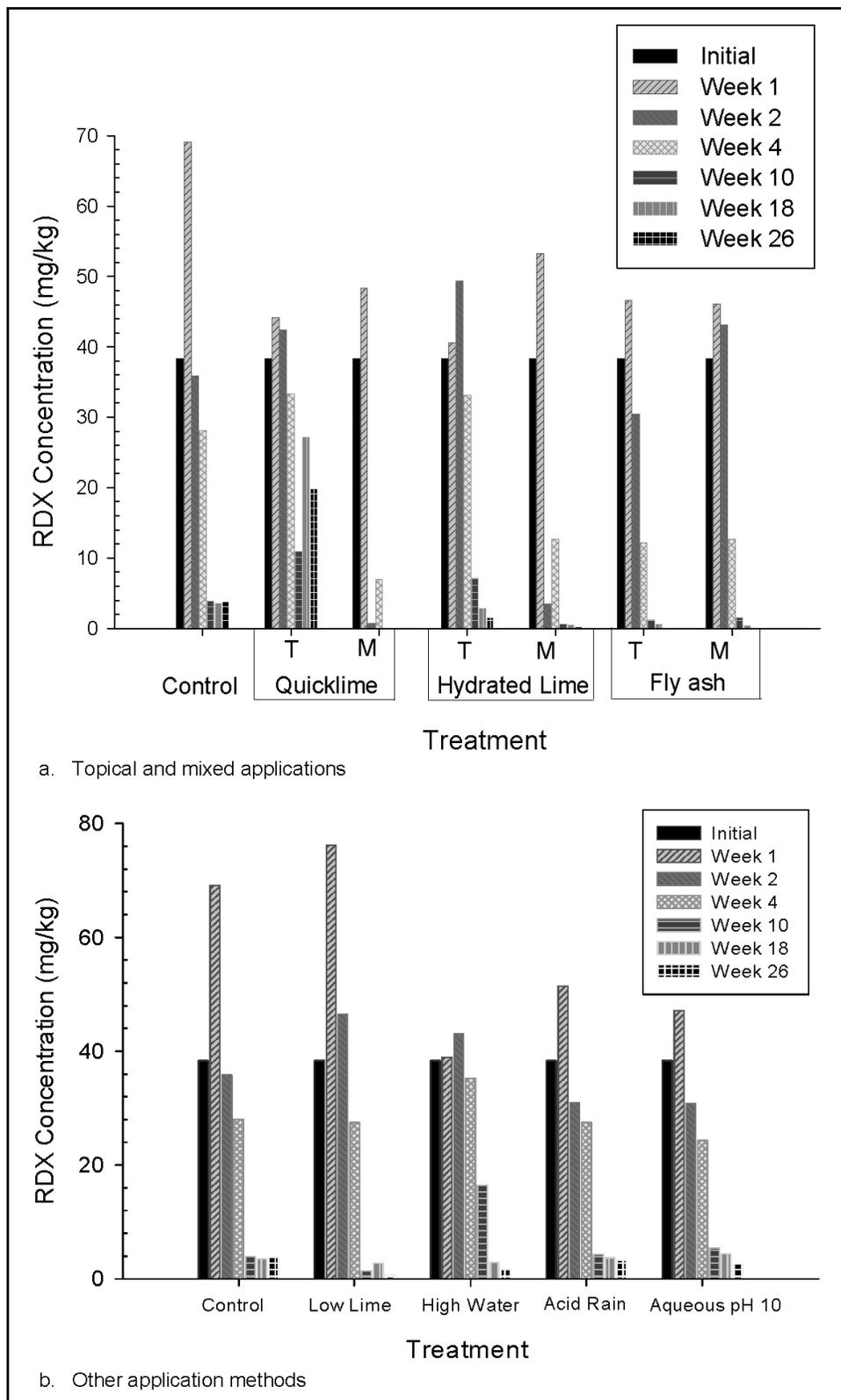


Figure 16. RDX removal from mesocosm soil over 26-week treatment time. A comparison of alkaline source and application method

As shown in Figure 16, the RDX concentration in the control also declined over the experimental duration. One possible explanation for these observations is in situ biodegradation of RDX, which will be discussed further in the section entitled “Mesocosm Leachate.” A complete listing of soil explosives concentration results is available in Appendix B.

Microbiological assay

Initial plate counts to quantify numbers of aerobic bacteria present in the NOP soil indicated 10^2 CFU/gm soil. Mesocosms 9 and 10 had high soil pH and demonstrated no agar plate growth over the entire study. At the conclusion of the study (week 26), all mesocosms, except 9 and 10, had aerobic bacterial counts of 10^4 CFU/gram soil.

A spot check of dissolved oxygen concentrations in the leachate during week 13 of the study indicated the development of potentially anaerobic conditions (section entitled “Mesocosm Leachate”). Consequently, anaerobic plate count measurements were conducted during week 18. Results varied from 10^3 to 10^4 CFU/g soil in all mesocosms, except 9 and 10, which showed no agar plate growth. At week 26, the counts remained unchanged or showed a slight increase for all mesocosms, except 9 and 10. As a result of the microbial data, explosives analysis was modified to include biological degradation products MNX, DNX, and TNX in mesocosm soil and leachate. Complete microbial data are included in Appendix B.

Toxicological assay

The initial, untreated, NOP soil used in the mesocosms was evaluated by MicroTox and MutaTox (direct and S-9 activation) assays and was found to be toxic and mutagenic (avg. $IC_{50} = 2.5$) to the species examined. A low IC_{50} value indicates greater toxicity. Following 26 weeks of treatment, the soil in all the mesocosms demonstrated no toxicity, or reduced toxicity, and no mutagenicity, or reduced mutagenicity. These preliminary toxicological data are important because it indicates that the alkaline hydrolysis reaction intermediates and the end products are less toxic/mutagenic than the parent compounds in soils with mixtures of explosive compounds. Previously, toxicity studies have only dealt with single components in aqueous solutions.

After 26 weeks of treatment, MicroTox assay showed that the control, mesocosm 1, also had reduced toxicity over the initial soil samples. Mesocosms 2, 6, 7, 8, and 11 had IC_{50} values comparable to the control or better. These treatments were, low lime, acid rain over topical hydrated lime, topical fly ash, aqueous hydrated lime, pH 10, and mixed fly ash, respectively. The remaining mesocosms exhibited greatly reduced, nonquantifiable toxicity. These were mesocosm 3, topical hydrated lime; mesocosm 4, high water application; mesocosm 5, topical quicklime; mesocosm 9, mixed quicklime; and mesocosm 10, mixed hydrated lime. No distinct trends were observed with soil depth although a slight trend towards lower toxicity at greater depth was observed for mesocosms 1 through 5. Because of the natures and the endpoints of the

MicroTox and MutaTox test, the MicroTox data are more significant for the NOP soil.

Under the direct acting MutaTox test, the initial NOP soil was mutagenic at concentrations <1.9 mg/mL. Following 26 weeks of treatment, all mesocosms were either nonmutagenic or demonstrated reduced mutagenicity. The control, mesocosm 1, remained mutagenic, although the soil concentration required for mutagenicity increased by more than two, the same factor found in the other mesocosms that remained mutagenic. Nonmutagenic mesocosms were mesocosm 2, low lime; mesocosm 6, acid rain over topical hydrated lime; and mesocosm 7, topical fly ash. The MutaTox S-9 analysis for indirect toxicity was negative for all mesocosms, meaning the soils did not become mutagenic or increase in mutagenicity through metabolic activation. Toxicological data are presented in Appendix B.

Leachate

Leachate pH

The pH measured in the leachate from each mesocosm is shown in Figure 17. The pH measurements are presented as a function of the number of pore volumes flushed through the mesocosms, where the pore volume estimate in the mesocosm was based on the soil moisture measurements completed with each soil sampling episode. As expected, the leachate pH measurements were typically in agreement with the soil pH measurements. Elevated pH measurements of 12 to 12.5 were observed in the leachate from well-mixed mesocosms 9 and 10 essentially as soon as leachate was collected (within 7 days). The leachate pH measurement of 8 from well-mixed fly ash, mesocosm 11, was elevated relative to the pH values in the control of approximately 6.5 to 7.5 but less than the pH measured for the other well-mixed lime mesocosms. Class C fly ash contains a variety of metal oxides, of which approximately 30 percent or less are calcium oxide, which may account for the lower pH levels in the well-mixed fly ash mesocosms compared to the well-mixed hydrated and quicklime mesocosms. In the remaining mesocosms, the leachate pH values were all comparable to that measured in the control, ranging from 6.5, at the start of the experiment, to 7.5, at the end of the experiment.

Both soil and leachate pH measurements suggest that soil characteristics may prevent pH elevation in topical application systems to the levels required for alkaline hydrolysis of energetic contaminants. Other researchers have reported similar limitations. Farina et al. (2000a) reported success at ameliorating subsoil acidity with the use of topically applied gypsum, but pH effects were only seen after 4 years of treatment. Farina et al. (2000b) found little short-term, vertical or horizontal movement of the alkalinity through the soil layers even when they could see unreacted lime in the soil. Breit et al. (1979), in discussion of caustic water flooding of rock formations for the displacement of oil, made note in their model development of the fact that hydroxide ions were neutralized by reaction with both the reservoir rock and the groundwater.

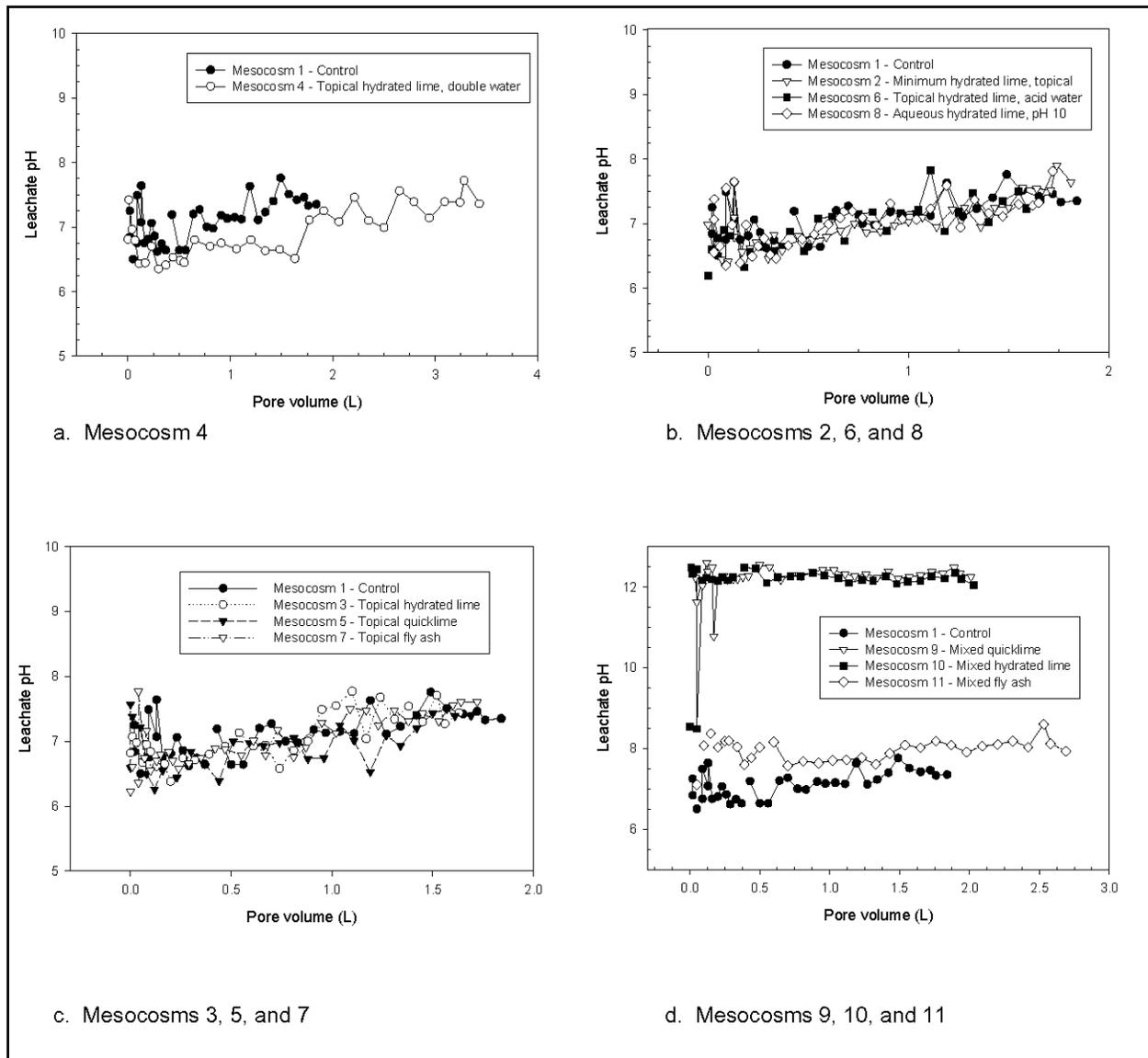


Figure 17. Mesocosm leachate pH by treatment

There are several possible explanations for the observed lack of pH change in the leachate. First, mass transfer limitations between the water and the lime or fly ash may have prevented hydroxide transport into the mesocosm soil. A second explanation is that the CEC of the NOP soil is high enough to buffer the hydroxide delivered by the aqueous input.

In a series of column experiments conducted to investigate potential limitations with topically applied alkaline material, the hydrated lime applied topically to sand yielded leachate with a pH >12 (control column). Water was added to the columns at a rate equivalent to 0.5-in. rainfall/week, equal to that applied to the mesocosms. The high pH was maintained in the sand column for more than four pore volumes. Furthermore, to investigate the possibility that scaling induced mass transfer limitations, a lime sample removed after 26 weeks from the topical

material in mesocosm 3 was shown to increase the pH of water to >12 immediately.

In additional columns run with 25, 50, and 75 percent NOP soil mixed with clean Ottawa sand, the leachate pH was lower than seen with the control column. Because the elevated pH in the sand column eliminates the possibility of mass transfer limitations between the alkaline material and the water, then soil effects, such as CEC, are most likely the reason for the lack of pH change in the NOP soil and leachate. The NOP soil had a low pH and a high CEC, which together appear to have prevented significant increases in soil pH. The ramifications of this are discussed in greater detail under Chapter 6, “Technology Application Guidelines.”

