

Literature Review:

Unexploded Ordnance of TNT, RDX, and Heavy Metals Disposition in Soils and Plants

U.S. ARMY ENGINEER DISTRICT, ALASKA

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Note: This is an example from a early draft report entirely researched, written, and formatted by Lori Jo Oswald of Wordsworth. Dr. Oswald completed the final report at the client's office; therefore, the final is not available as an example.

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1.0 INTRODUCTION

This section discusses the project objectives, the organization of this document, the research methods used, and the project limitations.

1.1 Objectives

The objective of this study is to provide a review of publications on trinitrotoluene (TNT) and cyclonite/hexahydro-1,3,5-trinitro, 1,3,4-triazine (RDX) contamination in soils, including articles that discuss uptake of these explosives by plants. This study also provides a review of publications about (1) the disposition of heavy metals in soils and (2) uptake of heavy metals by plants. For purposes of this study, "heavy metals" refers to the following: iron (Fe), zinc (Zn), lead (Pb), nickel (Ni), copper (Cu), chromium (Cr), antimony (Sb), cadmium (Cd), molybdenum (Mo), and Tin (Sn).

To meet these general objectives, this study used focuses on the following questions:

- What plants are known to take up and accumulate heavy metals and explosives?
- What are the physiological mechanisms that promote uptake of heavy metals and explosives (i.e., what plant tissues accumulate heavy metals and explosives?)
- What growing conditions promote absorption of explosives by plants?
- How are molecules of organic explosives incorporated into living tissue?

1.2 Organization of Document

To address the above objectives, this document has been organized in the following manner. As well as introductory and end matter materials, there are two major subdivisions: (1) Summary of Findings (about Fort Greely, explosives contamination, and heavy metals and plant uptake); and (2) Literature Abstracts (about TNT and RDX contamination in soils and plants,

heavy metals and their uptake by plants, and Alaska resources, particularly Fort Greely).

Section 1 - Introduction

The introduction guides the reader by clarifying the objectives, document organization, methods, and limitations.

Section 2 - Summary of Findings: Fort Greely, Alaska

This section provides a description and history of Fort Greely, as well as a list of reports about the area's environmental status and a summary of the findings of those reports related to the objectives of this Literature Review. It also provides details about activities at and maps and photographs of Washington Range.

Section 3 - Summary of Findings: TNT and RDX

This section summarizes the information found in the literature review about the objectives. It describes TNT and RDX, explosives and soil contamination, the biological degradation of TNT and RDX in soils, explosives and their disposition in plants, and remediation of TNT and RDX in soil.

Section 4 - Summary of Findings: Heavy Metals in Soil

This section summarizes the literature about metals in soils, metals and their disposition in plants, and heavy metal- and explosives-contaminated sites.

Section 5 - Literature Abstracts: TNT and RDX

This section provides information on and abstracts of articles relating to TNT and RDX in soil.

Section 6 - Literature Abstracts: Metals Disposition in Soil

This section provides information on and abstracts of articles related to excess heavy metals in soil and metals and uptake by plants.

Searches of literature related to the following metals and plant uptake were performed: Fe, Zn, Cu, Pb, Ni, Cr, Sb, Cd, Mo, and Sn.

Section 7 - Literature Abstracts: Explosives and Heavy Metals

This section provides summaries of articles that are about both explosives and heavy metals.

Section 8 - Literature Abstracts: Alaska

This section provides summaries of documents about Fort Greely, heavy metals in soils in Alaska, explosives contamination in Alaska, and Alaska flora at the Fort Greely site.

Section 9 - References

The References Section lists works cited in this document.

Additional Material

Also included are a glossary of terms and an acronym and abbreviations list.

1.3 Methods

Methods included using the University of Alaska library system, online and library databases, and the Internet to obtain abstracts, articles, reports, meeting proceedings, Web sites, and government documents related to the subject area.

1.4 Limitations

Because of budget and logistical considerations, the study is generally limited to a sampling of documents published from 1995 to March 2001 (with some earlier documents that are particularly relevant, mostly from 1994, and one later document, from April 2001), and generally is limited to United States documents, although particularly relevant articles or meeting proceedings from Canada, Great Britain, Germany, Russia, The Netherlands, and other countries are included. Best professional judgment asserts that a review of literature from

this time frame and this country will provide the information necessary to achieve the objectives discussed in Section 1.1. However, at USAED's request, and with additional funds, this report will be expanded in one or all of the following ways: (1) include more documents, (2) include more years of publication, or (3) include more literature from other countries.

While researching the topic areas called for in the scope of work, additional areas where this report could be enlarged were discovered. In particular, conversations with the contacts listed in the scope of work led to the inclusion of more heavy metals in the research criteria and to the expansion of the discussion of metals and plant uptake. In the Abstracts sections, sources relevant to enlarging the scope of work are mainly included as "Additional Resources," and abstracts for these are not included.

At the client's request, this document can be expanded to include discussions of and information about the following: (1) add explosives in addition to TNT and RDX in explosives research (such as Octahydro-1,3,5,7-tetranitro-1,3,5,6-tetrazacine [HMX]); (2) expand the plant inventory to include more plants found in the Fort Greely area, rather than focusing only on eight of the most common plants in Washington Range; (3) incorporate more detailed analysis of the articles listed in Sections 5, 6, 7, and 8 and expand the Summary of Findings in Sections 2, 3, and 4 beyond the current project scope of work; and (4) include new or expand existing topics at the client's request.

Other reasons for additional work may also include the following:

- More literature sources and/or more years of search are of interest
- Specific topics may require additional information than that provided in this review

- Specific sources of information may be expanded to provide more specific detail than that provided in this review.

The literature includes peer-reviewed journal articles, presentations from conferences, book chapters, reports, Web site information, government documents, and articles from newspapers and magazines. Inevitably, some of the information is redundant, and some literature might have been missed.

2.0 SUMMARY OF FINDINGS: FORT GREELY, ALASKA

This section describes the history of military involvement at Fort Greely, current military activities, and a site description. It also includes information on site investigations and environmental considerations relevant to this study. Finally, it provides specific information about Washington Range.

Military impact areas at Fort Greely are "located on lands withdrawn from the public domain under the Military Lands Withdrawal Act (Public Law 106-65); the withdrawal of land was recently renewed. As part of the Environmental Impact Statement prepared for the renewal, the Army has pledged to implement a program to identify possible munitions contamination and evaluate the potential for surface water and groundwater contamination" (Walsh et al., 2001).

2.1 History

The information in this Section is directly from the Fort Greely Web site:
<http://www.usarak.army.mil/3posts/fgapage.htm>

Mission Statement: Fort Greely conducts base operations, supports the Cold Regions Test Center (CRTC) and Northern Warfare Training Center (NWTC), and provides resources to support ALCOM, USARAK, and other training. Plans and executes an effective Base Realignment and Closure (BRAC) realignment.

History: In 1942, William L. Brame led 15 men to the Big Delta area to establish an Army Air Corps Base. Fort Greely operated as an Army Air Corps Base until 1945, when it was put on an inactive status. In April 1947, the War Department chose the Base as the site for the

first post-war cold weather maneuver, staged during the winter of 1947-1948.

The installation was reactivated May 1, 1947, and was officially transferred to the Department of the Army and redesigned as an Army Post. The post was named "United States Troops, Big Delta Alaska." On August 6, 1955, the Post was redesignated Fort Greely.

Fort Greely became part of the 172nd Infantry Brigade in 1974, after the disestablishment of the United States Army, Alaska. The Post was under the command of Forces Command, Fort McPherson, GA.

With the activation of the 6th Infantry Division and the U.S. Army Garrison Alaska, March 23, 1986, Fort Greely became one of the three Posts of the Divisions One Installation concept. Fort Greely is now the home to the CRTC and the NWTC.

Fort Greely is scheduled for realignment under BRAC in 2001.

2.2 Military Activities

Training and Impact Area: Fort Greely contains 629,000 acres of maneuver land and 254,000 acres of impact area (these overlap each other). All conventional weaponry of the U.S. Army, U.S. Air Force (USAF), Marine Corps, and Allied Services can be fired in the impact areas with the exception of uranium depleted and white phosphorus rounds.

Fort Greely contains varied terrain from forest to rolling hills. The 320,000 acres of wetlands are environmentally limited and accessible only during the winter. Fort Greely can support brigade light infantry training all year and up to division level light and heavy operations from November through March. By utilizing the 13-kilometer maneuver corridor between Fort Greely and the Tanana Flats training area at Fort Wainwright, a 1,222,000-acre contiguous training area is created, allowing Corps-level

force-on-force operations. This area is twice the size of the National Training Center.

The varied terrain at Fort Greely makes it a favorite training area for Army Special Forces, Navy SEALs, and British Commandos. The Oklahoma impact area and Delta Creek Bombing Range provide the USAF with one of the most sophisticated bombing ranges in the world. Restricted Airspace R2202 that covers all Fort Greely land west of Meadows Road is from the surface to unlimited.

Fort Greely's impact areas are centrally located and include numerous observation points. There are four major impact areas: Oklahoma, Mississippi, Delta Creek, and Lakes. Oklahoma and Delta Creek are used daily by the Air Force. These impact areas are surface cleared on a yearly basis, but they are still considered a hard (permanent) impact area. Mississippi is also a hard impact area. It is used throughout the year mainly by Army units to include CRTC. Because of Air Force Range clearing requirements, it is no longer used by the Air Force. The Lakes Impact Area is considered a maneuver/impact area (duds are cleared as they occur). Lakes impact area allows for live fire maneuver at the Brigade level.

Northern Warfare Training Center (NWTC) – Filling the need for special arctic warfare training is the United States Army's NWTC. An exclusive school that provides training in arctic survival, navigation of land and waterways, military skiing, mountaineering, and river crossing operations. The school trains not only active duty soldiers but soldiers from other services, reserve soldiers, Reserve Officers' Training Corps, West Point cadets, and allied military soldiers. Emphasis during the summer is placed on mountain warfare while the winter months are used to train soldiers on how to adapt to living in the field, clothing use and maintenance, and snowshoeing and military skiing. NWTC is also the home of the Army Mountaineering Team. Each year the team

joins soldiers from allied countries to attempt a multinational friendship climb up Mount McKinley.

Cold Regions Test Center (CRTC) - The United States Army, CRTC, is the Army's only natural environment test site for cold regions testing. It has existed under a variety of names since 1949. CRTC plans, conducts, and reports tests on a wide variety of Army developmental equipment, weapons, and clothing. Tests determine whether developmental materials meet requirements for use in cold regions and assist developers in designing equipment to withstand the rigors of use in cold environments. CRTC says on its Web site that its mission is to "plan, conduct, and report the results of winter, mountain, and northern environment phases of developmental testing. CRTC also provides advice and guidance on testing to material developers, material producers, sister services, and private industry" (<http://crtc-www.army.mil>, retrieved April 5, 2001).

2.3 Site Description

As described by Racine, Lichvar, and Duffy, "Fort Greely is located southeast of Fairbanks near Delta Junction, Alaska, between the Alaska Range and the Tanana River. The base covers about 231,479 hectares (0.66 million acres). Three large rivers and a tributary to one of these, fed by glaciers in the Alaska Range, flow from south to north across the base and empty into the Tanana River. Elevations range from about 400 to 1,000 m. The base covers portions of the Big Delta and Mt. Hayes U.S. Geological Survey (USGS) quadrangles" (2001). Walsh et al.'s description is similar, although they say elevations range from 400 to 1,800 m and describe its glaciated features: glacial moraines, glaciofluvial sediments, and loess (2001).

2.4 Washington Range

Washington Range (also called Washington Impact Area) is one of the testing ranges used by CRTC within Fort Greely and is of particular interest to this study. It has primarily been used for testing Air Defense Systems but “is ideally suited for testing any type of weapon or explosive” (USA, Fort Greely Web site). The following two photographs show Catapult Launched Fuel Air Explosives recently tested on Washington Range (CRTC Web site, retrieved April 5, 2001).

Washington Range is mainly used by the Army for “mortar, artillery, and other similar indirect fire weapon systems. In addition, [it] is used by [CRREL] for the test firing of a number of developmental weapons systems” (Walsh et al., 2001).

2.4.1 SITE DESCRIPTION

According to Charles H. Racine of CRREL, who conducted a study of the Washington Range, it is on a gravelly floodplain of the Delta River. “There is limited vegetation cover and relative few (plant) species there because it has poor, young soils” (e-mail, April 5, 2001).

Walsh et al. describe Washington Range as “within the floodplain of a glacially fed, gravel-braided river” and similar to a number of other impact areas at Fort Greely (2001).

The Washington Range “occupies at 1,650 ha (4,125 acres) along the Delta River.... The impact area, about one-half of the Washington Range or 800 ha (2000 acres) is located on a terrace elevated several meters above the active channel of the Delta River” (Walsh, et al., 2001).

Soils are described as alluvial silty, sandy gravel with cobble clasts up to 10-cm, as well as a “sporadic thin veneer of loess (wind-blown silt) in localized areas of the terrace” (Walsh, et al.).

2.4.2 RANGE USE

Walsh, Collins, Racine, Jenkins, and Gelvin (2000) list the following evidence of known firing events at Washington Range:

- Cratering
- Pieces of munitions
- Designation as a firing point.

Firing events at the Washington Range have included:

- tests of 81-mm mortars
- tube-launched optically tracked wire-guided missiles
- 40-mm high explosive cartridges
- sense and destroy armor

Walsh et al. also researched the types of munitions that have been fired at the Washington Range. Records had to be generated from Fort Greely and other Alaska Army sites, so they might not all apply to the Washington Range per se: anti-tank rockets, weapon rocket, hand grenades, firing points, low-order detonations, hand grenades, rockets.

2.4.3 EXPLOSIVES CONTAMINATION

Concerns about explosives in soil that are particularly relevant in Alaska include the following:

Frozen barriers. As Marion and Pelton write, “Because of the high solubility and ionic nature of explosives such as picric acid, there is concern that such explosives might leach into frozen barriers.” However, Marion and Pelton conclude that a stable frozen barrier is effective in restraining the movement of RDX, TNT, and picric acid.

During a July 2000 site visit, Walsh et al. collected 107 soil samples and detected explosives residue in 48 percent of them. RDX was the most common (39 percent). TNT was

found in 21 percent of the soil samples. The amino-dinitrotoluene transformation products of TNT were found in 10 percent of the samples. HMX was found in 11 percent of the samples.

For samples above the detection limit, Walsh et al. found:

- Median TNT concentration was 0.0004 $\mu\text{g/g}$.
- Median RDX concentration was 0.021 $\mu\text{g/g}$.

Walsh et al. conclude, "The greatest potential threat of contamination of surface and groundwater would be high numbers of low-order detonations or heavily used firing points located in groundwater recharge areas" (2001).

Table 2-1 shows Walsh et al.'s soil sampling findings regarding TNT and RDX at the Washington Range in July 2000.

Table 2-1 TNT and RDX Found in Washington Range Soil Samples

Description	RDX	TNT
Number of Detections	42	23
Above Detection Limit	39%	21%
Median Concentration ($\mu\text{g/g}$) of Samples Above Detection Limit	0.021	0.004
Maximum Concentrations ($\mu\text{g/g}$)	338	132

Tables 2-2 and 2-3, from the same report (Walsh et al., 2001), lists the risk-based concentrations (EPA) in soil and the maximum concentrations detected on the Washington Range.

Table 2-2 Risk-Based Concentrations ($\mu\text{g/g}$) of TNT and RDX at Washington Range

Concentrations	TNT	RDX
Industrial Concentrations	190	52
Residential Concentrations	21	5.8
Maximum Concentration Detected	132	338
Event	Low-order detonation	Low-order detonation

2.4.4 HEAVY METALS

Walsh et al. compared the concentrations of heavy metals found in Washington Range soils to natural heavy metal concentrations in the U.S. and in Alaska, as well as listed the Alaska Department of Environmental Conservation (ADEC) cleanup levels and the EPA risk-based concentrations. That information is summarized in this Section. All concentrations listed in this Section are in $\mu\text{g/g}$.

Antimony (Sb). Naturally occurring in the U.S. at 0.66 and not listed for Alaska. ADEC cleanup levels are 41 (ingestion) and 3.6 (migration to groundwater). EPA risk-based concentrations are 820 (industrial) and 31 (residential). The maximum concentration detected at Washington Range was 30.1.

Barium (Ba). Naturally occurring: 580 (U.S.), 595 (Alaska soil), and 811 (Alaska sediment). ADEC cleanup levels: 7,100 (ingestion) and 1,100 (migration to groundwater). EPA risk-based concentrations: 140,000 (industrial) and 5,500 (residential). Maximum concentration detected at Washington Range: 789.

Cadmium. Naturally occurring: 0.35 (U.S.), 1.3 (Alaska soil), and 2.6 (Alaska sediment). ADEC levels: 100 (ingestion) and 5 (migration to

groundwater). EPA concentrations: 1,000 (industrial) and 39 (residential). Detected at Washington Range: 18.1.

Chromium. Naturally occurring: 54 (U.S.), 50 total (Alaska soil), and 115 total (Alaska sediment). ADEC levels: 510(+6) (oxidation state +6) (ingestion), and 26(+6) migration to groundwater. EPA concentrations: 6,100(+6) (industrial) and 230(+6) (residential). Maximum detection at Washington Range: 45.

Copper. Naturally occurring: 25 (U.S.), 24 (Alaska soil), and 37 (Alaska sediment). ADEC levels: none given. EPA concentrations: 82,000 (industrial) and 3,100 (residential). Washington Range maximum detection: 1,120.

Iron. Naturally occurring: 26,000 (U.S.), 35,000 (Alaska soil), and 37,000 (Alaska sediment). ADEC levels not listed. EPA concentrations: 610,000 (industrial) and 23,000 (residential). Maximum concentration at Washington Range: 38,600.

Lead. Naturally occurring: 19 (U.S.) and 12 (Alaska soil and sediment). ADEC levels: 400 to 1,000 (industrial); none listed for residential. EPA concentration: none listed. Maximum concentration at Washington Range: 141.

Nickel. Naturally occurring: 19 (U.S.), 24 (Alaska soil), and 37 (Alaska sediment). ADEC levels: 2,000 (ingestion) and 87 (migration to groundwater). EPA concentrations: 41,000 (industrial) and 1,600 (residential). Maximum concentration at Washington Range: 45.

Zinc. Naturally occurring: 60 (U.S.), 70 (Alaska soil), and 157 (Alaska sediment). ADEC levels: 30,000 (ingestion) and 9,100 (migration to groundwater). EPA concentrations: 610,000 (industrial) and 23,000 (residential). Maximum concentration at Washington Range: 296.

2.5 Fort Greely Site Reports

This section provides summaries of some general Fort Greely reports.

2.5.1 RESOURCE MANAGEMENT PLANT/ENVIRONMENTAL IMPACT STATEMENT RECORD OF DECISION (1995)

The Resource Management Plan/Environmental Impact Statement (RMP/EIS) maintains the public's current access to Fort Greely, provides increased protection for wildlife habitat, and provides protection and interpretation potential for cultural resources. It also provides greater opportunities for recreation and the use of forest resources and savings in fire suppression costs through changes in policies and practices and through planning efforts targeted at better wildlife, recreation, cultural, forest, and fire management.

2.5.2 GERSTLE RIVER FUD FACT SHEET

The following information comes from the U.S. Army Corps of Engineers (USACE), Huntsville Center, Gerstle River Expansion Area and Test Site (GREATS) Formerly Used Defense Sites (FUDS) fact sheet, February 12, 1997.

GREAT is located 20 to 30 miles east of Delta Junction, about 100 miles southeast of Fairbanks, in the North Star Borough, Alaska. Its FUDS site number is F10AK098414, and the project number is F10AK098404. Its project category is ordnance and explosives (OE)/CWM.

Location: GREATS extends from the eastern boundary of Fort Greely along Granite Creek to the Gerstle River, and consists of two areas: the Gerstle River Test Site (GRTS) and the Gerstle River Expansion Area (GREA). The FUDS project is concerned with the GREA.

GREA consists of rolling terrain with sparse to dense vegetation. Work within the GREA is a

Defense Environmental Restoration Program for Formerly Used Defense Sites (DERP-FUDS). Work within GRTS is an Installation Restoration (OE) project, and is not included in this project.

History: GREATS was used by Dugway Proving Ground for chemical (G and V series) and high explosive testing from 1952 to 1962.

Surveillance testing of chemical munitions was conducted in the area from 1962 to 1967 by the Arctic Test Center. No munitions, except flame, have been tested in the area since 1967.

The GRTS, the original test site acquired by the U.S. Department of the Army in 1952, is a rectangular area approximately 34,000 feet by 24,000 feet, west of the Gerstle River, which remains under direct control of the Department of the Army.

The land is currently used by local residents for hunting and fishing and as a bison range. A number of cleanup operations have occurred on the land with varying degrees of effectiveness.

Issues and Concerns: The remoteness of this site makes access difficult, and the logistics support requirements are immense. The state of Alaska has not formally agreed to intrusive operations.

2.5.3 BRAC COMMISSION 1995-1996

According to the U.S. Department of Defense's (DoD's) Defense Technical Information Center (DTIC) at www.dtic.mil/environdod/derpreport96/vol2/appx/app-a/nara068.html, in July 1995 the BRAC Commission recommended realignment of Fort Greely. The realignment of the installation is scheduled to be completed by fiscal year 2002.

As part of this Web site report, DTIC lists the following contaminants found at Fort Greely: petroleum, oil, and lubricants (POLs); pesticides (such as DDE and DDT); and solvents.

In addition, the site lists the following information:

Media Affected: Soil

Funding to Date: \$5.4 million

Estimated Cost to Completion: \$72.4 million (Fiscal Year 14)

Site Types at the Installation: Underground storage tanks (USTs) and fire training areas.

To reduce environmental risk, the installation conducted interim actions, including the removal of USTs and POL-contaminated soils. The installation also used land farming, bioventing, and low-temperature thermal desorption to remediate contaminated soil.

In 1996, the installation conducted an Environmental Baseline Survey and continued remediation activities for UST and associated piping areas and the fire training areas.

Planned activities for 1997 were to begin the removal of contaminated pipe and associated soil from the nuclear power plant cooling water waste line, continue remediation of fire training areas, and conduct a lead-based paint survey and sampling.

Plans for 1998 included completing remediation of the fire training areas.

2.6 Environmental Considerations

Fort Greely consists of interior lowlands, uplands, montane, alpine, and riverine habitats (Racine, Lichvar, and Duffy, 2001).

2.6.1 FLORA OF FORT GREELY, ALASKA

Racine, Lichvar, and Duffy published a report in February 2001 that listed the 497 plant species found at Fort Greely. The study found the following:

- None of the plants found during the survey are currently listed by the U.S. Fish and

Wildlife Service (USFWS) as endangered or threatened.

- None are currently on the list of critically rare plants developed by the Alaska Rare Plant Working Group.
- Twenty-two of the plants are considered somewhat rare and are being tracked by the Alaska Natural Heritage Program's Biological and Conservation Database.
- Species found on Fort Greely with the largest range extensions include *Sisyrinchium montanum*, found at Buffalo Drop Zone and known from only one other site in Alaska, and *Potamogeton obtusifolius*, an aquatic species collected from Mark Lake, which is known from only two other locations in Alaska.

2.6.2 WASHINGTON RANGE PLANTS

This section lists the most common plants found in the Washington Range area of Fort Greely, Alaska, during a summer 2000 vegetation study of Washington Range conducted by CRREL (Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.E., Gelvin, A.B., and Ranney, T.A., 2001, not yet published). Also included is a brief definition of each of the three plant types this report is concerned with in this study.

Grasses

"Grass" refers to any plant of the family Gramineae, an important and widely distributed group of vascular plants. Most grasses are annual or perennial herbs with fibrous roots and, often, rhizomes. The stems are always nodded and are typically hollow and swollen at the nodes, although many genera have solid stems. The leaves have two parts: a sheath surrounding the stem (called the culm in grasses); and a blade, usually flat and linear. The flowers are of a unique form, the inflorescence being subdivided into spikelets, each containing one or more tiny florets. The

dry seedlike fruit is called a caryopsis, or grain (www.infoplease.com).

Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.E., Gelvin, A.B., and Ranney, T.A. found that the following are the dominant grasses at Fort Greely (common names, when available, are from Welsh [1974]):

- *Poa glauca* (Glaucous Bluegrass)
- *Carex supine* (Sedge)
- *Festuca rubra* (Red Fescue)
- *Agrostis sp.* (Bentgrass or Redtop)
- *Calamagrostis purpurescens* (Reedgrass)
- *Agropyron subsecundum* (Wheatgrass)

Forbs

A "forb" is defined as any herb that is not a grass (i.e., broad-leaved herbs). Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.E., Gelvin, A.B., and Ranney, T.A. (2001, not yet published) found that the following are the dominant forbs found at Fort Greely:

- *Oxytropis campestris* (Field Oxytrope)
- *Astragalus alpinus* (Standing Milk-vetch)
- *Draba sp.* (Rockcress)
- *Senecio sp.* (Groundsel)
- *Stellaria monantha* (Common Chickweed)
- *Minuartia sp.* (Sandwort)
- *Taraxacum sp.* (Dandelion)
- *Linum perenne* (Wild Flax)
- *Bupleurum triradiatum* (Thorough-wort)
- *Solidago decumbens* (Goldenrod)
- *Aster sibiricus* (Siberian Aster)

Woody Plants

The term "woody plants" refers to plants consisting of or containing wood (ligneous).

Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.E., Gelvin, A.B., and Ranney, T.A. identify the following low shrubs as the dominant woody plants in the Fort Greely area:

- *Elaeagnus commutata* (Silverberry)
- *Potentilla fruticosa* (Shrubby Cinquefoil)
- *Salix setchelliana* (Setchell Willow)
- *Shepherdia Canadensis* (Soapberry)

Charles Racine of CRREL says that the Washington Range is on a gravelly floodplain of the Delta River. "There is limited vegetation cover and relatively few species here because it has poor, young soils" (e-mail). Racine concludes that there are only seven plant species at Fort Greely, Washington Range, that should be of interest to this study:

Grasses: *Elymus* sp. (also called *Leymus mollis*) (Beach Rye), *Agropyron* sp. (Wheatgrass), and *Festuca rubra* (Red Fescue)

Forbs: *Potentilla multifida* (cinquefoil) and *Solidago* sp. (goldenrod)

Low shrubs: *Elaeagnus commutata* (buffalo berry – also called silverberry) and *Salix* spp. (several kinds of willows)

Trees: In addition, Racine mentioned that there are many balsam poplars at the Washington Range.

Others: Also found were lichens (*Stereocaulon* sp.) and mosses. These are not discussed in this report (see Limitations in Section 1.0).

Tables 2-3 through 2-6 provide details about each of these plants. The main source for descriptions is Anderson's Flora of Alaska and Adjacent Parts of Canada; other sources include additional books on Alaskan plants, Web sites (such as www.usda.gov), and dictionaries.

Table 2-3 Main Grasses at Washington Range

Scientific Name	Common Name	Description
<i>Elymus</i> sp. or <i>Leymus mollis</i>	Beach rye	Perennial tufted or rhizomatous herbs, culms hollow, leaf sheaths open, the blades flat, spikelets borne in a solitary terminal spike.
<i>Agropyron subsecundum</i>	Wheatgrass	Plants tufted, lacking rhizomes, mostly 1.5-5.5 dm tall, the nodes of culms almost always hairy, lower leaf sheaths usually glabrous. Found in woods, river banks, rock outcrops, gravel bars, and squirrel mounds in much of continental Alaska.
<i>Festuca rubra</i>	Red fescue	Plants perennial, loosely to rather densely tufted, 2-10 dm tall, stem bases clothed with persistent sheaths. Found in tidal flats, beaches, cliffs, muskegs, ridge tops, terraces, and bars throughout Alaska.

dm Decimeter

Table 2-4 Main Forbs at Washington Range

Scientific Name	Common Name	Description
<i>Potentilla multifida</i>	Cinquefoil	Perennial, nonglandular to glandular herbs, 0.7-8 dm tall, from a caudex; basal leaves 0.4-2.5 dm long, pinnately compound with 5-11 leaflets. Grows on open woods, meadows, heathlands, and tundra, including in the southeastern third of Alaska.
<i>Solidago multiradiata</i>	Northern goldenrod	Perennial herbs with short rhizomes or a caudex, the stems 1.5-4 dm tall, sparingly to moderately short-villous, especially above, basal leaves 1.5-20 cm long and 0.4-2 cm broad. Found in open woods, meadows, and slopes, throughout almost all Alaska.

cm Centimeter
dm Decimeter

Table 2-5 Main Shrubs at Washington Range

Scientific Name	Common Name	Description
<i>Eleagnus commutata</i> Bernh	Silverberry	Silverberry is a shrub 1 to 4 feet high. The leaves are silvery-scurfy on both sides. The flowers are small, crowded among the leaves at the upper end of the branch. The fruit is silvery, less than ½ inch long. This plant is found along well-drained banks of rivers. The berry is dry and mealy without much taste. The Interior Indians fry them in moose fat.
<i>Salix</i> sp.	Willow	Plants dioecious, dwarf or trailing to erect shrubs or occasionally trees, buds with a single visible scale, leaves alternate, simple, usually stipulate, staminate flowers with 2 stamens, with 1-2 basal glands, capsules 2-valved, seeds several, with long, copious hairs.

cm Centimeter
ft Foot
in. Inch
m Meter

Table 2-6 Main Trees at Washington Range

Scientific Name	Common Name	Description
<i>Populus balsamifera</i>	Balsam poplar	Tree of small to moderate size, mostly less than 10 m tall, trunks less than 6 dm in diameter, leaves long-petiolate. Found in stream sides, margins of lakes and seeps, and in mixed woods throughout continental Alaska.

dm Decimeter

m Meter

Although the list of 497 plants found at Fort Greely has been narrowed down to eight main plants found at Washington Range for the purposes of this report, the number of plants possibly affected by activities at Washington Range can perhaps be narrowed down further to just one plant. The dominant plant in the Washington Range is the silverberry shrub (Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.E., Gelvin, A.B., and Ranney, T.A., 2001). Much of the Washington Range is bare gravel "with localized areas of sparse shrubs" (ibid).

2.5.2 FORT GREELY FAUNA

The following list of wildlife found on Fort Greely is from the Alaska Army Lands Withdrawal Renewal: Final Legislative Environmental Impact Statement, Volume II (1999):

- Brown lemming
- Northern bog lemming
- Deer mouse
- Meadow jumping mouse
- Pygmy shrew
- Dusky shrew
- Masked shrew
- Tundra shrew
- Little brown bat
- Short-tailed weasel
- Long-tailed weasel
- Lease weasel
- Mink
- Hoary Marmot
- Woodchuck
- River otter
- Snowshoe hare
- Muskrat
- Arctic ground squirrel
- Porcupine
- Red squirrel
- Northern flying squirrel
- Beaver
- Marten
- Wolverine
- Brown (grizzly) bear
- Black bear
- Coyote
- Gray wolf
- Red fox
- Lynx
- Barren ground caribou
- Long-tailed vole
- Alaska (singing) vole
- Meadow vole
- Tundra vole
- Yellow-cheeked vole
- Redback (tundra) vole

- Moose
- Dall sheep
- Bison
- Fish found in Fort Greely waters include the following:
- Arctic lamprey
- Sheefish
- Humpback whitefish
- Round whitefish
- Chum salmon
- Coho (silver) salmon
- Chinook (king) salmon
- Rainbow trout (stocked)
- Northern pike
- Lake chub
- Longnose sucker
- Burbot
- Slimy sculpin
- Arctic grayling
- Least cisco
- Arctic char
- Lake trout (stocked)

The following amphibian is found at Fort Greely:

- Wood frog

There are also numerous species of birds found at Fort Greely, as listed in the above report, Appendix 3.12.

Species listed as endangered, threatened, species of concern, or sensitive are as follows (ibid, Volume I):

- American peregrine falcon
- Olive-sided flycatcher
- Gray-cheeked thrush

- Blackpoll warbler
- Osprey
- Trumpeter swan

A 1986 cooperative agreement identified an area along the Delta River on the Fort Greely West Training Area as important for migrating sandhill cranes. This area has a minimal disturbance period of April 25-May 15 and September 1-30.

Hunting of big game is allowed on the withdrawal lands. The following data is from 1997:

Black bear: one bear was taken in September

Grizzly bear: Approximately five bears are harvested annually from the Fort Greely West Training Area

Moose: The East Training Area is a seasonal moose range. In 1997, 38 moose were taken at Fort Greely. Population estimates for moose at Fort Greely was 700 to 1,000 animals in the fall of 1995.

Dall sheep: Dall sheep are found on the Fort Greely West Training Area. Researchers have identified 150 sheep in this area, with 100 residing there in the summer. Hunting is allowed; however, the annual harvest rate is about zero.

Caribou: The Fortymile Caribou Herd once ranged over Fort Greely, but the herd has dropped to 22,000 in 1995 from 568,000 animals in the 1920s. Caribou on Fort Greely today are part of the Delta Creek Herd, which is estimated at 4,600 animals that range over 3,000 square miles encompassing Fort Greely. Hunting is allowed on Fort Greely, but few have been taken there because most of the herd moves west, off the post, by hunting season.

Bison: In 1928, 23 bison were transplanted from Montana to the Big Delta-Delta Junction Area. A 1979 cooperative agreement designated areas on the Fort Greely West Training Area as

important bison calving and summer range. The agreement also listed a portion of Fort Greely West Training Area and all of Fort Greely East Training Area as important late summer and early winter range. A 1986 cooperative agreement identified bison calving and summer range within the West Training Area. Sensitive calving areas are around Buffalo Dome and the Texas Range. The fall/winter migration route includes the entire East Training Area and a small area of the West Training Area. Hunting is used to keep the Alaska Department of Fish and Game's pre-calving herd size objective of 360 animals with 430 to 440 animals before the hunting season.

Wolves: Information is not available on the number of wolves on Fort Greely. Wolves are hunted on the withdrawal lands.

Wolverines: Wolverines are hunted on the withdrawal lands but no information is available on wolverine populations at Fort Greely.

Washington Range Wildlife

During a summer 2000 site visit, Walsh et al. (2001) saw the following fauna at the Washington Range: American Bison ("which graze on various grasses and forbs like vetch but also eat silverberry") and ground squirrels.

3.0 SUMMARY OF FINDINGS: TNT AND RDX

Information generated by this study will be used to provide background information for a preliminary assessment of explosives contamination and heavy metals uptake in plants at Fort Greely, Alaska.

3.1 Background: Military Use of TNT and RDX

The U.S. Army has about 40 installations requiring cleanup of explosives-contaminated soils (U.S. Army Environmental Center [USAEC], "Toxicity," n.d.) as a result of past production and handling of conventional munitions (USAEC, "Windrow," n.d.). Soils at such installations can pose reactivity and toxicity hazards (ibid). There is also a concern about migration of explosives to groundwater as well as to plants and, through them, to animals.

The government has determined that such soils should be treated to eliminate possible threat to human health or the environment. As Crockett et al. write, "Evaluating sites potentially contaminated with explosives is necessary to carry out" Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA), and USDOE "policies on site characterization and remediation under the Superfund, Resource Conservation and Recovery Act (RCRA), Installation Restoration, Base Closure, and Formerly Used Defense Sites [FUDS] environmental programs" (EPA, "Overview," 1999).

This literature review focuses on two of those explosives: TNT and RDX – and methods used to treat them in soil. It also lists articles that address uptake of explosives by plants, as well as articles that describe plant uptake of certain heavy metals in soils.

Walsh et al. describe TNT and RDX as the "two most commonly used military explosives in projectiles, bombs, land mines or other weapons." RDX is used in Composition 4, which is used to "detonate unexploded ordnance during range maintenance activities." HMX, which this report does not specifically address, "is the explosive filler in many anti-tank weapons and it is an impurity in military grade RDX." In addition, nitroglycerin and 2,4-DNT "are ingredients in propellants" (2001).

3.2 TNT: General Description

2,4,6-Trinitrotoluene is "a yellow, odorless solid that does not occur naturally in the environment" (McFarlan, 2001). "It is commonly known as TNT and is an explosive used in military shells, bombs, and grenades, in industrial uses, and in underwater blasting."

In the United States, TNT is produced only at military arsenals (McFarlan, 2001), and accidental release of TNT "has contaminated groundwater and soil at numerous munition manufacturing sites" (McFarlan, 2001).

The EPA lists TNT as a priority pollutant and has recommended its removal from contaminated sites. McFarlan says, "TNT is toxic to algae and invertebrates and chronic exposure to TNT by humans causes harmful health effects, including anemia and abnormal liver function, cataract development, and skin irritation. The EPA has determined that TNT is a possible human carcinogen, based on animal studies."

The Agency for Toxic Substances and Disease Registry (ATSDR) provides the following information about federal government requirements regarding TNT and human health:

- Since 2,4,6-trinitrotoluene is explosive, flammable, and toxic, EPA has designated it as a hazardous waste.

- The Department of Transportation (DOT) specifies that when 2,4,6-trinitrotoluene is shipped, it must be wet with at least 10% water (by weight) and it must be clearly labeled as a flammable solid.
- The Occupational Safety and Health Administration (OSHA) set a maximum level of 1.5 milligrams of 2,4,6-trinitrotoluene per cubic meter of workplace air (1.5 mg/m³) for an 8-hour workday for a 40-hour workweek.
- The National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Governmental Industrial Hygienists (ACGIH) recommend an exposure limit of 0.5 mg/m³ in workplace air for a 40-hour workweek.

3.3 RDX: General Description

Hexahydro-1,3,5-trinitro-1,3,5-triazine, commonly known as RDX (Royal Demolition eXplosive) “is a hexacyclic ring containing six nitrogen atoms” (Roberts, 2000). Also known as cyclonite and hexagen, RDX is a synthetic product that is used widely by the military. In 1972, 102 million pounds of RDX was produced in the United States, Roberts said. RDX has been found in at least 16 of the 1,430 National Priorities List sites identified by the EPA (RDX, 1996).

It is estimated that up to 12 milligrams per liter (mg/L) of RDX “may be discharged into the environment through process wastewater used in RDX manufacturing” (Roberts, 2000). RDX contamination can also come from spills or leaks at hazardous waste disposal sites or from airborne contamination when RDX is burned.

Exposure to RDX occurs, Roberts says, “by breathing dust contaminated with RDX, getting RDX on your skin, or drinking water contaminated by RDX.” Low-level, long-term health effects are not known (although vomiting and nausea have been seen [RDX, 1996], but

long-term effects can include seizures, Roberts said (2000). The EPA has determined that RDX is a possible human carcinogen (RDX, 1996). The EPA’s drinking water guideline for RDX is 2 micrograms/liter (µg/L) RDX for lifetime exposure for adults (RDX, 1996).

The Agency for Toxic Substances and Disease Registry provides the following information about government regulations of RDX:

- The Department of Transportation (DOT) has many regulations on the transportation of explosives.
- The EPA recommends a drinking water guideline of 2 micrograms (µg/L) RDX per liter for lifetime exposure for adults.
- The National Institute for Occupational Safety and Health (NIOSH) has recommended an exposure limit of 1.5 milligrams RDX per cubic meter of air (1.5 mg/m³) for a 10-hour workday, 40-hour workweek. The NIOSH short-term exposure limit, which is the highest level of RDX that they recommend workers be exposed to for 15 minutes, is 3 mg/m³.
- The ACGIH also recommends an exposure limit of 1.5 mg/m³ in workplace air for an 8-hour workday, 40-hour workweek.

3.4 TNT and RDX: Water Quality Criteria

Table 3-1 shows water quality criteria for TNT and RDX (Jenkins, Walsh, Thorne, Milyares, Ranney, Grant, and Esparza, 1998).

Table 3-1 TNT and RDX Water Quality Criteria

Health Advisory Criteria (70-kg adult)	TNT	RDX
Longer term (mg/L) ¹	0.2	0.4
Drinking water equivalent level ²	0.02	0.1
Lifetime (mg/L) ³	0.002	0.002
Cancer risk at 10 ⁻⁴ (mg/L) ⁴	0.1	0.03

¹ Concentration that is not expected to cause any adverse noncarcinogenic effects up to 7 years of exposure, with a margin of safety.

² A lifetime exposure concentration protective of adverse, noncarcinogenic health effects. Assumes all exposure is through drinking water.

³ The concentration of a chemical that is not expected to cause any adverse noncarcinogenic effects over a lifetime of exposure, with a margin of safety.

⁴ TNT and RDX are in cancer group C (limited evidence from animal studies and inadequate or not data in humans).

3.5 Explosives and Soil Contamination

The DoD has made cleanup of explosives-contaminated soil a major priority (Marion and Pelton, 2000). According to The National Technology Transfer Center (NTTC) in “The Cleanup Pillar,” the Army is the DoD single service manager for explosives and as such manages munitions through their entire life cycle, from development and manufacture through disposal. “As a result, the Army has the lead for developing cleanup treatment technologies for explosives and propellants. This contamination primarily resulted from waste discharges during munitions manufacture and the destruction of out-of-date or off-specification material. In addition, the Army, due to its experience and capabilities, is the lead Service responsible for the development of innovative technologies to treat heavy metals,

organic compounds, and chemical agents” (n.d.)

3.5.1 MOBILITY

Marion and Pelton say that the mobility of explosives in soils is determined by the following:

- Advective-dispersive transport
- Solubility
- Sorption
- Volatilization
- Biotransformation
- Abiotic processes

3.5.2 EXPLOSIVES CLEANUP METHODS

In the past, explosives disposal practices “often result[ed] in soils contamination” (EPA, “Overview,” 1999).

According to the USAEC, currently, regulatory agencies “only approve incineration and composting as decontamination technologies” (“Toxicity,” n.d.). USAEC is investing in developing other biotreatment technologies because composting costs can be high “due to the necessary amendments needed for the composting process,” and incineration, which was commonly accepted in the 1980s, has now lost favor as a cleanup method due to cost.