Calcium concentration

Calcium and magnesium concentrations in the mesocosm leachate were monitored to confirm transport of the calcium hydroxide vertically in the soil system and to calculate hardness of the water. The changes by application method and alkaline source are shown in Figure 18. The tapwater applied to the soil systems had a calcium concentration of 14 mg/L. All mesocosm systems, including those with topical application of lime and aqueous alkali, demonstrated a rapid increase in calcium concentration indicating vertical transport of the calcium ion through the soil. Topical systems all showed calcium concentrations between 200 to 300 mg/L at week 1. As expected, the mixed systems (9, 10, and 11), and particularly the mixed fly ash (11), achieved much higher levels of

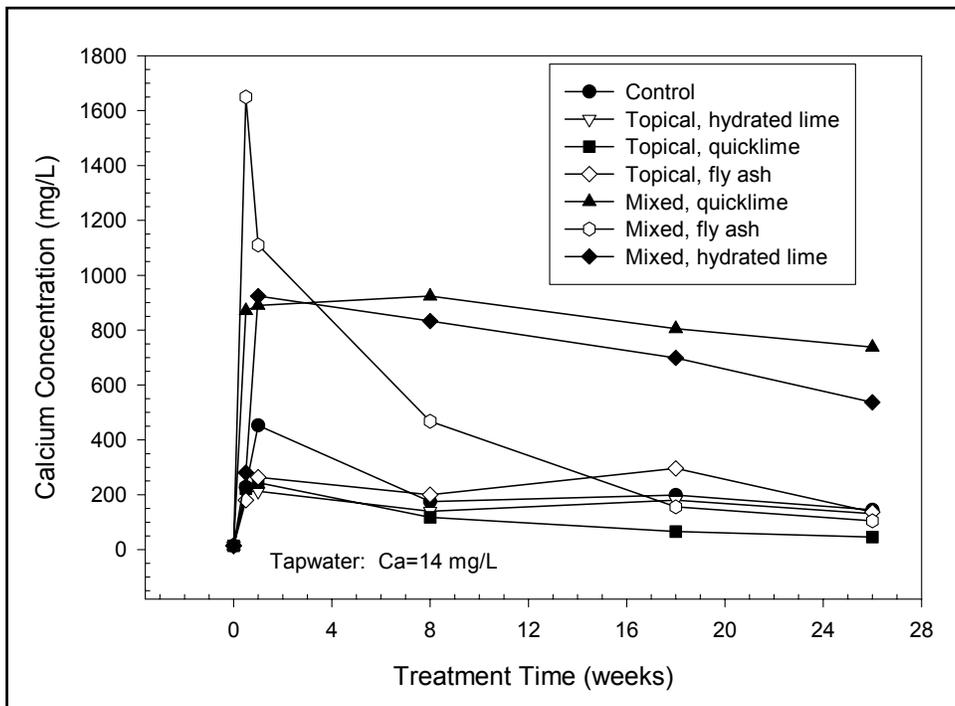


Figure 18. The effects of alkaline treatment on leachate calcium concentration

calcium than the topical systems, approximately 900 mg/L for the quicklime and hydrated lime, and 1,650 mg/L for the mixed fly ash. Calcium concentrations in the fly ash leachate quickly decreased to the levels shown by the topical systems. The fact that calcium appeared in the leachate but the hydroxide did not, appears to indicate consumption of the hydroxide ion in the soil.

Contaminant concentration

Figure 19 presents RDX concentrations measured in the leachate from each mesocosm as a function of the total pore volume of water flushed through the mesocosm. To facilitate method comparison between lime types, the mesocosm charts have been grouped by application method. Results from leachate sampling analysis were similar to soil sampling results. Complete data for all leachate contaminants is compiled in Appendix B.

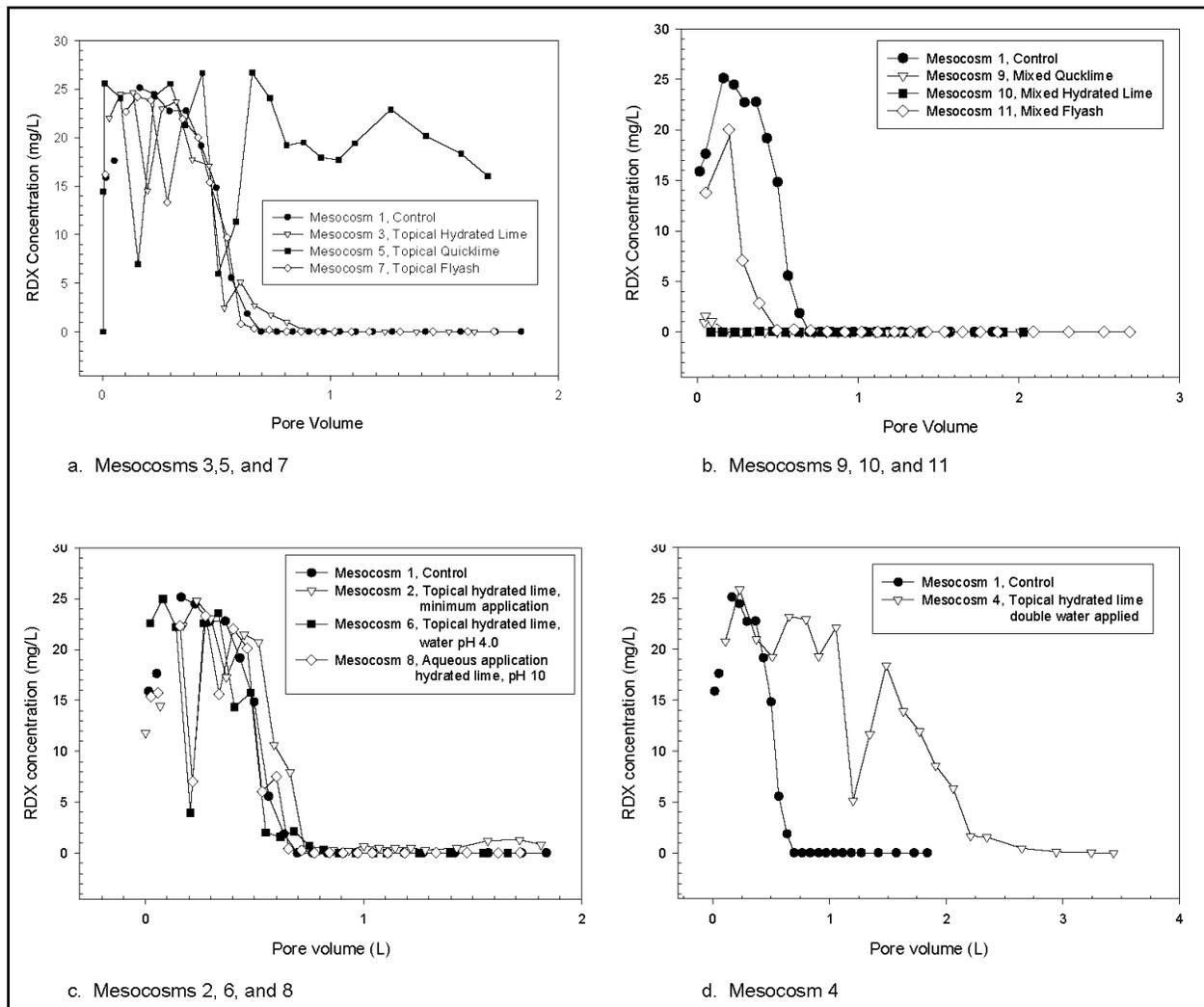


Figure 19. RDX removal from mesocosm leachate treated with various alkaline sources

In the well-mixed lime systems (mesocosms 9 and 10), RDX (as well as HMX and TNT) were removed rapidly from the leachate (Figure 19). However, in contrast to soil sampling results from the well-mixed fly ash, RDX concentrations in the leachate from the well-mixed fly ash mesocosm declined faster than the RDX concentration in the leachate from the control (mesocosm 1). Leachate concentrations from all mesocosms with the topical applications were similar to leachate concentrations from the control (Figure 19), with the exception of mesocosm 5. For the control and topical application mesocosms 3, 6, 7, and 8, the RDX concentration in the leachate declined to less than detection limits (0.02 mg/L) between 0.7 and 1.0 pore volumes. This decline in RDX concentration was unexpected given that pH measurements in the leachate (and soil) were less than necessary for alkaline destruction (pH 10, as shown in the microcosm study) and that the mass of RDX leached from the mesocosms was less than the RDX mass based on initial measurements of soil concentrations (Figure 20).

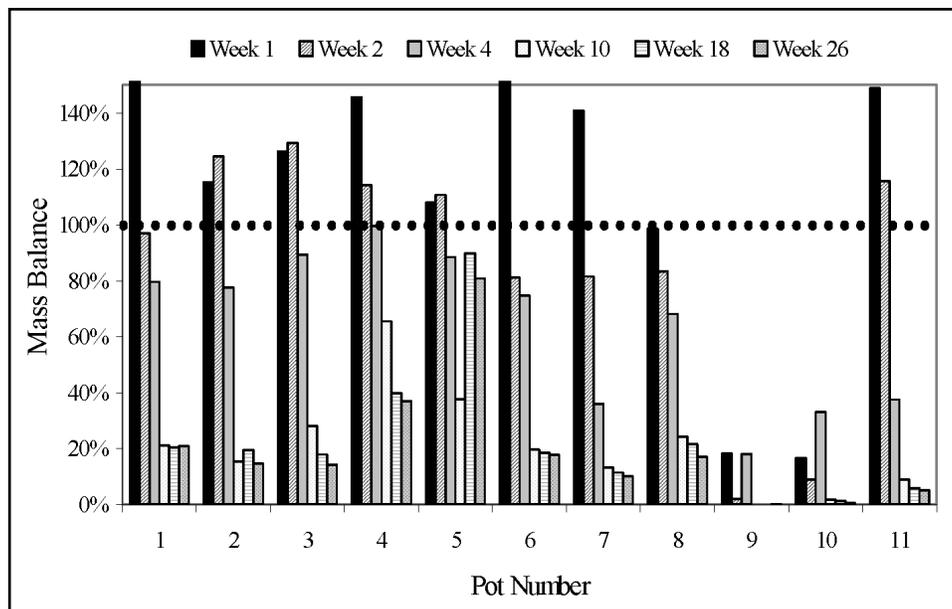


Figure 20. RDX mass balance

The most likely explanation for this observation is biotic degradation under anaerobic conditions. Low dissolved oxygen measurements were noted in 8 of the 11 mesocosms during a spot check in week 13. Dissolved oxygen concentrations ranged from approximately 1 to 2 mg/L in all mesocosms except, 5, 9, and 10, in which dissolved oxygen concentrations of 4, 7, and 7 mg/L were measured, respectively. McCormick et al. (1984), Adrian and Lowder (1999), Shen et al. (2000) and Waisner et al. (2002), as well as others, have demonstrated that RDX is degraded under anaerobic conditions. Beginning at week 12, microbial degradation products MNX, DNX, and TNX were measured in the mesocosm leachate. No TNX was detected, DNX was detected a limited number of times at low concentrations (0.5 mg/L or less) in leachate from mesocosms 3 through 7, and MNX was detected in leachate from mesocosms 2 through 8 at low concentrations (1.5 mg/L or less). A complete listing of concentration data is available

in Appendix B. Interestingly, MNX concentrations were most persistent in leachate from mesocosm 5, which also had the most persistent soil RDX concentration and an intermediate dissolved oxygen concentration. Leachate RDX concentrations in mesocosms 2, 4, and 5 were more persistent than the RDX concentrations in other mesocosms. Although not readily apparent in the graph, the RDX concentration in mesocosm 2 was similar to the control up to 0.8 pore volumes. At this point it remained relatively constant between 0.3 and 1.3 mg/L, possibly due to rate limited desorption or dissolution. The RDX concentration in mesocosm 4 eventually decreased to less than detection limits, but not until more than three pore volumes had been flushed through the mesocosm. It is possible that conditions in mesocosm 4 were not sufficiently anaerobic (possibly due to the higher applied flow rate in this mesocosm) to induce RDX biodegradation. The RDX concentration in mesocosm 5 was most persistent and remained around 20 mg/L over the entire experiment. It is not clearly evident why the RDX elution pattern was distinctly different in this mesocosm. This mesocosm had a topical application of quicklime, which created considerable heat (sufficient to produce steam) during the hydration process as water was initially applied to the mesocosm. While this may have sufficiently sterilized the soil in close proximity to the quicklime, it is doubtful that sufficient heat was generated to sterilize the entire mesocosm. However, microbiological assay showed that both aerobic and anaerobic bacterial counts were much lower in this treatment than in any of the others, excepting the well-mixed quicklime and hydrated lime. Heat was also noted in the well-mixed quicklime mesocosm, but no steam was observed. Another distinction noted in mesocosm 5 was that the dissolved oxygen concentration measured in the leachate during week 13 was higher in the leachate from this mesocosm (4 mg/L) compared to the other mesocosms (approximately 1 to 2 mg/L), also with the exception of the well-mixed lime mesocosms (approximately 7 mg/L). Taken together, the bacterial counts and the dissolved oxygen concentrations suggest that conditions in mesocosm 5 were not sufficiently anaerobic to induce RDX biodegradation.

6 Technology Application Guidelines

While it may seem premature, in light of the unanswered questions pointed out in Chapters 7 and 8, to discuss widespread application of this technology, preliminary guidelines can be established that will allow this technology to be taken to the field for testing under defined conditions. The selection of alkaline treatment as an energetic contaminant remedial technique must consider a number of factors. The advantages of alkaline treatment are that it is rapid, inexpensive, and has remote application possibility. General considerations are discussed in this section in light of results from this study as well as specific situations appropriate for field testing of alkaline hydrolysis of energetic contaminants.

Applicability

The selection of an appropriate remediation technology is dependant on a number of factors, including contaminant properties, site characteristics, and remedial goals. Alkaline treatment should be selected when there is a high probability of remedial success with minimal environmental impact. To ensure success, the first factor to consider is the energetic contaminant properties (spatial extent, treatment pH, fate and transport, retardation) and how susceptible it is to treatment by alkaline hydrolysis. For a number of energetic contaminants, this has been demonstrated (RDX and TNT). However, other energetic contaminants appear to be resistant to attack (2,4- and 2,6-DNT), and the extent to which others can be treated by alkaline hydrolysis needs further investigation (HMX, 2A- and 4A-DNT).

The efficiency of the alkaline hydrolysis reaction to remove explosive compounds from soil or leachate depends on bringing the explosive into direct contact with the hydroxide ion. Of primary concern will be the application of sufficient hydroxide material to elevate the soil pH to levels high enough to remediate the energetic contaminant in an acceptable time frame. Once it has been determined that the energetic contaminant can be treated by alkaline hydrolysis, the next most important question to address is the amount of alkaline material required to elevate the soil pH to levels that will treat the contaminant over a reasonable duration. The soil properties (soil pH, CEC, acid/base saturation, organic substances, etc.) will be the controlling factor in addressing this question. As a preliminary screening process, a batch study should be conducted

with a sample of the contaminated soil to estimate the amount of alkaline material required to elevate the soil pH level, similar to the process completed in the microcosm study. In general, the desired pH range is 10 to 12 to expedite contaminant removal in a timely manner. In combination with the spatial extent of the contaminant, the results from this test would provide an estimate of the amount of alkaline material needed to treat the impacted area.

Based on the microcosm studies, the minimum hydrated lime application required to raise the soil pH between 10 and 12 was generally 3 to 5 percent (alkaline mass to soil mass). Assuming a contaminant depth of 0.3 m and a bulk soil density of 1.5 g/cc, this equates to treatment applications of approximately 100 to 200 metric tons per hectare. This application dosage is substantially higher than those dosages generally applied for agricultural purposes; however, the pH goal is likewise much higher. At these application levels, it is necessary to carefully consider the benefits of application versus the cost and potential long-term impact to the environment.

Application Method

Three potential application scenarios are envisioned for alkaline treatment: well-mixed, topical, and reactive barrier (Table 14). Well-mixed applications are most efficient in getting the hydroxide ion in close contact with the energetic contaminant in the source zone and would result in the shortest treatment time as demonstrated in this study. Unfortunately, well-mixed applications require intrusive activities which are more costly than topical applications, and potentially dangerous where unexploded ordnances exist. Mixed applications may be most appropriate as a pollution prevention technique at new facilities. Topical applications are nonintrusive and would be the less expensive application option. Unfortunately, the aqueous transport of hydroxide ions may be severely hampered by soil properties, as observed in this study. However, topical applications may still be viable under some conditions, such as extremely surficial contamination, soil with low buffering capacity, or as a pollution prevention method. Topical lime applied to a range and then impacted with various ordnance could perform as a well-mixed system. The last option, reactive barriers, are in some ways similar to topical applications except that RDX is allowed to move into the alkaline zone rather than the hydroxide moving through the contaminated zone. From the stand point of a military range remedial technique, reactive barriers would be installed at a down-gradient location and treat the energetic contaminant as it is transported to the barrier. For new facilities, well-mixed or reactive barrier applications may be ideal pollution prevention technologies, especially for small areas with localized activities. For existing facilities, careful consideration must be given to the type of application. The potential safety concerns of intrusive activities associated with well-mixed and reactive barrier applications must be considered against the effectiveness of topical applications that rely on aqueous hydroxide ion transport.

Topical treatment is the preferred application method. An important consideration to range personnel is the reapplication rate of the lime. As a first step assessment, using the solubility concentration of the alkaline material and the

Table 14 Advantages and Disadvantages to Alkaline Treatment Application Methods		
Application	Advantages	Disadvantages
Well-Mixed	Efficient contact with contaminant, source zone remedial treatment.	Intrusive, more costly than topical, possible safety issues with UXO
Topical	Nonintrusive, more economical	Treatment efficiency may be limited by soil properties, hydroxide must "catch" contaminant
Reactive Barrier	Does not rely on aqueous hydroxide transport, alkaline material only needed in a limited location.	Intrusive, contaminant must travel to the barrier

spatial extent of the contaminant, the amount of water required to flush the area in a given duration can be estimated or, assuming natural precipitation, the length of time required to deliver the required alkaline material could be estimated. Assuming hydrated lime with a solubility of approximately 2 g/L, Figure 21 indicates the length of time it would take to deliver an alkaline material at various lime dosages as a function of annual precipitation estimates. This graph is based on an assumed soil bulk density of 1.5 g/cc. For reference, precipitation data were collected from the National Climatic Data Center (NCDC) of the National Oceanographic and Atmospheric Administration (NOAA) for the firing range sites examined in this study (Table 15).

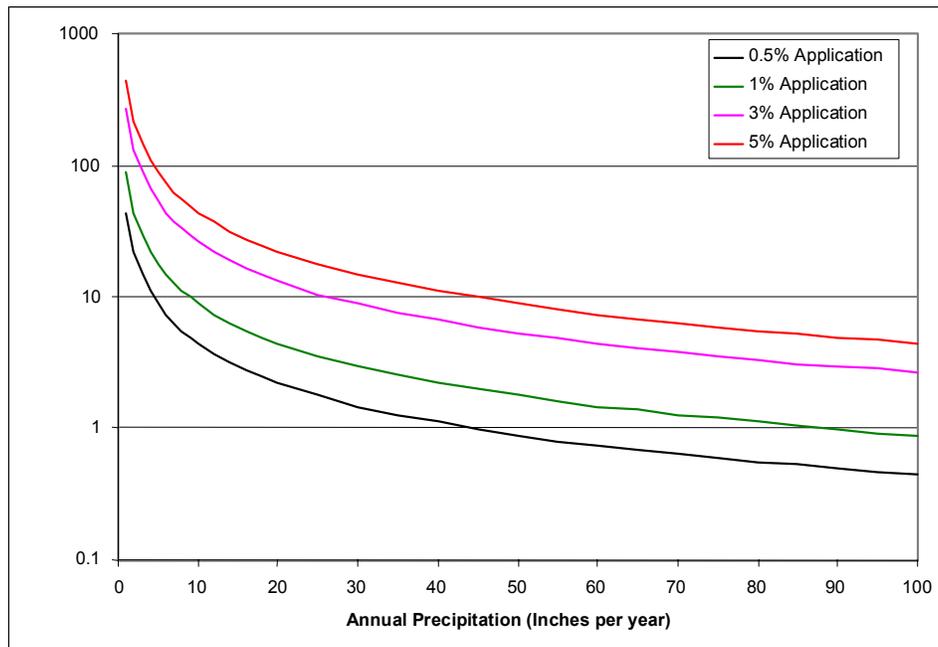


Figure 21. Persistence of alkaline pH (years) as a function of annual precipitation rates for several application dosages (Note: An assumed bulk density of 1.5 g/cc was used as a basis for the graph)

Site	Precipitation (yearly average, including snow, inches)
Fort Wainwright, AK	78
Fort Bliss, TX/NM	28
Fort Lewis, WA	37
Yakima Training Center, WA	8
Camp Guernsey, WY	13

For example, 2.57 kg of hydrated lime was well mixed with the soil in mesocosm 10 (a 5-percent mass application dosage), and the resulting soil pH was approximately 11. To deliver that much hydrated lime aqueously, approximately 1,285 L would be required to flow through the mesocosm assuming a hydrated lime solubility of approximately 2 g/L. At the water application rate used in the mesocosm study (1.6 L/week for most mesocosms), the experimental duration would have had to be extended for 15 years to reach this volume. This ensured that the amendment was not exhausted during the

course of this study. In this case, it is evident that the soil properties hamper the practicality of aqueous delivery of hydroxide ions, a conclusion supported by the results from mesocosm 3, the mesocosm with the topically applied hydrated lime, in which no significant increases in soil pH were measured over the experimental duration.

An example of the use of Table 15 and Figure 21 can be provided by the following scenario. Fort Lewis, located in Washington state, has active artillery and grenade training ranges. According to NCDC data reported in Table 15, it receives an average of 37 in. of precipitation per year, which includes winter snow and ice as well as rain. Turning to Figure 21, you can select 37 in. on the X-axis. A vertical line drawn at this point will intersect the lime application lines. A second line drawn from the intersection point to the Y-axis (pH persistence) indicates the length of time the lime will last, or in other words, how often will that dosage need to be reapplied under those rainfall conditions. Fort Lewis would need to reapply lime yearly at a 0.5-percent application rate. At a 5-percent application rate, the lime would need to be reapplied every 10 years. Knowing the annual precipitation does not preclude the necessity of conducting site-specific preliminary batch tests to determine the efficacy of alkaline hydrolysis on a particular soil. It does provide a starting point for site managers to use when considering use of this technology.

The well-mixed application method will be more feasible in small areas, such as around targets where munitions have been directed in a localized manner, rather than over large areas. Careful attention must be given to safety concerns prior to mixing operations. Based on the results from this study, the energetic contaminant will be rapidly treated, much sooner than the expected life of the alkaline material. As a result, high pH levels may persist for an extended period of time after the contaminant is gone. Figure 21 also indicates the duration over which well-mixed alkaline material will persist in the environment. For active ranges, this is advantageous from a pollution prevention standpoint. For closed ranges, this may not be advantageous, and steps may be required to reduce the soil pH following alkaline treatment, or at least minimize exposure to high pH soil.

Alkaline Material

The efficiency of the alkaline material used to increase soil pH depends on the composition of the material, the particle size of the material, its solubility in water, and its dissolution rate. Of the three alkaline materials used in the study, hydrated lime appears to be the best candidate for application in the field. The class C fly ash did not raise the pH in the soil or leachate to levels comparable to the quick lime or hydrated lime. Furthermore, the fly ash applied topically to mesocosm 7 created a hard layer that appeared to impede water infiltration and oxide mass transfer. The quicklime produced slightly higher pH levels than the hydrated lime, however, when hydrated, the quicklime undergoes a large exothermic reaction that can create safety concerns in the field.

7 Summary

The microcosm study showed that the major explosives common to training ranges, RDX, TNT and HMX, are removed from a variety of different type soils by alkaline hydrolysis in a well-mixed system. The reaction rate is fastest for TNT, then RDX, and last is HMX. Solid particles of these explosives, such as are found in contact with unexploded or incompletely detonated ordnance, will also be degraded by alkaline hydrolysis. The TNT metabolites, 2A- and 4A-DNT, are removed by alkaline hydrolysis, although the reaction requires more time and a higher pH (>12) than the parent compound. The propellants, 2,4- and 2,6-DNT, may be insensitive to alkaline hydrolysis.

The mesocosm study also showed that in well-mixed systems, the explosives RDX, HMX, and TNT were removed from both soil and leachate. However, in this soil system (high soil CEC), with topical applications, all explosive contaminants were not rapidly removed from soil or leachate. While RDX concentrations did decline in some mesocosms with topical applications, it is suspected that this was the result of anaerobic biodegradation rather than alkaline hydrolysis due to the low pH measurements in the soil and leachate. This suggests that under the proper conditions, anaerobic biodegradation is a faster remedial mechanism than topically applied alkaline material. However, it may not be practical to create these conditions in situ that will promote sufficient anaerobic degradation on training ranges.

Toxicity testing demonstrated that the reaction reduces soil toxicity and mutagenicity even in a complex soil system. The reaction intermediates and end products are less toxic than the parent compounds.

Transport of the hydroxide ion is affected by soil geochemical parameters, such as pH, CEC, and the base saturation. Results from this portion of the study suggest that topical application of alkaline material for remediation of RDX at depth, in soil with a high CEC and clay/metals content, as is the case of the NOP soil may not be effective. However, bioremediation was not faster than the removal rate in the well-mixed systems given that the kinetics of the alkaline hydrolysis reaction at elevated pH levels are fairly rapid.

8 Future Efforts

Plans for future research include:

- a.* Examining the effect of alkaline hydrolysis on HMX and the newly developed explosive, CL-20; determining the effect of the reaction on the RDX metabolites, MNX and DNX, and on TNT metabolites, 2A- and 4A-DNT; determining the effectiveness of the alkaline hydrolysis reaction on the propellants 2,4- and 2,6-dinitrotoluene, nitrocellulose, nitroglycerine, and nitroguanidine.
- b.* Identifying the intermediate and final transformation products of the alkaline hydrolysis of RDX and TNT; determining if the products are pH dependent; examining the humification potential of these products and studying the impact of various soil properties on the humification process in order to clarify the effects of humification versus transformation; establishing the biodegradability of the transformation products for both aerobic and anaerobic bacteria and determining the potential toxicity of the reaction intermediates and final products.
- c.* Establishing the effects, if any, of co-contamination on the removal of explosives by alkaline hydrolysis.
- d.* Studying the reactive transport of hydroxide through range soils with differing soil properties to quantify the effect of natural organic matter, CEC, and pH on the alkaline hydrolysis reaction; clarifying the effects of humification versus transformation. By delineating the soil parameters affecting the hydroxide reaction, guidelines can be written for site managers applying this technology to their situation.

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Appendix A

Microcosm Data

Table A1 Retention Times and Detection Limits of 8330 Explosives on the C18 Column		
Explosive	Retention Time, min	Machine Detection Limits mg/kg
HMX	3.4	0.020
RDX	4.7	0.020
TNB	6.4	0.020
DNB	7.8	0.020
TNT	10.7	0.020
4A-DNT	11.7	0.020
2A-DNT	coelutes w 4A	0.020
2,4 DNT	12.07	0.020
2,6 DNT	12.9	0.020
TNX	3.5	0.020
DNX	3.8	0.050
MNX	4.4	0.020

Parameters of the Alkaline Hydrolysis Reaction

Dose	Time, days	HMX ¹	RDX	TNB	TNT	4A-DNT	2A-DNT	Std. Dev.	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT	
1%	untreated	0	6.36	63.84	2.86	16.81	0.74	0.68	1%	1.71	13.90	0.89	3.83	0.14	0.10
		1	7.52	74.89	1.18	4.06	0.85	0.52		1.91	28.40	0.03	1.62	0.15	0.09
		3	5.40	56.36	1.83	3.81	0.65	0.45		0.79	20.16	0.48	1.04	0.05	0.07
		7	4.58	39.71	0.88	5.82	0.93	0.36		4.41	35.61	0.78	7.78	0.83	0.31
		14	4.66	45.27	0.43	0.60	0.96	0.41		2.48	22.79	0.67	0.49	0.38	0.19
		21	6.44	51.85	0.11	0.43	1.14	0.46		1.35	8.68	0.11	0.18	0.31	0.16
3%	untreated	0	6.36	63.84	2.86	16.81	0.74	0.68	3%	1.71	13.90	0.89	3.83	0.14	0.10
		1	6.14	17.97	0.00	0.19	0.73	0.32		1.14	3.35	0.00	0.10	0.17	0.07
		3	5.42	10.68	0.00	0.15	0.51	0.22		0.77	9.10	0.00	0.01	0.10	0.03
		7	4.97	11.99	0.00	0.15	0.53	0.09		1.92	19.70	0.00	0.02	0.08	0.08
		14	3.76	10.82	0.00	0.00	0.31	0.03		2.35	18.05	0.00	0.00	0.06	0.06
		21	3.85	0.14	0.00	0.09	0.52	0.13		1.26	0.12	0.00	0.02	0.12	0.04
5%	untreated	0	6.36	63.84	2.86	16.81	0.74	0.68	5%	1.71	13.90	0.89	3.83	0.14	0.10
		1	5.35	17.91	0.00	0.14	0.56	0.24		0.37	3.59	0.00	0.01	0.07	0.06
		3	4.31	4.97	0.00	0.17	0.39	0.16		0.55	2.32	0.00	0.13	0.02	0.02
		7	9.05	14.51	0.00	0.13	0.53	0.13		6.13	11.13	0.00	0.03	0.10	0.02
		14	3.00	1.37	0.00	0.00	0.21	0.00		0.67	2.05	0.00	0.00	0.02	0.00
		21	1.41	0.00	0.00	0.00	0.10	0.12		0.25	0.00	0.00	0.00	0.00	0.09

¹ Concentration units are mg/kg.

Type	Time, days	HMX ¹	RDX	TNB	TNT	4A-DNT	2A-DNT	24-DNT	Std. Dev.	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT	24-DNT		
RDX Crystal	untreated	0	57.54	1853.23	2.21	9.55	0.00	0.00	RDX	8.34	236.27	2.13	8.28	0.00	0.00	0.00		
		1	46.44	1569.65	0.00	0.00	0.00	0.00		16.18	283.61	0.00	0.00	0.00	0.00	0.00		
		3	66.72	1527.36	0.00	27.86	0.00	0.00		0.00	3.82	60.78	0.00	48.26	0.00	0.00	0.00	
		7	13.46	384.08	0.00	0.00	0.00	0.00		0.00	4.07	15.53	0.00	0.00	0.00	0.00	0.00	
		14	28.97	548.58	0.00	0.00	0.00	0.00		0.00	10.83	205.78	0.00	0.00	0.00	0.00	0.00	
		21	25.37	514.88	0.00	0.00	0.00	0.00		0.00	12.58	265.29	0.00	0.00	0.00	0.00	0.00	
TNT Whole grain	untreated	0	0.00	103.13	5.42	1203.98	0.00	0.00	TNT whole	0.00	43.51	1.57	66.89	0.00	0.00	0.00		
		1	0.00	19.73	8.93	687.04	1.68	0.45		0.00	0.00	16.31	5.71	596.06	2.90	0.78	0.00	
		3	0.00	13.43	4.23	977.36	0.00	0.00		0.00	0.00	1.82	3.09	702.42	0.00	0.00	0.00	
		7	0.57	1.04	0.00	242.29	0.00	0.00		0.00	0.81	1.81	0.00	59.24	0.00	0.00	0.00	
		14	0.00	0.00	2.05	370.97	2.57	0.00		0.00	0.00	0.00	0.00	0.66	109.40	2.38	0.00	0.00
		21	0.00	0.00	2.41	218.41	2.99	0.21		0.00	0.00	0.00	0.00	1.40	58.62	0.54	0.36	0.00
TNT Broken grain	untreated	0	24.65	68.46	3.26	1902.99	0.00	0.00	TNT broken	42.70	14.96	0.53	210.15	0.00	0.00	0.00		
		1	0.00	10.87	2.56	654.48	0.00	0.00		0.00	0.00	6.13	0.62	190.24	0.00	0.00	0.00	
		3	0.00	8.76	4.38	349.75	1.09	0.40		0.00	0.00	8.54	3.85	312.49	1.90	0.69	0.00	
		7	0.00	0.00	0.00	122.89	0.00	0.00		0.00	0.00	0.00	0.00	29.49	0.00	0.00	0.00	
		14	0.00	0.00	1.71	183.22	3.09	0.00		0.00	0.00	0.00	1.37	130.70	1.02	0.00	0.00	
		21	0.00	0.00	1.03	205.50	2.65	0.00		0.00	0.00	0.00	0.12	15.41	1.04	0.00	0.00	

¹ Concentration units are mg/kg.