The USAEC says that bioremediation—the use of living organisms to remove pollutants from soil or water—can be effective for removing TNT and RDX from soils. Two methods that are working well in field tests are soil slurry reactor treatment and windrow composting. USAEC reduced TNT by 99.7 percent and RDX by 99.8 percent by using the windrow composting method, while the aerobic bioslurry method removed more than 99 percent of TNT, HMX, and RDX at Joliet Army Ammunition Plant (USAEC, “Bioremediation,” n.d.).

NTTC describes the various past and present—and future—cleanup methods for explosives-contaminated soils and groundwater:

Research is conducted to develop biological, physical, and chemical methods for the treatment of explosive contaminated soils and groundwater. A number of new and innovative contaminated soil treatment technologies are currently under investigation. An example is the development of bioremediation technologies to treat explosives contaminated soils. Although incineration has been demonstrated as an effective treatment technology, the cost is high.

Bioremediation is an alternative treatment process with the potential to effectively degrade explosives, such as TNT, RDX, and HMX, at significantly lower cost. Full scale testing of composting for explosive-contaminated soil is now being conducted at Umatilla Army Depot Activity (UMDA). It is estimated that bioremediation at UMDA will reduce the cleanup cost by at least 50 percent over traditional cleanup methods such as incineration.

Longer range program objectives include the development of in situ processes for remediation of organic and explosives contaminated soils and groundwater. Basic research is being conducted into the microbiology of biodegradation in support of biotechnology development.

3.6 TNT and RDX Degradation

Degradation refers to the reduction of the complexity of a chemical compound.

3.6.1 TNT DEGRADATION IN SOILS

According to McFarlan (2000), “Unequivocal evidence for TNT mineralization or transformation to a compound of intermediate metabolism by a pure bacterial culture is still

lacking. Generally mineralization is only detected with bacterial consortia. Many of the products of TNT biodegradation are highly reactive and covalently bind to cellular components and any solid supports (such as soil) present in the medium. The latter prevents or prolongs the mineralization process, but also hinders a further spread of TNT contaminants. Several authors have noted the formation of as yet unidentified compounds during TNT biodegradation.”

3.6.2 RDX DEGRADATION IN SOIL

RDX does “not cling to soil very strongly and can move into the groundwater from soil,” dissolves in and evaporates from water very slowly, and can be broken down in air and water in a few hours but more slowly in soil, according to the Agency for Toxic Substances and Disease Registry (ATSDR)(RDX, 1996).

3.6 Biological Pathways of TNT and RDX in Soils

Potential environmental pathways for contaminants, including RDX and TNT, include groundwater, surface water, soil and sediment, and volatilization of contaminants or contaminants entrained in ambient air. In addition, bioaccumulation of contaminants in fish, waterfowl, wildlife or livestock, and wild plants and commercial agricultural products may be another environmental pathway.

Potential human exposures to contaminants include ingestion of and direct contact with groundwater, surface water, soil, and possible ingestion of bioaccumulated contaminants in the food chain. In addition, inhalation of volatilized contaminants or contaminants entrained in air is another potential source for human exposure.

Historically, as they produced weapons during and after World War II, “the nation’s munitions factories used the standard practices of the time

for handling waste. Waste streams were frequently discharged directly into lagoons or fields, and solid waste was often burned. Over time, residues of TNT and other explosives accumulated in these disposal areas. Depending on the types and concentrations of explosives waste, the disposal sites now are either barren or covered with plants. Citizens and government agencies have become concerned about possible environmental and human health risks from these contaminated fields. Could the explosives, their by-products and the products of their degradation be entering animal and human food chains through vegetation and crops growing on explosives-contaminated soils?" ("Explosive Plant Growth," n.d.).

3.7 Explosives and Their Disposition in Plants

Studies of crop plants seem to show that plants grown on former munitions fields do not become contaminated with TNT. However, according to "Explosive Plant Growth," contamination by other explosives "may pose a health problem." At one field where oat and rye grass were grown on TNT-contaminated soils with added ground grass hay, TNT uptake "was not affected in any aboveground crops. In fact, neither TNT nor its degradation products were found in aboveground plant tissues of existing vegetation at either ammunition plant" (ibid, no date).

At all sites where TDX was manufactured, though, "RDX was found in tops and roots of plants growing on RDX-contaminated soils" (ibid). Although RDX is not a listed carcinogen, "several of its potential degradation products may be carcinogenic. For this reason, the consumption of any plants growing on RDX-contaminated sites should be considered a potential health hazard" (ibid).

The Agency for Toxic Substances and Disease Registry of the U.S. DHHS provides the

following information about TNT and RDX and plant and animal uptake of these explosives (Table 3-2).

Table 3-2 Plant and Animal Uptake of TNT and RDX

Explosive	Behavior in Soil and Water	Plant and Animal Uptake
TNT	Moves in surface water and through soils to groundwater; in surface water, it is rapidly broken down into other chemical compounds by sunlight; it is broken down more slowly by microorganisms in water and sediment	Small amounts of TNT can build up in plants and in fish. (Other animals are not mentioned in source.)
RDX	Dissolves and evaporates very slow in water; does not cling to soil very strongly and can move into the groundwater from soil; can be broken down in air and water in a few hours, but it breaks down more slowly in soil.	RDX does not build up in fish or humans. (Other animals and plants are not mentioned._

At Iowa Army Ammunition Plant (IAAAP), RDX is the primary contaminant of concern. Forty-four sites at IAAAP were investigated for potential soil and sediment contamination. ATSDR concluded that soil and sediment contaminants do not pose a public health hazard because (1) publicly accessible areas contain contaminant concentrations too low to pose health hazards; (2) exposure (past, present, and future) to the general public has been prevented; and/or (3) remedial activities have reduced or will reduce contaminant

concentrations to levels that pose no public health threat.

Particularly relevant to this Section, ATSDR reviewed data on explosives uptake in agricultural produce, deer, and cattle to address community concerns about the safety of consuming local crops, venison, and beef. "Toxicologic and ecological studies indicate that IAAAP crops are not bioaccumulating RDX and that they are safe for human consumption. In addition, studies at other Army facilities and laboratory studies suggest that deer and cattle do not bioaccumulate RDX in their tissue" (Public Health Assessment, 1999). Remediation of TNT and RDX in Soil

Since the scope of work of this particular project is not concerned with remediation, this report will include only a very brief summary of this information.

TNT is usually found in the top few meters of soil ("Bacteria's Sweet-Tooth," 1996). Because of this, bioremediation alternatives such as plant uptake are being researched.

Much of the research that has been done since 1995 focuses on ways to replace the commonly used past method of incineration with bioremediation methods such as composting, bioslurry treatment, and phytoremediation.

USAEC provides the following cost estimates for remediation of explosives-contaminated soils ("Cost and Design," n.d.):

- Windrow Composting: \$250 to \$299/ton for 10,000 cubic yards (cy) (13,000 tons) of soil
- Anaerobic Bioslurry Process: \$314/ton
- Incineration: \$740/ton

3.7.1 BIOREMEDIATION

In recent years, ex-situ bioremediation techniques "such as composting and slurry digestion have gained favor as rapid and cost-effective solutions" for soils contaminated with

explosives (Thorne, 1999). "The toxicity of the finished compost and its release of toxic compounds during long-term weathering is acceptably low" (ibid).

The USAEC recommends using bioremediation to eliminate explosive compounds from soils (n.d.). At the cleanup of a Superfund site at Umatilla Army Depot, Oregon, windrow composting was used. TNT was reduced by as much as 99.7 percent, and RDX reduction was 99.8 percent. For sites where composting is too expensive because of the need to import materials, USAEC recommends soil slurry biotreatment (bioslurry). At Joliet Army Ammunition Plant, Illinois, aerobic bioslurry achieved 99 percent removal of TNT, HMX, and RDX.

NTTC provides the following information about cleanup costs of current technologies versus bioremediation technologies for explosives/organics contaminated soils in its discussion of current research and development for cleaning up explosives-contaminated soils and water (The Cleanup Pillar, n.d.):

- Incineration, current cost range: \$350-\$1500/cy
- Composting of Explosives: A variety of composting techniques will be developed with selection of process type based on site requirements. Estimated cost range is \$150-\$300/cy.
- Explosives Bioslurry Treatment: An on-site treatment technology that utilizes aboveground reactors comprised of soils slurried with water at a 30-50% w/w ratio. Estimated cost range is \$120-\$250/cy.
- Nitrate Ester Biodegradation: An enzyme system which destroys liquid nitrate esters for in situ cleanup of soil. Estimated cost range for this technology is \$250-400/cy.
- PAH Biocells: Biocell technology will be used to treat excavated soils contaminated

with polynuclear aromatic hydrocarbons (PAHs). Estimated cost range is \$30-\$100/cy.

- Enhanced Explosives Bioslurry: An improved biological system will be developed as an improvement to the fielded bioslurry system. Enhancements via use of surfactants, specialty organisms, and new cometabolites will be obtained. Estimated cost range using enhanced bioslurry systems is \$50-\$150/cy.

Thorne points out the problems with bioremediation at open burning/open detonation areas and firing ranges “that affects the cost of benefits of excavation and ex-situ remediation and disposal of remediated mixtures”: the high concentration of explosives residue, the fact that such contamination is usually in the top 15 cm of the soil, and, especially, the distribution of the contaminants is so mixed. “There are ‘hot’ spots and ‘non-detect’ spots in close proximity,” he says. “It would be inefficient to waste resources on remediating truckloads of excavated soil that may be, on average, below the target remediation goals. Without extensive sampling and analysis, it is unlikely that the total mass of explosives can be estimated accurately enough to provide design data for remediations such as composting or slurry digestions.” Instead, for such sites, he recommends phytoremediation.

3.7.2 PHYTOREMEDIATION

The EPA defines “phytoremediation” as the “direct use of living green plants for in situ, or in place, risk reduction for contaminated soil, sludges, sediments, and groundwater, through contaminant removal, degradation, or containment. Growing and, in some cases, harvesting plants on a contaminated site as a remediation method is an aesthetically pleasing, solar-energy driven, passive technique that can be used to clean up sites with shallow, low to moderate levels of contamination. This

technique can be used along with or, in some cases, in place of mechanical cleanup methods” (“Citizen’s,” 1998).

Phytoremediation is the subject of literature sources. It is thought to have potential value in that the technology may be shown useful for clean up of both metals and explosives, as well as pesticides, solvents, crude oil, polyaromatic hydrocarbons, and landfill leachates (EPA, “Citizen’s,” 1998).

P.G. Thorne (1999) writes that for phytoremediation to be successful, “the cost of treatment must be low enough so that large areas can be treated without the necessity of detailed spatial quantification of contamination.” Several years, he says, might be required for phytoremediation to be successful.

4.0 SUMMARY OF FINDINGS: HEAVY METALS IN SOILS

Preliminary assessments performed at Fort Greely, Alaska, noted a number of heavy metals (or elements) in the explosives-contaminated area. Therefore, this literature review focuses on these heavy metals (see Table 4-1) in soils, particularly as to plant uptake of those metals.

Table 4-1 Heavy Metals Evaluated for Literature Review

Element	Symbol
Iron	Fe
Zinc	Zn
Lead	Pb
Nickel	Ni
Copper	Cu
Chromium	Cr
Antimony	Sb
Cadmium	Cd
Molybdenum	Mo
Tin	Sn

In particular, this research focused on the following questions about heavy metals in soils:

- What are the effects of metals as related to soil texture and soil pH?
- How do each of the metals discussed interact with other metals?
- What is the relationship between soil and heavy metals mobility?
- In The Cleanup Pillar, the NTTC describes the importance to the government to clean up inorganic and heavy metal at military sites. New treatment technologies are required, NTTC says, “to reduce the volume of material requiring ultimate disposal and to reduce treatment cost for inorganic and

metal contaminated soils and sludges” (n.d.).

Inorganic and heavy metal contamination occurs at over 940 military sites in soils and sludges, according to NTTC. “Typical military activities resulting in heavy metal contamination include plating operations, firing ranges, motor pool activities, metal finishing, incineration activities, cooling water treatment, and burning pits. Few technologies currently exist for the treatment of metal-contaminated soils.”

4.1 Heavy Metals and Soils

The term “heavy metals” refers to some 38 elements of density greater than 5 g/cm³ (Etherington, 1982). All soils contain trace levels of metals (McLean and Bledsoe, 1992). Concentration of metals in uncontaminated soil “is primarily related to the geology of the parent material from which the soil is formed” (ibid). Table 4-2 lists the range of metals in uncontaminated soils, but, depending on the local geology, the concentration of metals in a soil may exceed the ranges listed here. “Only by direct analysis of uncontaminated soils can background levels of metals be determined” (McLean and Bledsoe, 1992).

Table 4-2 Content of Elements in Soils

Metal	Selected Average for Soils (mg/kg)	Common Range for Soils (mg/kg)
Fe (Iron)	38,000	7,000-550,000
Cu (Copper)	30	2-100
Zn (Zinc)	50	10-300
Cr (Chromium)	100	1-1,1000
Cd (Cadmium)	0.06	0.01-0.70
Ni (Nickel)	40	5-500
Sb (Antimony)	NOT IN SOURCE	NOT IN SOURCE
Pb (Lead)	10	2-200
Mo (Molybdenum)	NOT IN SOURCE	NOT IN SOURCE
Sn (Tin)	NOT IN SOURCE	NOT IN SOURCE

Source: Lindsay, 1979, in McLean and Bledsoe, 1992.

Note: McLean and Bledsoe’s report is concerned only with

the metals most commonly found at Superfund sites: Pb, Cr, Arsenic (As), Cd, Ni, Zn, Cu, Mercury (Hg), Silver (Ag), and Selenium (Se).

The relationship between metals and soil “depends much on the site and soil characteristics, and evaluation should therefore be site/soil/waste specific” (McLean and Bledsoe, 1992). Variation in soil nutrient levels, including metals, influences plant species composition and growth (Etherington, 1982). “Responses to local or regional nutrient variation may span the range from deficiency to toxicity and result in differential behaviour of plant species or ecotypes” (ibid).

Most plants absorb nutrients from soil-solution in their ionic form: the common metals are taken up as cations (Etherington, 1982).

4.1.1 METALS AND SOIL PH

In general, adsorption of cationic metals increases with increased pH. The pH of the soil affects “several mechanisms of metal retention by soils” (McLean and Bledsoe, 1992). Soil pH increases the absorption of all cationic metals. However, a study by Harter (1983) of Pb, Ni, Zn, and Cu concluded that the “retention of metals did not significantly increase until the pH was greater than 7” (cited in McLean and Bledsoe, 1992).

C.L. Johnson (1992) describes soil chemistry and acid-forming features: “soils become more acid when excess hydrogen (H) and aluminum (Al) ions replace basic cations such as Ca, Mg, K, and Na on the surface of clays and soil humans. Cations are positively charged ions and anions are negative charged ions. The basic cations are often leached below the root zone, leaving H and Al behind because they are more strongly attached to the negative charges on the soil surface.”

As far as increasing base-forming features, or alkalinity, “any process that will encourage high levels of the exchangeable base-forming

cations (Ca, Mg, K, Na) will contribute toward an increase in alkalinity,” Johnson says, including liming, weathering, content of water, and recycling of cations by deep-rooted plants, which can bring cations to the surface “and incorporate them in the topsoil.” When the soil pH is too high, “deficiencies of iron, manganese, and other micronutrients occur” (ibid, 1992).

According to McLean and Bledsoe, the “pH dependence of absorption reactions of cationic metals is due, in part, to the preferential adsorption of the hydrolyzed metal species in comparison to the free metal ion.... The proportion of hydrolyzed metal species increases with pH” (1992).

For the specific metals this report is concerned with, McLean and Bledsoe summarize the data (additional sources are noted):

Copper. Copper adsorption by soils shows a stronger pH dependence than Cd. Cu is absorbed to a greater extent by soils and soil constituents than the other metals studied, except Pb. Copper, however, has a high affinity for soluble organic ligands, and the formation of these complexes may greatly increase Cu mobility in soils. Cu hydrolysis at pH 6 increases its retention by soil.

Cu, however, has behaved differently from the other cationic metals in studies, actually decreasing with increased pH, when other factors are present: “The adsorption of Cu to montmorillonite, in the presence of water soluble ligands extracted from sludges and various other organic materials, decreased with increasing pH. This behavior is the opposite of the typical relationship between metal adsorption and pH” (McLean and Bledsoe, 1992). The explanation is that “at low pH, H⁺ competes with the Cu for complexation with the organic matter. As the pH increases, more of the Cu can be complexed with the organic matter and less is therefore adsorbed by the clay” (ibid).

Cadmium. Adsorption mechanisms may be the primary source of Cadmium removal from soils. As with all cationic metals, the chemistry of Cd in the soil environment is, to a great extent, controlled by pH. Under acidic conditions, Cd solubility increases and very little adsorption of Cd by soil colloids, hydrous oxides, and organic matter takes place. At pH values greater than 6, cadmium is absorbed by the soil solid phase or is precipitated, and the solution concentrations of cadmium are greatly reduced. Cd does not hydrolyze until pH 8.

Iron. Fe is considered pH dependent. Fe and manganese (Mn) play a principal role in the retention of metals by soil.

Zinc. Retention of Zn is increased with increasing pH. When the pH was increased above 7.5, however, the solution concentration of Zn increased. The greatest percent of the total Zn in polluted soils and sediments was associated with Fe and Mn oxides in studies. Zinc hydrolyzes at pH greater than 7.7, and these hydrolyzed species are strongly adsorbed to soil surfaces. Zinc forms complexes with inorganic and organic ligands that will affect its adsorption reactions with the soil surface. The normal zinc soil content, says Etherington, is between 10 and 300 $\mu\text{g g}^{-1}$ (1982).

Lead. At pH values above 6, Pb is either adsorbed on clay surfaces or forms lead carbonate. Of all the trace elements studied, Pb is retained by soils and soil constituents to the greatest extent under the conditions of these studies. Some have found decreased sorption of Pb in the presence of complexing ligands and competing cations. Lead has a strong affinity for organic ligands, and the formation of such complexes may greatly increase the mobility of Pb in soil. Gauch says, "The concentration of Fe in a soil solution is markedly affected by pH, since pH values of 7 or higher drastically reduce the availability of Fe to plants because of the precipitation of Fe in the soil" (1972).

Nickel. Ni does not form insoluble precipitates in unpolluted soils, and retention for Ni is, therefore, exclusively through adsorption mechanisms. Nickel will adsorb to clays, iron and manganese oxides, and organic matter and is thus removed from the soil solution. The formation of complexes of Ni with both inorganic and organic ligands will increase Ni mobility in soils.

Chromium. Chromium exists in two possible oxidation states in soils: the trivalent chromium, Cr(III) and the hexavalent chromium, Cr(VI). Trivalent Cr is readily absorbed by soils. In a study of the relative mobility of metals in soils at pH5, Cr(III) was found to be the least mobile. Hydrox species of Cr(III) precipitate at pH 4.5 and complete precipitation of the hydroxy species occurs at pH 5.5. Hexavalent Cr was found to be the only metal studied that was highly mobile in alkaline soils. The parameters that correlated with Cr(VI) immobilization in the soils were free iron oxides, total manganese, and soil pH, whereas the soil properties, cation exchange capacity, surface area, and percent clay had no significant influence on Cr(VI) mobility.

Molybdenum. Molybdenum occurs in natural soils as "the sulphid or the molybdate, usually entering soil solution as the molybdate anion" (Etherington, 1982). "The usual soil content is 1-10 $\mu\text{g g}^{-1}$, but most of this is insoluble" (ibid). "A few calcareous, P-rich soils show excessive Mo availability..." (ibid).

4.1.2 CATION EXCHANGE CAPACITY

The cation exchange capacity is the total amount of exchangeable cations that a soil can adsorb. It is sometimes called "total exchange capacity" "base exchange capacity," or "cation adsorption capacity." It is expressed in milliequivalents per 100 grams of soil or of other adsorbing materials such as clay.

Any element with a positive charge is called a cation. The amount of these positively charged cations a soil can hold is described as the CEC and is expressed in milliequivalents per 100 grams (meq/100g) of soil. The larger this number, the more cations the soil can hold. A clay soil will have a larger CEC than a sandy soil.

According to C.L. Johnson (1992), "the nutrient holding capacity of the soil is largely determined by the cation exchange capacity (CEC). Soil colloids with negative charges attract and hold cations (e.g., Ca, Mg, K, Na, Al, NH, H). Humus can hold cations in much the same way as clay minerals because of the negative charges on the humus particles. The clay and humus account for most of the CEC, but finer fractions of silt can have a limited number of exchange sites. The CEC is expressed as milliequivalents (meq) of positive charge that can be held (absorbed) by 100 grams of soil (oven-dry basis) or as centimoles of positive charge per kilogram of soil (cmol/kg); 1 meq/100 g=1 cmol/kg. Sandy soils have a lower CEC than clay soils because the coarse-textured soils are commonly lower in clay and humus content. The texture and organic matter of a soil influence the CEC. The CEC of a loam of silt loam soil could range from 10-25 meq/100 g."

4.1.3 HEAVY METALS MOBILITY

Generally, metals added to soil will stay at the soil surface. Movement to groundwater, surface water, or the atmosphere is minimal "as long as the retention capacity of the soil is not exceeded" (McLean and Bledsoe, 1992). Metals movement in soil is "related to the solution and surface chemistry of the soil and to the specific properties of the metal and associated waste matrix" (ibid).

Metals in soil are "subject to mass transfer out of the system by leaching to groundwater, plant uptake, or volatilization," write McLean and

Bledsoe (1992). "At the same time, metals participate in chemical reactions with the soil solid phase. The concentration of metals in the soil solution, at any given time, is governed by a number of interrelated processes, including inorganic and organic complexation, oxidation-reduction reactions, precipitation/dissolution reactions, and adsorption/desorption reactions."

Whether or not metals will move from the soil to the groundwater depends much on the type of soil. Generally, metals do not travel downward from the soil surface to any great extent.

McLean and Bledsoe explain: Metals movement in soil is directly related to the surface chemistry of the soil matrix and soil solution. When metals are introduced at the soil surface, "downward transportation does not occur to any great extent unless the metal retention capacity of the soil is overloaded, or metal interaction with the associated waste matrix enhances mobility. Changes in soil environmental conditions over time, such as the degradation of the organic waste matrix, changes in pH, redox potential, or soil solution composition, due to various remediation schemes or to natural weathering processes, also may enhance metal mobility."

Metals associated "with the aqueous phase of soils are subject to movement with soil water, and may be transported through the vadose zone to groundwater" (McLean and Bledsoe, 1992). "Metals, unlike the hazardous organics, cannot be degraded." However, some metals, such as Cr, can be transformed to other oxidation states in soil, reducing their mobility and toxicity (ibid).

4.1.3.1 Soil Organic Matter and Mobility

Soil organic matter consists of the following (McLean and Bledsoe, 1992):

- Living organisms. Soil organic matter can be the main source of soil cation exchange capacity, contributing more than 200meq/100 g of organic matter in surface mineral soils. Organic matter content,

however, decreases with depth, so that the mineral constituents of soil will become a more important surface for sorption as the organic matter content of the soil diminishes.

- Soluble biochemicals (amino acids, proteins, carbohydrates, organic acids, polysaccharides, lignin, etc). The biochemicals form water-soluble complexes with metals, increasing metal mobility.
- Insoluble humic substances. The humic substances consist of insoluble polymers of aliphatic and aromatic substances produced through microbial action. Binding of metals to organic matter involves a continuum of reactive sites, ranging from weak forces of attraction to formation of strong chemical bonds.

Jenne (1968) found that Fe and Mn oxides are the principal soil surface that control the mobility of metals in soils and natural water (in McLean and Bledsoe, 1992).

4.1.3.2 Soil Properties Affecting Adsorption

“Adsorption of metal cations has been correlated with such soil properties as pH, oxidation-reduction (redox) potential, clay, soil organic matter (SOM), Fe and Mn oxides, and calcium carbonate content” (McLean and Bledsoe, 1992). Adsorption processes are also affected by the form of the metal added to the soil and by the solvent introduced along with the metal (ibid). These interactions can either increase or decrease the movement of metals in soil water.

Soils with heavier textures and higher pHs are effective in attenuating metals, “while sandy soils and/or soils with low pH did not retain the metals effectively” (McLean and Bledsoe, 1992). Korte et al. (1976) found that lead and copper are the least of the cationic metals (in McLean and Bledsoe, 1992). Chromium is considered quite mobile.

4.2 Metals and Environmental Pathways

This section briefly discusses the pathways metals take through soils and plants. Further discussion is included in Section 4.3, Metals and Their Disposition in Plants.

Metals move through soils, plants, animals, and humans at various rates. Some metals are necessary for humans and other animals and plants to thrive; others are toxic to living organisms. Some metals might be necessary for one species to survive but are poisonous to another species.

Alloway (in Norman, 1968) charted the pathways of elements. Many of the links can cross to others in various ways, so the order of their presentation is not important here; instead, the different pathways are: man—waste disposal—oceans—sea foods—air—rocks—industrial products—mineral supplements—water—soils—plants—animals. Any of these pathways, Alloway says, has, “under certain circumstances, been responsible for the delivery of excessive amounts of one or more trace elements to plants or animals, and possibly to man.”

4.3 Metals and Their Disposition in Plants

Metals in soils can be either transferred out of soil through plant uptake (McLean and Bledsoe, 1992) or can remain in the soil but also be taken up by plants, affecting the plant in several ways.

In general, this literature review provides summaries of published articles that address plant uptake of heavy metals. Although the Fort Greely study is particularly focused on the how metal uptake might affect the growth rates of grasses, forbs, and woody plants — the three major plant types on Alaska ranges — most of the literature is concerned with crop plants.

Adriano (1992) lists some of the trace metals this report is concerned with in his table, "Mean of Some Total Trace Elements in Soils of Western Europe, in Comparison with the Contents of U.S., Canadian, and World Soils (mg/kg)." Table 4-3 is derived from that table.

Table 4-3 U.S. Mean of Trace Elements in Soils

U.S. Mean (mg/kg)		Canada Mean (mg/kg)	
Cu	25	Cu	22
Zn	54	Zn	74
Ni	20	Ni	20
Cr	53	Cr	43
Pb	20	Pb	20
Cd	0.50	Cr	0.30

4.3.1 PLANT UPTAKE OF HEAVY METALS

The challenges in writing a brief description of plant uptake in metals are many:

- Metals exist in various forms and levels in different soils.
- Uptake by plants varies per species and per metal.
- Most of the research that has been done focuses on crop plants.
- Similarly, most of the research that has been done on the animals that eat plants containing excess heavy metals has focused on livestock.

With these limitations in mind, this Section will provide a brief summary of the information from the sources listed in Section 6.

"Some of the most inhospitable environments on earth are those which contain high concentrations of toxic materials such as heavy metals..." (Etherington, 1982). Several of the heavy metals are required by plants: Fe, Mn, Cu, Zn, and Mo (ibid). Others that are normally present in soils at low concentrations but are toxic in very small quantities include Ag, Cd,

Hg, and Pb. The reasons for both essentiality and toxicity of metals in plants is explained by Etherington: "the heavy metals are transitional elements which are able to form stable coordination compounds with various inorganic and organic ligands, the metal cation acting as a Lewis acid and being donated an electron from the electron-rich ligand" (1982).

The focus of this review of literature is on the toxic levels of heavy metals in relation to plants, which can mean either a metal inessential to a particular plant or a required metal at a higher than normal concentration.

Many factors can expose plants to toxic levels of heavy metals, such as "geological fortuity, biological concentration during soil formation or mining, smelting and industrial emissions" (Etherington, 1982)

The Agency for Toxic Substances and Disease Registry (ATSDR) of the U.S. Department of Health and Human Services provides general information on some of the heavy metals that this literature review is concerned with. Table 4-3 summarizes this information as it relates to heavy metals and plant uptake.

In Phytoremediation (n.d.), the authors describe the two pathways for solubilized heavy metals in soils to enter a plant: apoplastic (extracellular) and symplastic (intracellular). "Apoplastic means are limited by a high cation exchange capacity of cell walls; however, this can be somewhat avoided if metals are transported as noncationic metal chelates. ... Symplastic transport is more regulated due to the selectively permeable plasma membranes of the cells that control access to the symplast by specific or generic metal ion carriers or channels." After a heavy metal has entered a plant's root, it is either stored in the root or translocated to the shoots.

The writers seem to generally agree that the mechanisms involved in the transport of heavy metals in plants are not yet fully understood.

Table 4-4 ATSDR Soil Activity and Plant Uptake of Certain Metals

Metal	Soil Activity	Plant Uptake
Fe (Iron)	NOT IN SOURCE	NOT IN SOURCE
Cu (Copper)	NOT IN SOURCE	NOT IN SOURCE
Zn (Zinc)	Zinc attaches to soil, sediments, and dust particles in the air; rain and snow remove zinc dust from the air; most of the zinc in soil stays bound to soil particles.	Zinc builds up in fish and other organisms, but it does not build up in plants.
Cr (Chromium)	Chromium sticks strongly to soil particles; small amounts move from soil to groundwater.	Fish do not take up or store chromium; plants are not mentioned in source.
Cd (Cadmium)	Binds strongly to soil particles; does not break down, but can change forms	Fish, plants, and animals take up cadmium from the environment.
Ni (Nickel)	Found with soil and sediments because nickel attaches to particles that contain iron or manganese, which are often present in soil and sediments.	Does not appear to collect in fish, plants, or animals used for food.
Sb (Antimony)	Most antimony ends up in soil, where it attaches strongly to particles that contain iron, manganese, or aluminum.	NOT IN SOURCE
Pb (Lead)	Most of the lead in soil comes from particles falling out of the air; lead sticks to soil particles; it does move from soil to groundwater or drinking water unless the water is acidic or "soft." It stays a long time in both soil and water.	NOT IN SOURCE.
Mo (Molybdenum)	NOT IN SOURCE	NOT IN SOURCE
Sn (Tin)	The time that each type of tin compound stays in the air, water, and soil differs for each compound.	Organotins build up in fish, other organisms, and plants.

W.H. Alloway discusses the typical concentrations and amounts of trace elements in different phases of their environmental cycles (in Norman, ed., 1968), including concentrations in plants, as shown in Tables 4-4 and 4-5. (He acknowledges the limitations of his findings due to the wide variations of elements in soils, the need to estimate plant uptake based on arable or grassland soils, and the necessity of estimating the time required for depletion of the soil supply of the trace elements.)

Table 4-5 Concentrations of Amounts of Selected Trace Elements in Various Phases of the Environment

Element	Concentration in Soils (total) (ppm) mean (range)	Concentration in Plants (ppm) (range); whether the metal is required or not by the plant ; toxicity	Annual Uptake by Grasses and Crops (kg) (units described in reference)
Cd	0.06 (0.01-7)	(0.2-0.8), not required; toxic	10
Cr	100 (5-3,000)	(0.2-1.0); not required; moderately toxic	10
Cu	20 (2-100)	Required at 1-10, dependent on Mo; low toxicity	10
Pb	10 (2-2,000)	Not required; normal 0.1-10; toxic in culture solution.	10
Mo	2 (0.2-5)	Required at less than 0.1; normal 1-100; low toxicity	10
Ni	40 (10-1,000)	Not required; normal 1; toxic at +50	10
Zn	50 (10-300)	Required at 8-15; toxic at +200	10

Table 4-6 Concentrations of Amounts of Selected Trace Elements in Various Phases of the Environment

Element	Critical Levels in Animal Diets (ppm) (whether the element is required; toxicity)	Concentration in Human Blood ($\mu\text{g}/100\text{ ml}$)	Soil Depletion Time (in years)
Cd	Not required; moderate to high toxicity	4; accumulates in kidney	10
Cr	Required at ? (varies), low toxicity	2	10
Cu	Required at 1-10, dependent on Mo; low toxicity	100	10
Pb	Not required; moderate toxicity	27	10
Mo	Required at less than 0.1; moderate to high toxicity, dependent on Cu	2	10
Ni	Not required; moderate to low toxicity	1-8	10
Zn	Required at 10-40; low toxicity	650	10

For most trace elements, the soil-to-plant route is “the major route of entry into the living tissues of plants, animals, and man,” Alloway says. Usually, the soil-plant system exerts an “effective buffering action on the environmental cycling of trace elements.” The concentration of elements found in plants is usually one hundred to one hundred thousand times lower than the amount found in soil. However, as discussed in the sections below, certain plants and plant tissues do accumulate certain metals.

Plant Species That Accumulate Metals

Alloway infers from his studies that “the total amount of many of the trace elements that is present in the soil within the plant rooting zone is greatly in excess of the annual uptake by plants.”

Even so, some plants are able to accumulate far more heavy metals than others—and even more than accumulate in the soil. “Different plant species growing on the same soil may contain markedly different concentrations of the different trace elements,” Alloway says (in Norman, 1968). Some plants are able to take up large amounts of metals; they are called hyperaccumulators.

Raskin, Kumar, Dushenkov, and Salt explain the concept of accumulation: “Certain plants can concentrate essential and nonessential heavy metals in their roots and shoots to levels far exceeding those present in the soil. Metal-accumulating plant species are invariably restricted to metalliferous soils found in different regions around the world. The mechanisms of metal accumulation, which involve extracellular and intracellular metal chelation, precipitation, compartmentalization, and translocation in the vascular system, are poorly understood” (1994).

4.3.2 TOXIC METAL LEVELS IN PLANTS AND PLANT TISSUES

What may be a “toxic” level of heavy metals varies with different plants, with the pathways (i.e., humans and/or other animals that eat those plants), and with the individual metal involved. This Section discusses some of these variables, particularly as they apply to the heavy metals this report is concerned with.

The soil-plant system, Alloway says, provides “an effective barrier against toxicity from arsenic, iodine, beryllium, fluorine, nickel, and zinc. Plant growth will cease or be greatly depressed before these elements will be taken up from the soil and accumulated in concentrations that would be dangerous for

animals.” He also concludes that it is possible “for food and food plants to grow at normal or near-optimum rates and still contain sufficient selenium, cadmium, molybdenum, or lead to cause either direct toxicity of metabolic imbalance in animals that eat those plants.”

Table 4-7 lists the approximate concentrations in soils and plants of some trace elements which may occur at toxic levels, as well as the normal soil levels (Etherington, 1982; Walsh et al., 2001):

Table 4-7 Heavy Metal Concentrations: Plants and Soils (mg/kg¹ unless otherwise noted)

Element	Normal Soil	Toxic Soil	Normal Plant	Tolerant Plants
Cd	0.5+	10-200+	0.1-0.5	10-10 ³
Cr	5+	10 ² -10 ³	0.1-0.5	10-10 ²
Cu	5-30	10 ² -10 ³	4-5	10 ² -10 ³
Ni	2-20	10 ² -10 ³	1-5	10 ² -10 ⁵
Pb	2-10	To 4 x 10 ⁴	1-15	10-10 ³
Zn	1-90	To 5 x 10 ⁴	10-50	10 ² -10 ⁴
Sb	0.66 μg/g ¹	Not in source	Not in source	Not in source
Sn	Not in source	Not in source	Not in source	Not in source

¹ – The information on Sb is the only item where the source is Walsh et al. 0.66 μg/g represents the naturally occurring level of antimony in U.S. soils.

Plant Maturity. Alloway also mentions plant maturity and concludes that “effects of maturity on trace element content are not highly consistent.”

The following provides additional information about the specific elements listed in Table 4-7 (except Sb and Sn: information was not in source) and their toxicity levels.

Cd. It is not certain, Alloway says (in Norman, 1968), “that levels of cadmium that would be detrimental to humans are moving from soil to plant and on into the food chain.”

Since he wrote this, new studies have shown that Cd can affect plants. Das and Rout studied the ecological, physiological, and biochemical aspects of cadmium toxicity on plants” (1997). De Toppi and Gabrielli found that Cd “evokes a number of parallel and/or consecutive events at molecular, physiological, and morphological levels” (1999). Di Cagno, Guidi, Stefani, and Sodatini studied the effects of Cd on sunflower seedlings and found that growth and leaf area were reduced by Cd (1999). Grant, Buckley, Bailey, and Selles found that plant uptake of Cd is dependent “on a system that is largely metabolically mediated and competitive with the uptake system for Zn and possibly other metals” (1998). Most Cd is retained in the root, they said, although some is translocated to the aerial portions of the plant and the seed. The amount of Cd uptake depends on the plant species and on soil, environmental, and management factors.

Cr. Most of the chromium in the earth’s mantle, writes Alloway, “is insoluble and of low availability to plants.” He adds that there is “little information on the degree to which the chromium contained in plants is absorbed and retained by animals.” More recently, Samantary, Rout, and Das evaluated the toxic and beneficial effects of chromium on plants and found that high concentrations of Cr caused “several chlorosis, necrosis, and a host of other abnormalities and anatomical disorders” (1998).

Cu. Copper can be taken up by plants, and there is a possibility of reduced plant growth “due to excessive additions” (Alloway, in Norman, 1968). Gauch says that toxic concentrations of Cu “occurs in highly leached, light sandy soils, in very sandy soils, or in soils that have accumulated excess Cu as a result of Cu sprays on plants” (1972).

Fe. Gauch says that Fe toxicity “has not been much in evidence under natural conditions, but when it occurs the symptoms usually first appear as necrotic spots on leaves” (1972).

Mo. Although molybdenum is needed by higher plants (Gauch, 1972) and animals, levels higher than 1.0 ppm of the dry diet for many species can “produce a disorder called molybdenosis or molybdenum-induced copper deficiency” (Alloway, in Norman, 1968). This can be a problem in areas where copper is low. In animals, “the levels of molybdenum in the blood are closely related to dietary molybdenum intake,” although it is not well-established for humans (ibid). Gauch notes that excesses of Mo “have caused poisoning of cattle when pasture grasses contained 20 ppm or more of Mo” (1972).

Ni. Generally, nickel does not appear to collect in fish, plants, or animals used for food (ATSDR, 1997). Soils normally contain about 100 ppm of Ni, while soils derived from ultrabasic igneous rocks (serpentine) may contain as much as 5000 ppm, “definitely a phytotoxic concentration” (Gauch, 1972). There are some plants that are nickel accumulators, as mentioned by Gharderian, Lyon, and Baker (2000).

Pb. Plants do appear to uptake lead from soil, and the amount may be affected by the state of maturity of the plants (Alloway, in Norman, 1968). Lead can be harmful to animals and humans who eat the plants containing it. Gauch notes that Pb is nonessential for plants, “and the element ordinarily occurs in very low concentrations in plants and soils” (1972). He gives an example of a study done on sheep fescue (*Festuca ovina*), where root growth was retarded by 10 ppm of Pb, markedly reduced by 30 ppm, and stopped by 100 ppm. Johnson concludes, “It is likely that lead is a selective agent that continues to act on and influence the genetic structure and future evolution of exposed plant and animal populations” (1998).

Zn. The zinc concentration in plants “often reflects the level of available zinc in the soil,” says Alloway (in Norman, 1968). However, zinc in plants is less available to animals than diets based on animal protein, and Alloway attributes this to “the presence of insoluble complexes of zinc with calcium and phytic acid in plants,” which makes the zinc less digestible. Zinc is also needed by higher plants for formation of natural plant growth, possibly to absorb water and synthesis of tryptophan (Gauch, 1972). Gauch reports that certain acid peats and soils derived from rocks high in Zn may naturally contain toxic levels of Zn (1972). One study of navy beans showed growth was normal in one variety while another variety’s growth was extremely reduced by 5 ppm Zn (ibid).

4.4 Heavy Metals and Remediation

According to the NTTC in *The Cleanup Pillar* (n.d., c. 1997), remediation of heavy metal contaminated sediments have in the past used one of three alternatives: (1) dredging and confined disposal or landfilling, (2) capping in place, and (3) dredging, solidification/stabilization (S/S), and disposal. The NTTC says that none of these alternatives remove the contaminant from the sediments, “thus long-term disposal liabilities remain a major problem. Both dredging and disposal and S/S technologies require a disposal site for the contaminated sediments and, in the future, land costs will escalate. Current costs for landfilling in a RCRA facility and S/S technologies are estimated at \$75-\$200/ton.” NTTC estimated that by the year 2000, “the RCRA landfill option may exceed \$350/ton by the year 2000. With the development of alternative aboveground and in-situ treatment and/or containment technologies for metal contaminated sediments, disposal costs can potentially be reduced by over 80%.”

Approximately 1,000 sites may require remediation for heavy metals (ibid). “Assuming an average of 2,000 tons per site, the cost

savings would range between \$600M and \$1,800M.” The new extraction technologies being developed offer the potential for recovery and recycling of heavy metals for some sites, NTTC says.

In another article, “Heavy Metals Contaminated Soil Project,” NTTC mentions that the DOE has “identified a need to develop, test, and demonstrate technologies for the remediation of soils contaminated by various metals.” Some of the technologies described to separate heavy metals and radionuclides from soil include:

- Air-sparged hydroclone
- Campbell Centrifugal Jig
- Centrifugal Gravity Concentrator
- Tall Column Flotation
- Automated Mechanical Flotation
- High Gradient Magnetic Separation
- The Sepor System

Phytoremediation

The ability of certain plants to take up heavy metals is sometimes used for removal of contaminants in soil (and water). This is called phytoremediation. This is a relatively new (within approximately the last 10 years) option for remediating organic and inorganic contaminants in soil and sediment (Phytoremediation, no date). Researchers are focusing on enhancing uptake rates and increasing the biomass capable of absorbing metals (ibid).

At metals-contaminated sites, plants are “used to either stabilize or remove the metals from the soil and groundwater through three mechanisms: phytoextraction, rhizofiltration, and phytostabilization” (EPA, “Citizen’s,” 1998).