Table A4					
Effect of Organic Matter Concentration on Removal of ¹⁴C-RDX by Treatment with 5-Percent Hydrated Lime					
Time (days)	Organic Carbon (concentration as % mass)				
	0% (sand)	1%	5%	10%	100% (peat moss)
0	30,030 ¹	25,761	10,604	5,532	753
1	25,224	21,940	17,534	13,491	2,675
3	27,158	22,605	16,509	12,300	3,936
7	25,874	21,477	16,243	12,618	2,496
14	27,756	20,818	17,104	13,266	2,513
21	26,632	21,493	15,798	12,973	494
pH Initial	12.95	12.94	12.92	12.79	12.59
pH final	12.59	12.61	12.56	12.39	11.70

¹ Units are ¹⁴C-RDX dpm/min.

Table A5										
Tracer Distribution Between the Solid Phase and the Supernatant when ¹⁴C-RDX is Treated with 5-Percent Hydrated Lime and Various Concentrations of Organic Matter										
Time days	A. Tracer (%) in Supernatant					B. Tracer (%) in Solid Phase				
	Organic Carbon Concentration					Organic Carbon Concentration				
	0%	1%	5%	10%	100%	0%	1%	5%	10%	100%
0	82.77	71.00	29.23	15.25	2.08	17.23	29.00	70.77	84.75	97.92
1	69.52	60.47	48.33	37.18	7.37	30.48	39.53	51.67	62.82	92.63
3	74.85	62.31	45.50	33.90	10.85	25.15	37.69	54.50	66.10	89.15
7	71.32	59.20	44.77	34.78	6.88	28.68	40.80	55.23	65.22	93.12
14	76.50	57.38	47.14	36.56	6.93	23.50	42.62	52.86	63.44	93.07
21	73.40	59.24	43.54	35.76	1.36	26.60	40.76	56.46	64.24	98.64

Ammunition Plant Soils

Table A6 Ammunition Plant Soils																	
Site	Time, days	HMX ¹	RDX	TNB	TNT	4A-DNT	2A-DNT	24-DNT	Std. Dev.	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT	24-DNT	
NOP CEC=42	untreated	0	6.36	63.84	2.86	16.81	0.74	0.68	0.00	NOP	1.71	13.90	0.89	3.83	0.14	0.10	0.00
		1	5.35	17.91	0.00	0.14	0.56	0.24	0.00		0.37	3.59	0.00	0.01	0.07	0.06	0.00
		3	4.31	4.97	0.00	0.17	0.39	0.16	0.00		0.55	2.32	0.00	0.13	0.02	0.02	0.00
		7	9.05	14.51	0.00	0.13	0.53	0.13	0.00		6.13	11.13	0.00	0.03	0.10	0.02	0.00
		14	3.00	1.37	0.00	0.00	0.21	0.00	0.00		0.67	2.05	0.00	0.00	0.02	0.00	0.00
		21	1.41	0.00	0.00	0.00	0.10	0.12	0.00		0.25	0.00	0.00	0.00	0.09	0.14	0.00
Crane CEC=8	untreated	0	0.00	49.94	0.00	0.34	0.00	0.23	0.00	Crane	0.00	7.85	0.00	0.19	0.00	0.20	0.00
		1	0.00	10.58	0.00	0.13	0.00	0.14	0.00		0.00	1.20	0.00	0.02	0.00	0.12	0.00
		3	0.00	4.63	0.00	0.00	0.00	0.00	0.00		0.00	2.43	0.00	0.00	0.00	0.00	0.00
		7	0.00	2.65	0.00	0.00	0.36	0.18	0.00		0.00	0.53	0.00	0.00	0.03	0.00	0.00
		14	0.00	1.00	0.00	0.02	0.04	0.11	0.00		0.00	0.29	0.00	0.06	0.01	0.03	0.00
		21	0.00	0.62	0.00	0.00	0.00	6.20	0.00		0.00	0.53	0.00	0.00	0.00	10.11	0.00
IAAP CEC=11	untreated	0	0.00	0.00	18.85	3.94	1.39	0.84	0.46	IAAP	0.00	0.00	0.34	0.04	0.05	0.05	0.01
		1	0.00	0.00	0.08	0.00	2.33	0.49	0.00		0.00	0.00	0.07	0.00	0.05	0.03	0.00
		3	0.00	0.00	0.03	0.00	2.32	0.27	0.00		0.00	0.00	0.06	0.00	0.06	0.01	0.00
		7	0.00	0.00	0.00	0.00	2.64	0.12	0.00		0.00	0.00	0.00	0.00	0.10	0.02	0.00
		14	0.00	0.00	0.00	0.00	1.89	0.00	0.00		0.00	0.00	0.00	0.00	0.35	0.00	0.00
		21	0.00	0.00	0.00	0.00	1.90	0.00	0.00		0.00	0.00	0.00	0.00	0.16	0.00	0.00
LOOW CEC=15	untreated	0	0.00	0.00	168.66	12905.47	0.00	65.20	0.00	LOOW	0.00	0.00	5.97	286.84	0.00	24.89	0.00
		1	0.00	0.00	58.53	1772.64	34.63	93.31	0.00		0.00	0.00	14.80	1842.17	4.45	59.46	0.00
		3	0.00	0.00	25.50	1860.70	29.75	53.46	0.00		0.00	0.00	3.11	374.05	6.67	28.84	0.00
		7	0.00	0.00	17.61	398.01	0.00	2.66	0.00		0.00	0.00	2.69	33.02	0.00	0.34	0.00
		14	0.00	0.00	15.24	326.63	25.19	4.39	0.00		0.00	0.00	5.67	277.17	7.51	4.58	0.00
		21	0.00	0.00	7.39	29.89	29.12	14.14	1.56		0.00	0.00	6.57	30.85	3.78	11.12	1.88
VAAP CEC=20	untreated	0	141.79	1360.70	0.00	8.46	0.00	0.00	0.00	VAAP	22.29	204.69	0.00	0.75	0.00	0.00	0.00
		1	137.56	731.34	0.00	0.00	2.24	1.62	0.00		8.65	45.39	0.00	0.00	0.13	0.04	0.00
		3	123.38	584.08	0.00	0.00	1.64	1.91	0.00		18.62	56.22	0.00	0.00	0.07	0.24	0.00
		7	39.73	127.04	0.00	0.00	0.00	0.00	0.00		12.16	113.58	0.00	0.00	0.00	0.00	0.00
		14	55.58	36.11	0.00	0.00	0.74	0.00	0.00		10.01	21.96	0.00	0.00	0.65	0.00	0.00
		21	77.26	24.77	0.00	0.00	1.67	0.49	0.00		7.58	16.61	0.00	0.00	0.02	0.04	0.00

¹ Concentration units are mg/kg.

Firing Range Soils

Table A7 Contaminant Removal from Fort Lewis Soil by Treatment with 5-Percent Hydrated Lime											
Time days	Contaminant and Concentration (mg/kg)										
FL1	HMX	RDX	4A-DNT	2,4-DNT	stdev	HMX	RDX	4A-DNT	2,4-DNT		
0	0.32	0.63	0.00	0.00		0.05	0.05	0.00	0.00		
0.5	0.33	0.22	0.05	0.00		0.09	0.14	0.00	0.00		
1	0.11	1.09	0.00	0.00		0.01	2.31	0.00	0.00		
3	0.09	0.00	0.03	0.49		0.16	0.00	0.05	0.76		
7	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		
14	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		
k	0.3842										
FLFR	HMX	TNB	2A-DNT	2,6-DNT	2,4-DNT	stdev	HMX	TNB	2A-DNT	2,6-DNT	2,4-DNT
0	0.86	0.16	0.00	0.00	86.39		1.50	0.28	0.00	0.00	15.02
0.5	0.00	0.42	0.00	0.00	64.06		0.00	0.16	0.00	0.00	35.63
1	0.00	0.00	0.00	1.04	82.70		0.00	0.00	0.00	1.29	27.82
3	0.00	0.00	1.24	1.00	86.84		0.00	0.00	1.15	0.37	26.61
7	0.00	0.00	0.00	0.57	92.37		0.00	0.00	0.00	0.98	9.29
14	0.00	0.00	0.00	2.08	149.91		0.00	0.00	0.00	0.71	22.09
k				0.0508	0.0464						
FLGS	HMX	RDX	TNB	TNT	4A-DNT	stdev	HMX	RDX	TNB	TNT	4A-DNT
0	2.50	11.96	0.26	0.50	0.16		0.15	1.96	0.25	0.05	0.05
0.5	2.12	1.75	0.00	0.00	0.19		0.08	0.52	0.00	0.00	0.01
1	1.62	1.94	0.00	0.00	0.44		0.20	0.85	0.00	0.00	0.03
3	0.79	1.78	0.00	0.00	3.52		0.69	2.15	0.00	0.00	4.05
7	0.81	0.33	0.00	0.00	0.30		0.36	0.10	0.00	0.00	0.06
14	0.00	0.00	0.00	0.00	0.31		0.00	0.00	0.00	0.00	0.02
k	0.159	0.379			0.00225						

**Table A8
Contaminant Removal from Fort Bliss and Fort Wainwright Soils by Treatment with 5-Percent Hydrated Lime**

FB		Contaminant Concentration (mg/kg)												
Time days	RDX	TNB	DNB	TNT	4A-DNT	2A-DNT	stdev	RDX	TNB	DNB	TNT	4A-DNT	2A-DNT	
0	0.00	1.80	0.00	656.34	8.09	0.00		0.00	0.04	0.00	70.29	0.12	0.00	
0.5	0.37	8.67	0.13	3.81	9.61	0.00		0.65	4.37	0.22	6.61	0.13	0.00	
1	0.00	7.58	0.00	500.25	20.16	0.00		0.00	8.24	0.00	727.60	6.83	0.00	
3	0.00	5.89	0.00	496.58	15.56	1.32		0.00	2.85	0.00	515.17	2.98	2.28	
7	0.00	0.00	0.00	164.51	15.15	0.00		0.00	0.00	0.00	202.76	0.96	0.00	
14	0.00	0.00	0.28	23.19	12.56	0.92		0.00	0.00	0.49	36.70	0.47	0.19	
21	0.00	0.00	0.00	2.37	11.32	0.48		0.00	0.00	0.00	2.46	0.73	0.04	
k		0.20368		0.18506		0.05456								
FW		HMX	RDX	TNB/DNB	TNT	4A-DNT	2A-DNT	stdev	HMX	RDX	TNB/DNB	TNT	4A-DNT	2A-DNT
0	4.03	32.47	0.35	1.11	2.73	0.00		0.47	1.61	0.01	0.60	2.64	0.00	
0.5	4.04	10.23	0.00	0.07	0.43	0.04		1.86	9.58	0.00	0.06	0.07	0.06	
1	1.84	1.72	0.00	0.03	0.21	0.00		0.42	1.49	0.00	0.05	0.05	0.00	
3	1.74	1.32	0.00	0.26	0.23	0.00		0.50	1.29	0.00	0.29	0.04	0.00	
7	0.66	0.50	0.00	0.00	0.28	0.00		0.84	0.16	0.00	0.00	0.14	0.00	
21	0.00	0.03	0.00	0.00	0.00	0.00		0.00	0.06	0.00	0.00	0.00	0.00	
k	0.2464	0.2676		0.09874	0.17878									

**Table A9
Contaminant Removal from Camp Guernsey Soil, Sites 32 and 48, by Treatment with 5-Percent Hydrated Lime**

GC32		Contaminant Concentration (mg/kg)												
Time days	HMX	TNB	TNT	4A-DNT	2A-DNT		stdev	HMX	TNB	TNT	4A-DNT	2A-DNT		
0	0.00	0.00	27.68	3.56	0.00			0.00	0.00	4.77	0.21	0.00		
0.5	0.04	0.09	1.12	4.38	0.00			0.08	0.08	0.75	0.21	0.00		
1	0.00	0.86	117.18	9.53	2.25			0.00	1.48	202.96	3.34	0.63		
3	0.00	0.00	1.94	4.27	0.95			0.00	0.00	3.36	0.57	0.04		
7	0.00	0.00	0.03	3.21	0.42			0.00	0.00	0.05	0.22	0.36		
14	0.00	0.00	0.06	2.23	0.41			0.00	0.00	0.06	0.17	0.05		
21	0.00	0.00		1.80	0.23			0.00	0.00	0.00	0.12	0.02		
k			0.457539	0.053704	0.0962									
GC48		HMX	RDX	TNT	4A-DNT	2A-DNT	24-DNT	stdev	HMX	RDX	TNT	4A-DNT	2A-DNT	24-DNT
0	11.41	112.61	25.88	0.00	0.00	0.00		6.17	32.49	17.90	0.00	0.00	0.00	
0.5	10.62	90.71	2.33	1.22	0.27	0.00		2.52	10.02	2.71	0.19	0.03	0.00	
1	5.63	41.32	0.60	0.62	0.17	0.00		1.55	16.91	0.69	0.16	0.06	0.00	
3	5.42	42.01	0.43	0.42	0.05	0.00		2.18	19.81	0.74	0.03	0.09	0.00	
7	11.74	47.66	0.00	0.21	0.04	0.00		9.24	39.28	0.00	0.18	0.08	0.00	
21	7.36	42.34	0.00	0.00	0.00	7.32		10.79	73.26	0.00	0.00	0.00	12.68	
k		0.0269	1.101877	0.232416	0.25904									

**Table A10
Contaminant Removal from Camp Guernsey Soil, Sites 51 and 52, by Treatment with
5-Percent Hydrated Lime**

GC51	Contaminant Concentration (mg/kg)												
Time days	RDX	TNB	TNT	4A-DNT	2A-DNT		stdev	RDX	TNB	TNT	4A-DNT	2A-DNT	
0	0.00	0.44	182.46	3.17	2.93			0.00	0.08	40.83	2.75	0.33	
0.5	0.00	0.22	19.75	6.93	3.15			0.00	0.22	21.94	1.05	0.41	
1	0.00	0.00	3.76	4.38	1.33			0.00	0.00	2.43	0.56	0.12	
3	0.00	0.67	96.67	4.81	1.02			0.00	1.16	164.80	3.94	0.59	
7	0.00	0.00	1.48	1.79	0.32			0.00	0.00	1.66	0.34	0.30	
21	0.33	0.00	0.00	0.26	0.00			0.58	0.00	0.00	0.06	0.00	
k			0.427533	0.143048	0.31066								
GC52	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT	stdev	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT
0	0.00	0.00	0.34	32.84	2.24	0.00		0.00	0.00	0.11	0.98	0.71	0.00
0.5	0.04	0.15	0.27	2.02	3.19	0.00		0.08	0.13	0.05	0.03	0.46	0.00
1	0.00	0.00	0.00	0.40	3.07	1.10		0.00	0.00	0.00	0.06	0.18	0.06
3	0.00	0.00	0.00	0.09	1.51	0.45		0.00	0.00	0.00	0.02	0.37	0.07
7	0.00	0.00	0.00	0.18	1.54	0.49		0.00	0.00	0.00	0.03	0.28	0.13
14	0.00	0.00	0.00	1.40	0.88	0.28		0.00	0.00	0.00	0.30	0.24	0.08
21	0.00	0.00	0.00	0.06	0.80	0.19		0.00	0.00	0.00	0.01	0.32	0.07
k			0.461047	0.135202	0.06252	0.079739							

**Table A11
Contaminant Removal from Yakima Training Center Soil, Sites 1, 2, and 4, by Treatment with 5-Percent Hydrated Lime**

YC1	Contaminant Concentration (mg/kg)														
Time days	HMX	RDX	TNT	4A-DNT	2A-DNT	26-DNT	24-DNT	stdev	HMX	RDX	TNT	4A-DNT	2A-DNT	26-DNT	24-DNT
0	53.43	4.13	0.51	0.60	3.04	0.00	0.00		4.61	0.22	0.29	0.35	0.02	0.00	0.00
0.5	51.70	3.98	0.00	0.60	3.18	0.00	0.00		2.27	0.35	0.00	0.35	0.03	0.00	0.00
1	13.60	0.00	0.00	0.36	3.22	0.00	0.10		2.99	0.00	0.00	0.04	0.02	0.00	0.06
3	14.67	2.03	0.15	0.11	2.31	0.13	0.35		3.27	0.94	0.25	0.20	0.27	0.23	0.45
7	4.47	0.91	0.00	0.00	0.00	0.00	0.00		0.07	0.12	0.00	0.00	0.00	0.00	0.00
21	0.65	0.29	0.06	0.00	0.00	0.00	0.00		0.72	0.50	0.06	0.00	0.00	0.00	0.00
k	0.1951	0.1246		0.5893	0.1067										
YC2	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT	24-DNT	stdev	HMX	RDX	TNB	TNT	4A-DNT	2A-DNT	24-DNT
0	62.26	0.00	0.00	0.00	0.23	2.04	0.00		14.33	0.00	0.00	0.00	0.39	0.05	0.00
0.5	98.81	2.00	0.05	0.42	0.88	2.28	0.23		31.08	3.47	0.09	0.37	0.09	0.27	0.23
1	49.06	3.13	0.00	0.39	0.44	0.00	0.00		9.80	1.63	0.00	0.06	0.05	0.00	0.00
3	48.29	0.94	0.00	0.50	0.37	2.07	0.00		14.12	0.93	0.00	0.10	0.12	0.08	0.00
7	42.51	0.40	0.00	0.00	0.13	0.00	0.00		16.06	0.05	0.00	0.00	0.23	0.00	0.00
21	8.98	0.00	0.00	0.04	0.03	0.00	0.00		1.06	0.00	0.00	0.06	0.06	0.00	0.00
k	0.0968	0.288			0.1259										
YC4	HMX	RDX	TNT	4A-DNT	2A-DNT	26-DNT		stdev	HMX	RDX	TNT	4A-DNT	2A-DNT	26-DNT	
0	30.33	0.00	0.18	0.07	0.79	0.00			1.58	0.00	0.16	0.12	0.04	0.00	
0.5	21.57	0.12	0.26	0.21	0.88	0.00			1.23	0.21	0.00	0.02	0.15	0.00	
1	5.11	0.58	0.19	0.24	0.00	0.00			0.15	0.34	0.03	0.42	0.00	0.00	
3	2.91	0.47	0.08	0.04	0.89	0.00			0.26	0.81	0.14	0.07	0.03	0.00	
7	1.68	1.07	0.07	0.06	0.00	0.08			0.37	0.21	0.12	0.11	0.00	0.14	
21	0.35	0.00	0.00	0.13	0.00	0.00			0.24	0.00	0.00	0.23	0.00	0.00	
k	0.1823	0.2378	0.182												

Appendix B

Mesocosm Data

Soil

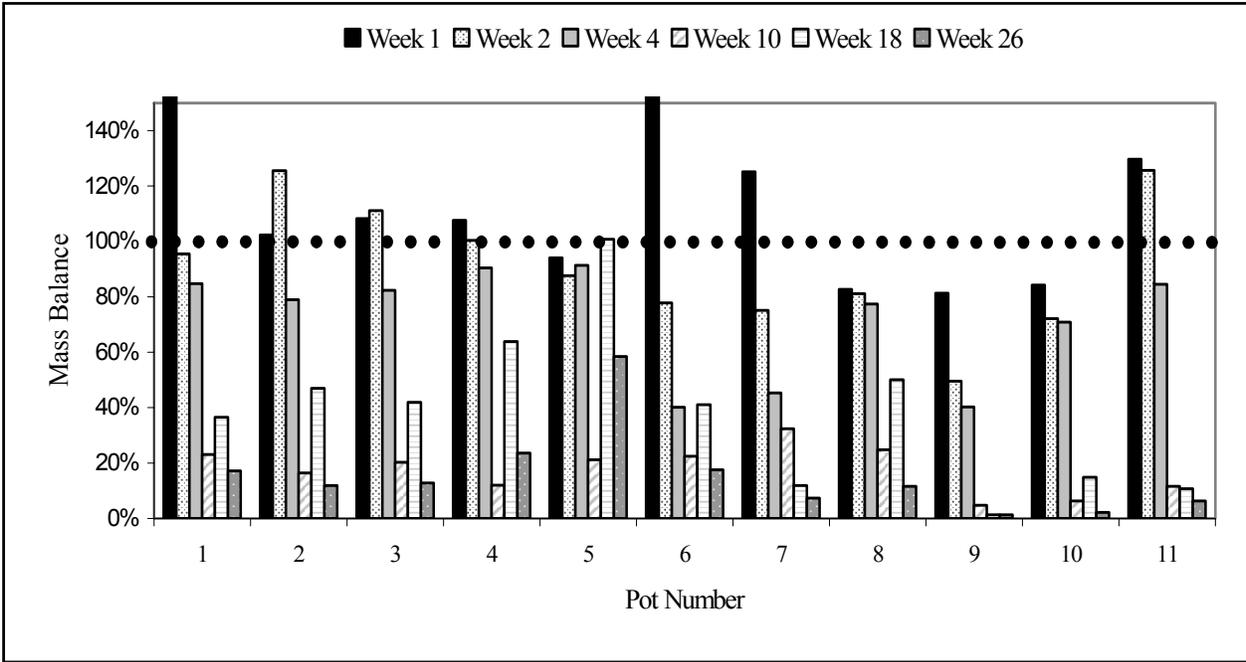


Figure B1. HMX mass balance

**Table B1
Initial and Final Soil CEC from Treated and Untreated Mesocosm Soil**

NOP soil	Initial CEC	42
Mesocosm #	Soil Layer - Treatment	Final CEC
1	Control	38
3	Top – topical hydrated lime	37
3	Middle – topical hydrated lime	38
3	Bottom – topical hydrated lime	38
5	Top – topical quicklime	38
5	Middle – topical quicklime	38
5	Bottom – topical quicklime	37
7	Top – topical fly ash	37
7	Middle – topical fly ash	38
7	Bottom – topical fly ash	37
9	Quicklime mixed	40
10	Hydrated lime mixed	41
11	Fly ash mixed	39

**Table B2
Mesocosm Soil Mass and Lime Application Rate**

Mesocosm	Treatment	NOP Soil Mass, kg	Alkali Mass kg	Application Rate	
				kg/m ²	tons ¹ /hectare
1	Control, no lime	55.60	0	0.0	0
2	Hydrated Lime, Topical, Minimum lime	56.52	0.1	0.8	8
3	Hydrated Lime, Topical	56.90	2.85	22.0	220
4	Hydrated Lime, Topical, Double water	58.40	2.92	22.5	225
5	Quicklime, Topical	56.60	2.83	21.8	218
6	Hydrated Lime, Topical, Acid water	56.45	2.82	21.7	217
7	Fly ash, Topical	56.40	2.82	21.7	217
8	Aqueous, pH 10, Topical	56.50	0.0000017	1.31054E-05	0.00013
9	Quicklime, Mixed	54.18	2.70	20.8	208
10	Hydrated Lime, Mixed	51.61	2.57	19.8	198
11	Fly ash, Mixed	41.05	2.05	15.8	158

¹ Metric ton.

Table B3 Microbiological Results of Aerobic Soil Incubation				
Mesocosm	Treatment Time (weeks)			
	Initial ¹	1	4	26
1	143 x 10 ²	57 x 10 ⁵	216 x 10 ³	104 x 10 ⁴
2	143 x 10 ²	148 x 10 ⁵	210 x 10 ³	152 x 10 ⁴
3	143 x 10 ²	88 x 10 ⁵	36 x 10 ⁴	136 x 10 ⁴
4	143 x 10 ²	80 x 10 ⁵	214 x 10 ³	139 x 10 ⁴
5	143 x 10 ²	142 x 10 ⁵	180 x 10 ³	39 x 10 ⁴
6	143 x 10 ²	93 x 10 ⁵	75 x 10 ⁴	56 x 10 ⁴
7	143 x 10 ²	118 x 10 ⁵	92 x 10 ⁴	63 x 10 ⁴
8	143 x 10 ²	218 x 10 ³	62 x 10 ⁴	158 x 10 ⁴
9	143 x 10 ²	0	0	0
10	143 x 10 ²	0	0	0
11	143 x 10 ²	168 x 10 ⁵	29 x 10 ⁴	74 x 10 ⁴

¹ CFU/gm soil.

Table B4 Microbiological Results of Anaerobic Soil Incubation		
Mesocosm	Treatment Time (weeks)	
	18 ¹	26
1	53 x 10 ⁴	99 x 10 ⁴
2	62 x 10 ⁴	53 x 10 ⁴
3	46 x 10 ⁴	137 x 10 ⁴
4	174 x 10 ³	89 x 10 ⁴
5	117 x 10 ³	110 x 10 ³
6	94 x 10 ⁴	52 x 10 ⁴
7	57 x 10 ³	71 x 10 ⁴
8	52 x 10 ⁴	91 x 10 ⁴
9	0	0
10	0	0
11	90 x 10 ³	269 x 10 ³

¹ CFU/gm soil.

**Table B5
Mesocosm Soil Toxicity by Microtox Assay**

Sample	IC ₅₀ , mg/ml	% Inhibition, 10mg/ml
Solvent control	Nontoxic	98.8
Initial - A	1.9	2.3
Initial – B	3.1	5.2
Initial – C	TNQ (40) ¹	67.8
1T	3.5	7.1
1M	6.4	24.6
1B	3.9	9.9
2T	8.6	39.7
2M	3.5	3.6
2B	NONTOXIC	95.6
3T	TNQ (19.8)	62.8
3M	TNQ (12)	51.5
3B	TNQ (13.5)	62.3
4T	4	8.3
4M	TNQ (14.2)	60.1
4B	TNQ (68.9)	82.7
5T	TNQ (10.6)	72
5M	TNQ (759.8)	88.5
5B	3.5	11.3
6T	TNQ (64)	80.9
6M	3.1	8.2
6B	1.7	2
7T	2.3	2.8
7M	2.8	4
7B	1.2	2.3
8T	5.2	27.8
8M	5.1	12.2
8B	3.6	4
9T	TNQ (4932)	88.6
9M	TNQ (2681)	92.9
9B	TNQ (1799.1)	83.4
10T	TNQ (2281.9)	84.2
10M	6.5	36.4
10B	TNQ (22.4)	66.6
11T	8.7	45.8
11M	TNQ (18)	72.3
11B	2.5	3.4

1 TNQ = toxicity, nonquantifiable, estimated IC₅₀ in parenthesis.

**Table B6
Mesocosm Soil Toxicity by Direct Acting Mutagenicity Assay**

Sample	Assay Result
Control soil	M (<0.3 mg/mL)
Initial A	NM
Initial B	M (<1.9 mg/mL)
Initial C	M (<1.9 mg/mL)
1T	NM
1M	M (3.8 mg/mL)
1B	M (3.8 mg/mL)
2T	M (3.8 mg/mL)
2M	NM
2B	NM
3T	NM
3M	M (3.8 mg/mL)
3B	M (3.8 mg/mL)
4T	M (3.8 mg/mL)
4M	M (3.8 mg/mL)
4B	M (7.5 mg/mL)
5T	M (3.8 mg/mL)
5M	M (7.5 mg/mL)
5B	M (3.8 mg/mL)
6T	NM
6M	NM
6B	NM
7T	NM
7M	NM
7B	NM
8T	M (3.8 mg/mL)
8M	NM
8B	M (3.8 mg/mL)
9T	M (7.5 mg/mL)
9M	M (3.8 mg/mL)
9B	M (3.8 mg/mL)
10T	M (3.8 mg/mL)
10M	M (3.8 mg/mL)
10B	NM
11T	M (1.7 mg/mL)
11M	M (3.4 mg/mL)
11B	NM

Note: M = Mutagenic; NM = Nonmutagenic; In () = Concentration required for mutagenicity.

**Table B7
Mesocosm Soil pH Changes**

Mesocosm	Week 1		Week 2		Week 4		Week 10		Week 18		Week 26	
	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev	Avg	Stdev
1	6.11	0.14	6.37	0.11	5.99	0.15	6.15	0.34	6.04	0.43	6.11	0.12
2	5.88	0.05	6.30	0.13	6.24	0.26	6.42	0.25	6.78	0.36	6.27	0.09
3	6.02	0.29	6.54	0.33	6.35	0.29	6.67	0.41	7.25	0.47	6.70	0.53
4	6.02	0.29	6.41	0.31	6.08	0.07	6.40	0.18	6.80	0.87	7.17	1.04
5	6.23	0.28	6.22	0.13	6.20	0.01	6.18	0.25	6.78	0.24	7.18	0.56
6	6.02	0.23	6.45	0.30	6.38	0.21	6.56	0.50	6.75	0.03	6.83	0.16
7	5.92	0.12	6.55	0.32	6.44	0.21	6.34	0.11	6.92	0.07	7.07	0.16
8	5.86	0.12	6.36	0.13	6.03	0.33	6.14	0.30	6.65	0.23	6.32	0.51
9	12.14	0.03	12.53	0.12	11.41	0.11	12.04	0.24	10.34	1.33	10.84	0.75
10	11.54	0.14	12.04	0.20	9.49	0.25	11.36	0.23	9.32	0.07	10.87	0.51
11	8.30	0.14	8.52	0.15	8.24	0.14	8.70	0.18	8.93	0.16	9.18	0.09

**Table B8
Effect of Treatment Method on HMX Removal from NOP Soil**

Mesocosm	Sampling Time (weeks)					
	1	2	4	10	18	26
1-T ¹	4.02 ^{2,3}	3.79	2.68	1.07	2.10	2.76
1-M	10.54	4.64	4.10	1.23	1.51	1.68
1-B	7.98	4.07	4.19	0.00	0.40	0.53
2-T	4.76	4.30	2.58	0.41	2.76	2.17
2-M	3.99	6.79	4.08	0.54	2.10	0.88
2-B	4.77	5.38	3.55	0.52	0.50	0.34
3-T	4.55	5.71	3.18	0.44	2.00	1.50
3-M	5.05	4.13	3.49	0.74	2.21	1.57
3-B	4.68	4.82	4.10	0.98	0.37	0.73
4-T	4.15	4.72	3.84	0.83	1.57	1.47
4-M	5.82	4.69	3.79	2.04	2.38	2.49
4-B	4.23	3.79	4.07	2.16	2.28	0.00
5-T	3.21	3.96	3.48	0.60	3.44	3.25
5-M	4.13	4.03	4.07	0.82	4.81	5.63
5-B	5.08	3.58	4.45	1.00	3.99	4.83
6-T	5.43	3.38	1.39	0.98	2.46	3.50
6-M	13.29	3.34	0.42	0.75	1.66	3.26
6-B	5.22	3.56	3.38	0.76	0.56	0.83
7-T	8.43	2.50	2.98	0.67	<0.02	<0.02
7-M	3.64	3.83	1.67	0.83	0.26	<0.02
7-B	4.45	3.48	1.17	2.13	<0.02	<0.02
8-T	3.64	4.04	3.32	1.09	2.96	2.94
8-M	3.05	3.49	3.39	0.73	0.85	0.52
8-B	4.23	3.07	3.34	0.86	2.11	0.37
9-T	2.99	1.79	1.12	0.17	<0.02	<0.02
9-M	3.77	1.98	1.73	0.24	<0.02	<0.02
9-B	3.98	2.71	2.36	0.11	<0.02	<0.02
10-T	4.11	3.29	4.40	0.27	0.59	0.66
10-M	3.97	3.58	2.67	0.21	<0.02	0.31
10-B	3.04	2.60	2.15	0.21	<0.02	<0.02
11-T	7.88	6.51	1.79	0.53	0.37	0.73
11-M	4.22	5.69	5.54	0.42	<0.02	0.30
11-B	5.02	4.25	3.46	<0.02	0.18	<0.02

¹ Letters indicate soil core depth. T = top(0-4 "), M = middle (4-8"), B = bottom (8-12").