The uptake and translocation of metal contaminants in the soil by plant roots into the aboveground portions of plants is called phytoextraction or phytoaccumulation (EPA,

“Citizen’s,” 1998). Certain plants are used that are known to absorb large amounts of metals. Plants are harvested and then incinerated or composted. There are 400 known plants that take up high amounts of metals; Ni, Zn, and Cu are the “best candidates for removal by phytoextraction,” says the USEPA (ibid).

Rhizofiltration is usually used for contaminated groundwater rather than soil, and involves the absorption of metal into plant roots.

Phytostabilization is used to immobilize soil contaminants through adsorption and accumulation by plant roots. This “reduces bioavailability for entry into the food chain” (EPA, ibid). Sometimes this technique is used to “reestablish vegetative covers at sites where natural vegetation is lacking due to high metals concentrations” (ibid). Also, metal-tolerant plants can be used.

Phytoremediation has been used to clean up metals and explosives, as well as other contaminants, and can be used in combination with other cleanup approaches as a “finishing” step, according to the EPA (“Citizen’s,” 1998). Phytoremediation limits include the following:

- Can take longer than other methods (most heavy metal-accumulating plants are slow growing)
- Reaches depths that are within the reach of the plant roots
- Is usable only at sites with low to medium contaminant concentrations
- Needs further research on how it affects animals in the food chain and on whether contaminants can collect in tree leaves

In addition, selecting crops “for avoiding deficiencies or excesses of trace elements in plants for animals (or humans) that consume these plants is most often effective on soils where the available supply of a trace element is on the margin of either deficiency or excess” (Alloway, in Norman, 1968).

Sites where phytoremediation has been used to remove heavy metals or explosives include Trenton, New Jersey (heavy metals in soil with Indian mustard); Milan, Tennessee (explosives wastes in groundwater with duckweed and parrotfeather); Beaverton, Oregon (metals with cottonwood); Anderson, South Carolina (heavy metals in soil with hybrid poplar and grasses) (EPA, "Citizen's, 1998).

4.5 Heavy Metals and Explosives-Contaminated Sites

Barium, lead, chromium, cadmium, zinc, and antimony "are metals used in various primers" by the military in its munitions. At the Fort Greely Washington Range, Walsh et al. sampled for the following heavy metals in soils as well as explosives, iron, zinc, lead, nickel, copper, chromium, barium, antimony, and cadmium (2001).

Perhaps because of the munitions, some heavy metals appear to be present in areas where there are known to have been explosions of TNT and RDX. The difficulty is that, unlike explosives, metals have natural background concentrations, which can vary from site to site, and even within a site.

Walsh et al. (2001) found increased heavy metals in soils at the following areas at the Washington Range:

TOW Missile Targets. Increased "concentrations of copper, zinc, lead, chromium, and antimony" were found around targets used in tests of Tube-launched Optically-tracked Wire-guided (TOW) Missiles. Soil samples from both TOW sites at Washington Range showed higher concentrations of two metals: cadmium and antimony (the only detection of antimony above the detection limit was at the TOW sites). Soil samples collected 10 m or greater from the second TOW site revealed metal concentrations "similar to naturally occurring concentrations." The source of the metals at the TOW sites

"could have been either the missiles or the tank or both," since the soil samples were collected next to target tanks.

40-mm Impact Berm and Firing Point.

"Concentrations of copper were elevated well above background in all of the samples from the berm. The source of the copper was probably the grenade ogive, which is 4 percent copper."

Lead and Plant Uptake

A number of DoD installations have soils requiring remediation for heavy-metal contamination, according to the U.S. Army Environmental Center (USAEC). Lead is of particular concern because of its toxicity and the quantity discharged.

USAEC says, "The contamination consists of both particulate and ionic metals. The metallic particulates were often deposited as the result of firing range use. The ionic metals were commonly deposited when metal-bearing propellants, ammunitions, and powders were burned at explosive disposal sites or when metal-bearing particulates in the soil were dissolved and converted into the ionic forms."

Phytoextraction, an in situ remediation method in which plants are used to remove ionic metals from contaminated soils, is being considered by USAEC for remediation of lead-contaminated DoD sites.

USAEC says, "During the phytoextraction process, water-soluble metals are taken up by plant species selected for their ability to take up large quantities of Pb. The metals are stored in the plant's aerial shoots, which are harvested and either smelted for potential metal recycling/recovery or are disposed of as a hazardous waste." (Phytoremediation of Lead-Contaminated Soil, no date).

In Phytoremediation, the authors write that there are two main limiting factors involved with the phytoextraction of Pb: (1) Pb's low Bioavailability in soil, and (2) Pb's poor

translocation from the roots to shoots of a plant (no date). Research is being done on the effects “of altering the pH of soil through the use of ammonium containing fertilizers as well as organic acids like citric acid. Numerous studies show that decreasing the pH of soil lowers heavy metals’ ability to absorb, which then increases their bioavailability and hence phytoextraction” (ibid).

5.0 LITERATURE ABSTRACTS: TNT AND RDX

This Section lists articles, books, reports, and Web sites related to TNT and RDX in soils. Each of the literature abstracts section is organized in the following way: reference information for each source is included in a gray box; items are alphabetized by the last name of the first author listed on the original document or, when there is no author, by title; and additional resources that were not summarized but could be of use to future studies are included at the end of each section without abstract information attached. Some of the abstracts are taken verbatim from the original sources or databases; others were written to focus specifically on the topic areas addressed in this report.

5.1 TNT Contamination in Soils

5.1.1 GENERAL ARTICLES

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for 2,4,6-trinitrotoluene (update). (1995). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service. Web site: [www.
http://www.atsdr.cdc.gov/tfacts81.html?clkd=iw](http://www.atsdr.cdc.gov/tfacts81.html?clkd=iw)
m. Retrieved: April 8, 2001.

Discusses exposure pathways, health effects of contamination, and federal exposure limits.

McFarlan, S. 2-4-6-Trinitrotoluene Pathway Map. (2000). University of Minnesota: 3 pp. http://umbbd.ahc.umn.edu/tnt/tnt_map.html. Retrieved March 17, 2001.

Shows aerobic TNT degradation pathway.

Myers, T.E., and Townsend, D.M. (1996). TNT Breakthrough Curves for Aquifer Materials from the Louisiana Army Ammunition Plant,

Shreveport, LA. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: [http://
www.ecc.ksu.edu/HSRC/Abstracts96.html](http://www.ecc.ksu.edu/HSRC/Abstracts96.html). Retrieved April 1, 2001.

The Louisiana Army Ammunition Plant (LAAP) produced ammunition for World War II, the Korean Conflict, and the Vietnam Conflict. Some groundwaters at LAAP contain as much as 10 mg/L of TNT. Groundwater contamination was caused by disposal of explosive-laden wastewaters into unlined surface impoundments. The potential for plume advancement off the LAAP boundaries is a major concern. TNT breakthrough curves (BTCs) for four aquifer materials from LAAP were obtained under steady flow conditions using packed columns 15.2 centimeters (cm) in length and 4.45 cm in diameter. Several TNT reductive transformation products (monoamino-dinitrotoluenes, diamino-nitrotoluenes, and azoxytoluenes) were also measured. An advection-dispersion model with linear equilibrium-controlled sorption and first-order decay was fit to the TNT BTCs. BTCs showed that TNT was highly mobile in all four aquifer materials. Analysis of sectioned columns showed no retention of TNT or TNT transformation products by the aquifer materials. Trace amounts of monoamino-dinitrotoluenes were eluted, but no diamino-nitrotoluenes or azytoluenes were eluted. In general, retardation by sorption was low, and disappearance (reductive transformation, irreversible sorption, etc.) was almost negligible. The TNT BTCs for LAAP aquifer materials are in sharp contrast to TNT BTCs obtained in previous studies of soils from Vicksburg, Mississippi, in which reductive transformation to diamino-nitrotoluenes accounted for 60 percent of the TNT introduced to soil columns. The mobility difference for LAAP aquifer materials and Mississippi soils is hypothesized to be caused by differences in aquifer material or soil

oxidation-reduction potential under saturated conditions.

Valsaraj, K. T., Qaisi, K. M., and Constant, W. D. (1998). Diffusive Transport of 2,4,6-trinitrotoluene (TNT) from Contaminated Soil to Overlying Water. *Journal of Hazardous Materials* 59(1): 1-12.

Understanding the transport mechanism of TNT and other compounds is necessary in order to implement an effective phyto- or bioremediation scheme for explosives-contaminated soil. The transport of TNT from two contaminated soils into overlying water was investigated by using a laboratory sheet-flow leaching bed reactor. The first soil (Soil I) had a low contamination of TNT (11 ± 1 mg kg⁻¹), whereas the second soil (Soil II) had very high contamination of TNT ($22,874 \pm 518$ mg kg⁻¹). The results showed a decrease in aqueous effluent TNT concentration and flux with time in both cases, indicating the diffusive nature of the process ($t^{-1/2}$ dependence). The results showed slow diffusive transport of TNT through the soil. The initial flux from Soil II was approximately 50 times higher than from Soil I. The final steady state flux was larger than that from Soil I since the initial porewater TNT concentration was much higher for Soil II. From the experiments, the authors calculated that the characteristic time for transport is estimated to be about 7 years, whereas the first order degradation rate by plant enzymes is about 70 minutes. The slow transport of TNT from the soil bed will be a limiting factor in the phyto- or bioremediation of explosives-contaminated soils.

Additional Resources:

Hwang, P., Chow, T., and Adrian, N.R. (1998). Transformation of TNT to Triaminotoluene by Mixed Cultures Incubated Under Methanogenic Conditions. USACE, Construction Engineering Research Laboratories.

5.1.2 DETECTION

Hilmi, A., Luong, J. H. T. (2000). Micromachined Electrophoresis Chips with Electrochemical Detectors for Analysis of Explosive Compounds in Soil and Groundwater. *Environmental Science and Technology* 34(14): 3046-3050.

A capillary electrophoresis (CE) microsystem with amperometric detection has been developed to form a reusable, sensitive, and low-cost analytical device. As part of an electrochemical detection system, the working gold electrode was inserted into a specially designed detection cell, with its sensing area positioned just outside the separation channel outlet to provide high-sensitivity detection with negligible interferences from the separation electric field. Electrophoretic separations of TNT and four other nitroaromatic explosives in under 4 minutes ... demonstrated the good resolution as well as sensitivity of the CE microchip. The system was applicable for analysis of the explosive content of soil extracts and groundwater, yielding results in good agreement with the standard procedure. This truly reusable detection system is particularly useful for several applications that require frequent surface cleaning or electrode replacement as a result of severe surface poisoning.

5.1.3 TNT CONTAMINATION AND DESORPTION

Sheremata, T.W., and Hawari, J. (2000). Cyclodextrins for Desorption and Solubilization of 2,4,6-Trinitrotoluene and Its Metabolites in Soil. *Environmental Science and Technology* 34(16): 3462-3468.

This study demonstrates the effectiveness of cyclodextrins (CDs) in decontaminating a variety of soils containing both high and low levels of TNT and some of its metabolites. The two CDs were also assessed for their ability to

remove TNT from a highly contaminated topsoil (5265 milligrams per kilogram [mg/kg]) obtained from a former manufacturing facility. This study demonstrates the effectiveness of CDs in decontaminating a variety of soils containing both high and low levels of TNT and some of its associated metabolites.

5.1.4 TNT AND BIODEGRADATION

Hughes, J., Rudolph, F., and Bennett, G. Anaerobic Biodegradation of 2,4,6-Trinitrotoluene and Other Nitroaromatic Compounds by *Clostridium acetobutylicum*. (No date.) National Center for Environmental Research, Office of Research and Development, USEPA: 3 pp. Web site: http://es.epa.gov/ncercqa_abstracts/centers/hsrc/bioremed/ssw-hughes2.html. Retrieved March 22, 2001.

This describes a proposal to investigate the anaerobic biotransformation of TNT and other nitroaromatics under highly controlled conditions by using cultures of *Clostridium acetobutylicum*. Research has demonstrated the ability of *C. acetobutylicum* to rapidly transform many nitroaromatics. This also briefly reviews previous studies that have focused on the rate and extent of TNT reduction in *C. acetobutylicum* cultures.

5.1.5 TNT CONTAMINATION IN SOILS AND REMEDIATION

Emmrich, M. (2001). Kinetics of the Alkaline Hydrolysis of Important Nitroaromatic Co-contaminants of 2,4,6-Trinitrotoluene in Highly Contaminated Soils. *Environmental Science and Technology* 35(5): 874-877.

The findings suggest that if TNT is the only contaminant or if it is accompanied by certain lower concentrated nitroaromatics, alkaline hydrolysis is a valuable remediation technology, especially for soils that are highly contaminated. RDX was not evaluated.

Hawthorne, S.B., Lagadec, A.J.M., Kalderis, D., Lilke, A.V., and Miller, D.J. (2000) Pilot-Scale Destruction of TNT, RDX, and HMX on Contaminated Soils Using Subcritical Water. *Environmental Science and Technology* 34(15): 3224-3228

Subcritical (hot/liquid) water was used in a simple static (nonflowing) vessel to treat two soils from former defense sites which were contaminated with the explosives TNT (12 wt %) or RDX (0.32 wt %) and HMX (0.08 wt %). Laboratory studies demonstrated that significant degradation of RDX began at 100°C and at 125°C for TNT and HMX. For highly contaminated soils, the bulk of the undegraded explosives remained in the soil rather than in the water phase. Based on high-performance liquid chromatography/ultraviolet (HPLC/UV) analysis, intermediate degradation products formed but quickly degraded at <250°C. Pilot-scale remediations using 4 L of water at 275°C for 1 hour (with 2-hour heat-up time) of real soils resulted in >99.9% destruction of TNT and RDX and about 98% destruction of HMX. None of the mutagenic nitroso derivatives of RDX and HMX were formed. "Microtox" acute toxicity tests with *Vibrio fischeri* showed no significant (compared to background) residual toxicity in either the process wastewaters or leachates from the treated soils.

Hofstetter, T.B., Heijman, C.G., Haderlein, S.B., Holliger, C., and Schwarzenbach, R.P. (1999). Complete Reduction of TNT and Other (Poly)nitroaromatic Compounds under Iron-Reducing Subsurface Conditions. *Environmental Science and Technology* 33(9): 1479-1487.

This work demonstrates that (poly)nitroaromatic compounds [(P)NACs] such as TNT can be completely reduced to the corresponding aromatic polyamines by Fe(II) present at the surface of Fe(III)(hydr)oxides or, less efficiently, by hydroquinone moieties of (natural) organic matter in the presence of hydrogen sulfide

(H₂S). The authors conclude that iron-reducing conditions are favorable as a first step in a two-stage anaerobic/aerobic treatment of PNAC-contaminated sediments, since aromatic polyamines are biodegradable and/or bind irreversibly to the solid matrix under oxic conditions.

Additional Resource:

Maloney, S.W. (1994). TNT Redwater Treatment by Wet Air Oxidation. Champaign, Illinois: USACE, Construction Engineering Research Laboratories.

5.1.6 TNT AND BIOREMEDIATION

Acetone Helps Microbes Remediate TNT-Contaminated Soil. (2000). BioCycle 41(8): 38-39.

This article details a study on the use of acetone in composting contaminated soil conducted at the DOE's Indiana National Engineering and Environmental Laboratory. Problems associated with composting, effectiveness of acetone in dissolving TNT contained in soil, and criteria for the solvent selection are discussed.

Arienzo, M, Comfort, S.D., Shea, P.J., and Li, Z.M. (1996). Optimizing TNT Destruction in Contaminated Water and Soil by Fenton Oxidation. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

The Fenton reagent (H₂O₂ and Fe²⁺) represents one of the simplest and most effective oxidation technologies available for remediating munitions-contaminated soil and water. Previous research on Fenton oxidation using ferrous sulfate (FeSO₄) and hydrogen peroxide (H₂O₂) has shown that destruction of recalcitrant organics is optimum at pH 3.0, but can also be efficient at higher pH in the

presence of iron-complexing ligands. To improve the process of TNT destruction in water, ferrous oxalate (FeOx) was substituted for FeSO₄ and used in combination with H₂O₂ to initiate Fenton oxidation. The effects of FeOx concentration and pH were determined. TNT destruction time was 20 min to 2 h, depending on the amount of iron present. These high destruction rates may be explained in part by the continuous source of Fe²⁺ provided by the iron (II)-oxalate. Adjusting solution pH had little effect on reaction kinetics. This may be due to an acidifying effect of FeOx + H₂O₂ on the TNT solution, since pH decreased to 3.0 within minutes of initiating the reaction. Preliminary results indicate that use of FeOx may increase the efficiency of TNT destruction in contaminated water and soil.

Beltz, L.A., Neira, D.R., Axtell, C.A., Iverson S., Deaton, W., Waldschmidt, T.J., Bumpus, J.A., and Johnston, C.G. Immunotoxicity of Explosives-Contaminated Soil Before and After Bioremediation.

Soils from the Yorktown Naval Base contaminated with TNT and other explosives were used to prepare eluates before and after bioremediation using microbial growth amendments in the presence (P1 eluates) or absence (P2 eluates) of exogenous white rot fungus. The results suggest that treatment of the soil with microbial growth amendments in the absence but not the presence of exogenous white rot fungi lead to partial bioremediation as assessed by lymphocyte functions.

Bruns-Nagel, D., Knicker, H., Drzyzga, O., Butehorn, U., Steinbach, K., von Low, E., Gemsa, D. (2000). Characterization of 15N-TNT Residues After an Anaerobic/Aerobic Treatment of Soil/Molasses Mixtures by Solid-State 15N NMR Spectroscopy. 2. Systematic Investigation of Whole Soil and Different Humic Fractions. Environmental Science and Technology 34(8): 1549-1556.

An anaerobic/aerobic composting experiment with ^{15}N -TNT spiked soil was performed to investigate the fate of the explosive under the applied conditions. For a qualitative description of TNT-residues formed during the composting process, bulk soil and different soil fractions were subjected to solid-state ^{15}N nuclear magnetic resonance (NMR) spectroscopy. Major resonance signals could be detected in the chemical shift regions of five-ring heterocyclic nitrogen and in the area of aniline derivatives and primary amines. Distinct nitro peaks were found in the bulk samples and in the humic fractions obtained with a mild extraction procedure. This signal disappeared in the material extracted with a more drastic procedure. Quantitative investigations of the ^{15}N distribution in the composted material revealed that 33% of the stable nitrogen isotope was incorporated into the humic- and fulvic acid, and 23% was present in the humin. Furthermore, 38.8% of the ^{15}N present in the composted material could be allotted to condensed TNT residues, whereas 1.9% are assigned to nitro functions and 15.2% to amino functions. In the investigation presented here a bioremediation method was simulated with ^{15}N -TNT spiked soil. The nonradioactive label allowed a qualitative and quantitative characterization of residues of the explosive. The authors say the results give strong evidence for a stable incorporation of the nitroaromatics into the humic material of soils. However, further investigations will be necessary to prove a long-term stability of bound TNT residues and to assess toxicological effects of the treated soil.

Gilcrease, P.C., Murphy, V.G., and Reardon, K.F. (1996). Bioremediation of Solid TNT Particles in a Soil Slurry Reactor: Mass Transfer Considerations. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

The bioremediation of TNT-contaminated soils is complicated by the fact that TNT is often present in the form of solid particles as large as 1 cm in diameter. Since biodegradation is an aqueous-phase process, the dissolution of solid TNT particles can limit the overall treatment rate. Slurry-phase reactors can be used to enhance the biodegradation of solid TNT particles because dissolution rates are increased with agitation. The focus of this research was to test the effect of solid/liquid mass transfer on the slurry phase biotreatment of solid TNT particles. Special emphasis was placed on the effects of particles other than TNT. Soil slurry bioreactors contain up to 50 wt% solids, most of which are soil particles rather than TNT. Non-TNT solids (soil) can potentially affect the biodegradation of TNT solids in three ways: (1) changes in $k_L a$ as a result of slurry properties and TNT particle attrition, (2) biofilm resistances resulting from association of the biomass with the solid phase, and (3) sorption of TNT by other solids. In this study, the first two processes were investigated with the use of idealized experimental systems; their importance in real soil slurry bioreactors is discussed. Results indicate that attrition of TNT particles can significantly increase the overall degradation rate.

Li, Z.M., Shea, P.J., Comfort, S.D., Zhang, T.C., and Erickson, L.E. (1996). Fenton Oxidation Of TNT in Soil Slurries as Influenced by Temperature, Dissolved Organic Matter, and Clay Minerals. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

TNT-contaminated soil and water is an environmental problem at sites where munitions were formerly manufactured, stored, or demilitarized. Previous research demonstrated that Fenton oxidation effectively destroyed TNT in aqueous extracts of contaminated soil. However, direct application of the Fenton

technique to destroy TNT in a soil slurry system would be more efficient and likely more cost-effective. Experiments were conducted to determine Fenton oxidation of TNT in soil slurries. The effects of temperature, dissolved organic matter (DOM), and clay minerals on oxidation efficiency were also determined. Results indicate that Fenton oxidation can effectively destroy TNT in a soil slurry containing 4,875 mg TNT kg⁻¹ (1:5 w/v soil:H₂O); this process was more efficient at 45°C than 23°C. DOM (humic and fulvic acids) had little effect on the total amount of TNT destroyed within 24 hours, although a possible catalytic effect of fulvic acid was observed. Montmorillonite and kaolinite differed in their effects on TNT oxidation. Adding a small amount of montmorillonite (0.1-1% w/v) appeared to catalyze TNT destruction in solution, but as the amount of clay was increased (>1% w/v), adsorption of TNT slowed the process. Kaolinite exhibited minimal adsorption of TNT, but slowed TNT oxidation, possibly by quenching reactive free radicals at the mineral surface. Data were fitted to a two-compartment model to predict TNT destruction by Fenton oxidation in soil slurries.

Additional Resource:

Ex-Situ Bioremediation Technology for Treatment of TNT-Contaminated Soils. (1995). Cincinnati, Ohio: National Risk Management Research Laboratory, Office of Research and Development, EPA.]

5.1.7 TNT AND PLANT UPTAKE

Davis, L.C., and Chou, N.C. (1996). Metabolism of TNT Associated with Roots of Higher Plants. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

Recent reports (c.f. van Beelen and Burris, 1995, *Environmental Toxicology and Chemistry* 14:2115-2123) have indicated that nitroreductase enzymes found in sediments of streams or ponds may reduce TNT to different aminodinitrotoluenes and/or further reduced materials. The same or similar reductase activity has been reported to be associated with aquatic plants (Schnoor et al., 1995, *Environmental Science Technology* 29:318A-323A). The authors conducted a survey of several genera of higher plants growing hydroponically to determine whether nitroreductase activity might be associated with the roots of these plants. The main analytical tool has been HPLC to monitor disappearance of TNT and appearance of metabolites. A Hamilton PRP-1 column was used with 65 percent acetonitrile, 1 mM KOH. Scanned spectra were obtained for some of the eluted peaks but it proved difficult to reliably identify compounds by their UV spectral characteristics. Most plants that were tested showed relatively similar rates of TNT disappearance when expressed on a root fresh weight basis. Monocots examined included sorghum, maize, papyrus, and cattails. Dicots included soybean, alfalfa, sunflower, pumpkin, tomato, amaranthus, poplar, and tamarix. When intact plants were incubated in a solution of 50 mg/L TNT plus 1 mM phosphate buffer pH 6.8, at a ratio of near 1 g root tissue per 50 milliliters (ml) solution, there was nearly complete loss of TNT within 24 hours. Initially a more polar metabolite, believed to be aminodinitrotoluene, appeared. At later times a still more polar metabolite peak was observed, at the same time that the heights of all peaks diminished. Activity was decreased several fold by separating roots from the plant and even more by freezing roots overnight.

During the short exposure times studied here, a few days, plants were not obviously injured when phosphate buffer was provided. Tamarix was treated repeatedly with a lower

concentration of TNT (10 mg/L) without apparent injury. In contrast, a water plant, milfoil, was rapidly killed at this same concentration and disintegrated within 2 days. An earlier study with yellow nutsedge (Palazzo and Leggett, *Journal of Environmental Quality* 15:49-52) found severe inhibition of plant growth at TNT concentrations as low as 5 mg/L, but in that case the ratio of root to solution was very small, and the authors replenished the TNT after 3 weeks. In that study, high concentrations of metabolites were found within the root systems (including rhizomes and tubers) of the plants after 42 days. The authors did not examine plants for accumulation of metabolites because no isotopic tracers were used and the accumulation time was relatively short. Disappearance of TNT and metabolites from solution suggests that there was in fact uptake into the plants.

5.2 RDX Contamination in Soils

5.2.1 GENERAL ARTICLES

Price, C.B., Brannon, J.M., Yost, S.L., and Hayes, C.A. (2001). Relationship Between Redox Potential and pH on RDX Transformation in Soil-Water Slurries. *Journal of Environmental Engineering* 127(1): 26-31.

The presence of RDX in surface soil, the vadose zone, and groundwater can present serious environmental problems. The processes governing the release and transformation of RDX into soils and the aquatic environment are not well understood. The objective was to determine the effects of differing environmental conditions as reflected by redox potential and pH on the fate of RDX in soil. Results indicated that RDX was unstable under highly reducing conditions (-150 millivolts [mV]) and relatively stable over the short term (15 days) under oxidizing and moderately reducing conditions at all pHs. RDX in areas of intense reduction would not persist. However, RDX deposited or moving into areas under moderately reducing or

oxidizing conditions would be highly mobile and persistent.

Public Health Assessment, Iowa Army Ammunition Plant, Middletown, Iowa. (1999). CERCLIS No. IA7213820445. Federal Facilities Assessment Branch, Division of Health Assessment and Consultation, Agency for Toxic Substances and Disease Registry. Web site: http://www.atsdr.cdc.gov/HAC/pha/iowaarmy/iaa_toc.html. Retrieved April 8, 2001.

Even though RDX is a major contaminant of concern at this site, it was not found to be of risk to humans, animals, or plants in the area. RDX -- IAAAP discharges have contaminated on-site soils and surface waters. Plants (corn and soybeans are mentioned) grow in some contaminated areas and may be irrigated with RDX-contaminated water. Deer and cattle may eat these plants and/or drink contaminated surface water. Toxicologic and ecological studies indicate that IAAAP crops are not bioaccumulating RDX in their tissue and that they are safe for human consumption. Toxicologic and ecological studies indicate that deer and cattle do not tend to bioaccumulate RDX in their tissue and that IAAAP venison and beef is safe for human consumption.

RDX. (1996). Agency for Toxic Substances and Disease Registry, Public Health Service, U.S. Department of Health and Human Services. Web site: www.atsdr.cdc.gov/tfacts78.html. Retrieved March 17, 2001.

Discusses health risks, pathways, and regulations.

Roberts, Jeff. (2000). Hexahydro-1,3,5-Trinitro-1,3,5-Triazine Pathway Map. University of Minnesota. Web site: http://wwwdev.engineeringlabs.com/project/rdx/rdx_map.htm. Retrieved March 17, 2001.

This article provides a text-format RDX degradation pathway map. It also provides a brief description of RDX and health risks associated with it. (Map is included in Appendix of this document.)

Sheremta, T.W., Halasz, A., Paquet, L., Thiboutot, S., Ampleman, G., and Hawari, J. (March 2001). The Fate of the Cyclic Nitramine Explosive RDX in Natural Soil. *Environmental Science and Technology* 35(6): 1037-1040.

The behavior of RDX was examined in sterilized and nonsterilized topsoil. Results indicate that although RDX is not extensively sorbed by the topsoil, sorption is nearly irreversible.

Furthermore, there was no difference in the sorption behavior for sterile and nonsterile topsoil. However, over the long term, RDX completely disappeared within 5 weeks in nonsterile topsoil. Only traces of RDX were mineralized to carbon dioxide (CO₂) and nitrous oxide (N₂O) by the indigenous microorganisms in nonsterile topsoil.

5.2.2 RDX: REMEDIATION

Boopathy, R., Gurgas, M., Ullian, J., and Manning, J.F. (1998). Metabolisms of Explosive Compounds by Sulfate-Reducing Bacteria. *Current Microbiology* 37(2): 127-131.

The metabolism of TNB (not TNT), RDX, and HMX by a sulfate-reducing bacterial consortium, *Desulfovibrio* spp., was studied. The results indicated that the *Desulfovibrio* spp. used all of the explosive compounds studied as their sole source of nitrogen for growth. The concentrations of TNB, RDX, and HMX in the culture media dropped to below the detection limit (less than 0.5 parts per million [ppm]) within 18 days of incubation. The sulfate-reducing bacteria may be useful in the anaerobic treatment of explosives-contaminated soil.

Singh, J., and Comfort, S.D. (1999). Iron-Mediated Remediation of RDX Contaminated

Water and Soil Under Controlled Eh/pH. *Environmental Science & Technology* 33(9), 1488+ (7 pp.)

This article describes the use of zero-valent iron to remediate RDX-contaminated water and soil. The effects of varying Eh/pH on RDX destruction rates in water and soil and the increase of RDX destruction at lower Eh and neutral pH 7 during iron treatment are also discussed.

Additional Resource:

Adrian, N.R., and Sutherland, K. (1998). RDX Biodegradation by a Methanogenic Enrichment Culture Obtained from an Explosives Manufacturing Wastewater Treatment Plant. Champaign, Illinois: USACE, Construction Engineering Research Laboratories.

5.2.3 RDX: DETECTION

Groom, C. A., Beaudet, S., Halasz, A., Paquet, L., and Hawari, J. (2001). Detection of the Cyclic Nitramine Explosives RDX and HMX and their Degradation Products in soil Environments. *Journal of Chromatography* 909(1): 53-60.

RDX and HMX were examined in field and microcosm soil samples to detect their patterns of degradation and environmental fates. Ryegrass (*Lolium perenne*) present in field samples was found to accumulate HMX from soil without further degradation. In all cases (except the plant samples), the indigenous microbes or amended domestic anaerobic sludge consortia degraded the cyclic nitramine explosives eventually to produce N₂O and CO₂.

5.3 TNT and RDX Contamination in Soil

This section summarizes articles about both TNT and RDX in soils.

5.3.1 GENERAL ARTICLES

Brauer, M., Eitzer, B., et al. (March 1, 1998) Breakdown of Explosives. *Environmental Science & Technology* 32(5): 146-152.

This article comments on concerns about environmental contamination caused by the production and disposal of explosives. Reference to the explosive hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX); How a study of RDX was conducted.

Trett, M.W., Calvo Urbano, B., Forster, S.J., Hutchingson, J.D., Feil, R.L., Trett, S.P., and Best, J.G. (2000). Terrestrial Meiofauna and Contaminated Land Assessment. *Environmental Science and Technology* 34(8): 1594-1602.

Following the development of aquatic pollution monitoring techniques using metazoan meiofauna (microscopic interstitial invertebrates), the value of this group in the assessment of contaminated terrestrial sites has been investigated. Communities present in a former explosives burning ground were sampled at 30 sites with coring techniques and examined in the laboratory. Nematoda were numerically dominant at each of the sites and were the most diverse invertebrate group present (60 species). Structurally modified assemblages of these were identified and correlated significantly with elevated soil heavy metal concentrations. Assemblages associated with elevated metal concentrations exhibited increased dominance and reduced species richness. Using principal components analyses (PCA) and redundancy analyses (RA), the relationships between individual species, the metals, and the structures of the nematode communities were described. Tolerant and resistant species were also identified. It is concluded that the technique is a valuable method of assessing metal contamination status, and it is recommended that further studies be made of sites contaminated with organic materials.

CRREL Publications:

Crockett, A.B., Jenkins, T.F., Craig, H.D., and Sisk, W.E. (1998). Overview of On-Site Analytical Methods for Explosives in Soil. U.S. Army Engineering Research Development Center (ERDC)/CRREL Special Report 98-4.

On-site analytical methods for explosives in soil were reviewed. Current methods emphasize the detection of TNT and RDX. Methods that have undergone significant validation fall into two categories: colorimetric-based methods and enzyme immunoassay methods. Discussions include considerations of specificity, detection limits, extraction, cost, and ease of use. A discussion of the unique sampling design considerations is also provided, as well as an overview of the most commonly employed laboratory method for analyzing explosives in soil. A short summary of ongoing development activities is provided.

Hewitt, A.D., and Jenkins, T.F. (1999). On-Site Method for Measuring Nitroaromatic and Nitramine Explosives in Soil and Groundwater Using GC-NPD: Feasibility Study ERDC/CRREL Special Report 99-9.

An on-site method for estimating concentrations of TNT, RDX, 2,4-DNT, and the two most commonly encountered environmental transformation products of TNT, 2-amino-4,6-dinitrotoluene and 4-amino-2,6-dinitrotoluene, in soil and groundwater using gas chromatography and the nitrogen-phosphorus detector (NPD) is described. One of the major advantages of this method over currently available colorimetric and enzyme immunoassay on-site methods is the ability to quantify individual target analytes that often coexist in soils and groundwater contaminated with explosive residues. This method will be particularly useful at military antitank firing ranges where it is necessary to quantify residual concentrations of RDX in the presence of high concentrations of HMX, and when the

transformation products of TNT need to be identified.

Jenkins, T.F., Leggett, D.C., and Ranney, T.A. (1999). Vapor Signatures from Military Explosives. Part 1: Vapor Transport from Buried Military-Grade TNT ERDC/CRREL Special Report 99-21.

Crystals of military-grade TNT were placed beneath 2.5 cm of soil in enclosed 40-mL amber vials, and the accumulation of signature vapors in the headspace above the soil was determined as a function of time. Three different soils—sand, silt, and clay—were investigated at three different moisture contents: air dry, low moisture, and high moisture. The results indicate that for detection of buried mines, the largest mass of signature chemicals will be present in the surface soil rather than the overlying air.

Jenkins, T.F., Ranney, T.A., Miyares, P.H., Collins, H.H., and Hewitt, A.D. (2000). Use of Surface Snow Sampling to Estimate the Quantity of Explosives Residues Resulting from Land Mine Detonations ERDC/CRREL Technical Report 00-12.

The surface concentrations of TNT were similar to those resulting from a buried mine. The rate of transformation of TNT is rapid, however, and concentrations would rapidly decline without a continuing source of TNT. Thus the residues resulting from a mine detonation do not seem to pose a serious background problem for the use of chemical sensors to detect the presence of buried land mines. The utility of conducting these types of tests on a snow-covered range was demonstrated.

Jenkins, T.F., Ranney, T.A., Walsh, M.E., Miyares, P.H., Hewitt, A.D., and Collins, N.H. (2000). Evaluating the Use of Snow-Covered Ranges to Estimate the Explosives Residues that Result from Detonation of Army Munitions. ERDC/CRREL Technical Report 00-15.

Estimating the amounts of residues remaining after munitions detonate is complicated by the presence of residues from previous detonations and the difficulty in easily obtaining adequately sized samples to overcome spatial heterogeneity in residue deposition. This study was conducted to assess the use of snow-covered ranges to provide these types of estimates. The locations where residues were deposited were identified by the presence of soot from the detonation of TNT on the surface of the otherwise clean snow. The major residues produced were RDX and nitroglycerine, with lesser amounts of HMX and TNT.

Jenkins, T.F., Schumacher, P.W., Mason, J.G., and Thorne, P.G. (1996). On-Site Analysis for High Concentrations of Explosives in Soil: Extraction Kinetics and Dilution Procedures. ERDC/CRREL Special Report 96-10.

Soils containing high concentrations (>10%) of secondary explosives might detonate from shock or flame, resulting in human injuries or equipment damage during remediation activities. In lieu of expensive and time-consuming protocols involving impact tests, friction tests, and shock gap tests, compositional analysis has been recommended as an expedient method to assess the risk of detonation from heavily contaminated soils. A number of methods now available allow determination of TNT and RDX on site. All of these methods specify solvent extraction with either acetone or methanol to transfer the analyte from the soil matrix to a solvent as the first step in the determination. The rate of extraction of TNT and RDX, when present at percent levels in soil, has not been determined. Protocols currently in use specify very short extraction times (one to three minutes) and results could be biased low if extraction kinetics are slow. The objective of this work was to document the rate of extraction of secondary explosives by acetone and methanol and make recommendations for possible modification of

current protocols if warranted. Because solvent extracts from highly contaminated soils will have very high concentrations of secondary explosives, compared with the range of concentrations that can be determined using the various on-site methods, large dilutions will be required. Recommendations are made for a field-expedient method making appropriate.

Jenkins, T.F., Walsh, M.E., Thorne, P.G., Miyares, P.H., Ranney, T.A., Grant, C.L., and Esparza, J.R. (1998). Site Characterization for Explosives Contamination at a Military Firing Range Impact Area. ERDC/CRREL Special Report 98-9.

No currently available on-site method for RDX was found to be adequate in the presence of much higher concentrations of HMX.

Miyares, P.H., Reynolds, C.M., Pennington, J.C., Coffin, R.B., Jenkins, T.F., and Cifuentes, L. (1999). Using Stable Isotopes of Carbon and Nitrogen as In-Situ Tracers for Monitoring the Natural Attenuation of Explosives ERDC/CRREL Special Report 99-18.

The use of carbon and nitrogen stable isotope measurements from TNT was examined as a possible tool for monitoring the natural attenuation of TNT. Results indicated that no measurable changes in the $d^{13}C$ or $d^{15}N$ value of the soil or $d^{13}C$ values for TNT could be detected as the concentration of TNT decreased.

Thorne, P.G., and Leggett, D.C. (1999). Investigations of Explosives and Their Conjugated Transformation Products in Biotreatment Matrices. ERDC/CRREL Special Report 99-3.

Samples of soil that had been aerobically composted or anaerobically digested were extracted with solvent, then hydrolyzed with base and then acid. The concentrations of extractable TNT and its monoamino and diamino transformation products fell rapidly

after the first days of treatment. Hydrolysis of the solvent-extracted residues released significant quantities of intact transformation products. The concentrations of RDX and HMX were reduced in a similar fashion without the appearance of significant quantities of transformation products.

Additional Resources:

Jenkins, T.F., Pennington, J.C., Pennington, T.A., Ranney, T.E., Berry, Jr., T.E., Miyares, P.H., Walsh, M.E., Hewitt, A.D., Perron, N., Hayes, C., and Wahlgren, E. (2001). Characterization of Explosives Contamination at Military Firing Ranges. ERDC Technical Report (in review).

Selim, H.M., and Iskandar, I.K. (1994). Sorption-Desorption and Transport of TNT and RDX in Soils. Prepared for Office of the Chief of Engineers, USACE, CRREL.

Thorne, P.G., and Myers, K.F. (1997). Evaluation of Commercial Enzyme Immunoassays for the Field Screening of TNT and RDX in Water ERDC/CRREL Special Report 97-32.

5.3.2 MICROBIAL DEGRADATION OF TNT AND RDX

Amoebae-Associated Bacteria in Biodegradation and Bioremediation. (No date). Center for Global Environmental Studies, Oak Ridge National Laboratory. Web site: <http://www.ornl.gov/CGES/Afinding/iab8-11.htm>. Retrieved March 22, 2001.

Application of biodegradation and bioremediation techniques may potentially provide the only viable solution to the removal of TNT, RDX, and HMX in soils.

Hawari, J., Beaudet, S., Halsz, A., Thiboutot, S., and Ampleman, G. (2000). Microbial Degradation of Explosives: Biotransformation

Versus Mineralization. *Applied Microbiology and Biotechnology* 54(5): 605-618.

TNT is a reactive molecule that biotransforms readily under both aerobic and anaerobic conditions to give aminodinitrotoluenes. The resulting amines biotransform to give several other products, including azo, azoxy, acetyl, and phenolic derivatives, leaving the aromatic ring intact. Although some Meisenheimer complexes, initiated by hydride ion attack on the ring, can be formed during TNT biodegradation, little or no mineralization is encountered during bacterial treatment. Also, although the ligninolytic physiological phase and manganese peroxidase system of fungi can cause some TNT mineralization in liquid cultures, little to no mineralization is observed in soil. Therefore, despite more than two decades of intensive research to biodegrade TNT, no biomineralization-based technologies have been successful to date. RDX lacks the electronic stability enjoyed by TNT or its transformed products. Predictably, a successful enzymatic change on one of the N-NO₂ or C-H bonds of the cyclic nitramine would lead to a ring cleavage because the inner C-N bonds in RDX become very weak. Recently this hypothesis was tested and proved feasible, when RDX produced high amounts of carbon dioxide and nitrous oxide following its treatment with either municipal anaerobic sludge or the fungus *Phanaerocheate chrysosporium*. Research aimed at the discovery of new microorganisms and enzymes capable of mineralizing energetic chemicals and/or enhancing irreversible binding (immobilization) of their products to soil is currently receiving considerable attention from the scientific community.

Hawthorne, S.B., and Lagadec, A.J.M. (2000). Pilot-Scale Destruction of TNT, RDX, and HMX on Contaminated Soils Using Subcritical Water. *Environmental Science & Technology* 34(15): 3224+ (5 pp.).

This study investigates the degradation of three types of explosives on historically contaminated soils. The use of pure water and contaminated soils in heated stainless-steel vessels under static conditions, the formation of intermediate degradation products, and the toxicity in wastewaters or leachates from the treated soils.

Pennington, J.C., Brannon, J.M., Gunnison, D., Harrelson, D.W., Zakikhani, M., Clarke, J., Miyares, P., Jenkins, T.F., Hayes, C., Ringleberg, D., Perkins, E., and Fredrickson, H. (2001). Monitored Natural Attenuation of Explosives. *Soil and Sediment Contamination* 10(1): 45-70.

5.3.3 TNT AND RDX: DETECTION AND ON-SITE ANALYSIS

Craig, H., Ferguson, H., Markos, G., Kusterbeck, A., Shriver-Lake, L., Jenkins, T., and Thorne, P. (1996). Field Demonstration of On-Site Analytical Methods for TNT and RDX in Groundwater. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

A field demonstration was conducted to assess the performance of eight commercially available and emerging colorimetric, immunoassay, and biosensor on-site analytical methods for explosives TNT and RDX in groundwater at the Umatilla Army Depot Activity, Hermiston, Oregon, and Naval Submarine Base, Bangor, Washington, Superfund sites. Groundwater samples were analyzed by each of the on-site methods and results compared to laboratory analysis using HPLC (EPA SW-846 Method 8330). The commercial methods evaluated include the D-TECH/EM Science TNT and RDX immunoassay test (EPA SW-846 Methods 4050 and 4051), the EnSys, Inc., TNT and RDX colorimetric test (EPA SW-846 Methods 8515 and 8510) with a solid phase extraction step, and the Ohmicron TNT immunoassay test. The

emerging methods tested include the antibody-based Naval Research Laboratory (NRL) Continuous-flow Immunosensor (CFI) for TNT and RDX, and fiber optic biosensor (FOB) for TNT. Precision and accuracy of the on-site methods were evaluated using relative percent difference (RPD) and linear regression analysis. Over the range of conditions tested, colorimetric methods for TNT and RDX showed the highest accuracy of the commercially available methods, and the CFI showed the highest accuracy of the emerging methods for TNT and RDX. The colorimetric method was selected for routine groundwater monitoring at the Umatilla Army Depot Activity site, and further field testing on the NRL CFI and FOB biosensors will continue at both Superfund sites. The primary use for these analytical methods would be for influent and effluent monitoring for granular activated carbon (GAC) groundwater and leachate treatment systems, which are projected to operate for a period of 10 to 30 years.

Crockett, A.B., Jenkins, T.F., Craig, H.D., and Sisk, W.E. (1999). Overview of On-Site Analytical Methods for Explosives in Soil. USACE CRREL Special Report 93-4.

This article surveys the current status of field sampling and on-site analytical methods for detecting and quantifying secondary explosives compounds in soils. It also includes a brief discussion of EPA Method 8330, the reference analytical method for the determination of 14 explosives and co-contaminants in soil.

Immunosensor for Explosives. (1997). *Analytical Chemistry* 69(13): 396.

This article focuses on the evaluation of a CFI to detect TNT and RDX in samples from two U.S. military bases. It also discusses the proliferation of explosives present in the soil and water at U.S. military bases.

Hilmi, A., Luong, J.H.T., and Nguyen, A.L. (1999). Development of Electrokinetic Capillary

Electrophoresis Equipped with Amperometric Detection for Analysis of Explosive Compounds. *Analytical Chemistry* 71(4): 873-878.

Cyclic voltammograms of TNT and other explosive compounds were obtained by using glassy carbon, platinum, nickel, gold, and silver electrodes, which revealed the applicability of gold and silver in capillary electrophoresis amperometric detection. Discusses the methods used and compares results to the those obtained by the liquid chromatographic method recommended by the EPA.

Jenkins, T.F., Grant, C.L., Brar, G.S., Thorne, P.G., Ranney, T.A., and Schumacher, P.W. (1996). Assessment of Sampling Error Associated with Collection and Analysis of Soil Samples at Explosives-Contaminated Sites. ERDC/CRREL Special Report 96-15.

This study is an assessment of short-range heterogeneity in contaminant concentrations within surface soils at explosives-contaminated sites. The report concluded that to improve the quality of site characterization data, emphasis should be placed on reducing sampling error by the use of composite sampling strategies. Characterization of explosives-contaminated sites using composite sampling, in-field sample homogenization, and on-site analysis is an efficient method of producing data that are accurate and precise, and also representative of the area.

Nam, S. (1997). On-Site Analysis of Explosives in Soil: Evaluation of Thin-Layer Chromatography for Confirmation of Analyte Identity. USACE CRREL, Special Report 97-21: 14 pp.

This study investigates the use of thin-layer chromatography as a simple on-site method to confirm the identity of analytes detected using colorimetric on-site methods. The major limitation is detection capability, which was estimated to be about 0.1 micrograms (μg) of analyte.

Van Bergen, S.K., Balkalcheva, I.B., Lundgren, J.S., and Shriver-Lake, L.C. (2000). On-Site Detection of Explosives in Groundwater with a Fiber Optic Biosensor. *Environmental Science and Technology* 34(4): 704-708.

Two primary explosives involved in groundwater contamination, TNT and RDX, were detected on-site at low parts per billion (ppb) levels with a semiautomated FOB. Validation of the Analyte 2000 (manufactured by Research International Inc., Woodinville, Washington) for TNT and RDX detection was performed at two Superfund sites, Umatilla Army Depot and Naval Surface Weapons Center Crane. Samples from monitoring wells were split for analysis with the FOB on-site and using EPA SW-846 Method 8330 (reverse-phase HPLC) in an off-site laboratory. The Analyte 2000, a multifiber probe fluorimeter, was coupled to a fluidics unit for semiautomated operation. The FOB assay is based on a competitive fluorescent immunoassay performed on the silica core of a fiber probe. From these studies, the limit of detection was determined to be 5 µg/L for both TNT and RDX. In addition to the field samples, extensive laboratory analyses were performed to determine cross-reactivity, matrix effects, and false positive/negative rates.

Wallenborn, S.R., and Bailey, C.G. (2000). Separation and Detection of Explosives on a Microchip Using Micellar Electrokinetic Chromatography and Indirect Laser-Induced Fluorescence. *Analytical Chemistry* 72(8): 1872-1878.

Presents a new approach for sensitive detection on a microfabricated chip. Indirect laser-induced-fluorescence was used to detect explosive compounds, including TNT and RDX, after separation by micellar electrokinetic chromatography.

Wollin, K.M., and Levsen, K. (1999). Field Screening Methods for Explosives from Military Contaminated Sites. *Umweltwiss. Schadst.-Forsch* 11(6): 353-364. (Written in German.)

A review with 48 references on field screening methods for the analysis of explosives in military contaminated sites. These techniques include immunoassays, photometric methods, bio- and chemical sensors, and thin layer chromatography. Basic aspects of these techniques are discussed, their validation is presented, and their application to water and soil samples from hazardous ammunition waste sites is described. These techniques can be applied successfully for both the exploration of suspected contaminated sites and their sanitation. These methods are used on-site. In general, they allow short analysis times and a high sample throughput, thus leading to a significant reduction of the number of samples to be analyzed in the laboratory and the costs.

Additional Resources:

Bart, J.C., Judd, L.L., and Hoffman, K.E. (1997). Application of a Portable Immunosensor to Detect the Explosives TNT and RDX in Groundwater Samples. *Environmental Science and Technology* 31: 1505-11.

Cragin, J.H., et al. (1985). TNT, RDX, and HMX Explosives in Soils and Sediments: Analysis Techniques and Drying Losses. U.S. Army Toxic and Hazardous Materials Agency, USACE, CREEL.

Jenkins, T.F. (1990). Development of a Simplified Field Method for the Determination of TNT in Soil. CRREL Special Report 90-38.

Jenkins, T.F., Leggett, D.C., and Ranney, T.A. (1999). Vapor Signatures from Military Explosives. Hanover, New Hampshire: USACE, CRREL.

Jenkins, T.F., Schumacher, P.W., Mason, J.G., and Thorne, P.G. (1996). On-Site Analysis for High Concentrations of Explosives in Soil: Extraction Kinetics and Dilution Procedures. USACE CRREL Special Report 96-10.

Jenkins, T.F., Thorne, P.G., and Walsh, M.E. (No date). Field Screening Method for TNT and RDX in Groundwater. Hanover, NH: USACE, CRREL.

Thorne, P.G., and Myers, K.F. (1997). Evaluation of Commercial Enzyme Immunoassays for the Field Screening of TNT and RDX in Water. Hanover, New Hampshire: USACE, CRREL.

Walsh, M.E., and Ranney, T.A. (1998). Determination of Nitroaromatic, Nitramine, and Nitrate Ester Explosives in Water Using SPE and GC-ECD: Comparison with HPLC. USACE CRREL Technical Report 98-2.

Walsh, M.E., and Ranney, T.A. (1999). Determination of Nitroaromatic, Nitramine, and Nitrate Ester Explosives in Soils Using GC-ECD. USACE CRREL Technical Report 99-12.

5.3.4 TNT AND RDX: REMEDIATION

Assessing Phytoremediation of Explosives-Contaminated Groundwater at Volunteer Army Ammunition Plant. (1997). U.S. Army. Web site: <http://www.wes.army.mil/el/resbrief/phytovol.html>. Retrieved March 24, 2001.

This article describes an outdoor phytoremediation study to quantify the cleanup ability of native aquatic and wetlands plants (in Tennessee) and explains explosives removal rates.

Beltz, L.A., Neira, D.R., Axtell, C.A., Iverson, S., Deaton, W., Waldschmidt, T.J., Bumpus, J.A., and Johnston, C.G. (2001). Immunotoxicity of Explosives-Contaminated Soil Before and After Bioremediation. Archives of Environmental Contamination and Toxicology 40(3): 311-317.

Soils from the Yorktown Naval Base contaminated with TNT and other explosives were used to prepare eluates before and after bioremediation using microbial growth amendments in the presence or absence of exogenous white rot fungus. The results

suggest that treatment of the soil with microbial growth amendments in the absence but not the presence of exogenous white rot fungi lead to partial bioremediation as assessed by lymphocyte functions.

Best, E.P.H. (1999). Phytoremediation of Explosives in Groundwater Using Constructed Wetlands. (U.S. Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). Web site: <http://www.wes.army.mil/el/resbrief/phytoexp.html>. Retrieved March 24, 2001.

Following are important considerations when using aquatic and wetland plants to remove explosives from constructed wetlands: plant persistence at the explosives level to which it is exposed, specific plant-mass-based explosives removal rates, plant productivity, and fate of parent compounds in water, plants, and sediments. Uptake and fate of TNT and RDX by three aquatic and four wetland plants were studied.

Bioremediation of Explosives-Contaminated Soil. (No date.) USAEC, 2 pp. Web site: <http://aec-www.apgea.army.mil:8080/prod/usaec/et/restor/biorem.htm>. Retrieved March 24, 2001.

This article briefly discusses bioremediation alternatives for treating soil and groundwater contaminated with explosives, including composting, bioslurry, and anaerobic soil-slurry. It concludes that because of modest equipment and monitoring requirements, "windrow composting is a cost-effective technology, with a high degree of treatment effectiveness for explosives-contaminated soils at low process cost."

EPA. Industry Profile Fact Sheets. Ordnance Sites. Brownsfields EPA Region III. Web site: <http://www.epa.gov/reg3hwmd/brownfld/industry.htm>. Retrieved March 24, 2001.

This fact sheet provides a general description of site conditions and contaminants which may be encountered at the site.

INDUSTRY, PROCESS, OR SITE

DESCRIPTION: Ordnance consists of a wide variety of military munitions and weaponry including rifle rounds, shells, bombs, grenades, mines, explosives, and special-purpose explosive agents. Ordnance sites include a range of facilities that manufactured, assembled, disposed of, or stored military ordnance or associated components. Some of these facilities date back to pre-World War I, while others were operated for specialty purposes for only a few months or years. In many cases, the facilities are not identified with any special markings, signs or warnings. Some facilities were associated with specific military posts. Characteristic features may include increased security (high, barbed-wire fencing), bunker-style/mounded buildings, unusually remote or uncharacteristic industrial locations, and well-spaced small buildings.

CHARACTERISTIC RAW MATERIALS:

Because of their specialty nature, ordnance facilities may include various chemicals used in the final stages of explosives manufacturing. The following chemical compounds are common raw materials, chemical intermediates or waste products encountered in the manufacturing of explosives: di and tri-nitro benzene, di and tri-nitro phenol, di and tri-nitro toluene reactive metals, ketones, nitroglycerin, strong acids, mercury, phenols, ethers, ammoniated compounds, ethyl alcohol, ethylene glycol, formaldehyde, and sodium hydroxide.

WASTE STREAMS AND POTENTIALLY AFFECTED ENVIRONMENTAL MEDIA: On-site waste piles and burial pits were common treatment/disposal techniques before the promulgation and enforcement of the RCRA of 1976. Common waste products encountered at Superfund assessment and remediation

projects include buried spent ordnance, unexploded ordnance (UXO) and ordnance components, such as di- and tri-nitro compounds (commonly used in explosives), solvents (e.g., toluene, formaldehyde), and fuels (gasoline, diesel, and aircraft fuels). These compounds may be encountered in contaminated soils, surface water, and/or groundwater. Additionally, contaminated buildings, asbestos-containing material, and associated demolition debris may be encountered at abandoned or inactive sites. Decontamination and analytical testing of this material may be required before disposal in an off-site landfill.

SAMPLING STRATEGIES: It should be noted that UXO and the associated components may represent a serious fire, explosion, and fragmentation hazard to assessment personnel. Explosive intermediate chemicals and waste products may represent a serious inhalation, ingestion, or direct contact hazard. Ordnance facilities should be screened for UXO by specially training individuals using established military standard procedures. Visually identified UXO or associated components should be marked and left undisturbed until explosives experts can be mobilized.

Once the site has been cleared of UXO, a series of soil screening kits and techniques are available to detect TNT, the explosive compound RDX, and fuel contamination in soil. Waste piles and burial pits should be characterized by collecting several representative samples for laboratory analysis. Surface and subsurface soil sampling should be performed from the suspected contaminated areas outward to the suspected clean areas. The application of non-intrusive subsurface geophysics as opposed to conventional drilling and boring should be evaluated to detect underground burial pits, process lines and chemical storage tanks. Special precautions must be taken when using intrusive investigation techniques (e.g., drilling, boring

operations) because of the potential for buried explosive materials. Once the primary contaminated areas are established, grid or random sampling may be performed to confirm the extent of contamination.

On-site and local wells may be sampled if groundwater is an environmental concern. Installation of monitoring wells or other groundwater sampling techniques should be considered only if it is necessary to fill data gaps.

SUGGESTED ANALYTICAL PARAMETERS:

Heavy Metals Analysis: Antimony, Arsenic, Beryllium, Cadmium, Chromium, Copper, Lead, Mercury, Nickel, Selenium, Silver, Thallium, and Zinc.

Kitts, C.L., Green, C.E., Otley, R.A., Alvarez, P.J. (2000). Type I Nitroreductases in Soil Enterobacteria Reduce TNT and RDX. *Canadian Journal of Microbiology* 46(3): 278-282.

Many enteric bacteria express a type I oxygen-insensitive nitroreductase, which reduces nitro groups on many different nitroaromatic compounds under aerobic conditions. Enzymatic reduction of nitramines was also documented in enteric bacteria under anaerobic conditions. This study indicates that nitramine reduction in enteric bacteria is carried out by the type I, or oxygen-insensitive nitroreductase, rather than a type II enzyme. The enteric bacterium *Morganella morganii* strain B2 with documented RDX nitroreductase activity, and *Enterobacter cloacae* strain 96-3 with documented TNT nitroreductase activity, were used here to show that the explosives TNT and RDX were both reduced by a type I nitroreductase. The authors conclude that neither TNT nor RDX nitroreductase activity was detected in nitrofurazone-resistant mutants of *M. morganii*. They also conclude that a type I nitroreductase present in these two enteric bacteria was responsible for the nitro reduction of both types of explosive.

Hawthorne, S.B., Lagadec, A.J.M., Kalderis, D., Lilke, A.V. (2000). Pilot-Scale Destruction of TNT, RDX, and HMX on Contaminated Soils Using Subcritical Water. *Environmental Science and Technology* 34(15): 3224-3228.

Subcritical (hot/liquid) water was used in a simple static (nonflowing) vessel to treat two soils from former defense sites that were contaminated with TNT or RDX and HMX. Laboratory studies demonstrated that significant degradation of RDX began at 100°C and at 125°C for TNT and HMX. For highly contaminated soils, the bulk of the undegraded explosives remained in the soil rather than in the water phase. Pilot-scale remediations using 4 liters (L) of water at 275°C for 1 hour of real soils resulted in 99.9 percent destruction of TNT and RDX.

Hilmi, A., and Luong, J.H.T. (2000). Micromachined Electrophoresis Chips with Electrochemical Detectors for Analysis of Explosive Compounds in Soil and Groundwater. *Environmental Science and Technology* 34(14): 3046-3050.

A capillary electrophoresis (CE) microsystem with amperometric detection has been developed to form a reusable, sensitive, and low-cost analytical device. The system was applicable for analysis of the explosive content of soil extracts and groundwater, yielding results in good agreement with the standard procedure. This truly reusable detection system is particularly useful for several applications that require frequent surface cleaning or electrode replacement due to severe surface poisoning.

Marion, G.M., and Pelton, D.K. (2000). Frozen Soil Barriers for Explosives Containment. USACE, CRREL, ERDC Technical Report ERDC/CRREL TR-00-19.

Many uncertainties exist about the mobility and stability of explosives in soils. The goals of this work were to test the efficacy of frozen barriers to restrain movement of RDX, TNT, and picric

acid through soils; test the concept of leaching contaminated soils above a frozen barrier as a method for soil cleanup; and compare the mobility and stability of explosives in an aged, field-contaminated soil versus a freshly contaminated soil. The study concluded that a stable frozen barrier is effective in restraining the movement of RDX, TNT, and picric acid in soils, particularly TNT, as "there was a rapid transformation of TNT into unknown products or unextractable forms in soils.

National Technology Transfer Center. The Cleanup Pillar. (No date). Web site: <http://www.nttc.edu/env/dod/grnbkclp.html>. Retrieved April 1, 2001.

Describes environmental cleanup of DoD sites, including sections on explosives and heavy metals.

Novel Cleanup of Explosives. (2000). *Environmental Science & Technology* 34(15): 354.

This reports on the study that uses subcritical water for treating explosives-contaminated soils and achieved 99.99 percent destruction of TNT and RDX.

Report of the NATO Advanced Research Works on Destruction of Military Toxic Waste. 22-27 May 1994. Modified 29 April 1997. Naaldwijk, The Netherlands: <http://www.opcw.nl/chemhaz/arwnaal1.htm>. Retrieved March 17, 2001.

This report discusses worldwide military toxic waste, including the following related to TNT and RDX contamination in the United States: "Groundwater contaminated with explosives is a major problem. Near-term treatments include reactions with UV/ozone, peroxide/ozone, and adsorption. Biodegradation of these materials is not yet a mature technology: there are apparent "dead ends" in the degradation chain short of complete mineralization; these dead ends

account for about 80 percent of the material in the best results to date.

Explosive materials may become more bound and less accessible to remediation in soil with time. Treatments of contaminated soils (ranked from presently available to increasingly distant possible technologies) are: incineration, physical separation, composting, bioslurry, in-situ biodegradation, chemical extraction, electrokinesis. Physical separation refers to adoption of techniques from the mining industry that depend on selective adsorption of the contaminant by different soil fractions; so one can separate fractions enriched in explosives by screening for size, airjet separation.

The Army has used incineration of contaminated soil on a large scale: nearly 100,000 tons were incinerated at the Louisiana Ammunition Plant; costs were about \$300/ton. A transportable high-pressure unit has been designed and built at Los Alamos National Laboratory for explosives disposal. The reactor is a 3-mm inner diameter, 17-meter-long tube with a capacity of 400 L/day. It is made of Inconel 625. Noble metal liners can be used for neutral to basic feed solutions. and Ti may be used for acids. Liners are not currently being used.

Explosives decompose rapidly in water above 200°C to small, water soluble organic and inorganic molecules. Subsequent reactions with oxygen at higher temperatures take these intermediate products to carbon dioxide and other inorganic products.

Several methods were explored to prepare solid explosive for the reactor. A solution in organic solvents has the disadvantage of solvent handling. Preparation of water slurries requires use of water jets or grinding which are potentially dangerous. The preferred method, hydrolysis at about 90°C in aqueous NaOH or NH₄OH, leads to non-energetic, soluble products suitable for subsequent treatment by hydrothermal processing. Dissolution of several

kg chunks of solid energetic material loaded at 1 g per 10 ml of 2M NaOH and stirred at 90°C until no solid remains requires a few hours. It appears that each nitro group on the energetic materials requires an equivalent of base....

Metal and Metal Oxide Catalysis: Finely divided (nano-crystalline) metal oxides[19] have been shown to mediate the mineralization of chemical weapon agent stimulants by oxygen and peroxide. These materials have a large surface/volume ratio with, presumably, enhanced surface absorption or intercalation. Their small size and open structure enables a large capacity for oxidizer uptake. They are semiconductors and are activated by light.

Materials that have exhibited these properties include the oxides of Zn, Ti, Fe, Mn, Ag, Sn, Zr, Nb and the sulfides of Fe and Mo.

Studies with malathion in aqueous suspensions of TiO₂ have shown degradation under relatively mild conditions: slow degradation occurs in air at 70 C; reaction rates increase with more powerful oxidizers (air peroxide persulfate periodate). Addition of Fe⁺³, which coats the TiO₂ particles, increases the reaction rate.

The Swiss have used these methods on groundwater contaminated by explosives with initial total organic carbon of 12,000 ppm.

The high activity of Fe⁺³ suggests its use on old munitions to dissolve the case corrosively and subsequently to catalyze the oxidative destruction of the chemical weapon agent and explosives....

Recommendations from the Workshop: The working groups developed recommendations for toxic material destruction based on the scenarios and provided brief descriptions of: (1) First Choice of Technology and Rationale and Resources Required,(2) Second Choice, (3) Unsuitable Technologies. Their combined recommendations follow.

Scenario 1: 30,000 m³ of explosives-contaminated (1%) soil near a small town. Cleanup of contamination to < 1 mg/kg.

First Choice of Technology: Remove soil to a location where the pollutant cannot reach the groundwater. Use size separation (e.g. froth flotation) to concentrate the contamination, followed by composting or other bioremediation.

Rationale: Removal of the soil to a concrete pad or plastic sheet would prevent the explosives from reaching the groundwater. This would not be cheap, but is technologically straightforward. This process also gives time to deal with the remediation of the soil.

Reduction of the volume of soil reduces the cost and difficulty of subsequent steps. However, it may not be advisable to reduce the volume of soil by the maximum amount possible because the resulting high concentrations of explosives may be toxic to the composting organisms. The explosive particles may be less dense than soil particles leading to effective concentration by froth flotation.

Bioremediation of the soil will produce a material that can be returned to the original site.

Resources Required: Separation and treatment units near the contaminated site; soil brought to separation unit by draglines. Composting equipment. Composting additives and carbon sources.

Second Choice of Technology: Oxidize physically separated and concentrated contaminants using wet air or super critical water.

Rationale: A "hot water" method may be cheaper (\$100-200/ton) than incineration and is likely to prove more publicly acceptable and less damaging to the soil. At the end of the operation, the system can be used by the town for treatment of sewage sludge.

Resources Required: Equipment to dig up and move the soil; hydrothermal reactor. Cost of both units estimated at \$5,000,000.

Third Choice of Technology: Incinerate physically separated concentrate.

Rationale: Incineration is a proven technology for remediation of soil contaminated with explosives. Some problems may be anticipated if large pieces of energetic materials are present in the soil.

Resources Required: Incinerator and all required equipment including scrubbers.

Unsuitable Technologies: In-situ bioremediation is unlikely to reach required residual levels in one year.

Roberts, D.J., Ahmad, F., and Pendharkar, S. (1996). Optimization of an Aerobic Polishing State to Complete the Anaerobic Treatment of Munitions-Contaminated Soils. *Environmental Science and Technology* 30(6): 2021-2026.

The addition of an external carbon source to allow the creation of anaerobic conditions for the remediation of soils contaminated with nitroaromatic compounds has been successfully applied to soils contaminated with TNT. The addition of an aerobic stage to remove excess external carbon after the anaerobic stage produces a treated soil with a lower oxygen demand than the soil, which is presently left after the anaerobic stage. The use of acetate, soluble starch, glucose, and insoluble starch as sources of external carbon for the creation and maintenance of anaerobic conditions was examined. The addition of glucose to statically incubated soil reactors allowed for the fastest reduction in redox potential and produced cultures with the lowest redox potentials. The amount of glucose added was optimized, resulting in the use of 0.25 percent (w/v) glucose to treat a sandy soil contaminated with TNT, RDX, and HMX. In these treatments, the anaerobic stage was complete within 14 days,

and an additional 7-day aerobic stage resulted in total organic compound concentrations of 30 mg/L remaining in the aqueous phase.

The Clean-Up Pillar. (No date). Joint Service Pollution Prevention Technical Library, Naval Facilities Engineering Service Center. Web site: <http://enviro.nfesc.navy.mil/p2library>. Retrieved: March 17, 2001.

Treatment: The Army is the DoD single service manager for explosives and therefore manages munitions through their entire life cycle, from development and manufacture through disposal. As a result, the Army has the lead for developing cleanup treatment technologies for explosives and propellants. This contamination primarily resulted from waste discharges during munitions manufacture and the destruction of out-of-date or off-specification material. In addition, the Army, because of its experience and capabilities, is the lead service responsible for the development of innovative technologies to treat heavy metals, organic compounds, and chemical agents. Research is conducted to develop biological, physical, and chemical methods for the treatment of explosives-contaminated soils and groundwater. A number of new and innovative contaminated soil treatment technologies are currently under investigation. An example is the development of bioremediation technologies to treat explosives-contaminated soils. Although incineration has been demonstrated as an effective treatment technology, the cost is high. Bioremediation is an alternative treatment process with the potential to effectively degrade explosives, such as TNT, RDX and HMX at significantly lower cost. Full-scale testing of composting for explosive-contaminated soil is now being conducted at Umatilla Army Depot Activity (UMDA). It is estimated that bioremediation at UMDA will reduce the cleanup cost by at least 50 percent over traditional cleanup methods such as incineration. Longer-range program objectives include the development of in situ processes for remediation of organic and

explosives-contaminated soils and groundwater. Basic research is being conducted into the microbiology of biodegradation in support of biotechnology development.

Low temperature thermal desorption of soil to remove volatile and semi-volatile contaminants from soils has been developed and fielded. The U.S. Army Engineer Waterways Experiment Station (WES) operates a low-temperature thermal desorption test facility to conduct treatability studies on specific soil matrices. A study sponsored by the EPA used the unit to evaluate low temperature thermal desorption for removal of volatile and semi-volatile compounds from soils at Jennison Wright, Granite City, Illinois. The USAEC sponsored a WES evaluation for contaminated soils contaminated with volatile organic compounds from Letterkenny Army Depot. Additional research is being conducted on physical separation processes, chemical treatment, in-situ microwave destruction, metal extraction and immobilization. Basic research is being conducted to better understand the physical, chemical, and biological mechanisms driving several proposed remediation technologies.”

Toxicity Studies for Biotreatment of Explosives-Contaminated Soils. (No date.) USAEC: 3 pp. Web site: <http://aec-www.apgea.army.mil:8080/prod/usaec/et/restor/bioreem.htm>. Retrieved March 24, 2001.

This article evaluates the use of biotreatment of explosives-contaminated soil at Joliet Army Ammunition Plant, Oregon.

USAEC. Bioremediation of Explosives-Contaminated Soil. Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.

USAEC. Field Demonstration: Soil Slurry Reactor. (No date.) Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.

Past production and handling of conventional munitions has left explosives in soils at many Army installations. Depending on the concentrations of explosives—mainly TNT, RDX, and HMX—the affected soils can pose reactivity and toxicity hazards. Because these explosives can migrate from the soils into groundwater, the affected soils should be treated to eliminate any threat to human health or the environment. Incineration is the traditional proven cleanup technology, but it is costly and not readily accepted by regulators. The Army has searched since the 1980s for alternatives to incineration. Extensive tests have shown that bioremediation—the use of living organisms to remove pollutants from soil or water—could be a cost-effective treatment. The USAEC has field tested several bioremediation methods, including soil slurry reactor treatment and windrow composting. USAEC demonstrated that the windrow bioslurry process effectively degraded the explosives and their metabolic byproducts, posting a 99.6 percent removal rate. Metabolic fate studies at the end of the treatment showed substantial amounts of the explosives had been broken down to carbon dioxide and carbon fragments in the cell mass.

USAEC. (No date). Cost and Design for Application of Biotreatment Technologies for Explosives-Contaminated Soil. Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.

Provides cost and design information on two bioremediation alternatives to incineration of explosives-contaminated soils: windrow composting and bioslurry.

Additional Resources:

Hofstetter, T.B., Heijman, C.G., Haderlein, S.B., Holliger, C., and Schwarzenbach, R.P. (1999). Complete Reduction of TNT and Other (Poly)nitroaromatic Compounds under Iron-Reducing Subsurface Conditions.

Environmental Science and Technology 33(9): 1479-1487.

Sheremata, T.W., and Hawari, J. (2000). Cyclodextrins for Desorption and Solubilization of 2,4,6-Trinitrotoluene and Its Metabolites from Soil. Environmental Science and Technology 34(15): 3224-3228.

Thorne, P.G., and Leggett, D.C. (1999). Investigations of Explosives and Their Conjugated Transformation Products in Biotreatment Matrices. USACE CRREL, Technical Report 99-3.

USAEC. (No date). Field Demonstration: Soil Slurry Reactor. Web site: <http://www.aec.army.mil:8080/prod/usaec/et/resor/soil.html>. Retrieved March 24, 2001.

Williams, R.T., Ziegenfuss, P.S., and Sisk, W.E. (No date). Composting of Explosives and Propellant Contaminated Soils Under Thermophilic and Mesophilic Conditions.

6.0 LITERATURE ABSTRACTS: HEAVY METALS

This section provides a review of the literature about certain heavy metals (see Table 4-1) in soils, particularly literature about plant uptake of those metals.

Table 6-1 Heavy Metals Evaluated for Literature Review

Element	Symbol
Iron	Fe
Zinc	Zn
Lead	Pb
Nickel	Ni
Copper	Cu
Chromium	Cr
Antimony	Sb
Cadmium	Cd
Molybdenum	Mo
Tin	Sn

The aim of this second part of the work is to study, on the one hand, the growth and concentration of trace elements in the shoots and roots of rye grass, and on the other hand, the interactions between the chemical extraction of soil trace elements and the biological concentration of these elements in earthworms and in the two vegetable parts of rye grass. The vegetable biomass of these two parts were increased with soil contamination and the presence of earthworms, with the exception of the root biomass in 100% contaminated soils. The concentration of trace elements is more important in the roots than in the foliar parts. Generally, the presence of *L. terrestris* increased the concentration of trace elements in the two vegetable parts with the exception of that of Fe and Pb in the roots. The trace element contents of rye grass, in particular their roots, have been better correlated with that of soils than the earthworm tissue contents. The presence of earthworms increased the number of positive correlations between the trace element concentrations in the two vegetable parts of rye grass.

Aide, M.T. and Cwick, G.J. (1998). Chemical Weathering in Soils from the Glacial Lake Agassiz Region of Manitoba, Canada. *Environmental Geology* 33(2/3): 115-121.

6.1 Metals Disposition in Soil: Articles on Metals in General

Abdul Rida, A.M.M. (1996). Concentrations and Growth of Earthworms and Plants in Soils Contaminated by Cadmium, Copper, Iron, Lead and Zinc: Interactions Plant-Soil-Earthworm. *Soil Biology & Biochemistry* 28(8): 1037-1044.

Three microcosms have been prepared from soils which differ in their contents of five trace elements (Cd, Cu, Fe, Pb and Zn). All prepared soils were planted with rye grass, *Lolium perenne* L., and an earthworm *Lumbricus terrestris* L. was introduced in only half of them.

Recently, there has been considerable interest in categorizing the availability of plant essential nutrients and selected transition metals in the soil environment so as to predict their effects on ecosystem health and the efficacy of potential management practices. Researchers desire to isolate important soil properties, determinant biotic activities and fundamental pedogenic processes that control biogeochemical cycling and are potentially modifiable for the goal of ecosystem sustainability. In a relative sense, a significant portion of this scientific effort has been directed toward temperate and tropical forest ecosystems, with relatively less attention given toward understanding the boreal forest ecosystem. Consequently, an investigation was

undertaken near Thompson, Manitoba, to (1) determine the extent of weathering of the principal soils, (2) employ a selective-sequential chemical extraction method to categorize the soil-chemical fractions responsible for nutrient availability, and (3) infer the importance of selected soil forming processes responsible for soil genesis and nutrient availability. Preliminary findings suggest that nutrient availability is related to the nutrient concentration in the cation exchange fraction and/or to nutrients sequestered by the organic fraction. The metals in the manganese, noncrystalline and crystalline iron oxide fractions may be bound so tightly to these oxides that they are largely unavailable to plants; however, they are largely responsible for buffering the more labile pools against gradually changing vegetational and climatic conditions.

Anderson, P., Davidson, C.M., Duncan, A.L., Littlejohn, D., Ure, Allan M., and Garden, L.M. (2000). Column Leaching and Sorption Experiments to Assess the Mobility of Potentially Toxic Elements in Industrially Contaminated Land. *Journal of Environmental Monitoring* 2(3): 234-239.

Made-up ground collected from layers of a trial pit excavated on a former industrial site was treated with artificial rainwater in a series of column leaching and sorption experiments. Metal mobility and the ability of various layers of material obtained from the pit to act as sources or sinks of potentially toxic elements were assessed. Samples from different layers varied in their abilities to raise the pH of rainwater, and this was reflected in the amounts of metals mobilized by the rainwater as it percolated through the soil column. Material from the top two layers of the pit released cadmium, copper, manganese, lead, nickel and zinc to the aqueous phase, but the lower layers, with higher buffering capacity, were able to resist acidification even when the equivalent of 12 months' rainfall (western UK) was applied. Column sorption experiments confirmed the ability of material from layer 4 to take up

copper, manganese and zinc. Metals were determined in the leachates by flame and electrothermal atomic absorption spectrometry and principle anions by ion chromatography.

Banuelos, G.S., and Ajwa, H.A. (1999). Trace Elements in Soils and Plants: An Overview. *Journal of Environmental Science and Health, Part A—Toxic/Hazardous Substances and Environmental Engineering* 34(4): 951-974.

This article discusses the movement of essential and nonessential trace elements through agricultural ecosystems and food chains. It focuses on As, boron (B), Cd, Cr, Cu, mercury (Hg), Ni, Pb, selenium (Se), uranium (U), vanadium (V), and Zn and discusses the elevated concentrations of these as a result of human activities. The article discusses their mobility and uptake by and transport in plants.

Camobreco, V.J., Richards, B.K., Steenhuis, T.S., Preverly, J.H., and McBride, M.B. (1996). Movement of Heavy Metals Through Undisturbed and Homogenized Soil Columns. *Soil Science* 161(11): 740-750.

The results indicate that previous laboratory metal leaching studies performed on homogenous soils might have greatly overestimated metal mobility in the field and that preferential flow, both alone and in combination with organic-facilitated transport, can accelerate metal leaching through soils.

Dudka, S., Piotrowska, M., Terelak, H. (1996). Transfer of Cadmium, Lead, and Zinc from Industrially Contaminated Soil to Crop Plants: A Field Study. *Environmental Pollution* 94(2): 181-188.

The documented adverse health effects of soil Cd and Pb have led to public concern over soil contamination with metals. This experiment studied the transfer of Cd, Pb, and Zn from soil contaminated by smelter flue-dust to crop plants grown in rotation. The treated soil was strongly contaminated with metals (Cd 3.2-106 mg/kg,

Pb 146-3452 mg/kg, Zn 465-11,375 mg/kg). The highest metal concentrations were found in potato tubers, meadow bluegrass, and barley straw. The soil pH was neutral. Soil with Cd concentrations of up to 30 mg/kg is still safe for production of these crop plants.

Grusak, M.A., Pearson, J.N., and Marentes, E. (1999). The Physiology of Micronutrient Homeostasis in Field Crops. *Field Crops Research* 60(1-2): 41-56.

Plants have developed a number of transport mechanisms to control the acquisition, partitioning, and deposition of the micronutrients iron, copper, zinc, and manganese. Points of control include various root-system processes, movement and partitioning along the xylem pathway, temporary storage in vegetative compartments, and mobilization via the phloem pathway. The regulation of these control points is not fully understood, although it appears that certain functions may be influenced by interorgan communication. Current evidence does indicate that these processes can be controlled to various degrees.

Leyval, C., Turnau, K., and Haselwandter, K. (1997). Effect of Heavy Metal Pollution on Mycorrhizal Colonization and Function: Physiological, Ecological and Applied Aspects. *Mycorrhiza* 7(3): 139-153.

This article discusses how high concentrations of heavy metals have an adverse effect on microorganisms and microbial processes, particularly among mycorrhizal fungi, which provide a direct link between soil and roots, and can therefore be of great importance in heavy metal availability and toxicity to plants.

McLean, J.E., and Bledsoe, B.E. (1992). Behavior of Metals in Soils. EPA Ground Water Issue, EPA 540-S-92-018: 25 pp.

This article discusses metals most commonly found at Superfund sites in terms of the processes affecting their behavior in soils as

well as laboratory methods available to evaluate this behavior. The retention capacity of soil is also discussed in terms of the movement of metals between the other environmental compartments including groundwater, surface water, or the atmosphere. Long-term changes in soil environmental conditions resulting from the effects of remediation systems or natural weathering processes, are also discussed with respect to the enhanced mobility of metals in soils.

Sauve, S.; Hendershot, W.; Allen, H. E. (2000). Solid-Solution Partitioning of Metals in Contaminated Soils: Dependence on pH, Total Metal Burden, and Organic Matter. *Environmental Science and Technology* 34(7): 1125-1131.

Environmental risk assessment of metals depends to a great extent on modeling the fate and the mobility of metals based on soil/liquid partitioning coefficients. A large variability is observed among the reported values that could be used to predict metal mobility and bioavailability. To evaluate this, soil/liquid partitioning coefficients (K_d) for many elements but especially for the metals cadmium, copper, lead, nickel, and zinc were compiled from over 70 studies of various origins collected from the literature. The relationships between the reported values are explored relative to variations in soil solution pH, soil organic matter (SOM), and concentrations of total soil metal. The results of multiple linear regressions show that K_d values are best predicted using empirical linear regressions with pH ... or with pH and either the log of SOM or the log of total metal.... A semi-mechanistic model based on the competitive adsorption of metal and H^+ [dependent on solution pH, total metal content, and $\log(SOM)$] was a better tool to predict dissolved metal concentrations..., with the exception of Pb (at 0.35).

Additional Resources:

Adriano, D.C. (1992). *Biogeochemistry of Trace Metals*. Boca Raton, Florida: Lewis Publishers.

Atanassova, I. (1999) Competitive Effect of Copper, Zinc, Cadmium and Nickel on Ion Adsorption and Desorption by Soil Clays. *Water, Air, & Soil Pollution* 113(1/4): 115-125.

Awad, F., and Romheld, V. (2000). Mobilization of Heavy Metals from Contaminated Calcareous Soils by Plant Born, Microbial and Synthetic chelators and Their Uptake by Wheat Plants. *Journal of Plant Nutrition* 23(11/12): 1847-1855.

Azadpour, A., and Mathews, J.E. (1996). Remediation of Metal-Contaminated Sites Using Plants. *Remediation* 6(3): 1-18.

Bjerre, G.K, and Shierup, H. (1985). Uptake of Six Heavy Metals by Oat as Influenced by Soil Type and Additions of Cadmium, Lead, Zinc, and Copper. *Plant and Soil* 88(1): 57-69.

Church, S.E., et al. (1997). Source, Transport, and Partitioning of Metals Between Water, Colloids, and Bed Sediments of the Animas River, Colorado. U.S. Dept. of Interior (DOI), USGS.

Cox, D.E. (1969). Map Showing Citrate-Soluble Heavy Metals in Stream Sediments, Ossipee Lake Quadrangle, Carroll County, New Hampshire. Washington, D.C.: USGS.

Elzinga, E.J. and Sparks, D.L. (1999). Nickel Sorption Mechanisms in a Pyrophyllite–Montmorillonite Mixture. *Journal of Colloid and Interface Science* 213(2): 506-512.

Ford, K.L. (No date). Risk Management Criteria for Metals at BLM Mining Sites. DOI, Bureau of Land Management (BLM), Service Center.

Foulkes, E.C., ed. (1990). *Biological Effects of Heavy Metals*. Boca Raton, Florida: CRC Press.

Jeffers, T.H., Bennett, P.G., and Corwin, R.R. (1993). *Biosorption of Metal Contaminants*

Using Immobilized Biomass: Field Studies. DOI, Bureau of Mines.

Jensen, D.L., Holm, P.E., and Christensen, T. H. (2000). Soil and Groundwater Contamination with Heavy Metals at Two Scrap Iron and Metal Recycling Facilities. *Waste Management and Research* 18(1): 52-63.

Kabata-Pendias, A., and Pendias, H. (2001). *Trace Elements in Soils and Plants*, 3rd ed. Boca Raton, FL: CRC Press.

Logan, T.J., Goins, L.E., and Lindsay, B.J. Field Assessment of Trace Element Uptake by Six Vegetables from N-Viro Soil. (1997). *Water Environment Research* 69(1): 28-33.

Lombi, E., and Gerzabek. M.H. (1998). Determination of Mobile Heavy Metal Fraction in Soil: Results of a Pot Experiment with Sewage Sludge. *Communications in Soil Science and Plant Analysis* 29(17-18): 2545-2556.

Molecular Bonding System for Heavy Metals Stabilization. (1997). Washington, DC: Solucorp Industries Ltd. For EPA, Superfund Innovative Technology Evaluation.

Moore, B.W., Froisland, L.J., and Petersen, A.E. (1995). Rapid Separation of Heavy Rare-Earth Elements. DOI, Bureau of Mines.