² Concentrations are mg/kg soil.

³ Individual samples are a combination of three replicates.

Table B9
Effect of Treatment Method on RDX Removal from NOP Soil

Mesocosm	Sampling Time (weeks)					
	1	2	4	10	18	26
1-T ¹	55.04 ^{2,3}	30.41	16.65	6.54	5.40	7.21
1-M	100.72	44.04	39.59	5.16	4.29	2.88
1-B	51.58	33.09	27.96	<0.02	1.03	1.15
2-T	29.60	22.48	15.01	1.34	4.19	1.57
2-M	48.22	65.12	33.92	1.77	3.35	0.79
2-B	54.69	52.07	33.51	0.88	0.82	<0.02
3-T	38.58	55.89	25.38	5.02	3.29	1.27
3-M	55.75	44.51	37.76	8.03	4.90	2.27
3-B	50.77	47.65	36.29	8.40	0.54	1.05
4-T	41.43	35.49	20.51	8.69	0.91	0.72
4-M	78.45	56.19	39.05	19.59	4.08	1.65
4-B	47.73	37.39	46.27	21.15	3.67	2.65
5-T	24.78	41.92	23.17	6.30	11.26	4.01
5-M	40.33	44.94	39.33	10.35	41.64	24.07
5-B	59.07	40.35	37.46	16.25	28.74	31.47
6-T	48.40	27.23	14.63	5.36	4.71	4.31
6-M	164.67	29.58	38.20	6.05	5.36	4.50
6-B	51.08	36.12	29.65	1.36	1.04	1.27
7-T	83.08	21.73	15.66	0.41	0.60	<0.02
7-M	33.75	35.89	10.16	1.35	0.46	<0.02
7-B	45.15	33.82	10.56	2.04	0.64	<0.02
8-T	42.55	29.50	19.52	8.64	9.73	6.01
8-M	34.82	31.69	27.50	3.73	1.70	1.20
8-B	35.90	31.25	25.88	3.97	1.70	0.71
9-T	2.60	0.53	<0.02	<0.02	<0.02	0.18
9-M	9.78	0.28	<0.02	<0.02	<0.02	<0.02
9-B	8.63	1.38	6.93	<0.02	<0.02	<0.02
10-T	11.88	2.92	21.74	<0.02	0.50	0.56
10-M	4.14	5.55	12.48	<0.02	<0.02	<0.02
10-B	3.10	1.96	3.72	1.97	<0.02	<0.02
11-T	77.76	42.78	6.76	3.00	0.67	<0.02
11-M	41.51	51.82	27.83	1.69	<0.02	0.38
11-B	51.80	34.69	3.30	<0.02	0.18	<0.02

¹ Note: Letters indicate soil core depth. T = top(0-4 "), M = middle (4-8"), B = bottom (8-12").

² Concentrations are mg/kg soil.

³ Individual samples are a combination of three replicates.

Table B10						
Effect of Treatment Method on TNT Removal from NOP Soil						
Mesocosm	Sampling Time (weeks)					
	1	2	4	10	18	26
1-T ¹	2.70 ^{2,3}	1.48	0.81	0.17	0.39	0.63
1-M	1.60	0.55	2.13	0.08	0.48	0.19
1-B	0.81	0.58	0.56	<0.02	0.16	<0.02
2-T	0.60	0.53	0.20	<0.02	0.63	0.24
2-M	3.05	4.63	0.24	<0.02	0.09	<0.02
2-B	8.28	3.24	0.28	0.03	<0.02	<0.02
3-T	1.17	2.21	1.40	<0.02	0.27	0.22
3-M	5.46	1.13	2.47	<0.02	0.10	0.11
3-B	2.90	2.24	1.21	0.12	<0.02	0.22
4-T	1.71	0.68	0.81	0.35	0.49	0.14
4-M	23.21	5.54	1.30	0.50	0.26	0.17
4-B	4.20	2.70	3.53	0.37	<0.02	<0.02
5-T	1.19	5.48	2.55	0.16	0.50	0.42
5-M	1.00	2.07	0.75	1.37	0.81	0.83
5-B	2.66	3.02	2.29	0.20	0.51	0.44
6-T	1.26	0.53	<0.02	0.15	0.50	0.34
6-M	108.35	1.28	0.73	0.33	0.14	1.23
6-B	2.61	3.51	0.57	<0.02	<0.02	0.22
7-T	6.13	0.17	<0.02	<0.02	<0.02	<0.02
7-M	1.26	0.42	<0.02	<0.02	<0.02	<0.02
7-B	4.00	1.07	<0.02	<0.02	<0.02	<0.02
8-T	0.67	0.71	0.41	0.29	0.25	0.35
8-M	0.44	1.37	1.19	<0.02	<0.02	<0.02
8-B	2.81	1.23	0.35	<0.02	<0.02	<0.02
9-T	0.07	<0.02	<0.02	<0.02	<0.02	<0.02
9-M	0.09	<0.02	<0.02	<0.02	<0.02	<0.02
9-B	0.08	<0.02	<0.02	<0.02	<0.02	<0.02
10-T	0.08	<0.02	<0.02	<0.02	<0.02	<0.02
10-M	0.26	<0.02	<0.02	<0.02	<0.02	<0.02
10-B	0.06	<0.02	<0.02	<0.02	<0.02	<0.02
11-T	2.05	0.58	0.97	0.23	0.15	2.47
11-M	3.30	1.27	1.00	0.09	<0.02	0.43
11-B	1.47	0.41	0.21	<0.02	0.09	<0.02

¹ Note: Letters indicate soil core depth. T = top(0-4 "), M = middle (4-8"), B = bottom (8-12").
² Concentrations are mg/kg soil.
³ Individual samples are a combination of three replicates.

Table B11
Effect of Treatment Method on 4A-DNT Removal from NOP Soil

Mesocosm	Sample Weeks					
	1	2	4	10	18	26
1-T ¹	1.13 ^{2,3}	1.25	1.12	0.39	<0.02	0.83
1-M	1.67	0.85	1.02	0.13	<0.02	0.28
1-B	1.14	0.59	0.34	<0.02	<0.02	<0.02
2-T	1.10	1.04	0.41	0.16	<0.02	0.74
2-M	0.71	1.35	0.48	0.08	<0.02	0.27
2-B	1.16	2.10	0.54	<0.02	<0.02	<0.02
3-T	1.44	1.58	1.07	0.17	<0.02	0.62
3-M	1.38	1.34	1.00	0.18	<0.02	0.26
3-B	1.02	1.23	1.73	<0.02	<0.02	0.09
4-T	1.37	1.14	1.40	0.40	<0.02	0.48
4-M	1.24	1.44	1.56	0.82	<0.02	0.69
4-B	1.18	0.81	0.98	0.61	<0.02	0.48
5-T	0.93	1.40	1.13	0.28	<0.02	0.97
5-M	1.21	1.40	1.17	0.51	<0.02	1.77
5-B	1.13	0.84	1.37	0.45	<0.02	1.38
6-T	1.50	0.91	0.57	0.47	<0.02	0.91
6-M	1.73	0.69	0.39	0.27	<0.02	1.23
6-B	1.18	0.79	<0.02	<0.02	<0.02	<0.02
7-T	1.31	0.66	<0.02	<0.02	<0.02	<0.02
7-M	1.19	0.85	<0.02	<0.02	<0.02	<0.02
7-B	0.89	0.74	<0.02	<0.02	<0.02	<0.02
8-T	1.20	1.11	<0.02	0.43	<0.02	0.75
8-M	0.99	0.99	<0.02	0.14	<0.02	0.18
8-B	1.15	0.64	<0.02	<0.02	<0.02	<0.02
9-T	0.60	0.38	<0.02	0.08	<0.02	<0.02
9-M	0.58	0.38	<0.02	0.09	<0.02	0.16
9-B	0.63	0.46	<0.02	<0.02	<0.02	0.13
10-T	0.60	0.51	<0.02	0.20	<0.02	0.31
10-M	0.73	0.53	<0.02	0.15	<0.02	0.22
10-B	0.61	0.47	<0.02	0.09	<0.02	0.20
11-T	1.80	1.07	<0.02	0.42	<0.02	0.84
11-M	1.49	0.72	<0.02	0.12	<0.02	0.26
11-B	1.47	0.48	<0.02	<0.02	<0.02	<0.02

¹ Note: Letters indicate soil core depth. T = top(0-4 "), M = middle (4-8"), B = bottom (8-12").

² Concentrations are mg/kg soil.

³ Individual samples are a combination of three replicates.

Table B12
Effect of Treatment Method on 2A-DNT Removal from NOP Soil

Mesocosm	Sample Weeks					
	1	2	4	10	18	26
1-T ¹	0.79 ^{2,3}	0.98	0.77	0.40	1.73	1.08
1-M	1.36	0.83	1.04	0.25	1.63	0.35
1-B	1.10	0.66	1.13	<0.02	<0.02	<0.02
2-T	0.92	0.80	0.53	0.21	<0.02	0.74
2-M	0.55	1.00	0.74	0.10	<0.02	<0.02
2-B	0.82	1.65	0.79	0.09	<0.02	0.04
3-T	0.95	0.99	0.78	0.17	<0.02	0.51
3-M	0.83	0.80	0.67	0.29	<0.02	0.21
3-B	0.66	0.61	1.00	0.50	<0.02	0.19
4-T	0.87	0.71	0.91	0.36	<0.02	0.47
4-M	0.82	0.87	0.95	0.54	<0.02	0.59
4-B	0.79	0.44	0.50	0.53	<0.02	0.33
5-T	0.69	0.86	0.78	0.26	<0.02	0.94
5-M	0.58	0.75	0.79	0.43	<0.02	1.66
5-B	0.60	0.51	0.76	0.35	<0.02	1.07
6-T	0.84	0.65	0.42	0.00	<0.02	0.89
6-M	0.85	0.60	0.81	0.00	<0.02	1.33
6-B	0.67	0.47	<0.02	0.17	<0.02	0.23
7-T	0.95	0.46	<0.02	<0.02	<0.02	<0.02
7-M	0.72	0.58	<0.02	<0.02	<0.02	<0.02
7-B	0.58	0.54	<0.02	0.16	<0.02	<0.02
8-T	0.76	0.68	<0.02	0.51	<0.02	0.97
8-M	0.76	0.71	<0.02	0.14	<0.02	0.16
8-B	0.65	0.45	<0.02	<0.02	<0.02	<0.02
9-T	0.23	<0.02	<0.02	<0.02	<0.02	<0.02
9-M	0.12	<0.02	<0.02	<0.02	<0.02	<0.02
9-B	0.10	<0.02	<0.02	<0.02	<0.02	<0.02
10-T	0.21	0.06	<0.02	<0.02	0.40	<0.02
10-M	0.20	0.07	<0.02	<0.02	<0.02	<0.02
10-B	0.16	0.05	<0.02	<0.02	<0.02	<0.02
11-T	0.63	0.49	<0.02	<0.02	<0.02	0.38
11-M	0.61	0.56	<0.02	<0.02	<0.02	<0.02
11-B	0.65	0.47	<0.02	<0.02	<0.02	<0.02

¹ Note: Letters indicate soil core depth. T = top(0-4 "), M = middle (4-8"), B = bottom (8-12").

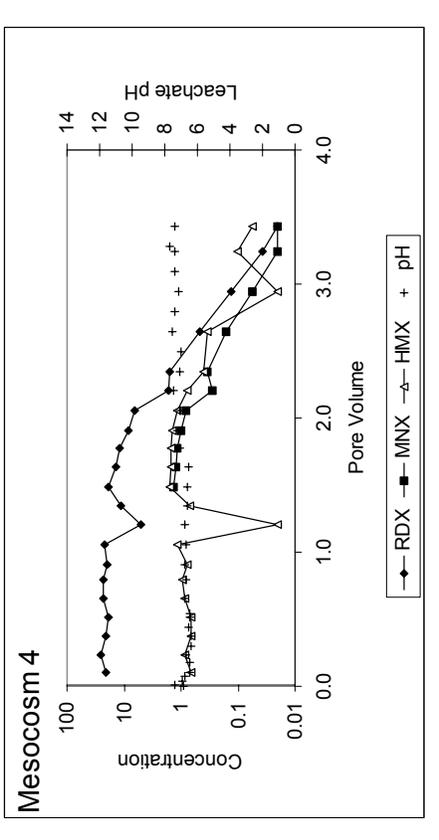
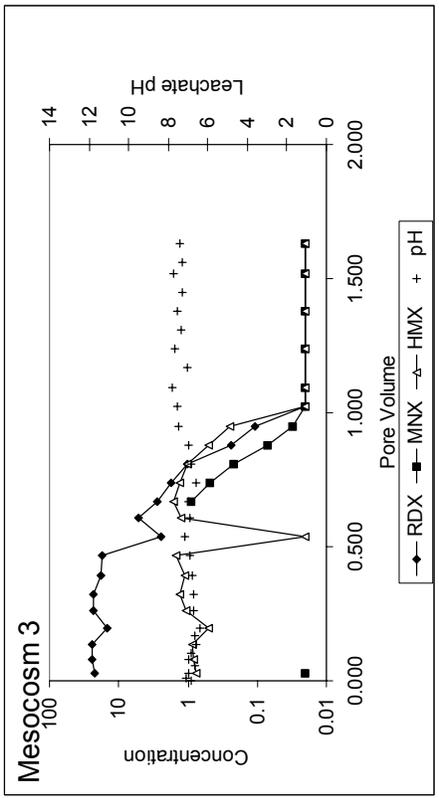
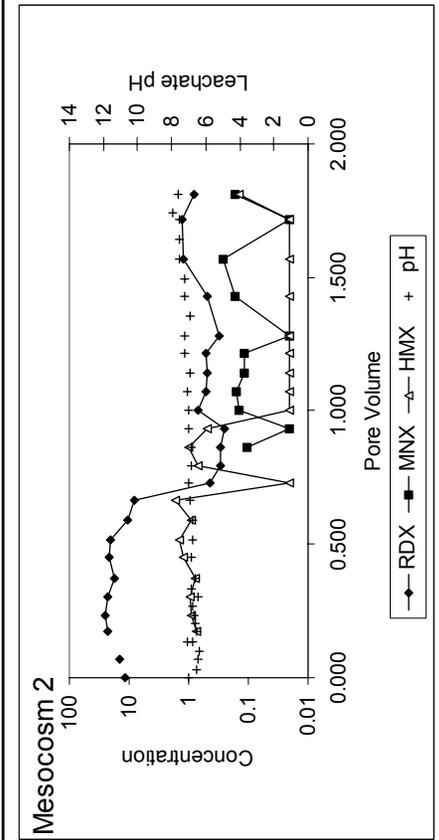
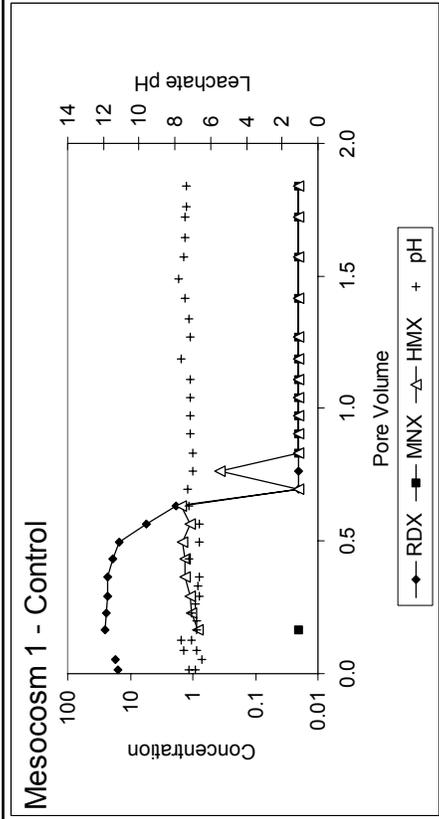
² Concentrations are mg/kg soil.