Nash, J.T., et al. (1996). Geochemical Characterization of Mining Districts and Mining-related Contamination in the Prescott National Forest Area, Yavapai County. DOI, USGS.

Norman, A.G. *Advances in Agronomy*, Vol. 20. (1968). New York: Academic Press.

NTTC. Heavy Metals Contamination Soil Project. (No date). Web site: http://www.nttc.edu/env/Heavy_Metals/heavy_metals_chap1.html. Retrieved: April 11, 2001.

Odum, H.T., et al. (2000). *Heavy Metals in the Environment: Using Wetlands for Their Removal*. Boca Raton: Lewis Publishers.

Parker, D.R., and Pedler, J.F. Reevaluating the Free-Ion Activity Model of Trace Metal Availability to Higher Plants. (1997). *Plant and Soil* 196(2): 223-228.

Plant Adaptation to Mineral Stresses in Problem Soils. (1975). U.S. Department of Agriculture, Agricultural Research Service. (372) 47-55.

Preliminary Characterization, Silver Crescent Mill Tailings and Mine Site, East Fork Moon Creek, Shoshone County, Idaho. (1996). Prepared by the Western Field Operations Center and Spokane Research Center, U.S. Bureau of Mines, Spokane, Washington. DOI, Bureau of Mines.

Price, L.C., Dewitt, E., and Desborough, G. (1998). Implications of Hydrocarbons in Carbonaceous Metamorphic and Hydrothermal Ore-deposit Rocks as Related to the Hydrolytic Disproportionation of Organic Matter. DOI, USGS.

Shaw, A.J. ed. (1990). *Heavy Metal Tolerance in Plants: Evolutionary Aspects*. Boca Raton, Florida: CRC Press.

Schnoor, J.L., et al. (1987). Processes, Coefficients, and Models for Simulating Toxic Organics and Heavy Metals in Surface Waters. Environmental Research Laboratory, Office of Research and Development, EPA.

Sposito, G. (1989). *The Chemistry of Soils*. New York: Oxford University Press.

U.S. Geological Survey Heavy Metals Program Progress Report 1968 – Topical Studies. (1969). Washington: DOI, USGS.

Vernet, J.P., ed. (1992). *Impact of Heavy Metals on the Environment*. New York: Elsevier.

Waldron, H.A., ed. (1980). *Metals in the environment*. London: Academic Press.

Wild, A. (1993). *Soils and the Environment: An Introduction*. Cambridge: Cambridge University Press.

6.2 Metals Disposition in Soil: Articles on Individual Metals

The following sections describe how each potential pollutant constituent will be represented.

6.2.1 IRON (FE)

Babanin, V.F., Shpilkina, I.V., and Ivanov, A.V. (1994). The Testing of Action of Chemical Extracts on Soils by Magnetic Methods (abstract). *Journal of Applied Physics* 75(10): 7183.

The participation of soil iron in the formation of physics-chemical features in feed of plants and microorganisms is well known. Because of the active role of Fe in soil landscapes, the Fe state is taken into account in investigations of the genesis of soils. In spite of a relatively high content of iron in soils up to 40%–45% (relative to Fe), its numerical forms are diagnosed in a complex way by Ronthgen diffractometry, differential thermal analysis, and microscopy. Thus, chemical extracts are widely used in soil science. Extracted Fe is considered to be of amorphous, strong or weak crystallized forms. These gradations are of wide use but they are not correct.

Burd, G.I., Dixon, D.G., and Glick, B.R. (2000). Plant Growth-Promoting Bacteria that Decrease Heavy Metal Toxicity in Plants. *Canadian Journal of Microbiology* 46(3): 237-245.

Kluyvera ascorbata SUD165 and a siderophore-overproducing mutant of this bacterium, *K. ascorbata* SUD165/26, were used to inoculate tomato, canola, and Indian mustard seeds, which were then grown in soil for 25 to 42 days in the presence of either nickel, lead, or zinc.

Stairs, N. (1998). Powerful pH. *Landscape Management* 37(7): 54 (3 pp).

This article discusses the effect of hydrogen-ion concentration (pH) on the availability of various

soil elements. Use of sulphur in an alkaline soil; Significance of pH and nutrient availability; Most commonly deficient micronutrient in the landscape; Symptoms of iron toxicity.

The Gene that Keeps Plants off Geritol. (1996). *Science News* 149(25): 399 (5 pp.).

Reports that researchers have found the gene that encodes the iron-transporting protein which enables plant to take in oxidized iron compounds that are normally unusable. Gene named iron-regulated transporter 1 (IRT1); How researchers hope to utilize the gene in plant uptake of iron and cadmium; Research of David Eide and his colleagues in May 28, 1996 'Proceedings of the National Academy of Sciences'; Possible link to metal-transporting proteins.

Zhang, X., Yi, C., and Zhang, F. (1999) Iron Accumulation in Root Apoplasm of Dicotyledonous and Graminaceous Species Grown on Calcareous Soil. *The New Phytologist* 141(1): 27-31.

Solution culture studies have demonstrated that apoplasmic iron (Fe) deposited in the roots of dicotyledonous and graminaceous plants can be mobilized to improve plant iron status in conditions of limited Fe supply. The present study investigated the formation of the apoplasmic Fe pool in dicotyledonous (soybean and cucumber) and graminaceous (wheat) plants in a pot experiment. The pots had three compartments such that plants could take up Fe and other nutrients from two calcareous soils treated with different Fe forms without their roots touching with soil directly. In this way overestimating Fe accumulation in root apoplasm was avoided. The results showed that while the root d. wt of wheat did not vary when soils were supplied with different Fe resources, the root d. wt of soybean and cucumber supplied with FeEDTA decreased compared with the control (without Fe treatment). Supplying FeEDTA in the side compartment increased shoot d. wt and Fe

concentration in shoots of all species. However, supplying Fe(OH)₃ had no effect on shoot d. wt or Fe concentration in the shoots of any species. Soybean and cucumber accumulated little or no Fe in the root apoplasm in controls or in Fe(OH)₃ treatments. By contrast, a large amount of Fe was deposited in the root apoplasm of wheat grown in similar conditions. Remarkably, when FeEDTA was supplied in the soils, large apoplasmic iron pools were formed in the roots of all three species. Therefore, in dicotyledonous plants grown on calcareous soils, little or no apoplasmic iron pool forms, because there is not enough available Fe in the soil solution and the plants have little ability to mobilize Fe³⁺ in the soil. By contrast, a larger apoplasmic iron pool could form in graminaceous plants at lower concentrations of available soil-Fe possibly by enhancing the release of phytosiderophores which could mobilize Fe³⁺ in the soil and then transfer the Fe³⁺-complexes to the root apoplasm.

Zohlen, A., and Tyler, G. (2000). Immobilization of Tissue Iron on Calcareous Soil: Differences Between Calcicole and Calcifuge Plants. *Oikos* 89(1): 95-106.

Deficiency of phosphorus (P) and sometimes of micronutrients, especially Fe, is of importance to the calcicole–calcifuge behaviour of plants. Calcifuge species are unable to solubilize these elements or keep them metabolically active in sufficient amounts on calcareous soils. To demonstrate if calcicole, calcifuge and 'soil indifferent' species differ in Fe nutrition dynamics, samples of such species were transplanted on a slightly acid silicate soil (pH BaCl₂ ca 4.0) and on a calcareous soil (pH BaCl₂ ca 7.2). Plants were grown in a computer-controlled greenhouse at a soil moisture content of 50–60% water holding capacity and with additional light. The calcifuge species developed chlorosis when grown on the calcareous soil, whereas the other species did not. Calcareous-soil grown plants had less 1,10-phenanthroline extractable Fe in their leaf

tissues than the silicate-grown plants whereas total leaf Fe showed more species specific properties. The ratio of 1,10-phenanthroline extractable to total Fe in the leaves was significantly lower in the calcifuges than in the calcicoles when grown on the calcareous soil. 'Soil indifferent' species did not differ much from the calcicoles. Root Fe, fractionated as DCB extractable 'plaque' on the root surface and Fe remaining in the root after DCB extraction, showed no distinct pattern of DCB-Fe related to the different categories, but remaining root Fe tended to be lower in the calcifuges compared to the two other categories. Leaf color estimated by a color scale correlated well with chlorophyll a+b content measured in the leaves of two calcifuges. Leaf P concentrations did not differ between the different categories but were more species dependent. The authors conclude that chlorosis in calcifuge species is related to an immobilization of Fe in physiologically less active forms in the tissue, if plants are forced to grow on a calcareous soil, whereas calcicole and 'soil indifferent' species are able to retain a much higher share of their leaf Fe in metabolically active form. This probably decreases the vitality and may exclude calcifuge plants from calcareous soil. The authors consider this property, previously almost unconsidered in an ecological context, as important to the calcifuge–calcicole behaviour of plants.

Additional Resource:

Caris, C. (1998). Studies of Iron Transport by Arbuscular Mycorrhizal Hyphae from Soil to Peanut and Sorghum Plants. *Mycorrhiza* 8(1): 35-39.

6.2.2 ZINC (ZN)

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological Profile for Zinc. (1995). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.

Zinc is an essential element for human bodies, so too little zinc can be harmful. So can too much zinc. The chemical has been found in at least 801 of 1,416 NPL sites identified by the EPA. Zinc is one of the most common elements in the earth's crust. It is found in air, soil, and water, and is present in all foods. Pure zinc is a bluish-white shiny metal. Zinc combines with other elements to form zinc compounds. Common zinc compounds found at hazardous waste sites include zinc chloride, zinc oxide, zinc sulfate, and zinc sulfide. Some zinc is released into the environment by natural processes, but most comes from activities of people such as mining, steel production, coal burning, and waste. Zinc attaches to soil, sediments, and dust particles in the air. Rain and snow remove zinc dust particles from the air. Zinc compounds can move into the groundwater and into lakes, streams, and rivers. Most of the zinc in soil stays bound to soil particles. Zinc builds up in fish and other organisms, but it does not build up in plants. Zinc has not been classified for carcinogenicity by DHHS.

Cakmak, I. (2000). Possible Roles of Zinc in Protecting Plant Cells from Damage by Reactive Oxygen Species. *New Phytologist* 146(2): 185-205.

There are a number of physiological impairments in Zn-deficient cells causing inhibition of the growth, differentiation, and development of plants. Zinc interferes with membrane-bound NADPH oxidase producing reactive oxygen species. In Zn-deficient plants, the iron concentration increases.

He, Y., Schwab, A.P., and Banks, M.K. (1996). The Transport of Zinc in Soil as Affected by Citrate. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

Low molecular weight organic acids released by plant roots or soil microbes may affect the adsorption of heavy metals by soils, and thereby influence the fate and transport of heavy metals in soils. A soil column experiment was conducted to investigate the effect of citrate, an important organic ligand released by plant roots, on the movement of zinc in soil. Solutions with 750 mM Zn and varying concentrations of citrate ranging from 0 to 5,000 mM were pumped continuously through the columns at a flow rate of 0.16 ml min⁻¹. Column effluent was collected daily and measured for Zn, Fe, Ca, and citrate. Finally, the columns were cut to four sections, and a sequential extraction experiment was performed for each section in order to investigate zinc-retaining mechanisms, to assess the distribution of zinc in soil columns, and to obtain a mass balance of zinc. The results showed that zinc transport rate decreased, and the zinc-retaining capacity of soil increased with increasing citrate concentration. This may be due to the citrate serving as a substrate for soil microbes and the increase of biomass in soil-enhanced zinc-retaining capacity.

6.2.3 LEAD (PB)

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for Lead. (1993). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.

Exposure to lead happens mostly from breathing workplace air or dust and eating contaminated foods. Children can be exposed from eating lead-based paint chips or playing in contaminated soil. Lead can damage the nervous system kidneys, and the immune systems. Lead has been found in at least 922 of 1,300 NPL sites identified by the EPA. Lead is a naturally occurring bluish-gray metal found in small amounts in the earth's crust. It has no special taste or smell. It can be found in all parts of the environment. Most of it comes from

human activities such as mining, manufacturing, and burning of fossil fuels. Lead is used in ammunition. Lead itself does not break down in the environment, but lead compounds are changed by sunlight, air, and water. When released to the air from industry or burning of fossil fuels or waste, it stays in the air about 10 days. Most of the lead in soil comes from particles falling out of the air. Lead sticks to soil particles. It does not move from soil to underground water or drinking water unless the water is acidic or "soft." It stays a long time in both soil and water. Exposure can occur from breathing or ingesting contaminated soil, dust, air, or water near waste sites or from eating contaminated food grown on soil containing lead or food covered with lead-containing dust. DHHS has determined that lead acetate and lead phosphate may reasonably be anticipated to be carcinogens based on studies in animals.

Bund, K., Bricka, M., and Morales, A. (1996). An Electrochemical Approach for Investigating Corrosion of Small Arms Munitions in Firing Ranges. Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 39180-6199 Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

Spent small arms munitions have been accumulating for decades at firing ranges operated by the DoD, law enforcement agencies, and commercial firms. Because (1) in many cases the used bullets are outdoors and subjected to weathering and other sources of moisture, (2) many munitions use lead alloys in their construction, and (3) the toxicity associated with lead is well documented, there is increasing concern that these accumulations represent a potential source of pollution to water and soil. To guide both assessments of the severity of this problem and potential remediation efforts at particular sites, it is necessary to quantify how rapidly bullets are

actually corroding and to learn about the soil variables which foster electrochemical dissolution of munitions. The corrosion behavior of iron and steel alloys in soils is well known, due to the importance of this topic to the gas industry. Much less information is available about the performance of lead alloys in soil, however, and no prior studies have documented investigations of the rate of corrosion of bullets exposed to soil conditions. This research project was undertaken to start to remedy these deficiencies. The situation experienced by spent copper-jacketed lead bullets in soil suggests that both galvanic corrosion and crevice corrosion mechanisms can occur in certain circumstances. To allow these mechanisms to be potentially operative and to facilitate linear polarization measurements, in this study M16 bullets were sectioned longitudinally and an insulated copper wire was attached. The bullets were buried in a corrosion cell containing samples of soil taken from Louisiana army firing ranges. Four environmental conditions were investigated to simulate possible situations in which bullets could be exposed to moisture in the field: rain water, acid rain, sea water, and a 50% sea water/50% acid rain mixture. The soil moisture content was adjusted to either 15% or saturation using a Denver Instrument Co. IR-100 Moisture Analyzer. These conditions span a rather wide range of soil corrosive aggressiveness and allow the generality of the techniques used here to be assessed. The three electrode technique was used to measure the corrosion response of four samples for each moisture content/type condition listed above. Graphite rods were used for the counter electrodes, and a saturated calomel electrode was used as the reference. A specially constructed salt bridge was used to make the connection between the reference electrode and the soil environment. The electrochemical measurements themselves were conducted using a computer-controlled EG&G PARC Model 273A potentiostat and M270 and

Headstart software packages. For accurate corrosion rate determinations in environments of high ohmic resistance such as soil, it is essential that the value of the electrical resistance R_0 of the soil be measured. This allows compensation for the soil resistance contribution to the nominal polarization resistance to be made. In this study the soil resistance was first determined by applying a potential pulse to the bullet and doing chronoamperometric monitoring. The polarization resistance (compensated for R_0 as described above), R_p , was then measured. Finally a potentiodynamic polarization curve measurement was taken. From the latter measurement, corrosion current I_c (a direct measure of the rate of corrosion) could be determined using Tafel extrapolation. The anodic and cathodic Tafel slopes, B_a and B_c respectively, were determined via the linear regression routine of a Quattro Pro for Windows software package. This allowed the corrosion current also to be estimated via the Stern-Geary equation: $I_c = (1/(2.3 R_p))(B_a B_c)/(B_a + B_c)$. Corrosion potential E_c was available from these measurements and from the Headstart program. Corrosion currents of the bullets were observed to sensitively depend on environmental conditions. The rate of corrosion was found to increase with decreasing pH and increasing chloride and moisture contents. The chloride content was the most influential of these variables. High soil resistance and noble corrosion potential were found to be associated with low corrosion rates. This is an important result since both soil resistivity and potential can be readily measured under field conditions. These tests have demonstrated the validity and utility of employing electrochemical techniques to gain insight into the corrosion of small arms munitions in soil. Tests involving long-term exposure of bullets to these and other soil corrosion environments and measurements of resulting weight loss are ongoing. Comparison of these two types of measurements will allow the usefulness of electrochemical methods for

predicting the corrosiveness of different soil and precipitation/moisture conditions to be determined. Eventually it is hoped that this work will lead to test methods to be used in the field which will allow the status of and hazards posed by corroding munitions in soil to be assessed.

Johnson, F.M. (1998). The Genetic Effects of Environmental Lead. *Mutation Research* 410(2): 123-140.

This article reviews the effects of lead on genetic systems in the context of lead's various other toxic effects and its abundance and distribution in the environment. It is likely that lead is a selective agent that continues to act on and influence the genetic structure and future evolution of exposed plant and animal populations.

Phytoremediation of Lead-Contaminated Soil. (No date.) Environmental Center, U.S. Army. Web site: <http://aec-www.apgea.army.mil:8080/prod/usaec/et/restor/phyremld.htm>. Retrieved: March 24, 2001.

Discusses the higher contamination of lead at DoD sites and the use of plants to take up lead during a 1998 field study using corn and white mustard plants.

Additional Resources:

Chaney, R.L., and Ryan, J.A. (1994). Risk Based Standards for Arsenic, Lead, and Cadmium on Urban Soils. Frankfurt, Germany: DECHEMA.

Xiong, Z.T. (1998). Lead Uptake and Effects on Seed Germination and Plant Growth in a Pb Hyperaccumulator *Bassica Pekinensis* Rupr. *Bulletin of Environmental Contamination and Toxicology* 60: 285-91.

6.2.4 NICKEL (NI)

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological Profile for Nickel. (1997). Atlanta, GA.: U.S. Department

of Health and Human Services, Public Health Service.

Nickel is a hard, silvery-white metal that is found in at least 709 of the 1,430 NPL sites identified by the EPA. It is a very abundant element found primarily combined with oxygen (oxides) or sulfur (sulfides). It is found in all soils and is emitted from volcanoes. Small nickel particles in the air settle to the ground or are taken out of the air in rain. Much of the nickel in the environment is found with soil and sediments because nickel attaches to particles that contain iron or manganese, which are often present in soil and sediments. Nickel does not appear to collect in fish, plants, or animals used for food. The major source of exposure for humans is by eating food containing nickel. Nickel is required to maintain health in animals. A small amount of nickel is probably essential for humans, although a lack of nickel has not been found to affect the health of humans. DHHS has determined that nickel and certain nickel compounds may reasonably be anticipated to be carcinogens. The EPA recommends that children drink water containing no more than 0.04 milligrams of nickel per liter of water for 1-10 days of exposure. OSHA has set an occupational exposure limit of 1 milligram of nickel per cubic meter of air for an 9-hour workday, 40-hour workweek.

Barceloux, D. (1999). Nickel. *Journal of Toxicology - Clinical Toxicology* 37(2): 239-258.

Nickel is an essential element for at least several animal species. These animal studies associate nickel deprivation with depressed growth, reduced reproductive rates, and alterations of serum lipids and glucose. Although there is substantial evidence of an essential status for nickel in animals, a deficiency state in humans has not been clearly defined.

Nickel is a silver-white metal with siderophilic properties that facilitate the formation of nickel-

iron alloys. In contrast to the soluble nickel salts (chloride, nitrate, sulfate), metallic nickel, nickel sulfides, and nickel oxides are poorly water-soluble. Nickel carbonyl is a volatile liquid at room temperature that decomposes rapidly into carbon monoxide and nickel. Drinking water and food are the main sources of exposure for the general population with the average American diet containing about 300–119g Ni/d. Nickel is highly mobile in soil, particularly in acid soils. There is little evidence that nickel compounds accumulate in the food chain. Nickel is not a cumulative toxin in animals or in humans.

Almost all cases of acute nickel toxicity result from exposure to nickel carbonyl. The initial effects involve irritation of the respiratory tract and nonspecific symptoms. Patients with severe poisoning develop intense pulmonary and gastrointestinal toxicity. Diffuse interstitial pneumonitis and cerebral edema are the main cause of death. Sodium diethyldithiocarbamate is an investigational drug used to chelate nickel following exposure to nickel carbonyl.

Nickel is a common sensitizing agent with a high prevalence of allergic contact dermatitis. Nickel and nickel compounds are well-recognized carcinogens. However, the identity of the nickel compound or compounds, which cause the increased risk of cancer, remains unclear. Currently, there are little epidemiological data to indicate that exposure to metallic nickel increases the risk of cancer, or that exposure to the carcinogenic forms of nickel causes cancer outside the lung and the nasal cavity.

Davis, M.A. and Boyd, R.S. (2000). Dynamics of Ni-based Defence and Organic Defences in the Ni Hyperaccumulator, *Streptanthus polygaloides* (Brassicaceae). *The New Phytologist* 146(2): 211-217.

Plants use chemical defenses to reduce damage from herbivores and the effectiveness of these defenses can be altered by biotic and

abiotic factors, such as herbivory and soil resource availability. *Streptanthus polygaloides*, a Ni hyperaccumulator, possesses both Ni-based defenses and organic defenses (glucosinolates), but the extent to which these defenses interact and respond to environmental conditions is unknown. *S. polygaloides* plants were grown on high-Ni and low-Ni soil and concentrations of Ni and glucosinolates were compared with those of the congeneric non-hyperaccumulator, *S. insignis* spp. *insignis*, grown under the same conditions. Ni contents were highest in *S. polygaloides* plants grown on high-Ni soil. Glucosinolate content was significantly higher in *S. insignis* than in *S. polygaloides*, suggesting that plants defended by Ni produce a lower concentration of organic defenses. In a separate experiment, high-Ni *S. polygaloides* plants were exposed to simulated herbivory or live folivores to determine the inducibility of Ni-based and organic defenses. Contents of Ni were not affected by either herbivory treatment, whereas glucosinolate concentrations were >30% higher in damaged plants. The authors conclude that the Ni-based defense of *S. polygaloides* is not induced by herbivory.

Ghaderian, Y.S.M., Lyon, A.J.E., Baker, A.J.M. (2000). Seedling Mortality of Metal Hyperaccumulator Plants Resulting from Damping Off by *Pythium* spp. *The New Phytologist* 145(2): 219-224.

Seedling mortality of *Alyssum serpyllifolium* ssp. *lusitanicum* and *A. murale*, both nickel hyperaccumulators, was reduced by increasing concentrations of metal within plant tissues when inoculated with the fungi *Pythium mamillatum* or *P. ultimum*, both of which cause damping-off disease of seedlings. *Pythium mamillatum*, isolated from nickel-rich serpentine soil, was more tolerant of nickel than *P. ultimum*, isolated from low-metal control soil, and was more pathogenic than *P. ultimum* toward seedlings containing high concentrations of metal. These results support the hypothesis

that metal hyperaccumulation by plants is closely linked to increased protection against disease. Robinson, G.H., Brooks, R.R., and Clothier, B.E. (1999). Soil Amendments Affecting Nickel and Cobalt Uptake by *Berkheya coddii*: Potential Use for Phytomining and Phytoremediation. *Annals of Botany* 84(6): 689-694.

Plants with inordinately high concentrations of heavy metals (hyperaccumulators) can be used for phytoremediation (removal of contaminants from soil) or phytomining (growing a crop of plants to harvest the metals). Study was done to a South American plant using the addition of magnesium, sulfur, and acid mine tailings and indicated that calcium inhibits the uptake of both cobalt and nickel, while sulphur and acid mine tailings caused a highly significant increase in nickel and cobalt uptake. Sulphur could be used as a low-cost soil amendment to enhance the metal uptake of crops grown on ultramafic soils.

Additional Resources:

Poulsen, I.F., and Bruun Hansen, H.C. (2000). Soil Sorption of Nickel in presence of Citrate or Arginine. *Water, Air, & Soil Pollution* 120(3/4): 249-259.

Yaman, M. (2000). Nickel Speciation in Soil and the Relationship with Its Concentration in Fruits. *Bulletin of Environmental Contamination and Toxicology* 65(4): 545-552.

6.2.5 COPPER (CU)

Eisler, R. (1997). Copper Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review. *Biological Science Report* 0(2): 1-99.

This is a selective review and synthesis of the technical literature on copper and copper salts in the environment and their effects primarily on fishes, birds, mammals, terrestrial and aquatic invertebrates, and other natural resources. Subtopics include copper in field collections of

abiotic materials and living organisms and lethal and sublethal effects on terrestrial plants.

Additional Resources:

Shuman, L.M., and McCracken, D.V. (1999). Tillage, Lime, and Poultry Litter Effects on Plant Concentrations of Zinc, Manganese, and Copper. *Journal of Plant Nutrition* 22(3): 609-620.

6.2.6 CHROMIUM (CR)

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological Profile for Chromium. (1993). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.

Chromium is a naturally occurring element found in rocks, soil, plants, animals, and in volcanic dust and gases. Chromium has three main forms: chromium(0), chromium(III), and chromium(VI). Chromium(III) compounds are stable and occur naturally in the environment. Chromium(0) does not occur naturally, and chromium(VI) occurs only rarely. Chromium(III) is an essential nutrient in human diets, but only a very small amount is needed. Other forms of chromium are not needed by humans. Manufacturing, disposal of products or chemicals containing chromium, or burning of fossil fuels release chromium to the air, soil, and water. Chromium particles settle from air in less than 10 days. Chromium sticks strongly to soil particles. Most chromium in water sticks to dirt particles that fall to the bottom; on a small amount dissolves. Small amounts move from soil to groundwater. Fish do not take up or store chromium in their bodies. Chromium(VI) is more toxic than chromium(III). DHHS has determined that certain chromium(VI) compounds are known carcinogens. The EPA sets a maximum level for chromium(III) and chromium(IV) in drinking water of 100 micrograms of chromium per liter of water. The National Research Council (NRC) recommends

a dietary intake of chromium(III) of 50-2000 µg/day.

Samantaray, S., Rout, G.R., and Das, P. (1998). Role of Chromium on Plant Growth and Metabolism. *Act Physiologiae Plantarum* 20(2): 201-212.

The beneficial as well as toxic effects of chromium with regard to its absorption, translocation, and accumulation in different parts of plants were reviewed. High concentrations of chromium exhibited severe chlorosis, necrosis and a host of other abnormalities and anatomical disorders. The regulation of the mineral metabolism, enzyme activity, and other metabolic processes by chromium in plants is discussed.

6.2.7 ANTIMONY (SB)

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological Profile for Antimony. (1995). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.

Antimony is a silvery-white metal that is found in the earth's crust. Antimony ores are mined and then mixed with other metals to form antimony alloys or combined with oxygen to form antimony oxide. Antimony has been found in at least 403 of 1,416 NPL sites identified by the EPA. Antimony oxide is used in fireworks. Antimony is released to the environment from natural sources or from industry. In the air, antimony is attached to very small particles that may stay in the air for many days. Most antimony ends up in soil, where it attaches strongly to particles that contain iron, manganese, or aluminum. Antimony is found at low levels in some rivers, lakes, and streams. Because antimony is found naturally in the environment, the general population is exposed to low levels of it every day, primarily in food, drinking water, and air. It may be found in air near industries that process or release it, such

as smelters, coal-fired plants, and refuse incinerators. DHHS has not classified antimony as to its human carcinogenicity. The EPA allows 0.006 parts of antimony per million parts of drinking water.

Casiot, C., Barciela Alonso, M.C., Donard, O.F.X., Potin-Gautier, M., Barciela Alonso, M.C., and Boisson, J. (1998). Simultaneous Speciation of Arsenic, Selenium, Antimony and Tellurium Species in Waters and Soil Extracts by Capillary Electrophoresis and UV Detection. *Analyst* 123(12): 2887-2893.

Capillary electrophoresis with indirect UV detection was used to determine simultaneously arsenic, selenium, antimony and tellurium compounds.

De Gregori, I., Pinochet, H., Fuentes, E., and Potin-Gautier, M. (2001). Determination of Antimony in Soils and Vegetables by Hydride Generation Atomic Fluorescence Spectrometry and Electrothermal Atomic Absorption Spectrometry. Optimization and Comparison of Both Analytical Techniques. *Journal of Analytical Atomic Spectrometry (JAAS)* 16(2): 172-178.

Two sensitive analytical atomic spectrometry methods, electrothermal atomic absorption spectrometry (ET-AAS) and hydride generation coupled to atomic fluorescence spectroscopy (HG-AFS), were optimized for determining total antimony in soils and plant (alfalfa) matrices.

Pilarski, J., Waller, P., and Pickering, W. (1995). Sorption of Antimony Species by Humic Acid. *Water, Air, and Soil Pollution* 84: 51-59.

The authors note that total antimony (Sb) content is included in numerous environmental surveys because of the toxicity of some antimony compounds. Trivalent (III) compounds seem to be more toxic than pentavalent (V) Sb compounds. Not surprisingly, environmental concentrations are greater in industrial areas, e.g., proximity to copper mines and copper

smelters. Apparently, Sb is rapidly sorbed from highly dilute $\text{Sb}(\text{OH})_3$ solutions by the hydrous oxides of Mn, Fe, and aluminum. Other examples also are given. In seawater, high concentrations of Sb are associated with humic acid. The authors surmise that the retention of Sb by humic acid that occurs in seawater also could occur in soils and sediments. This article describes their investigation of this possibility. Materials and methods are described in detail. Various subsections describe experiments focused on humic acid aspects, antimony solutions, sorption studies, studies on humic acid and salinity, and a discussion of the results.

Additional Resource:

Lindemann, T., Prange, A., Dannecker, W., and Neidhart, B. (2000). Stability Studies of Arsenic, Selenium, Antimony and Tellurium Species in Water, Urine, Fish and Soil Extracts Using HPLC/ICP-MS. *Fresenius' Journal of Analytical Chemistry* 368(2/3): 214-220.

6.2.8 CADMIUM (CD)

Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological Profile for Cadmium. (1993). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.

Cadmium is a natural element in the earth's crust. It is usually found as a mineral combined with other elements such as oxygen (cadmium oxide), chlorine (cadmium chloride), or sulfur (cadmium sulfate, cadmium sulfide). Cadmium has been found in at least 388 of 1,300 NPL sites identified by the EPA. All soils and rocks, including coal and mineral fertilizers, have some cadmium in them. The cadmium that industry uses is extracted during the production of other metals such as zinc, lead, and copper. Cadmium enters air from mining, industry, and burning coal and household wastes. Cadmium particles in air can travel long distances before

falling to the ground or water. It enters water and soil from waste disposal and spills or leaks at hazardous waste sites. It binds strongly to soil particles. Some cadmium dissolves in water. It does not break down in the environment, but it can change forms. Fish, plants, and animals take up cadmium from the environment. Cadmium stays in the body a very long time and can build up from many years of exposure to low levels. Breathing high levels of cadmium severely damages the lungs and can cause death. Animals given cadmium in food or water show high blood pressure, iron-poor blood, liver disease, and nerve or brain damage. It is unknown whether humans get any of these diseases from eating or drinking cadmium. DHHS has determined that cadmium and cadmium compounds may reasonably be anticipated to be carcinogens. The EPA allows 5 parts of cadmium per billion parts of drinking water. The EPA also limits how much cadmium can enter lakes, rivers, waste sites, and cropland.

Das, P., Samantaray, S., and Rout, G.R. (1997). Studies on Cadmium Toxicity in Plants: A Review. *Environmental Pollution* 98(1): 29-36.

This review with regards to ecological, physiological, and biochemical aspects of cadmium toxicity on plants may help in interdisciplinary studies to assess the ecological significance of metal stress.

De Toppi, L.S., and Gabbrielli, R. (1999). Response to Cadmium in Higher Plants. *Environmental and Experimental Botany* 41(2): 105-130.

This article summarizes present knowledge in the field of higher plant responses to cadmium. Cadmium evokes a number of parallel and/or consecutive events at molecular, physiological, and morphological levels.

Di Cagno, R., Guidi, L., Stefani, A., and Sodatini, G.F. (1999). Effects of Cadmium on

Growth of *Helianthus annuus* Seedlings: Physiological Aspects. *The New Phytologist* 144(1): 65-71.

Sunflower seedlings (*Helianthus annuus* hybrid Select) were grown in a complete nutrient solution in the absence or presence of Cd²⁺. Analyses were performed to establish whether there was a differential effect of Cd²⁺ on mature and young leaves. After 7 d the growth parameters as well as the leaf area had decreased in both mature and young leaves. Accumulation of Cd²⁺ in the roots exceeded that in the shoots. Seedlings treated with Cd²⁺ exhibited reduced contents of chlorophyll and CO₂ assimilation rate, with a greater decrease in young leaves. The photochemical efficiency of photosystem II (PSII) was not altered by Cd²⁺ treatment in either mature or young leaves, although during steady-state photosynthesis in young leaves there was a significant alteration in the following parameters: quantum yield of electron transport by PSII, photochemical quenching (qP), non-photochemical quenching (qNP), and excitation capture efficiency of PSII.

Grant, C.A., Buckley, W.T., Bailey, L.D., and Selles, F. (1998). Cadmium Accumulation in Crops. *Canadian Journal of Plant Science* 78(1): 1-17.

Plant uptake of Cd at levels present in the soil solution is dependent on a system that is largely metabolically mediated and competitive with the uptake system for Zn and possibly other metals. Much of the Cd is retained in the root, but a portion is translocated to the aerial portions of the plant and into the seed. The amount of Cd accumulated and translocated in plants varies with species and with cultivars within species. Soil, environmental, and management factors impact the amount of Cd accumulated in plants. Also discussed: methods of reducing Cd intake in plants.

Horstmeier, G.D. (1998). Heavy Metal Fertilizer. *Farm Journal* 122(6): 12 (2 pp.).

This article focuses on the effects of cadmium in fertilizers used for agriculture in the United States. It includes the following parts: What is cadmium; Indication that cadmium is linked to illness in humans and animals; Comments from Robert Smith, a veterinarian and animal nutritionist at Pennsylvania State University; How cadmium gets into soil; Regulations proposed as a result of concerns over hazardous materials in fertilizers.

Joner, E.J., and Leyval, C. (1998). Uptake of 109Cd by Roots and Hyphae of a *Glomus mosseae*/*Trifolium subterraneum* Mycorrhiza from Soil Amended with High and Low Concentrations of Cadmium. *The New Phytologist* 135(2): 353-360.

Subterranean clover (*Trifolium subterraneum* L.) in symbiosis with *Glomus mosseae* (Nicol. & Gerd.) Gerdemann & Trappe was grown in compartmented pots. Side compartments were filled with soil where recently added (1 wk) radio-labeled cadmium (Cd) at three levels of non-labeled Cd could be accessed by either roots or arbuscular mycorrhizal hyphae. All treatments were replicated with non-mycorrhizal plants. After a growth period of 52 days, roots and shoots were analyzed for 109Cd, and lengths of roots and hyphae in respective labeled compartments determined. Cadmium uptake by roots was not significantly influenced by the mycorrhizal status of the plant. Uptake of Cd from hyphal compartments was higher in mycorrhizal than in non-mycorrhizal plants, corresponding to 96, 127 and 131% of that in non-mycorrhizal plants when 1, 10 and 100 mg Cd kg⁻¹ was added, respectively. A large proportion of the increased Cd content of mycorrhizal plants was sequestered in the roots. It is concluded that extraradical hyphae of AM fungi can transport Cd from soil to plants, but that transfer from fungus to plant is restricted due to fungal immobilization. No reduction of hyphal growth into soil with up to 20 mg extractable Cd kg⁻¹ was observed.

Pilon-Smits, E.A.H., Zhu, Y.L., Sears, T., and Terry, N. (2000). Overexpression of Glutathione Reductase in *Brassica juncea*: Effects on Cadmium Accumulation and Tolerance. *Physiologia Plantarum* 110(4): 455-460.

To determine the importance of glutathione reductase (GR, EC 1.6.4.2) for heavy metal accumulation and tolerance, a bacterial GR was expressed in Indian mustard (*Brassica juncea* L.), targeted to the cytosol or the plastids. GR activity in the cytosolic transgenics (cytGR) was about two times higher compared to wild-type plants; in the plastidic transgenics (cpGR) the activity was up to 50 times higher. When treated with ... CdSO₄, cytGR plants did not differ from wild type in cadmium tolerance or accumulation. CpGR plants, however, showed enhanced cadmium tolerance at the chloroplast level: in contrast to wild-type plants they showed no chlorosis, and their chlorophyll fluorescence parameters Fv/Fm and photochemical quenching were higher. Cadmium tolerance at the whole-plant level (plant growth) was not affected. The lower cadmium stress experienced by the cpGR chloroplasts may be the result of reduced cadmium uptake and/or translocation: cadmium levels in shoots of cpGR plants were half as high as those in wild-type shoots. These differences in cadmium tolerance and accumulation may result from increased root glutathione levels, which were up to two times higher in cpGR plants than in the wild type.

Stroinski, A. (1999). Some Physiological and Biochemical Aspects of Plant Resistance to Cadmium Effect. *Acta Physiologiae Plantarum* 21(2): 175-188.

Studies on the effect of cadmium on plants have shown that it causes intensification of two types of unfavorable processes in plants: inactivation of macromolecules and cellular structures and induction of oxidative stress. In response, the plant organism activates processes restoring its homeostatis, i.e., those

which remove reversible and irreversible changes. The strategy of stress tolerance plays an important role in the plant resistance to cadmium and other toxic metals.

Tsai, K., Hsu, C., and Rosen, B.P. (1997). Efflux Mechanisms of Resistance to Cadmium, Arsenic, and Antimony in Prokaryotes and Eukaryotes. *Zoological Studies* 36(1): 1-16.

Resistance to toxic metals is ubiquitously found in prokaryotes, both gram positive and gram negative, and in all types of eukaryotes, including fungi, plants, protozoans, and animals. In both prokaryotes and eukaryotes, toxic metals are extruded from [cells] through efflux transport systems to confer this resistance. Among these efflux mechanisms of resistance to heavy metals...bacterial cadmium resistance is mediated by a primary transporter while the thiol-linked efflux systems have developed for cadmium resistance in eukaryotes. The biochemical aspects of the efflux mechanisms related to cadmium, arsenic, and antimony resistance in prokaryotes and eukaryotes are discussed in detail.

Van Lune, P., and Zwart, K.B. Cadmium Uptake by Crops from the Subsoil. (1997). *Plant and Soil* 189(2): 231-237.

For most investigated crops, Cd uptake increased linearly with increasing depth of Cd addition to the soils and for some crops the increase was exponential (decreasing increase). Cd uptake by crops on sand was higher than on sandy loam. Ploughing down a Cd-contaminated topsoil into the subsoil is a risk for the safe production of food and feed crops. Acceptable Cd concentration levels in soils should not only be based on the Cd concentration in the topsoil but also on that in the rooted subsoil.

Additional Resource:

Ouzounidou, G., Moustakas, M., and Eleftheriou, E.P. (1997). Physiological and

Ultrastructural Effects of Cadmium on Wheat (*Triticum aestivum* L.) Leaves. Archives of Environmental Contamination and Toxicology 32(2): 154-160.

6.2.9 MOLYBDENUM (MO)

Chikhalikar, S., and Patel, K.S. (1997). Field determination of *molybdenum* in soils. Fresenius' Journal of Analytical Chemistry 357(3): 355-356

A new procedure for the field characterization of the available amount of molybdenum in soil extract is described. It is based on the preconcentration of the Mo(V)-SCN-complex into toluene solution of N-octylacetamide (OAA) and subsequent heating of the extract for ... 10 minutes at 60 °C over a water bath. ...It provides a significantly increased tolerance limit for iron (up to 1000 ppm) and is applicable to the field characterization of Mo in soil.

Hyvarinen, H. and Nygren, T. (1993). Accumulation of Copper in the Liver of Moose in Finland. Journal of Wildlife Management 57(3): 469, 6 pp.

Studies the differences in accumulation of Cu, Zn, and Mo in the liver of moose in Finland relative to age and the concentrations of Cu in the soil in different regions of the country. Results indicate a higher concentration of Cu in the livers of moose fetuses; increase of Cu concentration with age. Article discusses risk factors for ischemic heart disease in human males in eastern Finland.

Moose and Molybdenum Don't Mix. (1996). Current Science 82(1): 13.

This article reports on the effect of the trace element molybdenum found in lime in soil on the health of moose. It describes feeding of moose on oats and other crops spread with lime to offset effects of acid rain and the number of moose that have died since 1986 in acidified areas in Sweden.

No Change Expected in Part 503 Cadmium Limit. (1995). BioCycle 36(5): 8.

This article reports on the conflict between the US Department of Agriculture (USDA) and the EPA about the limits for cadmium concentration in soil. The article discusses the USDA's argument on the need to lower the limit; EPA's lack of plans to change the limits for cadmium; and EPA's plan to issue a limit for molybdenum.

Tomati, U., Galli, E., and Pasetti, L. (1996). Effect of Earthworms on Molybdenum-dependent Activities. Biology and Fertility of Soils 23(4): 359-361.

Pot experiments performed in an alkaline, silty clay soil showed that the presence of *Allolobophora caliginosa* increased nitrate reductase activity in maize seedlings and nitrogen fixation in the soil, but did not affect photosynthesis and biomass of maize seedlings and oxygen consumption in the soil. The increase in molybdenum-dependent activities is ascribed to the greater availability of molybdenum recorded in the presence of earthworms.

Additional Resource:

Jongruaysup, S., Dell, B., Bell, R.W., O'Hara, G.W., and Bradley, J.S. (1997). Effect of Molybdenum and Inorganic Nitrogen on Molybdenum Redistribution in Black Gram (*Vigna mungo* L. Hepper) with Particular Reference to Seed Fill. Annals of Botany 79(1): 67-74.

6.2.10 TIN (SN)

Agency for Toxic Substances and Disease Registry (ATSDR). (1992). Toxicological Profile for Tin. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

Exposure to tin results mostly from eating food and breathing air that contains tin. Tin has been found in at least 202 of 1,416 NPL sites identified by the EPA. Tin is a natural element in

the earth's crust. It is a soft, white, silvery metal that does not dissolve in water (although some tin compounds do dissolve in water). Tin metal, as well as inorganic and organic tin compounds, can be found in the air, water, and soil near places where they are naturally present in the rocks, or where they are mined, manufactured, or used. Tin is released into the environment by both natural processes and human activities such as mining, coal and oil combustion, and the production and use of tin products. In water, tin attaches to the soil and sediments. In the atmosphere, tin exists as gases and fumes, and attaches to dust particles. Organotins (tin combined with materials that contain carbon), build up in fish, other organisms, and plants. DHHS, the International Agency for Research on Cancer, and the EPA have not classified tin for carcinogenicity. OSHA has set a maximum concentration limit of 0.1 milligrams per cubic meter (mg/m^3) of air for organotin compounds and 2.0 mg/m^3 for tin and inorganic tin compounds.

6.3 Heavy Metals and Plant Uptake

6.3.1 PLANT BIOLOGY

Etherington, J.R. (1982). *Environment and Plant Ecology*, 2nd ed. Chichester: John Wiley & Sons: 487 pp.

Eyre, S.R. (1968). *Vegetation and Soils: A World Picture*. London: Edward Arnold Publishers Ltd.: 328 pp.

Gibbons, B. (1984). *How Flowers Work: A Guide to Plant Biology*. Dorset: Blandford Press: 160 pp.

Wareing, P.F., and Phillips, I.D.J. (1981). *Growth and Differentiation in Plants*, 3rd ed. Oxford: Pergamon Press: 343 pp.

6.3.2 GENERAL ARTICLES ON HEAVY METALS AND PLANT UPTAKE

Brooks, R.R., ed. (1998). *Plants That Hyperaccumulate Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral Exploration, and Phytomining*. Wallingford, UK: 380 pp.

This book discusses plants that hyperaccumulate heavy metals.

Brown, S.L., Chaney, R.L., Angle, J.S., and Baker, A.J.M. (1995). Zinc and Cadmium Uptake by Hyperaccumulator *Thlaspi caerulescens* Grown in Nutrient Solution. *Soil Science Society of America Journal* 59(1): 125-133.

Phytoremediation of heavy-metal-contaminated soils can be an inexpensive means to remove hazardous metals from soil. Zn and Cd uptake and tolerance were characterized. Results suggest that *T. caerulescens* may be a candidate for the phytoremediation of Zn-contaminated soils.

Burckhard, S.R., Schwab, A.P., and Banks, M.K. (1996). The Effect of Vegetation on the Transport of Heavy Metal in a Contaminated Soil: A Column Study. (HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

Vegetation grown in contaminated soils may provide various pathways for the transport of heavy metals, including preferential flow paths, chelation of metals by root exudates, adsorption/desorption, and precipitation/dissolution reactions. This column study, designed to simulate field conditions, investigates the changes in the soil's physical and chemical properties resulting from the presence of vegetation. Changes in the water content of the soil will be quantified as a function of time along with the growth of the

plants' roots. Leachate will be collected and the heavy metal solution species will be quantified. The collected data will be used to assess the overall transport of heavy metal within and out of the vegetated contaminated soil system.

Cataldo, D.A., and Wildung, R.E. (1978). Soil and Plant Factors Influencing the Accumulation of Heavy Metals by Plants. *Environmental Health Perspective* 27: 149-159.

The use of plants to model heavy metal pollution in the terrestrial environment must be based on a cognizance of the complicated, integrated effects of pollutant source and soil-plant variables. To be detectable in plants, pollutant sources must significantly increase the plant available metal concentration in soil. The major factor governing metal availability to plants in soils is the solubility of the metal associated with the solid phase, since in order for root uptake to occur, a soluble species must exist adjacent to the root membrane for some finite period. The rate of release and form of this soluble species will have a strong influence on the rate and extent of uptake and, perhaps, mobility and toxicity in the plant and consuming animals. The factors influencing solubility and form of available metal species in soil vary widely geographically and include the concentration and chemical form of the element entering soil.

Chiou, C.T., Sheng, G., and Manes, M. (2001). A Partition-Limited Model for the Plant Uptake of Organic Contaminants from Soil and Water. *Environmental Science and Technology* 35(7): 1437-1444.

In dealing with the passive transport of organic contaminants from soils to plants (including crops), a partition-limited model is proposed in which (1) the maximum (equilibrium) concentration of a contaminant in any location in the plant is determined by partition equilibrium with its concentration in the soil interstitial water, which in turn is determined essentially by the concentration in the soil

organic matter (SOM) and (2) the extent of approach to partition equilibrium, as measured by the ratio of the contaminant concentrations in plant water and soil interstitial water, depends on the transport rate of the contaminant in soil water into the plant and the volume of soil water solution that is required for the plant contaminant level to reach equilibrium with the external soil-water phase. Through reasonable estimates of plant organic-water compositions and of contaminant partition coefficients with various plant components, the model accounts for calculated values ... in several published crop-contamination studies, including near-equilibrium values for relatively water-soluble contaminants and lower values for much less soluble contaminants; the differences are attributed to the much higher partition coefficients of the less soluble compounds between plant lipids and plant water, which necessitates much larger volumes of the plant water transport for achieving the equilibrium capacities. The model analysis indicates that for plants with high water contents the plant-water phase acts as the major reservoir for highly water-soluble contaminants. By contrast, the lipid in a plant, even at small amounts, is usually the major reservoir for highly water-insoluble contaminants.

Ernst, W.H.O. (1996). Bioavailability of Heavy Metals and Decontamination of Soils by Plants. *Applied Geochemistry* 11(1/2): 163-167.

This article discusses the use of hyperaccumulating higher plants for the decontamination of metal-polluted soils.

Felix, H. (1997). Field Trials for In Situ Decontamination of Heavy Metal Polluted Soils Using Crops of Metal-Accumulating Plants. *Zeitschrift für Pflanzenernährung und Bodenkunde* 160(5): 525-529.

Certain wild plants as well as crop plants, so-called hyperaccumulators, are able to accumulate large amounts of heavy metals in their aboveground parts. The ability of various

plants to accumulate Zn and Cd were compared in field trials. The wild species *Thlaspi caerulescens* and *Alyssum mulale* and the tree *Salix viminalis* showed a strong ability to accumulate zinc and cadmium.

Harper, J. (2000). Heavy Metal Pumps in Plants. Final Report. Work Performed Under Contact No. DE-FG07-96ER20252 for the DOE by the Scripps Research Institute.

The goal of this project is to understand how heavy metals are taken up from the soil and translocated throughout the plant. Metals discussed include Cu, Fe, and Cd. Findings indicate that a mutant screen for plants with altered accumulation of mineral nutrients was a viable approach to identify transport systems for different metals.

Huizenga P., and Tracy, J.C. (1996). Modeling Heavy Metal Movement in a Rooted Soil. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

Prediction of the movement of heavy metals through a rooted soil requires an understanding of both the hydrogeology and geochemistry of a site. Current models describing the transport of dissolved constituents through a rooted soil have been developed and shown to provide reliable predictions. Geochemical models that predict equilibrium states for a heavy metal in a soil-water environment have also been developed and shown to be useful. However, incorporating a geochemical model into a soil-water transport model is impractical in many situations due to the highly non-linear behavior of geochemical models. An alternative to incorporating a full geochemical model into a solute transport model is to use an empirical model representation of the immobile and mobile phases of the heavy metal, which is calibrated using the geochemical model. Using this approach, the authors developed an empirical model for lead using the

MINTEQA2/PRODEFA2 geochemical assessment model for incorporation into a root-zone fate and transport model, BIOROOT.

Jain, S.K. (1994). Heavy Metal Tolerance, Plant Evolution and restoration Ecology. Conservation Genetics: 407-410.

Studies of genetic variation in metal tolerance of any plant species are discussed, as well as the successful choice of species and genotypes for revegetating derelict areas.

Keltjens, W.G. and van Beusichem, M.L. (1998). Phytochelatins as Biomarkers for Heavy Metal Stress in Maize (*Zea mays* L.) and Wheat (*Triticum aestivum* L.): Combined effects of Copper and Cadmium. Plant and Soil 203(1): 119-126.

Soils contaminated with heavy metals often show increased levels of more than one metal, for example copper (Cu), cadmium (Cd), zinc (Zn), lead (Pb), or nickel (Ni). In case such soils are used for crop production, prediction of yield reduction or quality decline from heavy metals in the soil is inadequate when based only on chemical soil analysis. The use of biomarkers such as phytochelatins (PC), non-protein thiols specifically induced in plants upon exposure to heavy metals, may be an additional tool or diagnostic criterion in heavy metal research and in practice. Cu and Cd uptake and induction of PC synthesis were studied with hydroponically grown maize and wheat plants exposed to mixtures of the two metals. The authors observed a close positive relationship between the concentrations of Cd and PC in the plant shoot material. A decreased shoot concentration of Cd after addition of Cu, due to metal competition at common root absorption sites, coincided with lower shoot PC levels. Also differences in metal uptake and xylary metal transport among the two plant species were reflected in corresponding differences in PC concentration. The observed direct relationship between shoot PC concentration and the degree of metal-induced growth inhibition

makes the use of PC promising for the purpose tested for.

Knoop, B. (1996). The micronutrients: Fe, Mg, Mn, Ca, Zn, B. *Landscape Management* 35(10): 22.

This article discusses the role of micro-nutrients in plant growth. Subjects include adequacy of supply of Fe for plant to produce chlorophyll; nutrient deficiencies that cause chlorosis; the problem of magnesium (Mg) and manganese (Mn) deficiency in the soil; quantities of other nutrients such as Ca, Zn and boron (B); and testing tips to determine levels of minor nutrients.

Makhon'ko, K.P., Vertinskii, Y.K., and Raspopova, T.G. (1987). Accumulation of Microelements by Plants on Watersheds in the Permafrost-Taiga Zone. *Soviet Journal of Ecology* 18(4): 200-204.

The background concentrations of Pb, Cd, Hg, Mn, Ni, Cu, and Zn were determined in individual plant species, and the coefficients of accumulation (K) of these metals by plants were found in the biogencenose of watersheds in the permafrost-taiga zone.

McGrath, S.P., Sidoli, C.M., Baker, A.J.M, and Reeves, R.D. (1994). Using Plants to Clean Up Heavy Metals in Soils. 15th World Congress of Soil Science, Acapulco, Mexico, 10-16 July 1994. *Transactions, Vol. 4a: Commission III symposia*: 362-363.

This article describes the method of using plants that hyperaccumulate metals (Cd, Co, Cu, Pb, Ni, Mn, and Zn) for their removal from soils. Mixtures of species rather than monocultures was considered appropriate. Mechanisms for the subsequent disposal of the metal-rich plant matter are highlighted.

Mengoni, A., Gonnelli, C., Galardi, F., Gabbrielli, R., and Bazzicalupo, M. (2000). Genetic Diversity and Heavy Metal Tolerance in Populations of *Silene paradoxa* L.

(Caryophyllaceae): A Random Amplified Polymorphic DNA Analysis. *Molecular Ecology* 9(9): 1319-1324.

Metal-contaminated sites can occur naturally in serpentine outcrops or as consequence of anthropogenic activities, such as mining deposits, aerial fallout from smelters, and industrial processes. Serpentine outcrops are characterized by high levels of Ni, Co, and Cr and present a typical vegetation which includes endemisms and plants which also live in uncontaminated soils. These latter metal-tolerant populations provide the opportunity to investigate the first steps in the differentiation of plant populations under severe selection pressure and to select plants to be used in the phytoremediation of industrially contaminated soils. In this report, eight populations of *Silene paradoxa* L. (Caryophyllaceae) growing in copper mine deposits, in serpentine outcrops, or in noncontaminated soil in central Italy were analyzed using random amplified polymorphic DNA (RAPD) markers to investigate the pattern of genetic variation. The genetic diversity observed in populations at copper mine deposits was found to be at least as high as that of the neighboring serpentine populations. Analysis of molecular variance (amova) of the RAPD markers gave high statistical significance to the groupings of populations in accordance with their geographical location and with the metals present in the soil of origin (Cu vs. Ni), indicating that RAPD markers detected a polymorphism related to the soil contamination by Cu. Finally, two RAPD bands exclusive to Cu-tolerant populations were identified.

Peterson, P.J. (1993). Plant Adaptation to Environmental Stress: Metal Pollutant Tolerance. Paper in *Plant Adaptation to Environmental Stress*. Fowden, L, Mansfield, T., and Stoddart, J., eds. London, UK: Chapman and Hall Ltd.

This paper is concerned with possible tolerance mechanisms that may enable plants to adapt to

metals in soils, whether of geological origin or from mine and industrial waste contamination. It mainly uses examples from grass and forb species.

Rao, K.J., and Shantaram, M.V. (1995). Effect of the Application of Garbage on the Soil-Plant System: A Review. *Agricultural Reviews—Agricultural Research Communication Centre* 16(3): 105-116.

The effect of refuse application is evaluated: application of refuse to soils improves soil physical, chemical, and biological properties. However, hazards of salts, sodium, and heavy metals accumulation in soils may cause phytotoxicity in the long term. Uptake of micronutrients and heavy metals by crops varied depending on plant species and plant parts. Some heavy metals remained in the roots and were not translocated to edible plant parts.

Raskin, I., Kumar, N., Dushenkov, S., and Salt, D.E. (1994). Bioconcentration of Heavy Metals by Plants. *Current Opinion in Biotechnology* 5:285-290.

Certain plants can concentrate essential and nonessential heavy metals in their roots and shoots to levels far exceeding those present in the soil. Metal-accumulating plant species are invariably restricted to metalliferous soils found in different regions around the world. The mechanisms of metal accumulation, which involve extracellular and intracellular metal chelation, precipitation, compartmentalization, and translocation in the vascular system, are poorly understood. The article also discusses phytoremediation.

Ross, S.M., ed. (1994). *Toxic Metals in Soil-Plant Systems*. Chichester, UK: John Wiley & Sons.

Plants are classified relative to their affinity for heavy metals, and the uptake mechanisms are described in terms of passive and active adsorption.

Salt, D.E., Smith, R.D., and Raskin, I. (1998). Phytoremediation. *Annual Review of Plant Physiology & Plant Molecular Biology* 49: 643-668.

This article concentrates on the most developed subsets of phytoremediation technology and on the biological mechanisms that make phytoremediation of toxic heavy metals and organic pollutants a potential solution to cleaning contaminated soil and water. Discusses the remarkable ability of plants to concentrate elements and compounds from the environment and to metabolize various molecules in their tissues, i.e., the use of plants for the removal of pollutants from the environment.

Samantaray, S., Rout, G.R., and Das, P. (1999). Studies on the Uptake of Heavy Metals by Various Plant Species on Chromite Minespoils in Sub-tropical Regions of India. *Environmental Monitoring and Assessment* 55(3): 389-399.

The presence of heavy metals (Cr, Ni, and Fe) in soil and accumulated by herbs, shrubs, and trees regenerated naturally on the minewaste-dumps of Sukinda chromite mines (TISCO sector) were investigated. There was significant correlation between Cr and Fe in the soil where a tree species (*Catunaregam spinosa*) occurred. *Guazuma ulmifolia* and *Diospyros montana* also showed significant correlation between leaf, stem, and soil for Cr, Ni, and Fe. Among the shrubs (*Calotropis gigantea*, *Chromolaena odorata*, *Phyllanthus reticulatus* and *Woodfordia fruticosa*), significant and positive correlations were obtained for Cr and Ni in soil and Fe and Ni in leaf and Cr and Ni in stem. Among the annual herbs, whole plant of *Tephrosia purpurea* and *Borrevia articularis* showed significant and positive correlation with Cr and Ni with the maximum correlation coefficient value. It was concluded that the above information would be useful in

revegetation programs in subtropical regions having seasonal rainfall.

Shaw, A.J., ed. (1990). *Colonization and Establishment of Plants in Contaminated Sites*. Boca Raton, Florida: CRC Press.

This book discusses heavy metal tolerance in plants.

Williams, L.E., Pittman, J.K., and Hall, J.L. (2000). *Emerging Mechanisms for Heavy Metal Transport in Plants*. *Biochim Biophys Acta* 1465(1-2): 104-126.

This article concentrates on three classes of membrane transporters that have been implicated in the transport of heavy metals in a variety of organisms and could serve such a role in plants. It gives an overview of the main features of these transporters in plants in terms of structure, function, and regulation, drawing on information from studies in a wide variety of organisms.

Ylaranta, T. (1996). *Uptake of Heavy Metals by Plants from Airborne Deposition and Polluted Soils*. *Agricultural & Food Science in Finland* 5(4): 431-447.

The concentrations of S, Zn, Cu, Pb, and Cd in spring wheat, grain and straw, Italian ryegrass, timothy, and lettuce were studied in a field in southern Finland. A pot experiment with Cu- and Ni-contaminated soils was also discussed. Ni, Cd, and Cu were easily accumulated by plants from air deposition. In the pot experiment, high Ni concentrations in soil were more phytotoxic for oats than were high copper concentrations. In acidic soil, Ni concentrations lower than 20 and 100 mg/kg of soil, respectively, decreased the dry matter yield of oat shoots. Liming clearly decreased copper and nickel phytotoxicity. In the most highly contaminated soil, the addition of Cu 20 mg/kg decreased the yield of oat shoots.

Zhu, D., Schwab, A.P., Banks, M.K., and Wang, E.X. (1996). *The Impact Of Vegetation On*

Heavy Metal Movement. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

The establishment of vegetation in mining areas is a primary method to minimize metal contamination through wind erosion, runoff, and infiltration. Plants may decrease heavy metal leaching by plant uptake, stimulating microbial immobilization of metals in the rhizosphere, and decreasing water flow. However, organic compounds, especially organic acids exuded by plants and microbes, may increase heavy metal solubility. Also, channels created by the plant root system may greatly increase metal movement through preferential flow. The authors evaluated the effects of a warm-season grass and cool-season grass on the leaching of Zn, Cd, and Pb from mine tailings. The leaching experiment was conducted under unsaturated conditions using multilayered columns. Metals leached were monitored for 10 months, and total mass of leached metal was calculated. The subsoil in the columns will be extracted and the heavy metals in the plant biomass will be analyzed after the leaching experiment is concluded. These laboratory results will provide us with important information concerning the use of vegetation for mining site remediation.

Additional Resources:

Adriano, D.C. (1992). *Bioengineering of Trace Metals*. *Advances in Trace Substances Research*. Lewis, Boca Raton, FL: 513 pp.

Adriano, D.C. (1986). *Trace Elements in the Terrestrial Environment*. Springer-Verlag, NY: 533 pp.

Alloway, B.J. (1990). *Soil Processes and the Behaviour of Metals*. In: B.J. Alloway (Ed.) *Heavy Metals in Soils*. Blackie, Glasgow, pp. 7-28.

- Allen, E.B., and Cunningham, G.L. (1983). Effects of Vesicular-Arbuscular Mycorrhizae on *Distichlis spicata* Under Three Salinity Levels. *New Phytologist* 93: 227-236.
- Allen, M.F., and MacMahon, J.A. (1985). Impact of Disturbance on Cold Desert Fungi: Comparative Microscale Dispersion Patterns. *Pedobiologia* 28: 215-224.
- An, Z.Q., Guo, B.Z., and Hendrix, J.W. (1993). Populations of Spores and Propagules of Mycorrhizal Fungi in Relation to the Life Cycles of Tall Fescue and Tobacco. *Soil Biology and Biochemistry* 25: 813-817.
- An, Z.Q., Hendrix, J.W., Hershman, D.E., Ferriss, R.S., and Henson, G.T. (1993). The Influence of Crop Rotation and Soil Fumigation on a Mycorrhizal Fungal Community Associated with Soybean. *Mycorrhiza* 3: 171-182.
- Andersson, S., and Soderstrom, B. (1995). Effects of Lime (CaCO₃). *Scandinavian Journal of Forest Research* 10: 149-154.
- Awad, F., and Roemheld, V. (2000). Mobilization of Heavy Metals from Contaminated Calcareous Soils by Plant Born, Microbial and Synthetic Chelators and their Uptake by Wheat Plants. *Journal of Plant Nutrition* 23(11-12): 1847-1855.
- Baker, A.J.M., and Brooks, R.R. (1989). *Biorecovery* 1: 81.
- Baker, A.J.M., McGrath, S.P., Sidoli, C.M.D., and Reeves, R.D. (1994). *Resources, Conservation and Recycling* 11:41.
- Banks, M.K., Schwab, A.P., Fleming, G.R., and Hetrick, B.A. (1994). Effects of Plants and Soil Microflora on Leaching of Zinc from Mine Tailings. *Chemosphere* 29: 1691-1699.
- Barrow, N.J., and Mendoza, R.E. 1990. Equations for Describing Sigmoid Yield Responses and Their Application to Some Phosphate Responses by Lupins and Subterranean Clover. *Fertilizer Research* 22: 181-188.
- Baumgartner, D.J., Glenn, E.P., Kuehl, R.O., Thompson, T.L., Artiola, J.F., Menke, S.E., Saar, R.A., Moss, G.S., and M. A. Algharaibeh, M.A. (2000). Response to Metals and Nitrate in Simulated Uranium Mill Tailings Contaminated Groundwater. *Water, Air, & Soil Pollution* 118 (1/2): 115-129.
- Bellgard, S.E. 1993. The Topsoil as the Major Store of the Propagules of Vesicular-Arbuscular Mycorrhizal Fungi in Southeast Australian Sandstone Soils. *Mycorrhiza* 3: 19-24.
- Berry, C.R., and Marx, D.H. (1980). Significance of Various Soil Amendments to Borrow Pit Reclamation With Loblolly Pine and Fescue. *Reclamation Reviews* 3: 87-94.
- Best, G.R., Wallace, P.M., Dunn, W.J., and Feiertag, J.A. (No date). Enhancing Ecological Succession. 4. Growth, Density, and Species Richness of Forest Communities Established from Seed on Amended Overburden Soils. *Proceedings*.
- Blaylock, M.J., Salt, D.E., Dushenkov, O., Zakharova, O., Gussman, C., Kapulnik, Y., Ensley, B.D. and Raskin, I. (1997). *Environmental Science Technology*, 31:860.
- Body, P.E., Inglis, G.R. and Mulcahy, D.E. (1988). Lead Contamination in Port Pirie, South Australia. South Australian Department of Environment and Planning Report No.101. Adelaide, SA.
- Brown, R.T., and Mikola, P. (1974). The Influence of Fruticose Soil Lichens upon the Mycorrhizae and Seedling Growth of Forest Trees. *Acta Forestalia Fennica* 141: 4-22.
- Browning, M.H.R., and Whitney, R.D. (1992). The Influence of Phosphorus Concentration and Frequency of Fertilization on Ectomycorrhizal Development in Containerized Black Spruce and Jack Pine Seedlings. *Canadian Journal of*

Forest Research = Revue Canadienne de Recherche Forestiere Sep: 1263-1270.

Browning, M.H.R., and Whitney R.D. (1992). Field Performance of Black Spruce and Jack Pine Inoculated with Selected Species of Ectomycorrhizal Fungi. Canadian Journal of Forest Research 22: 1974-1982.

Brunner, I., and Scheidegger, C. 1994. Effects of High Nitrogen Concentrations on Ectomycorrhizal Structure and Growth of Seedlings of *Picea abies* (L.) Karst. New Phytologist 129: 83-95.

Bücking, H., and Heyser, W. (1994). The Effect of Ectomycorrhizal Fungi on Zn Uptake and Distribution in Seedlings of *Pinus sylvestris* L. Plant and Soil 167: 203-212.

Buckner, E.R. (No date). A Test of Selected Cultural Treatments for Improving the Chemical and Physical Characteristics of Reclaimed Surface Mine Spoil for the Growth of Loblolly Pine in East Tennessee. Reclamation Review: n.p.

Brooks, R.R. 1998. Plants That Hyperaccumulate Heavy Metals. n.p: CABI Publishing: 392 pp.

Burns, R.G., Rogers, S., and McGhee, I. (1996). Remediation of Inorganics and Organics in Industrial and Urban Contaminated Soil. In: R. Naidu, R.S. Kookana, D.P. Oliver, S. Rogers and M.J. McLaughlin (eds.): Contaminants and the Soil Environment in the Australasia-Pacific Region. London: Kluwer Academic Pub. Pp. 125-181.

Cappelli, M., Colpi, C., and Accordi, E.M.M. (1995). Effects of Simulated Acid Rain on Norway Spruce Seedlings. Monti e Boschi 46: 40-49.

Castellano, M.A. (1994). Current Status of Outplanting Studies using Ectomycorrhiza-Inoculated Forest Trees. p. In: Pfleger, F.L., and R.G. Linderman (ed.). Mycorrhizae and Plant

Health. St. Paul, Minnesota: APS Press, American Phytopathological Society.

Chakravarty, P., and Chatarpaul. L. (1990). Effect of Fertilization on Seedling Growth, Ectomycorrhizal Symbiosis, and Nutrient Uptake in *Larix laricina*. Canadian Journal of Forest Research = Journal Canadien de Recherche Forestiere Feb: 245-248.

Chaudhry, T.M., Hayes, W.J., Khan, A.G., and Khoo, C.H. (1997a). Metal Accumulator Plants from Two Contaminated Sites of New South Wales, Australia. Abs. Fourth Annual Conference Aust. Soc. Ecotoxicology, 17-19 July, Brisbane. p 10. Griffith Uni. Brisbane, Australia.

Chaudhry, T.M., Khan, A.G., Khoo, C.S., and Hayes, W.J. (1997b). Assessment of a Metal Contaminated Abandoned Mine near Lithgow, NSW, Australia. Abs. p 6. 2nd International Conf on Environmental Chemistry and Geochemistry in the Tropics, April 7 - 11, 1997. University of Malaya, Kuala Lumpur, Malaysia.

Claassen, V.P., and Zasoski, R.J. (1993). Enhancement of Revegetation on Construction Fill by Fertilizer and Topsoil Application: Effect on Mycorrhizal Infection. Land Degradation & Rehabilitation 4: 45-57.

Cooper, W.S. (1931). A Third Expedition to Glacier Bay, Alaska. Ecology 12: 61-95.

Coutts, M.P., and Nicoll B.C. (1990). Growth and Survival of Shoots, Roots, and Mycorrhizal Mycelium in. Canadian Journal of Forest Research: 861-868.

Cuenca, G., and Lovera, M. (1992). Vesicular-Arbuscular Mycorrhizae in Disturbed and Revegetated Sites from La Gran Sabana, Venezuela. Can. J. Bot./J. Can. Bot. 70: 73-79.

Cullings, K.W., Szaro, T.M., and Bruns, T.D. (1996). Evolution of Extreme Specialization Within a Lineage of Ectomycorrhizal Epiparasites. Nature 379: 63-66.

- Cumming, J.R. (1990). Nitrogen Source Effects on Al Toxicity in Nonmycorrhizal and Mycorrhizal Pitch Pine (*Pinus rigida*) Seedlings. II. Nitrate Reduction and NO₃- Uptake. Canadian Journal of Botany 68: 2653-2659.
- Cumming, J.R., and Weinstein, L.H. (1990). Nitrogen Source Effects on Al Toxicity in Nonmycorrhizal and Mycorrhizal Pitch Pine (*Pinus rigida*) Seedlings. I. Growth and Nutrition. Canadian Journal of Botany 68: 2644-2652.
- Currah, R.S., Hambleton, S., and Smreciu, A. (1988). Mycorrhizae and Mycorrhizal Fungi of *Calypso bulbosa*. American Journal of Botany 75: 739-752.
- Dahne, J., Klingelhofer, D., Ott, M., and Rothe, G.M. (1995). Liming Induced Stimulation of the Amino Acid Metabolism in Mycorrhizal Roots of Norway Spruce (*Picea abies* (L.) Karst.). Plant and Soil 173: 67-77.
- Dennis, R.M., Dworkin, D., and Zupko, A.J. (1994). Soil Washing Processes for Site Remediation. In: D.L. Wise and D.J. Trantolo (eds.): Remediation of Hazardous Waste Contaminated Soils. Pp 745-778. Marcel Dekker Inc. NY.
- Denny, H.J., and Ridge, I. (1995). Fungal Slime and Its Role in the Mycorrhizal Amelioration of Zinc Toxicity to Higher Plants. New Phytologist: (n.p.).
- Dighton, J. (1991). Acquisition of Nutrients from Organic Resources by mycorrhizal autotrophic plants. Experientia 47: 362-369.
- Dighton, J., and Coleman, D.C. (1992). Phosphorus Relations of Roots and Mycorrhizas of *Rhododendron maximum* L. in the Southern Appalachians, North Carolina. Mycorrhiza 1: 172-182.
- Dixon, R.K., Garrett, H.E., Bixby, J.A., Cox, G.S., and Tompson, J.G. (1981). Growth, Ectomycorrhizal Development, and Root Soluble Carbohydrates of Black Oak Seedlings Fertilized by Two Methods. Forest Science 27: 617-624.
- Elliot, H.A., Linn, J.H., and Shields, G.A. (1989). Hazardous Waste Hazardous Materials 6: 223 - 228.
- Ellis, B. (1992). On Site and In Situ Treatment of Contaminated Sites. In: F.J. Rees (ed.): Contaminated Land Treatment Technologies. Society of Chemical Industry. Elsevier Applied Science London. pp 30-46.
- Empirical Models for the Uptake of Inorganic Chemicals from Soil by Plants. (1998). Washington, DC: DOE, 116 pp.
- Erland, S., and Soderstrom, B. (1991). Effects of Lime and Ash Treatments on Ectomycorrhizal Infection of *Pinus sylvestris* L. Seedlings Planted in a Pine Forest. Scandinavian Journal of Forest Research 6: 519-525.
- Fellner, R., and Peskova, V. (No date). Effects of Industrial Pollutants on Ectomycorrhizal Relationships in Temperate Forests. Canadian Journal of Botany S1310-S1315.
- Ferm, A., and Polet, K.E. (1991). Developing Methods for Afforestation of fields - Interim Report Peltojen Metsitysmenetelmat - Tutkimushankkeen Valiraportti. Metsantutkimuslaitoksen Tiedonantoja: 120 pp.
- Fluckiger, W., and Braun, S. (No date). Revitalization of an Alpine Protective Forest by Fertilization. Plant and Soil: 481-488
- Flathman, P.E., Jerger, D.E. and Exner, J.H. (eds) (1994). Bioremediation Field Experiences. Boca Raton, Florida: CRC Press. 548pp.
- Galli, U., Schuepp, H., and Brunold, C. (1994). Physiol. Plant. 92,364.
- Gange, A.C., Brown, V.K., and Farmer, L.M. (1990). A Test of Mycorrhizal Benefit in an Early

Successional Plant Community. *New Phytologist* 115: 85-91.

Godbout, C., and Fortin, J.A. (1990). Cultural Control of Basidiome Formation in *Laccaria bicolor* with Container-grown White Pine Seedlings. *Mycological Research* 94: 1051-1058.

Gould, A.B., Hendrix, J.W., and Ferriss, R.S. (1996). Relationship of Mycorrhizal Activity to Time Following Reclamation of Surface Mine Land in Western Kentucky. I. Propagule and Spore Population Densities. *Canadian Journal of Botany* 74: 247-261.

Gould, A.B., Hendrix, J.W., and Ferriss, R.S. (1996). Relationship of Mycorrhizal Activity to Time Following Reclamation of Surface Mine Land in Western Kentucky. I. Propagule and Spore Population-Densities. *Canadian Journal of Botany* 74: 247-261.

Grossnickle, S.C., and Reid, C.P.P. (1982). The Use of Ectomycorrhizal Conifer Seedlings in the Revegetation of a High-elevation Mine Site. *Canadian Journal of Forest Research* 12: 354-361.

Huang, J.W., Chen, J., Berti, W.R. and Cunningham, S.D. (1997). *Environmental Science and Technology* 31: 800.

Jefferies, S.A. (1992). Remedial Barriers and Containment. In: J.F. Rees (Ed). *Contaminated Land Treatment Technologies*. Soc. Chem. Indus. London: Elsevier Applied Science.

Khan, A.G. and Chaudhry, T.M. (1996). Effects of Metaliferous Mine Pollution on the Vegetation and Their Mycorrhizal Associations at the Sunny Corner - a Silver Town of 1880's. Abs. First Intern. Conf. on Mycorrhiza, August 4-9, 1996. P70. University of California, Berkeley, USA.

Khan, A.G., Chaudhry, T.M., Hayes, W.J., Khoo, C.S., Hill, L., Fernandez, R., and Gallardo,

P. (1997). *Water, Air and Soil Pollution* (in press).

Khan, A.G., Hill, L., Fernandez, R., Gallardo, P. and Chaudhry, T.M. (1996). Population of Micro- and Macroflora in Zinc Waste Contaminated Filtercake Dump Area. Remade Lands International Conference on the Remediation and Management of Degraded Lands, Hong Kong, 3-6 December, 1996. P 13. Hong Kong Baptist University.

Kroopnick, P.M. (1994). Vapor Abatement Cost Analysis Methodology for Calculating Life Cycle Costs for Hydrocarbon Vapor Extracted During Soil Venting. In: D.L. Wise and D.J. Trantolo (Eds): *remediation of Hazardous Waste*. New York: Marcel Dekker Inc. pp 779-790.

Kumar, P.B.A., Dushenkov, V., Motto, H., Raskin, I. (1995). *Environmental Science and Technology* 29: 1232.

Markert, B. (1994). *Plants as Biomonitors for Heavy Metal Pollution of the Terrestrial Environment*. VCH, Weinheim.

McEldowney, S., Hardman, D.J and Waite, S. (1993). *Treatment Technologies*. In: S. McEldowney, J. Hardman and S. Waite (Eds.). *Pollution, Ecology and Biotreatment*, pp 48-58. Longman Singapore Publishers Pte. Ltd. Singapore.

McNeill, K.R. and Waring, S. (1992). *Vitrification of Contaminated Soils*. In: J.F. Rees (Ed.): *Contaminated Land Treatment Technologies*. Society of Chemical Industry, Elsevier Applied Science, London.

Meeussen, J.C.L., Keizer, M G., van Riemsdijk, W.H., and deHaan, F.A.M. (1994). *Jour. Environmental Quality* 23: 785-792.

Mench, M.J., Didier, V.L., Loffler, M., Gomez, A. and Masson, P. (1994). *Journal of Environmental Quality* 23: 58-63.

Mushgrove, S. (1991). *An Assessment of the Efficiency of Remedial Treatment for Metal*

Polluted Soil. In: M.C.R. Davies (Ed): Land Reclamation: an End to Dereliction. Intern Conf on Land Reclamation, April 1991, University of Wales. Essex, UK: Elsevier Science Publishers.

Peters, R.W., and Shem, L (1992). Applied Microbiological Biotechnology 40: 926-932.

Rao, P.S.C., Davis, G.B., and Johnston, C.D. (1996). Technologies for Enhanced Remediation of Contaminated Soils and Aquifers: an Overview, Analysis and Case Studies. In: R. Naidu, R.S. Kookana, D.P. Oliver, S. Rogers and M.J. McLaughlin (Eds): Contaminants and the Soils Environment in the Australasia-Pacific Region. P3610410. Kluwer Academic Pub. London.

Raskin, I., Nanda Kumar, P.B.A., Dushenkov, V. and Salt, D.E (1994). Current Opinion in Biotechnology, 5: 285.

Reed, D.T., Tasker, I.R., Cunnane, J.C. and Vandegrift, G.F (1992). Environmental Restoration and Separation Science. In: G.F. Vandgrift, D.T. Reed and I.R. Tasker (Eds): Environmental Remediation.

Removing Organic and Metal Ion Pollutants. American Chemical Society, Washington, DC.

Shetty, K.G., Hetrick, B.A.D., and Schwab, A.P. (1995). Environmental Pollution 88: 307

Shoebridge, L. (1993). A Review of Soil Remediation Practices in Australia. In: A. Langley and M. vanAlpen (eds.) The Health Risk Assessment and Management of Contaminant Sites. Proc. 2nd National Workshop on the Health Risk Assessment and Management of Contaminated Sites, Canberra 5-7 April, 1993. South Australian Health Commission, Adelaide, S.A.

Smith, B. (1993). Waste Management Environment 4: 24-30.

Thompson-Eagle, E.T., and Frankenburger Jr., W.T. (1992). Bioremediation of Soils Contaminated with Selenium. In; R. Lal and B.A

Stewart (Eds). Advances in Soil Science, 17: 261-310. Springer-Velag, NY.

Tuin, B.J.W., and Tels, M. (1991). Environmental Technology, 12, 178-190.

Wheeler, M (1994). Site Remediation: An Australian Perspective on "Best Practice." In Cole, J. (ed.) Environmental Management Industry Association of Australia Yearbook 1994. Waterloo, NSW, Australia: Executive Media, 156-160.

Williams, G.M. (1988). Integrated Studies into Ground Water Pollution by Hazardous Waste. In: J.R. Gronow, A.N. Schofield and R.K. Jain (Eds.). Land Disposal of Hazardous Waste, Engineering and Environmental Issues. Chichester, Sussex, UK: Ellis Horwood Ltd., 37-48.

Wills, B. (1988). Mineral Processing Technology. 4th Ed. Oxford: Pergamon Press,.

Yland, M.W.F., and Wachem, E.G. (1988). Soil Covering Systems as Remedial Action in Contaminated Housing Areas in The Netherlands. In: K. Wolf, W.J. van den Brink and F.J. Colon (Eds.) Contaminated Soil 88. Pp 597-599. Second Intern. TNO/BMFT Conference on Contaminated Soil, 11-15 April, 1988.

6.3.3 PHYTOREMEDIATION OF HEAVY METALS BY PLANTS

There are many sources on phytoremediation. This report includes only a select few because it is not a requirement in the scope of work.

Cornish, J.E., Goldberg, W.C., Levine. R.S., and Benemann. J.R. (1995). Phytoremediation of Soils Contaminated With Toxic Elements and Radionuclides. In Bioremediation of Inorganics, ed. R.E. Hinchee, J.L. Means, and D.R. Burris. Columbus, Ohio: Battalle Press. Pp. 55-63.

EPA. (August 1998). A Citizen's Guide to Phytoremediation. Technology Fact Sheet, EPA

542-F-98-011. EPA Office of Solid Waste and Emergency Response. Web site:

<http://www.clu-in.org/products/citguide/phyto2.htm>. Retrieved April 1, 2001.

EPA. (April 1998). Phytoremediation Bibliography. Web site:

<http://www.rtdf.org/pulic/phto/phtobib/biba-b.html>

Kelly, R.J. and Guerin, T.F. (1995) Feasibility of Using Hyperaccumulating Plants to Bioremediate Metal-Contaminated Soil. In Bioremediation of Inorganics, Hinchee, R.E., Means, J.L., and Burris, D.R. (eds.). Columbus, OH: Battelle Press, 25-32.

7.0 LITERATURE ABSTRACTS: DOCUMENTS CONCERNED WITH BOTH EXPLOSIVES AND HEAVY METALS IN SOILS

Craig, H., Wakeman, J., and Channell, M. (1996). Solidification/Stabilization of Metals and Explosives in Soil. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

Metals are often co-contaminants with explosives at munitions sites and may inhibit biological activity in soils. Metals toxicity and leachability could preclude the use of bioremediation technologies such as composting and slurry phase bioreactors. The current remediation approach for mixed metals and explosives in soil is incineration followed by solidification/stabilization (S/S). While this treatment train is effective, it is costly and requires the use of air pollution control equipment to capture metals air emissions during incineration. Direct S/S without incineration is a potentially cost-effective treatment option. An S/S treatability study was conducted for soils from the Ammunition Demolition Activity (ADA) open burn/open detonation (OB/OD) area at the UMDA, Hermiston, Oregon, Superfund site. The primary contaminants are metals such as Pb; Cd; nitroaromatics TNT and TNB; and nitramines RDX, and HMX. Various ratios of portland cement and fly ash were evaluated as inorganic binders and GAC as an organic binder. Leachability tests on the solidified matrix were conducted using the EPA Toxicity Characteristic Leaching Procedure (TCLP) (EPA SW-846 Method 1311) and explosives

laboratory analysis using HPLC (EPA SW-846 Method 8330). Results indicate an optimum S/S ratio of 30% concrete, 10% fly ash, and 5% GAC for Umatilla soils. Average TCLP leachate reductions were 99.6%, 96.9%, 99.96%, 96.4%, 97.1%, and 99.8% for Pb, Cd, TNT, TNB, RDX, and HMX, respectively. Leachate concentrations were below TCLP criteria for metals and below risk-based criteria for explosives. Based on treatability results, S/S was selected as the treatment technology for 20,000 cubic yards of ADA soils. The remedial action contractor will further evaluate treatment mixtures of cement, fly ash, and soluble silicates as inorganic binders, and GAC, organoclays, and rice hull ash as organic binders.