³ Individual samples are a combination of three replicates.

Table B13						
Effect of Treatment Method on MNX Removal from NOP Soil						
Mesocosm	Sample Weeks					
	1	2	4	10	18	26
1-T ¹	<0.02 ^{2,3}	<0.02			<0.02	<0.02
1-M	<0.02	<0.02			<0.02	<0.02
1-B	<0.02	<0.02			<0.02	<0.02
2-T	<0.02	<0.02			<0.02	<0.02
2-M	<0.02	<0.02			<0.02	<0.02
2-B	<0.02	<0.02			<0.02	<0.02
3-T	<0.02	<0.02			<0.02	<0.02
3-M	<0.02	<0.02			0.04	<0.02
3-B	<0.02	<0.02			<0.02	<0.02
4-T	<0.02	<0.02			<0.02	<0.02
4-M	<0.02	<0.02			<0.02	<0.02
4-B	<0.02	<0.02			0.04	<0.02
5-T	<0.02	<0.02			<0.02	<0.02
5-M	<0.02	<0.02			0.06	0.55
5-B	<0.02	<0.02			0.08	0.85
6-T	<0.02	<0.02			<0.02	<0.02
6-M	<0.02	<0.02			0.04	<0.02
6-B	<0.02	<0.02			<0.02	<0.02
7-T	<0.02	<0.02			<0.02	<0.02
7-M	<0.02	<0.02			<0.02	<0.02
7-B	<0.02	<0.02			<0.02	<0.02
8-T	<0.02	<0.02			<0.02	0.45
8-M	<0.02	<0.02			<0.02	<0.02
8-B	<0.02	<0.02			<0.02	<0.02
9-T	<0.02	<0.02			<0.02	<0.02
9-M	<0.02	<0.02			<0.02	<0.02
9-B	<0.02	<0.02			<0.02	<0.02
10-T	<0.02	<0.02			<0.02	<0.02
10-M	<0.02	<0.02			<0.02	<0.02
10-B	<0.02	<0.02			<0.02	<0.02
11-T	<0.02	<0.02			<0.02	<0.02
11-M	<0.02	<0.02			<0.02	<0.02
11-B	<0.02	<0.02			<0.02	<0.02

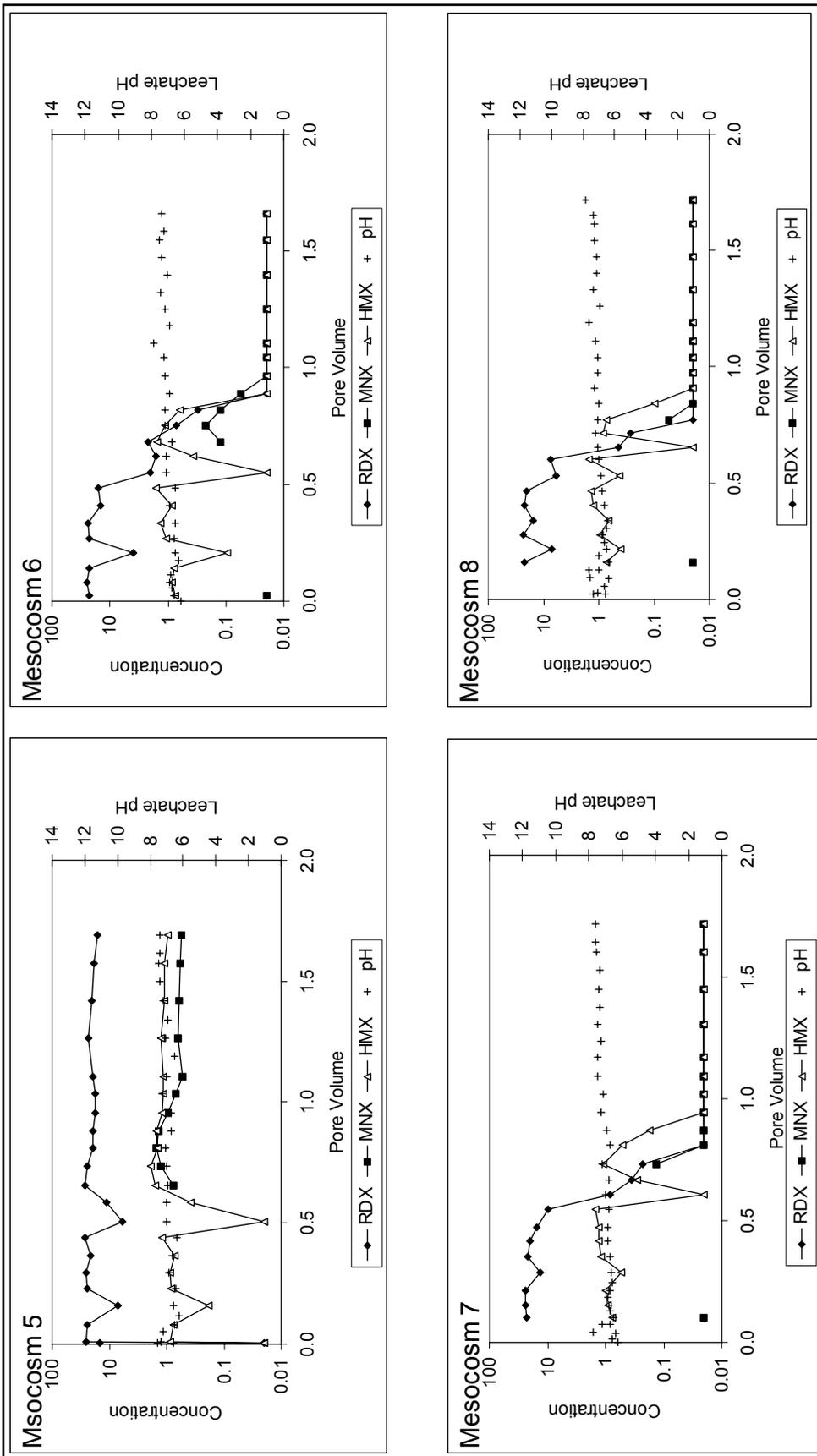
¹ Note: Letters indicate soil core depth. T = top(0-4 "), M = middle (4-8"), B = bottom (8-12").
² Concentrations are mg/kg soil.
³ Individual samples are a combination of three replicates.

Leachate



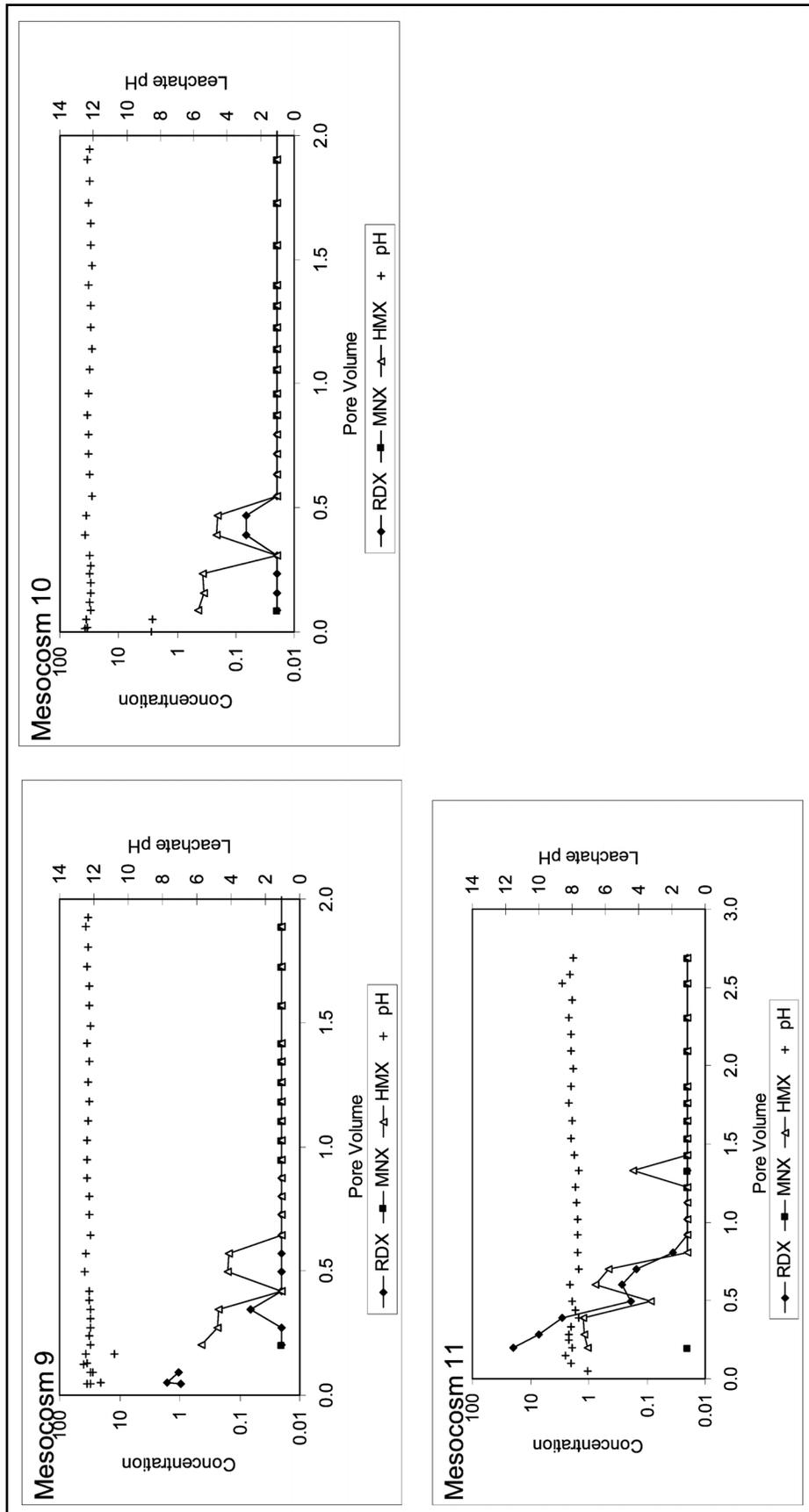
a. Mesocosms 1-4

Figure B2. Comparison of contaminant removal from mesocosm leachate (Sheet 1 of 3)



b. Mesocosms 5-8

Figure B2. (Sheet 2 of 3)



c. Mesocosms 9-11

Figure B2. (Sheet 3 of 3)

Table B14 Leachate Water Budget												
Mesocosm Leachate (Cumulative Volume)												
		1	2	3	4	5	6	7	8	9	10	11
In	L/day	0.227699	0.227699	0.227699	0.453755	0.227699	0.227935	0.227699	0.227699	0.227699	0.227699	0.227699
	L/week	1.593893	1.593893	1.593893	3.176287	1.593893	1.595546	1.593893	1.593893	1.593893	1.593893	1.593893
Out	L/day	0.200973	0.202216	0.19664	0.410938	0.200732	0.1931	0.192873	0.203598	0.207096	0.207826	0.207089
	L/week	1.406811	1.415511	1.376479	2.876569	1.405123	1.3517	1.350114	1.425184	1.449672	1.454779	1.449624
	in/week	0.426981	0.429621	0.417775	0.873067	0.426469	0.410254	0.409773	0.432557	0.43999	0.44154	0.439975
	Difference:	0.187082	0.178383	0.217414	0.299718	0.18877	0.243847	0.24378	0.16871	0.144221	0.139114	0.14427

Table B15 Change in Leachate pH over Time and by Treatment												
Date	Elapsed Time days	Mesocosm										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0	6.84		6.82	6.81	6.59	6.19	6.23	6.55	12.23	8.54	
16-Jan	1	7.25	6.98			7.57			7.38	12.40		
17-Jan	2		6.56						7.06	11.63		
18-Jan	3	6.50	6.44					6.61	6.65	12.19		7.10
22-Jan	7									12.04		
23-Jan	8	6.75	6.41					6.36	6.35	12.61	12.49	8.07
24-Jan	9	7.49			7.42			7.77	7.55	12.38	12.33	
25-Jan	10	7.07	6.79	7.07	6.96			6.74	6.98	12.48	12.44	8.37
28-Jan	13	7.64	7.10		6.79			7.17	7.65	10.78	8.49	
29-Jan	14	6.75	6.56	6.98	6.43		6.60	6.55	6.39	12.19	12.17	8.03
1-Feb	17	6.81	6.62	6.67	6.44		6.78	6.70	6.98	12.27	12.23	8.18
5-Feb	21	7.06	6.71	6.95	6.70	7.38	6.90	6.80	6.49	12.18	12.19	8.19
8-Feb	24	6.86	6.78	6.84	6.35	7.22	6.81	6.84	6.65	12.20	12.16	8.04
12-Feb	28	6.62	6.46	6.61	6.41	6.50		6.70	6.77	12.20	12.24	7.60
15-Feb	31	6.74	6.83	6.65	6.53	6.26	6.32	6.58	6.52	12.25	12.17	7.77
19-Feb	35	6.64	6.58	6.38	6.48	6.55	6.56	6.66	6.46	12.27	12.24	8.03
26-Feb	42	7.19	6.81	6.74	6.80	6.44	6.64	6.75	6.66	12.55	12.48	8.16
5-Mar	49	6.64	6.75	6.71	6.70	6.84	6.58	6.89	6.76	12.50	12.46	7.57
12-Mar	56	6.64	6.79	6.80	6.75	6.67	6.88	6.88	6.83	12.18	12.10	7.68
19-Mar	63	7.20	6.89	6.92	6.66	6.39	6.57	6.79	6.99	12.30	12.25	7.64
26-Mar	70	7.27	7.00	7.13	6.80	7.00	7.08	7.01	7.09	12.28	12.26	7.70
2-Apr	77	7.00	6.86	6.93	6.63	6.98	7.11	6.79	7.19	12.38	12.27	7.72
9-Apr	84	6.98	6.88	6.94	6.65	6.93	6.73	7.18	7.09	12.43	12.35	7.77
16-Apr	91	7.18	6.97	6.58	6.51	6.98	7.14	6.76	6.97	12.42	12.28	7.61
23-Apr	98	7.13	7.03	6.86	7.11	7.05	7.18	6.91	7.31	12.32	12.22	7.88
30-Apr	105	7.15	7.10	7.00	7.25	6.73	6.89	7.29	7.07	12.27	12.10	8.08
7-May	112	7.12	6.95	7.49	7.08	6.74	7.16	7.13	7.06	12.32	12.18	8.02
14-May	119	7.63	7.22	7.55	7.46	7.25	7.21	7.50	7.23	12.24	12.15	8.18
21-May	126	7.11	7.25	7.77	7.10	7.01	7.83	7.48	7.59	12.39	12.26	8.08
28-May	133	7.23	6.95	7.04	6.99	6.53	6.88	7.25	6.94	12.21	12.08	7.91
4-Jun	140	7.40	7.25	7.68	7.56	7.09	7.17	7.48	7.37	12.25	12.13	8.06
11-Jun	147	7.76	7.25	7.34	7.39	6.93	7.47	7.31	7.16	12.29	12.15	8.10
18-Jun	154	7.51	7.56	7.54	7.14	7.20	7.02	7.43	7.11	12.38	12.26	8.18
25-Jun	161	7.42	7.54	7.30	7.39	7.43	7.35	7.31	7.30	12.34	12.21	8.03
2-Jul	168	7.46	7.52	7.71	7.38	7.50	7.50	7.56	7.28	12.48	12.35	8.60
9-Jul	175	7.33	7.90	7.27	7.72	7.39	7.23	7.61	7.32	12.33	12.20	8.12
16-Jul	182	7.35	7.64	7.44	7.36	7.39	7.38	7.61	7.81	12.26	12.05	7.93
Average		7.11	6.97	7.06	6.93	6.95	6.97	7.02	7.02	12.25	12.01	7.95
StDev		0.33	0.36	0.37	0.39	0.37	0.37	0.40	0.37	0.30	0.91	0.29
Trend		0	0	0	0	0	0	0	0	0	0	0