Craig, H., Ferguson, G., Markos, A., Kusterbeck, A., Shiver-Lake, L., Jenkins, T., and Thome, P. (1996). Field Demonstration of On-Site Analytical Methods for TNT and RDX in Groundwater. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

A field demonstration was conducted to assess the performance of eight commercially available and emerging colorimetric, immunoassay, and biosensor on-site analytical methods for explosives TNT and RDX in groundwater at the UMDA, Hermiston, Oregon, and Naval Submarine Base, Bangor, Washington, Superfund sites. Groundwater samples were analyzed by each of the on-site methods and results compared to laboratory analysis using HPLC (EPA SW-846 Method 8330). The commercial methods evaluated include the D-TECH/EM Science TNT and RDX immunoassay test (EPA SW-846 Methods 4050 and 4051), the EnSys, Inc., TNT and RDX colorimetric test (EPA SW-846 Methods 8515 and 8510) with a solid phase extraction step, and the Ohmicron TNT immunoassay test. The emerging methods tested include the antibody-

based NRL CFI for TNT and RDX and FOB for TNT. Precision and accuracy of the on-site methods were evaluated using RPD and linear regression analysis. Over the range of conditions tested, colorimetric methods for TNT and RDX showed the highest accuracy of the commercially available methods, and the CFI showed the highest accuracy of the emerging methods for TNT and RDX. The colorimetric method was selected for routine groundwater monitoring at the UMDA site, and further field testing on the NRL CFI and FOB biosensors will continue at both Superfund sites. The primary use for these analytical methods would be for influent and effluent monitoring for GAC groundwater and leachate treatment systems, which are projected to operate for a period of 10 to 30 years.

Emery, D.D., and Faessler, P.C. (1996). First Production-Level Bioremediation of Explosives-Contaminated Soil in the U.S. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.

The first production-level bioremediation of explosives-contaminated soil in the U.S. is taking place at the Umatilla Army Depot Activity (UMDA) near Hermiston, Oregon. Soil from munitions washout lagoons contained high concentrations of TNT and RDX, as well as HMX. In addition to these primary contaminants, laboratory tests were performed on Tetryl (N-2,4,6-tetranitro-N-methylaniline), 4ADNT (4-amino-2,6-dinitrotoluene), 2 ADNT (2-amino-4,6-dinitrotoluene), 2,4 DNT (2,4-dinitrotoluene), 2,6 DNT (2,6-dinitrotoluene), TNB (1,3,5-trinitrobenzene), DNB (1,3-dinitrobenzene) and NB (nitrobenzene) during the pilot-scale treatability tests. The established cleanup goal is 30 mg/kg each for TNT and RDX. Both field screening and EPA Method 8330 analyses are being performed. Treatment time on a 2,700-cybatch (810 cy of soil) is 10 to 12 days. A composting technique developed by

the Army Environmental Center is being used at the site. Five compost amendments are being blended with the contaminated soil. Specialized soil fuming equipment mixes the compost for optimum biological action and homogeneity. Moisture and pH levels are closely monitored to ensure that thermophilic bacteria play a dominant role in the degradation process. Homogeneity of the compost mix ensures that all contaminants are rapidly degraded. Nearly 5,000 cy of soil have been successfully treated, with more than 70 percent of all analyses indicating non-detectable levels of both TNT and RDX. The USACE estimates that more than \$2.6 million is being saved using bioremediation at Umatilla.

Explosive Plant Growth: First-Ever Field Studies Conducted on TNT-Contaminated Crops. (No date). From: Frontiers: Research Highlights of Argonne National Laboratory. Web site: <http://gils.doe.gov:1782/cgi-bin/w3vdkhgw?qryQBB0RTZ0h;doecrawl-002098>. Retrieved March 17, 2001.

This document discusses a study conducted by Argonne soil scientists and agronomists who set out to answer the following question through research at two U.S. Army ammunition plants: "Could the explosives, their by-products and the products of their degradation be entering animal and human food chains through vegetation and crops growing on explosives-contaminated soils?" No data were available for plants in fields from previous studies, only for plants grown under greenhouse and hydroponic conditions. "The good news," the study concluded, "is that crops grown on the former munitions fields are not being contaminated with TNT. Contamination by other explosives, however, may pose a health problem." Vegetation, including oat and rye grass was planted on TNT-contaminated soils with added ground grass hay. Neither TNT nor its degradation products were found in aboveground plant tissues of existing vegetation at either site. However, at sites

where RDX was manufactured, "RDX was found in tops and roots of plants growing on RDX-contaminated soils. RDX is not a listed carcinogen, but several of its potential degradation products may be carcinogenic. For this reason, the consumption of any plants growing on RDX-contaminated sites should be considered a potential health hazard."

Lucero, M.E., Mueller, W., Hubstenberger, J., Phillips, G.C., and O'Connell, M.A. (1999). Tolerance to Nitrogenous Explosives and Metabolism of TNT by Cell Suspensions of *Datura Innoxia*. *In Vitro Cellular and Developmental Biology—Plant* 35 (6): 480-486.

Cell suspension cultures of *Datura innoxia* were incubated in the presence of TNT, RDX, and HMX. Cellular tolerance levels and TNT biotransformation kinetics were examined. Tolerance to TNT varied as cell suspensions aged. Concentrations of RDX or HMX in excess of reported solubility limits produced no observable changes in cell viability. GC/MS analysis of TNT-treated cell media and cell lysates revealed rapid removal of TNT. Within 12 hours, less than 1 percent of the initial TNT remained in the growth medium. This rapid metabolism of nitroaromatics by the *Datura* cell suspension system indicates the utility of this system for further molecular and biochemical studies.

Plant Uptake and Compost Weather Studies. (No date.) USAEC. Web site: <http://aec.army.mil/prod/usaec/et/restor/plantupt.htm>. Retrieved: March 24, 2001.

The Plant Uptake project tested the availability of TNT transformation products from composted soil for plant uptake or released in the soil by plant root exudates. USAEC was the lead agency and the Tennessee Valley Authority was the performer. TNT transformation products appear to be strongly bound to compost material and are unextractable. Studies are needed to determine if plants will

extract these transformation products of explosives from the composted soil before composted soil is returned to a site.

Thorne, P.G. Fate of Explosives in Plant Tissues Contaminated During Phytoremediation. (1999). CRREL Special Report 99-19.

Kenaf plants were grown in uncontaminated soil using irrigation water contaminated with TNT, RDX, and HMX, and in soil contaminated with TNT, RDX, and HMX using uncontaminated irrigation water. Plant growth was minimal in contaminated soil but unaffected by contaminated irrigation water. TNT and its free amino transformation products were recovered from root tissues by solvent extraction. The conjugated amino transformation products were recovered from root tissue by base/acid hydrolysis. RDX and HMX were recovered by solvent from the roots and foliar tissues of the plants. At harvest, the kenaf was chopped and mixed with soil, where it was allowed to humify. Very little TNT or its transformation products were recoverable either by solvent extraction, base/acid hydrolysis, or aqueous leaching. Both RDX and HMX were recovered in significant amounts by both solvent extraction and aqueous leaching; furthermore, the nitroso transformation products of RDX were detected in the leachates. Kenaf plants could be used to remediate contaminated groundwater by removing TNT from irrigation water and sequestering the residues as conjugated transformation products. These plants were ineffective for the remediation of groundwater contaminated with RDX and HMX.

Trett, M.W., Calvo Urbano, B., Forster, S.J., Hutchinson, J.D., Feil, R.L., Trett, S.P., and Best, J.G. (2000). Terrestrial Meiofauna and Contaminated Land Assessment. *Environmental Science and Technology* 34(8): 1594-1602.

Following the development of aquatic pollution monitoring techniques using metazoan

meiofauna (microscopic interstitial invertebrates), the value of this group in the assessment of contaminated terrestrial sites has been investigated. Communities present in a former explosives burning ground were sampled at 30 sites by using coring techniques and examined in the laboratory. Nematoda were numerically dominant at each of the sites and were the most diverse invertebrate group present (60 species). Structurally modified assemblages of these were identified and correlated significantly with elevated soil heavy metal concentrations. Assemblages associated with elevated metal concentrations exhibited increased dominance and reduced species richness. Using principal components analyses (PCA) and redundancy analyses (RA), the relationships between individual species, the metals, and the structures of the nematode communities were described. Tolerant and resistant species were also identified. It is concluded that the technique is a valuable method of assessing metal contamination status, and it is recommended that further studies be made of sites contaminated with organic materials.

Additional Resources:

Harvey, S.D., Fellows, R.J., Cataldo, D.A, and Bean, R.M. (1991). Fate of the Explosive [RDX] in Soil and Bioaccumulation in Bush Bean Hydroponic Plants. *Environmental Toxicology and Chemistry* 10: 845-855.

Hughes, J.B., Shanks, J., Vanderford, M., Lauritzen, J., and Bhadra, R. (1997). Transformation of TNT by Aquatic Plants and Plant Tissues Cultures. *Environmental Science and Technology* 31: 266-271.

Larson, B.M., Hertkorn, N., and Sandermann, Jr., H. (1999). Classification of Explosives Transformation Products in Plant Tissues. *Environmental Toxicology and Chemistry* 18: 1270-1276.

Microbial Weathering Study of Composted Explosive-Contaminated Soil Obtained from the Umatilla Army Depot Activity, Umatilla, Oregon. Report No. SFIM-AEC-ET-CR-98042, October 1998. Technology Transfer Center, U.S. Army.

Palazzo, A.J., and Leggett, D.C. (1986). Effect and Disposition of TNT in a Terrestrial Plant and Validation of Analytical Methods. CRREL Special Report 86-15.

Results of a Study Investigating the Plant Uptake for the Umatilla Army Depot Activity, Umatilla, Oregon. Report No. SFIM-AEC-ET-CR-98043. November 1998. U.S. Army. Technology Transfer Center, U.S. Army.

Simini, M., Wentzel, R.S, Checkai, R.T., Phillips, C.T., Chester, N.A., Majors, M.A., and Amos, J.C. (1995). Evaluation of Soil Toxicity at Joliet Army Ammunition Plant. *Environmental Toxicology and Chemistry* 14: 623, 630.

Thompson, P.L., Ramer, L.A., and Schnoor, J.L. (1998). Uptake and Transformation of TNT by Hybrid Poplar Trees. *Environmental Science and Technology* 32: 975-980.

Thorne, K.A. NMR Studies on the Covalent Binding of the Reductive Degradative Products of TNT to Humic Substances, Model Compounds and Peat. In *Explosives Conjugation Products in Remediation Matrices: Interim Report 2* (Pennington, J.C., et al., eds.). USACE Technical Report SERDP-98-12: 7-37.

8.0 LITERATURE

ABSTRACTS: ALASKA

This section provides summaries of a selection of articles and reports about Fort Greely, Alaska explosives research, Alaska heavy metals research, and Alaska flora.

8.1 Fort Greely: General

8.1.1 GENERAL

Alaska Army Lands Withdrawal Renewal: Draft Legislative Environmental Impact Statement, 2 vols. (1999). Prepared for United States Army Alaska by Center for Ecological Management of Military Lands, Colorado State University. Fort Collins, CO: Colorado State University, Center for Ecological Management of Military Lands.

Two volumes: Volume 1 Draft Environmental Impact Statement (EIS); Volume 2 Appendices, scoping summary.

Alaska Army Lands Withdrawal Renewal: Final Legislative Environmental Impact Statement/ (1999). Prepared for United States Army Alaska by Center for Ecological Management of Military Lands, Colorado State University. Publisher: Fort Richardson, United States Army Alaska.

Two volumes: Volume 1 is the final EIS and Volume 2 contains the Appendices and scoping summaries. The Appendices include lists of vegetation and wildlife at Fort Greely. Also provides tables showing explosives contamination in water and showing water and air quality data.

Bacon, Glenn. (1978). Final report on the Archeological Survey of the XM-1 Tank Range, Fort Greely, Alaska. For USACE, Alaska District.

Discusses a May 1978 study to conduct an archeological survey in advance of proposed improvements to the XM-1 Tank Range.

DOI, BLM, Steese/White Mountains District, DOD, U.S. Army, 6th Infantry Division (Light). 1994. Fort Greely Proposed Resource Management Plan, Final Environmental Impact Statement. Fairbanks, Alaska: The District, 1994: 144 pp.

Discusses environmental aspects, economic aspects, and the Military Lands Withdrawal Act of 1986 and provides summaries of five alternative resource management plans for the Fort Greely Maneuver Area and Air Drop Zone.

Draft Environmental Impact Statement on installation utilization for 172nd Infantry Brigade, Alaska at Fort Greely/U.S. Department of the Army. (1979). The Army: 505 pp.

Discusses environmental and economic aspects.

Final Environmental Impact Statement on proposed land withdrawal for the 172nd Infantry Brigade (Alaska) at Fort Greely / U.S. Department of the Army. (1980). The Army: 530 pp.

Fort Greely. (1996). A description of the U.S. DoD's Defense Technical Information Center (DTIC) BRAC Commission remediation activities 1995-1996. Web site: www.dtic.mil/environdod/derpreport96/vol2/appx/app-a/nara068.html. Retrieved April 2, 2001.

Fort Greely: Proposed Resource Management Plan, final EIS, prepared by DOI, BLM, Steese/White Mountains District; U.S. Department of Defense, U.S. Army, 6th Infantry Division (Light). (1994). Anchorage, Alaska: BLM: 144 pp.

Fort Greely Resource Management Plan/Environmental Impact Statement: Record of Decision. (1995). Prepared by DOI, BLM, Steese/White Mountains District.

Discusses approval of and decisions of the BLM and Army's proposed RMP/EIS at Fort Greely.

Jorgenson, M.T., Roth, J.E., Smith, M.D., Schlentner, S.F., Lentz, W., Pullman, E.R., and Racine, C.H. (2001). An Ecological Land Survey for Fort Greely, Alaska. U.S. Army Engineer Research and Development Center, CRREL, Technical Report TR-01-4.

Lichvar, R., and Sprecher, S. (1999). Wetland Delineation for Fort Greely, Alaska. Final report to U.S. Army Alaska, Fort Richardson, Alaska.

USACE, Huntsville Center. (12 February 2001). Gerstle River FUD Fact Sheet. Formerly Used Defense Sites Project Fact Sheets. Web site: <http://www.hnd.usace.army.mil/owe/factshts/factshts/gr197.html>. Retrieved: April 2, 2001.

Describes the location, history, and test sites.

8.1.2 EXPLOSIVES AND FORT GREELY

Alaska Army Lands Withdrawal Renewal: Final Legislative EIS, 2 vols. (1999). Prepared for United States Army Alaska. Prepared by Center for Ecological Management of Military Lands, Colorado State University. Fort Richardson, Alaska: United States Army.

Associated Press. (June 20, 1999). Military Land Leases Under Fire. Anchorage Daily News: B1.

“The military wants to extend its lease on vast training spaces in the Interior by 50 years, but critics worry that may mean unexploded ordnance and other contamination will go unaddressed for decades.” A two-piece 666,000-acre training area at Fort Greely and Fort Wainwright’s 248,000-acre Yukon Training Area are under discussion.

Environmental Assessment of the Upgrade of Target Arrays, Fort Wainwright and Fort Greely, Alaska/United States, 11th Air Force. (1992). Elmendorf Air Force Base, Alaska, 11th Air Force.

Discusses USAF tactical aviation, environmental aspects, and bombing and

gunnery ranges at Fort Greely and Fort Wainwright. Discusses Stuart Creek and Oklahoma Impact Areas. Does not discuss the Washington Impact Area.

Epler, Patti. (November 16, 1986). A Potentially Deadly Area: EPA Wants Army to Clean Up Old Chemical Weapons Test Site. Anchorage Daily News: A1.

This article discusses how from 1954 to 1967 the Gerstle River Test Site at Fort Greely was the Army’s primary coldwater laboratory for chemical warfare experiments. The article mentions nerve and mustard gases, bombs, and land mines. “The Army contends the testing areas were cleaned up years ago. All the rockets, shells, and mines were burned and buried, then exhumed and consolidated in two large pits, each several acres.” But the article says the Army does not know exactly what chemical and biological agents were tested at Gerstle River and Delta Creek and that vital records were destroyed when the program was ended in the late 1960s.

Hunter, D. (June 7, 2000). Groups: Greely Reactor Made Weapons Material. Anchorage Daily News: A1.

“A small reactor in use at Fort Greely during the 1960s was secretly used to produce material for battlefield nuclear weapons and may have left a radioactive footprint that continues to contaminate the area...according to a report issued...by three activist and environmental groups....A spokesman for the USACE said Fort Greely is monitored annually and that tests have never produced readings in excess of accepted tolerance levels.”

Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.F., Gelvin, A.B., and Ranney, T.A. (2001). Sampling for Explosives Residues at Fort Greely, Alaska: Reconnaissance Visit July 2000. ERDC/CRREL Technical Report (in review).

This report discusses the results of soil sampling for explosives and heavy metals at the Washington Range at Fort Greely. Explosives residue was found in 48 percent of the 107 samples collected. RDX was the most frequently detected explosive at 39 percent.

8.1.3 PLANTS AND FORT GREELY

Racine, C., Lichvar, R., and Duffy, M. (2001). An Inventory of the Vascular Flora of Fort Greely, Interior Alaska. USACE, CRREL TR-10-5: 44 pp.

Provides plant species lists for Fort Greely.

8.2 Alaska: Heavy Metals

8.2.1 HEAVY METALS CONTAMINATION

Allen, M.S., and Slaughter, K.E. (1990). Mineralogical Data and Sample Locality Map of Nonmagnetic, Heavy-mineral-concentrate Samples Collected from the Eastern Part of the Lime Hills Quadrangle, Alaska. USGS.

Barnes, P., Leong, K., and Gustafson, C. (1974). Map Showing Distribution of Copper, Lead, Zinc, Mercury, and Arsenic in the Sediments off the Coast of Northern Alaska. DOI, USGS.

Dale, B., and Stottlemeyer, R. (1982). Heavy Metal Concentrations in Soils, Sediments, and Surface Water of Mineral Licks, Dunkel Mine, Denali National Park and Preserve, Alaska. Alaska. No publisher listed.

Dixon, D.P., and Brown, E.J. (1987). The Effects of Surface Disturbances on the Leaching of Heavy Metals. Fairbanks: Water Research Center, Institute of Northern Engineering, University of Alaska Fairbanks.

Gould, L.P., Severson, R.C., and Shacklett, H.T. (1988). Element Concentrations in Soils and Other Surficial Materials of Alaska. U.S. Geological Survey Professional Paper 1458: 53 pp.

Gould, L.P., Peard, J.L., Severson, R.C., Shacklett, H.T., Tompkins, M.L., Stewart, K.C., and Briggs, P.H. (1984). Chemical Analyses of Soils and Other Surficial Materials, Alaska. U.S. Geological Survey Open-File Report 84-423: 77 pp.

Malcolm, M.J., Allen, M.S., and Slaughter, K.E. (1990). Analytical Results and Sample Locality Map of the Nonmagnetic, Heavy-mineral-concentrate Samples Collected from the Eastern Part of the Lime Hills Quadrangle, Alaska. [Denver, CO]: DOI, USGS.

Meyer, M.P., VandeWeb, D.A., and Shepherd, A.D. (2000). Mineral Assessment of Ahtna, Inc. Selections in the Wrangell-St. Elias National Park and Preserve, Alaska. BLM-Alaska Technical Report 34.

Snyder-Conn, E., et al. (1988). Persistence of Heavy Metals in Shallow Arctic Marine Sediments Contaminated by Drilling Effluents: Draft. Fairbanks, Alaska: USFWS Fairbanks Fish and Wildlife Enhancement Office.

West, R.L. (1982). Kantishna Hills Heavy Metals Investigations, Denali National Park. Fairbanks, Alaska: USFWS.

West, R.L., and Deschu, N.A. (1984). Kantishna Hills Heavy Metals Investigations: Denali National Park 1983. Fairbanks, Alaska: USFWS.

This article discusses a spruce-pine forest in the northern taiga zone and included five field sites treated with contaminants of different compositions (Cu and Ni contaminants). It discusses the effects on the plant leaves: "Easily water soluble contaminants damaged the epidermis of plant leaves to a greater extent than the hard soluble ones, epidermal cells were collapsed, cuticular structures and stomatal complex were destroyed."

Chiarenzelli, J.R., Aspler, L.B., Ozarko, D.L., Hall, G.E.M., Powis, K.B., and Donaldson, J.A. (No date). Heavy Metals in Lichens: Southern

District of Keewatin, Northwest Territories, Canada. (No publisher listed in BIOS.)

A suite of 12 saxicolous lichen species were collected from a remote site and analyzed for As, Cd, Cr, Cu, Ni, Pb, Sb, V, and Zn. Concentrations of these metals were comparable to results obtained elsewhere in the Northwest Territory and from Alaska and northern Quebec. Heavy metal concentrations of the lichens were compared to that of seven immediate substrates.

Additional Resources:

Hannenman, D. (1993). Heavy Metals in Rock Creek, Denali National Park. Available in the University of Alaska Anchorage/Alaska Pacific University Library Alaska Room Rare Book Collection.

Hermanson, M.H. Historical Accumulation of Atmospherically-Derived Pollutant Trace Metals in the Arctic as Measured in Dated Sediment Cores.

Major, E.B. (1997). Testing Application of Biological Criteria in the Mining Environment, Final Report. For EPA, Environment and Natural Resources Institute, University of Alaska Anchorage.

8.3 Alaska: Flora

8.3.1 BOOKS

Brown, J., Miller, P.C., Tieszen, L.L., and Bunnell, F.L. 1980. An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska. Stroudsburg, PN: Dowden, Hutchinson, & Ross.

Hulten, E. (1968). Flora of Alaska and Neighboring Territories: A Manual of the Vascular Plants. Stanford, California: Stanford University Press: 1008 pp.

Lellinger, D.B. (1985). A Field Manual of the Ferns and Fern-Allies of the United States and

Canada. Washington, DC: Smithsonian Institution Press: 389 pp.

Lipkin, R., and Murray, D.F. (1997). Alaska Rare Plant Field Guide. USFWS, National Park Service, BLM, Alaska Natural Heritage Program, and USFS.

McQueen, C.B. (1990). Field Guide to the Peat Mosses of Boreal North America. Hanover, New Hampshire: University Press of New England: 138 pp.

Murray, D.M., Parker, C., and Batten, A.R. (1994). Flora of Alaska (preliminary). Northern Plant Documentation Center Report 86. Herbarium, University of Alaska Museum, Fairbanks, Alaska.

Plants of Alaska, Alphabetical Listing. (1994). U.S. Department of Agriculture, U.S. Soil Conservation Service, Anchorage, Alaska.

Thomson, J.W. (1979). Lichens of the Alaskan Arctic Slope. Toronto, Ontario, Canada: University of Toronto Press: 314 pp.

Viereck, L.A., and Little, Jr., E.L. (1972). Alaska Trees and Shrubs. Agriculture Handbook No. 410, U.S. Forest Service.

Wild Edible and Poisonous Plants of Alaska. (1993). University of Alaska Fairbanks: Cooperative Extension Service, Bulletin 300C-0028.

Welsh, S.L. (1974). Anderson's Flora of Alaska and Adjacent Parts of Canada. Provo, Utah: Brigham Young University Press: 724 pp.

8.3.2 ARTICLES

Allen, E.B., Allen, M.F., Helm, D.J., Trappe, J.M., Molina, R., and Rincon, E. (1995). Patterns and Regulation of Mycorrhizal Plant and Fungal Diversity. Plant and Soil 170: 47-62.

Clark, M.H., and Kautz, D.R. (1999). Soil and Vegetation Survey of the Gulkana River Area, Alaska. BLM-Alaska Technical Report 20.

Collins, W.B., and Helm, D.J. (1997). Moose (*Alces alces*) Habitat Relative to Riparian Succession in the Boreal Forest, Susitna River, Alaska. *Canadian Field-Naturalist* 111: 567-574.

Elliott, C.L., McKendrick, J.D., and Helm, D. (1987). Plant Biomass, Cover, and Survival of Species Used for Stripmine Reclamation in South-Central Alaska, U.S.A. *Arctic and Alpine Research* 19: 572-577.

Guyer, S. (2000). Vegetation Survey of Campbell Tract, Anchorage, Alaska. BLM-Alaska Technical Report 35.

Helm, D. (1982). Multivariate Analysis of Alpine Snow-Patch Vegetation Cover Near Milner Pass, Rocky Mountain National Park, Colorado, USA. *Arctic Alpine Research* 14: 87-95.

Helm, D.J. (1982). Vegetation studies for the proposed Susitna Hydroelectric Project. *Agroborealis* 14: 52-55.

Helm, D.J. (1991). From Boreal Forest to Reclaimed Site: Revegetation at the Usibelli Coal Mine. *Agroborealis* 23: 45-50.

Helm, D.J. 1992. Of Moose and Mines. *Agroborealis* 24: 41-48.

Helm, D.J. (1994). Establishment of Moose Browse on Four Growth Media on a Proposed Mine Site in Southcentral Alaska. *Restoration Ecology* 2: 164-179.

Helm, D.J. (1995). Native Grass Cultivars for Multiple Revegetation Goals on a Proposed Mine Site in Southcentral Alaska. *Restoration Ecology* 3: 111-122.

Helm, D.J., and E.B. Allen. (1995). Vegetation Chronosequence near Exit Glacier, Kenai Fjords National Park, Alaska, U.S.A. *Arctic and Alpine Research* 27: 246-257.

Helm, D.J., Allen, E.B., and Trappe, J.M. (1996). Mycorrhizal Chronosequence Near Exit Glacier, Alaska. *Canadian Journal of Botany* 74: 1496-1506.

Helm, D.J., Allen, E.B., and Trappe, J.M. (1999). Plant Growth and Mycorrhiza Formation by Transplants on Deglaciated Land Near Exit Glacier, Alaska. *Mycorrhiza* 8: 297-304.

Helm, D.J., and Carling, D.E. (1993a). Use of Soil Transfer for Reforestation on Abandoned Mined Lands in Alaska. I. Effects of Soil Transfer and Phosphorus on Growth and Mycorrhizal Formation by *Populus balsamifera*. *Mycorrhiza* 3: 97-106.

Helm, D.J., and Carling, D.E. (1993b). Use of Soil Transfer for Reforestation on Abandoned Mined Lands in Alaska. II. Effects of Soil Transfers from Different Successional Stages on Growth and Mycorrhizal Formation by *Populus balsamifera* and *Alnus crispa*. *Mycorrhiza* 3: 107-114.

Helm, D.J., and Collins, W.B. (1997). Vegetation Succession and Disturbance on Boreal Forest Floodplain, Susitna River, Alaska. *Canadian Field-Naturalist* 111: 553-566.

Helm, D.J., McKendrick, J.D., and Collins, W.B. (1987). Fertilizer Effects on Annual Grass in Wet Sedge-Grass Vegetation Site, Susitna Basin, Alaska, U.S.A. *Arctic and Alpine Research* 19: 29-34.

Johnson, C.L. Soil Fundamentals. (1992). Alaska Cooperative Extension Crop Production and Soil Management Series: FGV-00242.

Klebesadel, L.J. 1976. Early Planting Is Important To Alaskan Growers Of Bluegrass And Red Fescue Seed. *Agroborealis* 8(1):22-24.

Klebesadel, L.J., and Helm, D. (1986). Food Reserve Storage, Low-Temperature Injury, Winter Survival, and Forage Yields of Timothy in Subarctic Alaska as Related to Latitude-of-Origin. *Crop Science* 26: 325-334.

Klebesadel, L.J., 1985. Hardening Behavior, Winter Survival, and Forage Productivity of

Festuca Species and Cultivars in Subarctic Alaska. *Crop Science* Vol. 25:441-447.

Klebesadel, L.J. 1993. Winterhardiness and Agronomic Performance of Wildryes (*Elymus* species) Compared With Other Grasses in Alaska, And Response of Siberian Wildrye to Management Practices. *Alaska Agricultural Experimental Station Bulletin* 97.

Klebesadel, L.J., Helm, D.J. 1992. Relationship of Latitude-of-Origin to Winter Survival and to Forage and Seed Yields of Wheatgrasses (*Agropyron* species) in Subarctic Alaska. *AK Agric. Exp. Stat. Bull.* 88.

Klebesadel, L.J. 1991. Performance of Indigenous and Introduced Slender Wheatgrass in Alaska, and Presumed Evidence of Ecotypic Evolution. *AK Agric Exp. Sta. Bull.* 85

Klebesadel, L.J. 1993. Fescue Grasses Differ Greatly in Adaptation, Winter Hardiness, and Therefore Usefulness in Southcentral Alaska. *AK Agric. Exp. Sta. Bull.* 92.

Klebesadel, L.J. (1992). Seasonal Distribution of Forage Yield and Winter Hardiness of Grasses from Diverse Latitudinal Origins Harvested Four Times Per Year in Southcentral Alaska. University of Alaska Fairbanks Agricultural and Forestry Experiment Station, *Bulletin* 90.

McKendrick, J.D. (1999). Wildlife and Vegetation Find Habitat Niches on Oil Field Gravel Pad. *Agroborealis* 31(1): 36-38.

Mitchell, W.W. (1972). Red Fescue and Bluegrass Rank High in Frequent-Cut Test. *Agroborealis* 4(1) 30-31.

Mitchell, W.W. (1965). The Status of Hybridization Between *Agropyron Sericeum* and *Elymus Sibiricus* in Alaska. *Canadian Journal of Botany* 43: 855-859.

Nelson, M.G., Packee, E.C., and Helm, D.J. (1995). Reclaiming an Abandoned Placer Mine in Alaska. *Mining Engineering* 47: 240-242.

Taylor, R.L. 1970. Red Fescue—A Valuable Species. *Agroborealis* 2(1):8,10.

8.3.3 GOVERNMENT REPORTS

ABR Inc. (1999). Assessment of Kimberlite as a Growth Medium for Wetland Creation. Prepared for BHP Diamonds, Inc., Yellowknife, NWT, Canada. Prepared by ABR Inc., Fairbanks, Alaska.

ABR did not detect significant amounts of metal uptake in the plants surveyed, as described in this report.

Burgess, R.M., Pullman, E.R., and Cater, T.C. (1999). Rehabilitation of Salt-Affected Land After Close-Out of Reserve Pits. Third annual report. Report prepared for ARCO Alaska, Inc., Anchorage, Alaska, by ABR, Inc., Fairbanks, Alaska

This report is not yet available to the public.

Kidd, J.G. (May 1999). Evaluation of Lake Sediment as a Growth Medium for Reclamation of the EKATI Diamond Mine, NWT, Canada. Prepared by ABR Inc., Fairbanks, Alaska, for BHP Diamonds, Inc. Yellowknife, Canada.

This report describes an experiment to test the suitability of lake sediment as a growth medium for plant species that may be used in the creation of wetlands on the cap of Long Lake. The test was conducted in 1998. The experiment was designed to evaluate the survival and growth of the various species (willow shrubs, legumes, upland grasses, and an emergent wetland grass) in lake sediment, and to assess whether trace metals in the sediment could accumulate in plant tissue to toxic levels.

Racine, C., Lichvar, R., and Duffy, M. (February 2001). An Inventory of the Vascular Flora of Fort Greely, Interior Alaska. USACE CRREL: 44 pp.

This inventory of the vascular flora of Fort Greely was conducted sporadically during the summers of 1996, 1997, and 1998. About 100 sites were visited and 723 collections were made, which represented 497 taxa of vascular plants from 64 families and 198 genera. A species list for the Fort Greely survey was

compiled and is presented in this article. It is estimated that the vascular plant inventory is relatively complete. The inventory includes 21 rare species being tracked by the Alaska Natural Heritage Program and 11 species representing significant range extensions (greater than 150 kilometers).

9.0 REFERENCES

- Abdul Rida, A.M.M. (1996). Concentrations and Growth of Earthworms and Plants in Soils Contaminated by Cadmium, Copper, Iron, Lead and Zinc: Interactions Plant-Soil-Earthworm. *Soil Biology & Biochemistry* 28(8): 1037-1044.
- ABR Inc. (1999). *Assessment of Kimberlite as a Growth Medium for Wetland Creation. Prepared for BHP Diamonds, Inc., Yellowknife, NWT, Canada. Prepared by ABR Inc., Fairbanks, Alaska.*
- Acetone Helps Microbes Remediate TNT-Contaminated Soil. (2000). *BioCycle* 41(8): 38-39.
- Adrian, N.R., and Sutherland, K. (1998). RDX Biodegradation by a Methanogenic Enrichment Culture Obtained from an Explosives Manufacturing Wastewater Treatment Plant. Champaign, Illinois: USACE, Construction Engineering Research Laboratories.
- Adriano, D.C. (1986). *Trace Elements in the Terrestrial Environment*. Springer-Verlag, NY: 533 pp.
- Adriano, D.C. (1992). *Bioengineering of Trace Metals. Advances in Trace Substances Research*. Lewis, Boca Raton, FL: 513 pp.
- Adriano, D.C. (1992). *Biogeochemistry of Trace Metals*. Boca Raton, Florida: Lewis Publishers.
- Agency for Toxic Substances and Disease Registry (ATSDR). (1992). *Toxicological Profile for Tin*. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological profile for 2,4,6-trinitrotoluene (update)*. (1995). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service. Web site: www.atsdr.cdc.gov/tfacts81.html?clkd=iwm. Retrieved: April 8, 2001.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological Profile for Zinc*. (1995). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological profile for Lead*. (1993). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological Profile for Nickel*. (1997). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological Profile for Chromium*. (1993). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological Profile for Antimony*. (1995). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.
- Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological Profile for Cadmium*. (1993). Atlanta, GA.: U.S. Department of Health and Human Services, Public Health Service.
- Aide, M.T. and Cwick, G.J. (1998). Chemical Weathering in Soils from the Glacial Lake Agassiz Region of Manitoba, Canada. *Environmental Geology* 33(2/3): 115-121.

- Alaska Army Lands Withdrawal Renewal: Draft Legislative Environmental Impact Statement, 2 vols. (1999). Prepared for United States Army Alaska by Center for Ecological Management of Military Lands, Colorado State University. Fort Collins, CO: Colorado State University, Center for Ecological Management of Military Lands.
- Alaska Army Lands Withdrawal Renewal: Final Legislative EIS, 2 vols. (1999). Prepared for United States Army Alaska. Prepared by Center for Ecological Management of Military Lands, Colorado State University. Fort Richardson, Alaska: United States Army.
- Alaska Army Lands Withdrawal Renewal: Final Legislative Environmental Impact Statement/ (1999). Prepared for United States Army Alaska by Center for Ecological Management of Military Lands, Colorado State University. Publisher: Fort Richardson, United States Army Alaska.
- Allen, E.B., Allen, M.F., Helm, D.J., Trappe, J.M., Molina, R., and Rincon, E. (1995). Patterns and Regulation of Mycorrhizal Plant and Fungal Diversity. *Plant and Soil* 170: 47-62.
- Allen, E.B., and Cunningham, G.L. (1983). Effects of Vesicular-Arbuscular Mycorrhizae on *Distichlis spicata* Under Three Salinity Levels. *New Phytologist* 93: 227-236.
- Allen, M.F., and MacMahon, J.A. (1985). Impact of Disturbance on Cold Desert Fungi: Comparative Microscale Dispersion Patterns. *Pedobiologia* 28: 215-224.
- Allen, M.S., and Slaughter, K.E. (1990). Mineralogical Data and Sample Locality Map of Nonmagnetic, Heavy-mineral-concentrate Samples Collected from the Eastern Part of the Lime Hills Quadrangle, Alaska. USGS.
- Alloway, B.J. (1990). Soil Processes and the Behaviour of Metals. In: B.J. Alloway (Ed.) *Heavy Metals in Soils*. Blackie, Glasgow, pp. 7-28.
- Amoebae-Associated Bacteria in Biodegradation and Bioremediation. (No date). Center for Global Environmental Studies, Oak Ridge National Laboratory. Web site: <http://www.ornl.gov/CGES/Afinding/iab8-11.htm>. Retrieved March 22, 2001.
- An, Z.Q., Guo, B.Z., and Hendrix, J.W. (1993). Populations of Spores and Propagules of Mycorrhizal Fungi in Relation to the Life Cycles of Tall Fescue and Tobacco. *Soil Biology and Biochemistry* 25: 813-817.
- An, Z.Q., Hendrix, J.W., Hershman, D.E., Ferriss, R.S., and Henson, G.T. (1993). The Influence of Crop Rotation and Soil Fumigation on a Mycorrhizal Fungal Community Associated with Soybean. *Mycorrhiza* 3: 171-182.
- Anderson, P., Davidson, C.M., Duncan, A.L., Littlejohn, D., Ure, Allan M., and Garden, L.M. (2000). Column Leaching and Sorption Experiments to Assess the Mobility of Potentially Toxic Elements in Industrially Contaminated Land. *Journal of Environmental Monitoring* 2(3): 234-239.
- Andersson, S., and Soderstrom, B. (1995). Effects of Lime (CaCO₃). *Scandinavian Journal of Forest Research* 10: 149-154.
- Arienzo, M, Comfort, S.D., Shea, P.J., and Li, Z.M. (1996). Optimizing TNT Destruction in Contaminated Water and Soil by Fenton Oxidation. Conference Paper. HSRC/WER Joint

- Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Assessing Phytoremediation of Explosives-Contaminated Groundwater at Volunteer Army Ammunition Plant. (1997). U.S. Army. Web site: <http://www.wes.army.mil/el/resbrief/phytovol.html>. Retrieved March 24, 2001.
- Associated Press. (June 20, 1999). Military Land Leases Under Fire. Anchorage Daily News: B1.
- Atanassova, I. (1999) Competitive Effect of Copper, Zinc, Cadmium and Nickel on Ion Adsorption and Desorption by Soil Clays. *Water, Air, & Soil Pollution* 113(1/4): 115-125.
- Awad, F., and Roemheld, V. (2000). Mobilization of Heavy Metals from Contaminated Calcareous Soils by Plant Born, Microbial and Synthetic Chelators and their Uptake by Wheat Plants. *Journal of Plant Nutrition* 23(11-12): 1847-1855.
- Awad, F., and Romheld, V. (2000). Mobilization of Heavy Metals from Contaminated Calcareous Soils by Plant Born, Microbial and Synthetic chelators and Their Uptake by Wheat Plants. *Journal of Plant Nutrition* 23(11/12): 1847-1855.
- Azadpour, A., and Mathews, J.E. (1996). Remediation of Metal-Contaminated Sites Using Plants. *Remediation* 6(3): 1-18.
- Babanin, V.F., Shpilkina, I.V., and Ivanov, A.V. (1994). The Testing of Action of Chemical Extracts on Soils by Magnetic Methods (abstract). *Journal of Applied Physics* 75(10): 7183.
- Bacon, Glenn. (1978). Final report on the Archeological Survey of the XM-1 Tank Range, Fort Greely, Alaska. For USACE, Alaska District.
- Baker, A.J.M., and Brooks, R.R. (1989). *Biorecovery* 1: 81.
- Baker, A.J.M., McGrath, S.P., Sidoli, C.M.D., and Reeves, R.D. (1994). Resources, Conservation and Recycling 11:41.
- Banks, M.K., Schwab, A.P., Fleming, G.R., and Hetrick, B.A. (1994). Effects of Plants and Soil Microflora on Leaching of Zinc from Mine Tailings. *Chemosphere* 29: 1691-1699.
- Banuelos, G.S., and Ajwa, H.A. (1999). Trace Elements in Soils and Plants: An Overview. *Journal of Environmental Science and Health, Part A—Toxic/Hazardous Substances and Environmental Engineering* 34(4): 951-974.
- Barceloux, D. (1999). Nickel. *Journal of Toxicology - Clinical Toxicology* 37(2): 239-258.
- Barnes, P., Leong, K., and Gustafson, C. (1974). Map Showing Distribution of Copper, Lead, Zinc, Mercury, and Arsenic in the Sediments off the Coast of Northern Alaska. DOI, USGS.
- Barrow, N.J., and Mendoza, R.E. 1990. Equations for Describing Sigmoid Yield Responses and Their Application to Some Phosphate Responses by Lupins and Subterranean Clover. *Fertilizer Research* 22: 181-188.
- Bart, J.C., Judd, L.L., and Hoffman, K.E. (1997). Application of a Portable Immunosensor to Detect the Explosives TNT and RDX in Groundwater Samples. *Environmental Science and Technology* 31: 1505-11.

- Baumgartner, D.J., Glenn, E.P., Kuehl, R.O., Thompson, T.L., Artiola, J.F., Menke, S.E., Saar, R.A., Moss, G.S., and M. A. Algharaibeh, M.A. (2000). Response to Metals and Nitrate in Simulated Uranium Mill Tailings Contaminated Groundwater. *Water, Air, & Soil Pollution* 118 (1/2): 115-129.
- Bellgard, S.E. 1993. The Topsoil as the Major Store of the Propagules of Vesicular-Arbuscular Mycorrhizal Fungi in Southeast Australian Sandstone Soils. *Mycorrhiza* 3: 19-24.
- Beltz, L.A., Neira, D.R., Axtell, C.A., Iverson, S., Deaton, W., Waldschmidt, T.J., Bumpus J.A., and Johnston, C.G. (2001). Immunotoxicity of Explosives-Contaminated Soil Before and After Bioremediation. *Archives of Environmental Contamination and Toxicology* 40(3): 311-317.
- Berry, C.R., and Marx, D.H. (1980). Significance of Various Soil Amendments to Borrow Pit Reclamation With Loblolly Pine and Fescue. *Reclamation Reviews* 3: 87-94.
- Best, E.P.H. (1999). Phytoremediation of Explosives in Groundwater Using Constructed Wetlands. (U.S. Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). Web site: <http://www.wes.army.mil/el/resbrief/phytoexp.html>. Retrieved March 24, 2001.
- Best, G.R., Wallace, P.M., Dunn, W.J., and Feiertag, J.A. (No date). Enhancing Ecological Succession. 4. Growth, Density, and Species Richness of Forest Communities Established from Seed on Amended Overburden Soils. *Proceedings*.
- Bioremediation of Explosives-Contaminated Soil. (No date.) USAEC, 2 pp. Web site: <http://aec-www.apgea.army.mil:8080/prod/usaec/et/restor/biorem.htm>. Retrieved March 24, 2001.
- Bjerre, G.K, and Shierup, H. (1985). Uptake of Six Heavy Metals by Oat as Influenced by Soil Type and Additions of Cadmium, Lead, Zinc, and Copper. *Plant and Soil* 88(1): 57-69.
- Blaylock, M.J., Salt, D.E., Dushenkov, O., Zakharova, O., Gussman, C., Kapulnik, Y., Ensley, B.D. and Raskin, I. (1997). *Environmental Science Technology*, 31:860.
- Body, P.E., Inglis, G.R. and Mulcahy, D.E. (1988). Lead Contamination in Port Pirie, South Australia. South Australian Department of Environment and Planning Report No.101. Adelaide, SA.
- Boopathy, R., Gurgas, M., Ullian, J., and Manning, J.F. (1998). Metabolisms of Explosive Compounds by Sulfate-Reducing Bacteria. *Current Microbiology* 37(2): 127-131.
- Brauer, M., Eitzer, B., et al. (March 1, 1998) Breakdown of Explosives. *Environmental Science & Technology* 32(5): 146-152.
- Brooks, R.R. 1998. *Plants That Hyperaccumulate Heavy Metals*. n.p: CABI Publishing: 392 pp.
- Brooks, R.R., ed. (1998). *Plants That Hyperaccumulate Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral Exploration, and Phytomining*. Wallingford, UK: 380 pp.
- Brown, J., Miller, P.C., Tieszen, L.L., and Bunnell, F.L. 1980. *An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska*. Stroudsburg, PN: Dowden, Hutchinson, & Ross.
- Brown, R.T., and Mikola, P. (1974). The Influence of Fruticose Soil Lichens upon the Mycorrhizae and Seedling Growth of Forest Trees. *Acta Forestalia Fennica* 141: 4-22.