Table B16
HMX (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	0.83	0.719	0.753	0.669	<0.02	0.753	0.759	0.739	0.426	0.445	1.051
5-Feb	21	1.055	0.914	0.835	0.843	0.853	0.859	0.932	0.4	0.238	0.352	1.216
12-Feb	28	1.079	0.937	0.881	0.66	0.756	0.765	0.99	0.944	0.229	0.361	1.236
19-Feb	35	1.303	0.756	0.497	0.658	0.189	0.093	0.538	0.659	<0.02	<0.02	0.087
26-Feb	42	1.308	1.209	1.08	0.864	0.833	1.079	1.201	1.23	0.156	0.214	0.774
5-Mar	49	1.478	1.458	1.314	0.949	0.888	1.34	1.316	1.385	0.152	0.201	0.453
12-Mar	56	1.108	0.922	1.099	0.778	0.727	0.869	1.333	0.414	<0.02	<0.02	<0.02
19-Mar	63	1.519	1.658	1.469	1.162	1.186	1.568	1.522	1.525	<0.02	<0.02	<0.02
26-Mar	70	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Apr	77	0.366	0.709	1.259	0.703	0.386	0.369	0.286	0.815	<0.02	<0.02	<0.02
9-Apr	84	<0.02	1.021	1.627	1.569	1.574	1.556	1.073	0.732	<0.02	<0.02	<0.02
16-Apr	91	<0.02	0.491	1.321	1.502	1.851	1.097	0.507	0.099	<0.02	<0.02	0.173
23-Apr	98	<0.02	<0.02	1.002	1.486	1.415	0.627	0.174	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	<0.02	0.501	1.411	1.51	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	<0.02	0.244	1.164	1.224	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	<0.02	<0.02	0.765	1.123	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	<0.02	<0.02	0.397	1.139	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	<0.02	<0.02	0.338	1.272	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	<0.02	<0.02	<0.02	1.117	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	0.102	1.084	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	0.146	<0.02	0.056	0.971	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table B17
RDX (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0	14.90								2.80		
16-Jan	1	15.89	11.83			14.46			15.41	0.95		
17-Jan	2									1.62		
18-Jan	3	17.63	14.45					16.19	15.75	1.05		13.79
22-Jan	7											
29-Jan	14	25.13	22.35	22.02	20.79	<0.02	22.59	22.67	22.32	<0.02	<0.02	20.03
5-Feb	21	24.47	24.82	24.49	25.88	25.6	24.97	24.20	7.04	<0.02	<0.02	7.09
12-Feb	28	22.73	23.06	24.62	21.00	24.08	22.21	23.83	23.29	0.07	<0.02	2.83
19-Feb	35	22.77	17.26	14.53	19.27	6.99	3.97	13.35	15.62	<0.02	<0.02	0.19
26-Feb	42	19.17	21.48	23.02	23.23	24.23	22.59	21.95	22.03	<0.02	0.07	0.27
5-Mar	49	14.85	20.74	23.71	22.93	25.55	23.57	20.00	20.14	<0.02	0.07	0.15
12-Mar	56	5.565	10.65	17.75	19.32	21.29	14.36	15.41	6.03	<0.02	<0.02	0.04
19-Mar	63	1.88	7.97	17.13	22.15	26.65	15.75	9.73	7.49	<0.02	<0.02	<0.02
26-Mar	70	<0.02	0.44	2.48	5.16	5.98	2.02	0.84	0.44	<0.02	<0.02	<0.02
2-Apr	77	<0.02	0.29	5.13	11.63	11.35	1.59	0.36	0.26	<0.02	<0.02	<0.02
9-Apr	84	<0.02	0.30	2.73	18.43	26.67	2.15	0.23	<0.02	<0.02	<0.02	<0.02
16-Apr	91	<0.02	0.26	1.75	13.91	24.06	0.72	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	<0.02	0.71	1.01	11.94	19.20	0.31	<0.02	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	0.52	0.23	8.58	19.51	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	0.50	0.11	6.36	17.96	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	0.51	<0.02	1.69	17.69	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	0.31	<0.02	1.55	19.43	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	0.50	<0.02	0.47	22.90	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	1.21	<0.02	0.13	20.16	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	1.30	<0.02	0.04	18.32	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	0.84	<0.02	<0.02	16.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table B18
MNX (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
5-Feb	21											
12-Feb	28											
19-Feb	35											
26-Feb	42											
5-Mar	49											
12-Mar	56											
19-Mar	63											
26-Mar	70											
2-Apr	77											
9-Apr	84	<0.02	0.10	0.91	1.32	0.77	0.13	0.13	0.06	<0.02	<0.02	<0.02
16-Apr	91	<0.02	0.02	0.48	1.23	1.28	0.22	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	<0.02	0.14	0.22	1.17	1.52	0.13	<0.02	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	0.16	0.07	1.02	1.38	0.06	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	0.11	0.03	0.83	0.94	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	0.12	<0.02	0.28	0.71	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	<0.02	<0.02	0.35	0.53	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	0.17	<0.02	0.16	0.62	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	0.26	<0.02	0.06	0.61	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	<0.02	0.57	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	0.16	<0.02	<0.02	0.54	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table B19
DNX (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
5-Feb	21											
12-Feb	28											
19-Feb	35											
26-Feb	42											
5-Mar	49											
12-Mar	56											
19-Mar	63											
26-Mar	70											
2-Apr	77											
9-Apr	84	<0.05	<0.05	0.49	0.16	<0.05	0.32	0.09	<0.05	<0.05	<0.05	<0.05
16-Apr	91	<0.05	<0.05	0.16	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
23-Apr	98	<0.05	<0.05	<0.05	0.29	0.21	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
30-Apr	105	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
7-May	112	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
14-May	119	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
21-May	126	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
4-Jun	140	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
18-Jun	154	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
2-Jul	168	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
16-Jul	182	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

**Table B20
TNX (mg/L) in Leachate over Time and by Treatment**

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
5-Feb	21											
12-Feb	28											
19-Feb	35											
26-Feb	42											
5-Mar	49											
12-Mar	56											
19-Mar	63											
26-Mar	70											
2-Apr	77											
9-Apr	84	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Apr	91	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

**Table B21
TNT (mg/L) in Leachate over Time and by Treatment**

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	<0.02	0.06	0.10	0.11	<0.02	0.08	0.05	<0.02	<0.02	<0.02	<0.02
5-Feb	21	<0.02	<0.02	<0.02	0.09	0.29	0.08	<0.02	<0.02	<0.02	<0.02	<0.02
12-Feb	28	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
19-Feb	35	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
26-Feb	42	0.03	0.02	<0.02	0.04	0.14	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
5-Mar	49	0.07	0.04	0.01	<0.02	0.08	0.01	0.03	<0.02	<0.02	<0.02	<0.02
12-Mar	56	0.15	0.06	<0.02	<0.02	<0.02	0.01	0.06	0.03	<0.02	<0.02	<0.02
19-Mar	63	0.21	0.21	<0.02	<0.02	<0.02	<0.02	0.14	0.22	<0.02	<0.02	<0.02
26-Mar	70	<0.02	0.06	<0.02	<0.02	<0.02	0.05	0.05	0.06	<0.02	<0.02	<0.02
2-Apr	77	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
9-Apr	84	<0.02	<0.02	0.18	0.07	<0.02	0.13	<0.02	<0.02	<0.02	<0.02	<0.02
16-Apr	91	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	<0.02	<0.02	<0.02	0.10	0.07	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table B22
4A-DNT (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	0.17	0.12	0.14	0.16	<0.02	0.17	0.17	0.15	<0.02	0.13	0.27
5-Feb	21	0.23	0.31	0.22	0.24	0.17	0.28	<0.02	0.09	<0.02	0.06	<0.02
12-Feb	28	<0.02	0.29	0.25	<0.02	<0.02	0.23	0.23	0.24	<0.02	<0.02	<0.02
19-Feb	35	0.11	<0.20	0.15	0.20	0.04	0.03	0.11	0.14	<0.02	<0.02	<0.02
26-Feb	42	0.03	0.10	0.22	0.24	0.20	0.18	0.13	0.11	0.01	0.03	<0.02
5-Mar	49	<0.02	<0.02	0.15	0.24	0.26	0.11	0.07	0.05	0.03	<0.02	<0.02
12-Mar	56	<0.02	<0.02	0.03	0.18	0.22	0.03	<0.02	<0.02	<0.02	0.01	<0.02
19-Mar	63	<0.02	<0.02	<0.02	<0.02	0.33	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
26-Mar	70	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Apr	77	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
9-Apr	84	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Apr	91	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	<0.02	<0.02	<0.02	<0.02	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	<0.02	<0.02	<0.02	0.11	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	<0.02	<0.02	<0.02	0.10	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	<0.02	<0.02	<0.02	0.11	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	<0.02	<0.02	<0.02	0.10	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	<0.02	<0.02	<0.02	0.15	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	<0.02	<0.02	<0.02	0.12	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	<0.02	0.09	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	<0.02	<0.02	<0.02	0.07	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table B23
2A-DNT (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14	0.11	<0.02	0.07	0.08	<0.02	0.08	0.08	<0.02	<0.02	<0.02	<0.02
5-Feb	21	0.20	0.16	0.10	0.11	0.07	0.14	<0.02	0.04	<0.02	<0.02	<0.02
12-Feb	28	<0.02	0.22	0.13	<0.02	<0.02	0.15	0.21	0.19	<0.02	<0.02	<0.02
19-Feb	35	0.35	0.20	0.09	0.12	0.03	0.04	0.14	0.16	<0.02	<0.02	<0.02
26-Feb	42	0.59	0.34	0.19	0.16	0.09	0.24	0.33	0.32	<0.02	<0.02	<0.02
5-Mar	49	1.13	0.67	0.29	0.19	0.13	0.36	0.54	0.54	<0.02	<0.02	<0.02
12-Mar	56	0.99	0.84	0.38	0.18	0.12	0.41	0.83	0.46	<0.02	<0.02	<0.02
19-Mar	63	0.65	1.41	0.91	0.30	0.21	1.06	1.12	1.17	<0.02	<0.02	<0.02
26-Mar	70	<0.02	0.18	0.37	0.09	0.05	0.36	0.21	0.17	<0.02	<0.02	<0.02
2-Apr	77	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
9-Apr	84	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Apr	91	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
30-Apr	105	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
7-May	112	<0.02	<0.02	<0.02	<0.02	0.54	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
14-May	119	<0.02	<0.02	<0.02	0.16	0.41	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
4-Jun	140	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	<0.02	<0.02	0.04	0.36	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table B24
2,4- and 2,6-DNT (mg/L) in Leachate over Time and by Treatment

Date	Elapsed Time days	Mesocosm Number										
		1	2	3	4	5	6	7	8	9	10	11
15-Jan	0											
22-Jan	7											
29-Jan	14											
5-Feb	21	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
12-Feb	28	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
5-Mar	49	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
12-Mar	56	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
19-Mar	63	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Apr	77	<0.02	<0.02	0.20	<0.02	<0.02	0.10	<0.02	0.07	<0.02	<0.02	<0.02
9-Apr	84	0.20	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
23-Apr	98	0.26	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.13	<0.02	<0.02	<0.02
14-May	119	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
21-May	126	0.09	0.07	0.09	<0.02	<0.02	0.09	<0.02	0.08	<0.02	<0.02	<0.02
4-Jun	140	<0.02	<0.02	<0.02	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
18-Jun	154	<0.02	0.04	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
2-Jul	168	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
16-Jul	182	<0.02	<0.02	<0.02	0.08	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

REPORT DOCUMENTATION PAGE

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14. ABSTRACT Energetic compounds, such as 2,4,6-trinitrotoluene (TNT) and hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and their degradation products can act as a source of contamination for soil on Department of Defense testing and training ranges. Base hydrolysis degrades nitroaromatics and nitramines, and the potential effectiveness of lime to induce this reaction has been demonstrated at the laboratory scale. The objective of this research was to further examine both basic and applied aspects of alkaline application as an inexpensive and effective means of reducing source-zone contamination on military ranges. Bench-scale microcosms were used to examine basic conditions that could affect the alkaline hydrolysis reaction, such as soil organic matter content, lime concentration, soil type, and contamination type. Results from experiments using soil from a variety of ammunition production facilities and training ranges, in general, support the use of explosive contaminant treatment by alkaline material in well-mixed systems. RDX in crystalline form was more resistant to treatment, possibly due to limitations associated with the dissolution of the RDX from the crystal to the aqueous phase. Larger-scale experiments, conducted in vessels packed with approximately 55 kg of soil, were used to investigate topical versus well-mixed applications of three alkaline materials (hydrated lime, quicklime, and Class C fly ash). TNT, RDX, and HMX in the mixed (Continued)					
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14. (Concluded)

system were removed quickly from both the leachate and soil. However, results from experiments with topical applications of alkali material indicated that the aqueous transport of hydroxide ion was not sufficient to overcome the buffering capacity of the soil. Consequently, the soil pH was not raised to the extent necessary for alkaline treatment of explosive compounds. This result is fundamentally related to the CEC properties of the soil and is consequently considered a soil specific (and therefore site specific) result. Topical application of alkali material may still be a viable treatment technique by taking advantage of circumstances unique to training ranges.

15. (Concluded)

Alkaline hydrolysis
Class C fly ash
Dinitrotoluene
Explosives
HMX
Hydrated lime
Munitions
pH
Quicklime
RDX
TNT
Training range