- Brown, S.L., Chaney, R.L., Angle, J.S., and Baker, A.J.M. (1995). Zinc and Cadmium Uptake by Hyperaccumulator *Thlaspi Caerulescens* Grown in Nutrient Solution. *Soil Science Society of America Journal* 59(1): 125-133.
- Browning, M.H.R., and Whitney R.D. (1992). Field Performance of Black Spruce and Jack Pine Inoculated with Selected Species of Ectomycorrhizal Fungi. *Canadian Journal of Forest Research* 22: 1974-1982.
- Browning, M.H.R., and Whitney. R.D. (1992). The Influence of Phosphorus Concentration and Frequency of Fertilization on Ectomycorrhizal Development in Containerized Black Spruce and Jack Pine Seedlings. *Canadian Journal of Forest Research = Revue Canadienne de Recherche Forestiere Sep*: 1263-1270.
- Brunner, I., and Scheidegger, C. 1994. Effects of High Nitrogen Concentrations on Ectomycorrhizal Structure and Growth of Seedlings of *Picea abies* (L.) Karst. *New Phytologist* 129: 83-95.
- Bruns-Nagel, D., Knicker, H., Drzyzga, O., Butehorn, U., Steinbach, K., von Low, E., Gemsa, D. (2000). Characterization of 15N-TNT Residues After an Anaerobic/Aerobic Treatment of Soil/Molasses Mixtures by Solid-State 15N NMR Spectroscopy. 2. Systematic Investigation of Whole Soil and Different Humic Fractions. *Environmental Science and Technology* 34(8): 1549-1556.
- Bücking, H., and Heyser, W. (1994). The Effect of Ectomycorrhizal Fungi on Zn Uptake and Distribution in Seedlings of *Pinus sylvestris* L. *Plant and Soil* 167: 203-212.
- Buckner, E.R. (No date). A Test of Selected Cultural Treatments for Improving the Chemical and Physical Characteristics of Reclaimed Surface Mine Spoil for the Growth of Loblolly Pine in East Tennessee. *Reclamation Review*: n.p.
- Bund, K., Bricka, M., and Morales, A. (1996). An Electrochemical Approach for Investigating Corrosion of Small Arms Munitions in Firing Ranges. Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 39180-6199 Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Burckhard, S.R., Schwab, A.P., and Banks, M.K. 1996). The Effect of Vegetation on the Transport of Heavy Metal in a Contaminated Soil: A Column Study. (HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Burd, G.I., Dixon, D.G., and Glick, B.R. (2000). Plant Growth-Promoting Bacteria that Decrease Heavy Metal Toxicity in Plants. *Canadian Journal of Microbiology*46(3): 237-245.
- Burgess, R.M., Pullman, E.R., and Cater, T.C. (1999). Rehabilitation of Salt-Affected Land After Close-Out of Reserve Pits. Third annual report. Report prepared for ARCO Alaska, Inc., Anchorage, Alaska, by ABR, Inc., Fairbanks, Alaska.
- Burns, R.G., Rogers, S., and McGhee, I. (1996). Remediation of Inorganics and Organics in Industrial and Urban Contaminated Soil. In: R. Naidu, R.S. Kookana, D.P. Oliver, S. Rogers and M.J. McLaughlin (eds.): *Contaminants and the Soil Environment in the Australasia-Pacific Region*. London: Kluwer Academic Pub. Pp. 125-181.

- Cakmak, I. (2000). Possible Roles of Zinc in Protecting Plant Cells from Damage by Reactive Oxygen Species. *New Phytologist* 146(2): 185-205.
- Camobreco, V.J., Richards, B.K., Steenhuis, T.S., Preverly, J.H., and McBride, M.B. (1996). Movement of Heavy Metals Through Undisturbed and Homogenized Soil Columns. *Soil Science* 161(11): 740-750.
- Cappelli, M., Colpi, C., and Accordi, E.M.M. (1995). Effects of Simulated Acid Rain on Norway Spruce Seedlings. *Monti e Boschi* 46: 40-49.
- Caris, C. (1998). Studies of Iron Transport by Arbuscular Mycorrhizal Hyphae from Soil to Peanut and Sorghum Plants. *Mycorrhiza* 8(1): 35-39.
- Casiot, C., Barciela Alonso, M.C., Donard, O.F.X., Potin-Gautier, M., Barciela Alonso, M.C., and Boisson, J. (1998). Simultaneous Speciation of Arsenic, Selenium, Antimony and Tellurium Species in Waters and Soil Extracts by Capillary Electrophoresis and UV Detection. *Analyst* 123(12): 2887-2893.
- Castellano, M.A. (1994). Current Status of Outplanting Studies using Ectomycorrhiza-Inoculated Forest Trees. p. In: Pflieger, F.L., and R.G. Linderman (ed.). *Mycorrhizae and Plant Health*. St. Paul, Minnesota: APS Press, American Phytopathological Society.
- Cataldo, D.A., and Wildung, R.E. (1978). Soil and Plant Factors Influencing the Accumulation of Heavy Metals by Plants. *Environmental Health Perspective* 27: 149-159.
- Chakravarty, P., and Chatarpaul, L. (1990). Effect of Fertilization on Seedling Growth, Ectomycorrhizal Symbiosis, and Nutrient Uptake in *Larix laricina*. *Canadian Journal of Forest Research = Journal Canadien de Recherche Forestiere* Feb: 245-248.
- Chaney, R.L., and Ryan, J.A. (1994). Risk Based Standards for Arsenic, Lead, and Cadmium on Urban Soils. Frankfurt, Germany: DECHEMA.
- Chaudhry, T.M., Hayes, W.J., Khan, A.G., and Khoo, C.H. (1997a). Metal Accumulator Plants from Two Contaminated Sites of New South Wales, Australia. Abs. Fourth Annual Conference Aust. Soc. Ecotoxicology, 17-19 July, Brisbane. p 10. Griffith Uni. Brisbane, Australia.
- Chaudhry, T.M., Khan, A.G., Khoo, C.S., and Hayes, W.J. (1997b). Assessment of a Metal Contaminated Abandoned Mine near Lithgow, NSW, Australia. Abs. p 6. 2nd International Conf on Environmental Chemistry and Geochemistry in the Tropics, April 7 - 11, 1997. University of Malaya, Kuala Lumpur, Malaysia.
- Chiarenzelli, J.R., Aspler, L.B., Ozarko, D.L., Hall, G.E.M., Powis, K.B., and Donaldson, J.A. (No date). Heavy Metals in Lichens: Southern District of Keewatin, Northwest Territories, Canada. (No publisher listed in BIOS.)
- Chikhalikar, S., and Patel, K.S. (1997). Field determination of *molybdenum* in soils. *Fresenius' Journal of Analytical Chemistry* 357(3): 355-356
- Chiou, C.T., Sheng, G., and Manes, M. (2001). A Partition-Limited Model for the Plant Uptake of Organic Contaminants from Soil and Water. *Environmental Science and Technology* 35(7): 1437-1444.

- Church, S.E., et al. (1997). Source, Transport, and Partitioning of Metals Between Water, Colloids, and Bed Sediments of the Animas River, Colorado. U.S. Dept. of Interior (DOI), USGS.
- Claassen, V.P., and Zasoski, R.J. (1993). Enhancement of Revegetation on Construction Fill by Fertilizer and Topsoil Application: Effect on Mycorrhizal Infection. *Land Degradation & Rehabilitation* 4: 45-57.
- Clark, M.H., and Kautz, D.R. (1999). Soil and Vegetation Survey of the Gulkana River Area, Alaska. BLM-Alaska Technical Report 20.
- Collins, W.B., and Helm, D.J. (1997). Moose (*Alces alces*) Habitat Relative to Riparian Succession in the Boreal Forest, Susitna River, Alaska. *Canadian Field-Naturalist* 111: 567-574.
- Cooper, W.S. (1931). A Third Expedition to Glacier Bay, Alaska. *Ecology* 12: 61-95.
- Cornish, J.E., Goldberg, W.C., Levine, R.S., and Benemann, J.R. (1995). Phytoremediation of Soils Contaminated With Toxic Elements and Radionuclides. In *Bioremediation of Inorganics*, ed. R.E. Hinchee, J.L. Means, and D.R. Burris. Columbus, Ohio: Battelle Press. Pp. 55-63.
- Coutts, M.P., and Nicoll B.C. (1990). Growth and Survival of Shoots, Roots, and Mycorrhizal Mycelium in. *Canadian Journal of Forest Research*: 861-868.
- Cox, D.E. (1969). Map Showing Citrate-Soluble Heavy Metals in Stream Sediments, Ossipee Lake Quadrangle, Carroll County, New Hampshire. Washington, D.C.: USGS.
- Cragin, J.H., et al. (1985). TNT, RDX, and HMX Explosives in Soils and Sediments: Analysis Techniques and Drying Losses. U.S. Army Toxic and Hazardous Materials Agency, USACE, CREEL.
- Craig, H., Ferguson, G., Markos, A., Kusterbeck, A., Shiver-Lake, L., Jenkins, T., and Thome, P. (1996). Field Demonstration of On-Site Analytical Methods for TNT and RDX in Groundwater. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Craig, H., Ferguson, H., Markos, G., Kusterbeck, A., Shriver-Lake, L., Jenkins, T., and Thorne, P. (1996). Field Demonstration of On-Site Analytical Methods for TNT and RDX in Groundwater. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Craig, H., Wakeman, J., and Channell, M. (1996). Solidification/Stabilization of Metals and Explosives in Soil. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Crockett, A.B., Jenkins, T.F., Craig, H.D., and Sisk, W.E. (1998). Overview of On-Site Analytical Methods for Explosives in Soil. U.S. Army Engineering Research Development Center (ERDC)/CRREL Special Report 98-4.
- Crockett, A.B., Jenkins, T.F., Craig, H.D., and Sisk, W.E. (1999). Overview of On-Site Analytical Methods for Explosives in Soil. USACE CRREL Special Report 93-4.
- Cuenca, G., and Lovera, M. (1992). Vesicular-Arbuscular Mycorrhizae in Disturbed and Revegetated Sites from La Gran Sabana, Venezuela. *Can. J. Bot./J. Can. Bot.* 70: 73-79.

- Cullings, K.W., Szaro, T.M., and Bruns, T.D. (1996). Evolution of Extreme Specialization Within a Lineage of Ectomycorrhizal Epiparasites. *Nature* 379: 63-66.
- Cumming, J.R. (1990). Nitrogen Source Effects on Al Toxicity in Nonmycorrhizal and Mycorrhizal Pitch Pine (*Pinus rigida*) Seedlings. II. Nitrate Reduction and NO₃- Uptake. *Canadian Journal of Botany* 68: 2653-2659.
- Cumming, J.R., and Weinstein, L.H. (1990). Nitrogen Source Effects on Al Toxicity in Nonmycorrhizal and Mycorrhizal Pitch Pine (*Pinus rigida*) Seedlings. I. Growth and Nutrition. *Canadian Journal of Botany* 68: 2644-2652.
- Currah, R.S., Hambleton, S., and Smreciu, A. (1988). Mycorrhizae and Mycorrhizal Fungi of *Calypso bulbosa*. *American Journal of Botany* 75: 739-752.
- Dahne, J., Klingelhofer, D., Ott, M., and Rothe, G.M. (1995). Liming Induced Stimulation of the Amino Acid Metabolism in Mycorrhizal Roots of Norway Spruce (*Picea abies* (L.) Karst.). *Plant and Soil* 173: 67-77.
- Dale, B., and Stottlemeyer, R. (1982). Heavy Metal Concentrations in Soils, Sediments, and Surface Water of Mineral Licks, Dunkel Mine, Denali National Park and Preserve, Alaska. Alaska. No publisher listed.
- Das, P., Samantaray, S., and Rout, G.R. (1997). Studies on Cadmium Toxicity in Plants: A Review. *Environmental Pollution* 98(1): 29-36.
- Davis, L.C., and Chou, N.C. (1996). Metabolism of TNT Associated with Roots of Higher Plants. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Davis, M.A. and Boyd, R.S. (2000). Dynamics of Ni-based Defence and Organic Defences in the Ni Hyperaccumulator, *Streptanthus polygaloides* (Brassicaceae). *The New Phytologist* 146(2): 211-217.
- De Gregori, I., Pinochet, H., Fuentes, E., and Potin-Gautier, M. (2001). Determination of Antimony in Soils and Vegetables by Hydride Generation Atomic Fluorescence Spectrometry and Electrothermal Atomic Absorption Spectrometry. Optimization and Comparison of Both Analytical Techniques. *Journal of Analytical Atomic Spectrometry (JAAS)* 16(2): 172-178.
- De Toppi, L.S., and Gabbrielli, R. (1999). Response to Cadmium in Higher Plants. *Environmental and Experimental Botany* 41(2): 105-130.
- Dennis, R.M., Dworkin, D., and Zupko, A.J. (1994). Soil Washing Processes for Site Remediation. In: D.L. Wise and D.J. Trantolo (eds.): *Remediation of Hazardous Waste Contaminated Soils*. Pp 745-778. Marcel Dekker Inc. NY.
- Denny, H.J., and Ridge, I. (1995). Fungal Slime and Its Role in the Mycorrhizal Amelioration of Zinc Toxicity to Higher Plants. *New Phytologist*: (n.p.).
- Di Cagno, R., Guidi, L., Stefani, A., and Sodatini, G.F. (1999). Effects of Cadmium on Growth of *Helianthus annuus* Seedlings: Physiological Aspects. *The New Phytologist* 144(1): 65-71.

- Dighton, J. (1991). Acquisition of Nutrients from Organic Resources by mycorrhizal autotrophic plants. *Experientia* 47: 362-369.
- Dighton, J., and Coleman, D.C. (1992). Phosphorus Relations of Roots and Mycorrhizas of *Rhododendron maximum* L. in the Southern Appalachians, North Carolina. *Mycorrhiza* 1: 172-182.
- Dixon, R.K., Garrett, H.E., Bixby, J.A., Cox, G.S., and Tompson, J.G. (1981). Growth, Ectomycorrhizal Development, and Root Soluble Carbohydrates of Black Oak Seedlings Fertilized by Two Methods. *Forest Science* 27: 617-624.
- Dixon, D.P., and Brown, E.J. (1987). The Effects of Surface Disturbances on the Leaching of Heavy Metals. Fairbanks: Water Research Center, Institute of Northern Engineering, University of Alaska Fairbanks.
- DOI, BLM, Steese/White Mountains District, DOD, U.S. Army, 6th Infantry Division (Light). 1994. Fort Greely Proposed Resource Management Plan, Final Environmental Impact Statement. Fairbanks, Alaska: The District, 1994: 144 pp.
- Draft Environmental Impact Statement on installation utilization for 172nd Infantry Brigade, Alaska at Fort Greely/U.S. Department of the Army. (1979). The Army: 505 pp.
- Dudka, S., Piotrowska, M., Terelak, H. (1996). Transfer of Cadmium, Lead, and Zinc from Industrially Contaminated Soil to Crop Plants: A Field Study. *Environmental Pollution* 94(2): 181-188.
- Eisler, R. (1997). Copper Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review. *Biological Science Report* 0(2): 1-99.
- Elliot, H.A., Linn, J.H., and Shields, G.A. (1989). Hazardous Waste Hazardous Materials 6: 223 - 228.
- Elliott, C.L., McKendrick, J.D., and Helm, D. (1987). Plant Biomass, Cover, and Survival of Species Used for Stripmine Reclamation in South-Central Alaska, U.S.A. *Arctic and Alpine Research* 19: 572-577.
- Ellis, B. (1992). On Site and In Situ Treatment of Contaminated Sites. In: F.J. Rees (ed.): *Contaminated Land Treatment Technologies*. Society of Chemical Industry. Elsevier Applied Science London. pp 30-46.
- Elzinga, E.J. and Sparks, D.L. (1999). Nickel Sorption Mechanisms in a Pyrophyllite–Montmorillonite Mixture. *Journal of Colloid and Interface Science* 213(2): 506-512.
- Emery, D.D., and Faessler, P.C. (1996). First Production-Level Bioremediation of Explosives-Contaminated Soil in the U.S. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Emmrich, M. (2001). Kinetics of the Alkaline Hydrolysis of Important Nitroaromatic Co-contaminants of 2,4,6-Trinitrotoluene in Highly Contaminated Soils. *Environmental Science and Technology* 35(5): 874-877.

- Empirical Models for the Uptake of Inorganic Chemicals from Soil by Plants. (1998). Washington, DC: DOE, 116 pp.
- Environmental Assessment of the Upgrade of Target Arrays, Fort Wainwright and Fort Greely, Alaska/United States, 11th Air Force. (1992). Elmendorf Air Force Base, Alaska, 11th Air Force.
- EPA. (April 1998). Phytoremediation Bibliography. Web site: <http://www.rtdf.org/pulic/phto/phtobib/biba-b.html>
- EPA. (August 1998). A Citizen's Guide to Phytoremediation. Technology Fact Sheet, EPA 542-F-98-011. EPA Office of Solid Waste and Emergency Response. Web site: <http://www.clu-in.org/products/citguide/phyto2.htm>. Retrieved April 1, 2001.
- EPA. Industry Profile Fact Sheets. Ordnance Sites. Brownsfields EPA Region III. Web site: <http://www.epa.gov/reg3hwmd/brownfld/industry.htm>. Retrieved March 24, 2001.
- Epler, Patti. (November 16, 1986). A Potentially Deadly Area: EPA Wants Army to Clean Up Old Chemical Weapons Test Site. Anchorage Daily News: A1.
- Erland, S., and Soderstrom, B. (1991). Effects of Lime and Ash Treatments on Ectomycorrhizal Infection of *Pinus sylvestris* L. Seedlings Planted in a Pine Forest. Scandinavian Journal of Forest Research 6: 519-525.
- Ernst, W.H.O. (1996). Bioavailability of Heavy Metals and Decontamination of Soils by Plants. Applied Geochemistry 11(1/2): 163-167.
- Etherington, J.R. (1982). Environment and Plant Ecology, 2nd ed. Chichester: John Wiley & Sons: 487 pp.
- Explosive Plant Growth: First-Ever Field Studies Conducted on TNT-Contaminated Crops. (No date). From: Frontiers: Research Highlights of Argonne National Laboratory. Web site: <http://gils.doe.gov:1782/cgi-bin/w3vdkhgw?qryQBB0RTZ0h;doecrawl-002098>. Retrieved March 17, 2001.
- Ex-Situ Bioremediation Technology for Treatment of TNT-Contaminated Soils. (1995). Cincinnati, Ohio: National Risk Management Research Laboratory, Office of Research and Development, EPA.]
- Eyre, S.R. (1968). Vegetation and Soils: A World Picture. London: Edward Arnold Publishers Ltd.: 328 pp.
- Felix, H. (1997). Field Trials for In Situ Decontamination of Heavy Metal Polluted Soils Using Crops of Metal-Accumulating Plants. Zeitschrift fur Pflanzenernahrung und Bodenkunde 160(5): 525-529.
- Fellner, R., and Peskova, V. (No date). Effects of Industrial Pollutants on Ectomycorrhizal Relationships in Temperate Forests. Canadian Journal of Botany S1310-S1315.
- Ferm, A., and Polet, K.E. (1991). Developing Methods for Afforestation of fields - Interim Report Peltojen Metsitysmenetelmat - Tutkimushankkeen Valiraportti. Metsantutkimuslaitoksen Tiedonantoja: 120 pp.

- Final Environmental Impact Statement on proposed land withdrawal for the 172nd Infantry Brigade (Alaska) at Fort Greely / U.S. Department of the Army. (1980). The Army: 530 pp.
- Flathman, P.E., Jerger, D.E. and Exner, J.H. (eds) (1994). Bioremediation Field Experiences. Boca Raton, Florida: CRC Press. 548pp.
- Fluckiger, W., and Braun, S. (No date). Revitalization of an Alpine Protective Forest by Fertilization. *Plant and Soil*: 481-488
- Ford, K.L. (No date). Risk Management Criteria for Metals at BLM Mining Sites. DOI, Bureau of Land Management (BLM), Service Center.
- Fort Greely Resource Management Plan/Environmental Impact Statement: Record of Decision. (1995). Prepared by DOI, BLM, Steese/White Mountains District.
- Fort Greely. (1996). A description of the U.S. DoD's Defense Technical Information Center (DTIC) BRAC Commission remediation activities 1995-1996. Web site: www.dtic.mil/envirodod/derpreport96/vol2/appx/app-a/nara068.html. Retrieved April 2, 2001.
- Fort Greely: Proposed Resource Management Plan, final EIS, prepared by DOI, BLM, Steese/White Mountains District; U.S. Department of Defense, U.S. Army, 6th Infantry Division (Light). (1994). Anchorage, Alaska: BLM: 144 pp.
- Foulkes, E.C., ed. (1990). *Biological Effects of Heavy Metals*. Boca Raton, Florida: CRC Press.
- Galli, U., Schuepp, H., and Brunold, C. (1994). *Physiol. Plant.* 92,364.
- Gange, A.C., Brown, V.K., and Farmer, L.M. (1990). A Test of Mycorrhizal Benefit in an Early Successional Plant Community. *New Phytologist* 115: 85-91.
- Ghaderian, Y.S.M., Lyon, A.J.E., Baker, A.J.M. (2000). Seedling Mortality of Metal Hyperaccumulator Plants Resulting from Damping Off by *Pythium* spp. *The New Phytologist* 145(2): 219-224.
- Gibbons, B. (1984). *How Flowers Work: A Guide to Plant Biology*. Dorset: Blandford Press: 160 pp.
- Gilcrease, P.C., Murphy, V.G., and Reardon, K.F. (1996). Bioremediation of Solid TNT Particles in a Soil Slurry Reactor: Mass Transfer Considerations. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Godbout, C., and Fortin, J.A. (1990). Cultural Control of Basidiome Formation in *Laccaria bicolor* with Container-grown White Pine Seedlings. *Mycological Research* 94: 1051-1058.
- Gould, A.B., Hendrix, J.W., and Ferriss, R.S. (1996). Relationship of Mycorrhizal Activity to Time Following Reclamation of Surface Mine Land in Western Kentucky. I. Propagule and Spore Population Densities. *Canadian Journal of Botany* 74: 247-261.
- Gould, A.B., Hendrix, J.W., and Ferriss, R.S. (1996). Relationship of Mycorrhizal Activity to Time Following Reclamation of Surface Mine Land in Western Kentucky. I. Propagule and Spore Population-Densities. *Canadian Journal of Botany* 74: 247-261.

- Gould, L.P., Severson, R.C., and Shacklett, H.T. (1988). Element Concentrations in Soils and Other Surficial Materials of Alaska. U.S. Geological Survey Professional Paper 1458: 53 pp.
- Grant, C.A., Buckley, W.T., Bailey, L.D., and Selles, F. (1998). Cadmium Accumulation in Crops. Canadian Journal of Plant Science 78(1): 1-17.
- Grossnickle, S.C., and Reid, C.P.P. (1982). The Use of Ectomycorrhizal Conifer Seedlings in the Revegetation of a High-elevation Mine Site. Canadian Journal of Forest Research 12: 354-361.
- Grould, L.P., Peard, J.L., Severson, R.C., Shacklett, H.T., Tompkins, M.L., Stewart, K.C., and Briggs, P.H. (1984). Chemical Analyses of Soils and Other Surficial Materials, Alaska. U.S. Geological Survey Open-File Report 84-423: 77 pp.
- Grusak, M.A., Pearson, J.N., and Marentes, E. (1999). The Physiology of Micronutrient Homeostasis in Field Crops. Field Crops Research 60(1-2): 41-56.
- Guyer, S. (2000). Vegetation Survey of Campbell Tract, Anchorage, Alaska. BLM-Alaska Technical Report 35.
- Hannenman, D. (1993). Heavy Metals in Rock Creek, Denali National Park. Available in the University of Alaska Anchorage/Alaska Pacific University Library Alaska Room Rare Book Collection.
- Harper, J. (2000). Heavy Metal Pumps in Plants. Final Report. Work Performed Under Contact No. DE-FG07-96ER20252 for the DOE by the Scripps Research Institute.
- Harvey, S.D., Fellows, R.J., Cataldo, D.A, and Bean, R.M. (1991). Fate of the Explosive [RDX] in Soil and Bioaccumulation in Bush Bean Hydroponic Plants. Environmental Toxicology and Chemistry 10: 845-855.
- Haug, J.W., Chen, J., Berti, W.R. and Cunningham, S.D. (1997). Environmental Science and Technology 31: 800.
- Hawthorne, S.B., and Lagadec, A.J.M. (2000). Pilot-Scale Destruction of TNT, RDX, and HMX on Contaminated Soils Using Subcritical Water. Environmental Science & Technology 34(15): 3224+ (5 pp.).
- Hawthorne, S.B., Lagadec, A.J.M., Kalderis, D., Lilke, A.V. (2000). Pilot-Scale Destruction of TNT, RDX, and HMX on Contaminated Soils Using Subcritical Water. Environmental Science and Technology 34(15): 3224-3228.
- Hawthorne, S.B., Lagadec, A.J.M., Kalderis, D., Lilke, A.V., and Miller, D.J. (2000) Pilot-Scale Destruction of TNT, RDX, and HMX on Contaminated Soils Using Subcritical Water. Environmental Science and Technology 34(15): 3224-3228
- He, Y., Schwab, A.P., and Banks, M.K. (1996). The Transport of Zinc in Soil as Affected by Citrate. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Helm, D. (1982). Multivariate Analysis of Alpine Snow-Patch Vegetation Cover Near Milner Pass, Rocky Mountain National Park, Colorado, USA. Arctic Alpine Research 14: 87-95.

- Helm, D.J. (1982). Vegetation studies for the proposed Susitna Hydroelectric Project. *Agroborealis* 14: 52-55.
- Helm, D.J. (1991). From Boreal Forest to Reclaimed Site: Revegetation at the Usibelli Coal Mine. *Agroborealis* 23: 45-50.
- Helm, D.J. (1994). Establishment of Moose Browse on Four Growth Media on a Proposed Mine Site in Southcentral Alaska. *Restoration Ecology* 2: 164-179.
- Helm, D.J. (1995). Native Grass Cultivars for Multiple Revegetation Goals on a Proposed Mine Site in Southcentral Alaska. *Restoration Ecology* 3: 111-122.
- Helm, D.J. 1992. Of Moose and Mines. *Agroborealis* 24: 41-48.
- Helm, D.J., Allen, E.B., and Trappe, J.M. (1996). Mycorrhizal Chronosequence Near Exit Glacier, Alaska. *Canadian Journal of Botany* 74: 1496-1506.
- Helm, D.J., Allen, E.B., and Trappe, J.M. (1999). Plant Growth and Mycorrhiza Formation by Transplants on Deglaciaded Land Near Exit Glacier, Alaska. *Mycorrhiza* 8: 297-304.
- Helm, D.J., and Carling, D.E. (1993a). Use of Soil Transfer for Reforestation on Abandoned Mined Lands in Alaska. I. Effects of Soil Transfer and Phosphorus on Growth and Mycorrhizal Formation by *Populus balsamifera*. *Mycorrhiza* 3: 97-106.
- Helm, D.J., and Carling, D.E. (1993b). Use of Soil Transfer for Reforestation on Abandoned Mined Lands in Alaska. II. Effects of Soil Transfers from Different Successional Stages on Growth and Mycorrhizal Formation by *Populus balsamifera* and *Alnus crispa*. *Mycorrhiza* 3: 107-114.
- Helm, D.J., and Collins, W.B. (1997). Vegetation Succession and Disturbance on Boreal Forest Floodplain, Susitna River, Alaska. *Canadian Field-Naturalist* 111: 553-566.
- Helm, D.J., and E.B. Allen. (1995). Vegetation Chronosequence near Exit Glacier, Kenai Fjords National Park, Alaska, U.S.A. *Arctic and Alpine Research* 27: 246-257.
- Helm, D.J., McKendrick, J.D., and Collins, W.B. (1987). Fertilizer Effects on Annual Grass in Wet Sedge-Grass Vegetation Site, Susitna Basin, Alaska, U.S.A. *Arctic and Alpine Research* 19: 29-34.
- Hermanson, M.H. Historical Accumulation of Atmospherically-Derived Pollutant Trace Metals in the Arctic as Measured in Dated Sediment Cores.
- Hewitt, A.D., and Jenkins, T.F. (1999). On-Site Method for Measuring Nitroaromatic and Nitramine Explosives in Soil and Groundwater Using GC-NPD: Feasibility Study ERDC/CRREL Special Report 99-9.
- Hilmi, A., and Luong, J.H.T. (2000). Micromachined Eletrophoresis Chips with Electrochemical Detectors for Analysis of Explosive Compounds in Soil and Groundwater. *Environmental Science and Technology* 34(14): 3046-3050.
- Hilmi, A., Luong, J.H.T., and Nguyen, A.L. (1999). Development of Electrokinetic Capillary Electrophoresis Equipped with Amperometric Detection for Analysis of Explosive Compounds. *Analytical Chemistry* 71(4): 873-878.

- Hofstetter, T.B., Heijman, C.G., Haderlein, S.B., Holliger, C., and Schwarzenbach, R.P. (1999). Complete Reduction of TNT and Other (Poly)nitroaromatic Compounds under Iron-Reducing Subsurface Conditions. *Environmental Science and Technology* 33(9): 1479-1487.
- Hofstetter, T.B., Heijman, C.G., Haderlein, S.B., Holliger, C., and Schwarzenbach, R.P. (1999). Complete Reduction of TNT and Other (Poly)nitroaromatic Compounds under Iron-Reducing Subsurface Conditions. *Environmental Science and Technology* 33(9): 1479-1487.
- Horstmeier, G.D. (1998). Heavy Metal Fertilizer. *Farm Journal* 122(6): 12 (2 pp.).
- Hughes, J., Rudolph, F., and Bennett, G. Anaerobic Biodegradation of 2,4,6-Trinitrotoluene and Other Nitroaromatic Compounds by *Clostridium acetobutylicum*. (No date.) National Center for Environmental Research, Office of Research and Development, USEPA: 3 pp. Web site: http://es.epa.gov/ncercqa_abstracts/centers/hsrc/bioremed/ssw-hughes2.html. Retrieved March 22, 2001.
- Hughes, J.B., Shanks, J., Vanderford, M., Lauritzen, J., and Bhadra, R. (1997). Transformation of TNT by Aquatic Plants and Plant Tissues Cultures. *Environmental Science and Technology* 31: 266-271.
- Huizenga P., and Tracy, J.C. (1996). Modeling Heavy Metal Movement in a Rooted Soil. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Hulten, E. (1968). *Flora of Alaska and Neighboring Territories: A Manual of the Vascular Plants*. Stanford, California: Stanford University Press: 1008 pp.
- Hunter, D. (June 7, 2000). Groups: Greely Reactor Made Weapons Material. *Anchorage Daily News*: A1.
- Hwang, P., Chow, T., and Adrian, N.R. (1998). Transformation of TNT to Triaminotoluene by Mixed Cultures Incubated Under Methanogenic Conditions. USACE, Construction Engineering Research Laboratories.
- Hyvarinen, H. and Nygren, T. (1993). Accumulation of Copper in the Liver of Moose in Finland. *Journal of Wildlife Management* 57(3): 469, 6 pp.
- Immunosensor for Explosives. (1997). *Analytical Chemistry* 69(13): 396.
- Jain, S.K. (1994). Heavy Metal Tolerance, Plant Evolution and restoration Ecology. *Conservation Genetics*: 407-410.
- Jefferies, S.A. (1992). Remedial Barriers and Containment. In: J.F. Rees (Ed). *Contaminated Land Treatment Technologies*. Soc. Chem. Indus. London: Elsevier Applied Science.
- Jeffers, T.H., Bennett, P.G., and Corwin, R.R. (1993). Biosorption of Metal Contaminants Using Immobilized Biomass: Field Studies. DOI, Bureau of Mines.
- Jenkins, T.F. (1990). Development of a Simplified Field Method for the Determination of TNT in Soil. CRREL Special Report 90-38.

- Jenkins, T.F., Grant, C.L., Brar, G.S., Thorne, P.G., Ranney, T.A., and Schumacher, P.W. (1996). Assessment of Sampling Error Associated with Collection and Analysis of Soil Samples at Explosives-Contaminated Sites. ERDC/CRREL Special Report 96-15.
- Jenkins, T.F., Leggett, D.C., and Ranney, T.A. (1999). Vapor Signatures from Military Explosives. Hanover, New Hampshire: USACE, CRREL Special Report 99-21.
- Jenkins, T.F., Pennington, J.C., Pennington, T.A., Ranney, T.E., Berry, Jr., T.E., Miyares, P.H., Walsh, M.E., Hewitt, A.D., Perron, N., Hayes, C., and Wahlgren, E. (2001). Characterization of Explosives Contamination at Military Firing Ranges. ERDC Technical Report (in review).
- Jenkins, T.F., Ranney, T.A., Miyares, P.H., Collins, H.H., and Hewitt, A.D. (2000). Use of Surface Snow Sampling to Estimate the Quantity of Explosives Residues Resulting from Land Mine Detonations ERDC/CRREL Technical Report 00-12.
- Jenkins, T.F., Ranney, T.A., Walsh, M.E., Miyares, P.H., Hewitt, A.D., and Collins, N.H. (2000). Evaluating the Use of Snow-Covered Ranges to Estimate the Explosives Residues that Result from Detonation of Army Munitions. ERDC/CRREL Technical Report 00-15.
- Jenkins, T.F., Schumacher, P.W., Mason, J.G., and Thorne, P.G. (1996). On-Site Analysis for High Concentrations of Explosives in Soil: Extraction Kinetics and Dilution Procedures. ERDC/CRREL Special Report 96-10.
- Jenkins, T.F., Schumacher, P.W., Mason, J.G., and Thorne, P.G. (1996). On-Site Analysis for High Concentrations of Explosives in Soil: Extraction Kinetics and Dilution Procedures. USACE CRREL Special Report 96-10.
- Jenkins, T.F., Thorne, P.G., and Walsh, M.E. (No date). Field Screening Method for TNT and RDX in Groundwater. Hanover, NH: USACE, CRREL.
- Jenkins, T.F., Walsh, M.E., Thorne, P.G., Miyares, P.H., Ranney, T.A., Grant, C.L., and Esparza, J.R. (1998). Site Characterization for Explosives Contamination at a Military Firing Range Impact Area. ERDC/CRREL Special Report 98-9.
- Jensen, D.L., Holm, P.E., and Christensen, T. H. (2000). Soil and Groundwater Contamination with Heavy Metals at Two Scrap Iron and Metal Recycling Facilities. Waste Management and Research 18(1): 52-63.
- Johnson, C.L. Soil Fundamentals. (1992). Alaska Cooperative Extension Crop Production and Soil Management Series: FGV-00242.
- Johnson, F.M. (1998). The Genetic Effects of Environmental Lead. Mutation Research 410(2): 123-140.
- Joner, E.J., and Leyval, C. (1998). Uptake of ¹⁰⁹Cd by Roots and Hyphae of a *Glomus mosseae/Trifolium subterraneum* Mycorrhiza from Soil Amended with High and Low Concentrations of Cadmium. The New Phytologist 135(2): 353-360.
- Jongruaysup, S., Dell, B., Bell, R.W., O'Hara, G.W., and Bradley, J.S. (1997). Effect of Molybdenum and Inorganic Nitrogen on Molybdenum Redistribution in Black Gram (*Vigna mungo* L. Hepper) with Particular Reference to Seed Fill. Annals of Botany 79(1): 67-74.

- Jorgenson, M.T., Roth, J.E., Smith, M.D., Schlentner, S.F., Lentz, W., Pullman, E.R., and Racine, C.H. (2001). An Ecological Land Survey for Fort Greely, Alaska. U.S. Army Engineer Research and Development Center, CRREL, Technical Report TR-01-4.
- Kabata-Pendias, A., and Pendias, H. (2001). Trace Elements in Soils and Plants, 3rd ed. Boca Raton, FL: CRC Press.
- Kelly, R.J. and Guerin, T.F. (1995) Feasibility of Using Hyperaccumulating Plants to Bioremediate Metal-Contaminated Soil. In Bioremediation of Inorganics, Hinchey, R.E., Means, J.L., and Burris, D.R. (eds.). Columbus, OH: Battelle Press, 25-32.
- Keltjens, W.G. and van Beusichem, M.L. (1998). Phytochelatins as Biomarkers for Heavy Metal Stress in Maize (*Zea mays* L.) and Wheat (*Triticum aestivum* L.): Combined effects of Copper and Cadmium. *Plant and Soil* 203(1): 119-126.
- Khan, A.G. and Chaudhry, T.M. (1996). Effects of Metaliferous Mine Pollution on the Vegetation and Their Mycorrhizal Associations at the Sunny Corner - a Silver Town of 1880's. Abs. First Intern. Conf. on Mycorrhiza, August 4-9, 1996. P70. University of California, Berkeley, USA.
- Khan, A.G., Chaudhry, T.M., Hayes, W.J., Khoo, C.S., Hill, L., Fernandez, R., and Gallardo, P. (1997). Water, Air and Soil Pollution (in press).
- Khan, A.G., Hill, Fernandez, R., Gallardo, P. and Chaudhry, T.M. (1996). Population of Micro- and Macroflora in Zinc Waste Contaminated Filtercake Dump Area. Remade Lands International Conference on the Remediation and Management of Degraded Lands, Hong Kong, 3-6 December, 1996. P 13. Hong Kong Baptist University.
- Kidd, J.G. (May 1999). Evaluation of Lake Sediment as a Growth Medium for Reclamation of the EKATI Diamond Mine, NWT, Canada. Prepared by ABR Inc., Fairbanks, Alaska, for BHP Diamonds, Inc. Yellowknife, Canada.*
- Kitts, C.L., Green, C.E., Otley, R.A., Alvarez, P.J. (2000). Type I Nitroreductases in Soil Enterobacteria Reduce TNT and RDX. *Canadian Journal of Microbiology* 46(3): 278-282.
- Klebesadel, L.J. (1993). Fescue Grasses Differ Greatly in Adaptation, Winter Hardiness, and Therefore Usefulness in Southcentral Alaska. *AK Agric. Agric. Exp. Sta. Bull* 92.
- Klebesadel, L.J. (1992). Seasonal Distribution of Forage Yield and Winter Hardiness of Grasses from Diverse Latitudinal Origins Harvested Four Times Per Year in Southcentral Alaska. University of Alaska Fairbanks Agricultural and Forestry Experiment Station, Bulletin 90.
- Klebesadel, L.J. (1976). Early Planting Is Important To Alaskan Growers Of Bluegrass And Red Fescue Seed. *Agroborealis* 8(1):22-24.
- Klebesadel, L.J. (1991). Performance of Indigenous and Introduced Slender Wheatgrass in Alaska, and Presumed Evidence of Ecotypic Evolution. *AK Agric Exp. Sta. Bull.* 85
- Klebesadel, L.J. (1993). Winterhardiness and Agronomic Performance of Wildryes (*Elymus* species) Compared With Other Grasses in Alaska, And Response of Siberian Wildrye to Management Practices. *Alaska Agricultural Experimental Station Bulletin* 97.

- Klebesadel, L.J. (1985). Hardening Behavior, Winter Survival, and Forage Productivity of Festuca Species and Cultivars in Subarctic Alaska. *Crop Science* Vol. 25:441-447.
- Klebesadel, L.J., and Helm, D. (1986). Food Reserve Storage, Low-Temperature Injury, Winter Survival, and Forage Yields of Timothy in Subarctic Alaska as Related to Latitude-of-Origin. *Crop Science* 26: 325-334.
- Klebesadel, L.J., Helm, D.J. (1992). Relationship of Latitude-of-Origin to Winter Survival and to Forage and Seed Yields of Wheatgrasses (*Agropyron* species) in Subarctic Alaska. *AK Agric. Exp. Stat. Bull.* 88.
- Knoop, B. (1996). The micronutrients: Fe, Mg, Mn, Ca, Zn, B. *Landscape Management* 35(10): 22.
- Kroopnick, P.M. (1994). Vapor Abatement Cost Analysis Methodology for Calculating Life Cycle Costs for Hydrocarbon Vapor Extracted During Soil Venting. In: D.L. Wise and D.J. Trantolo (Eds): *remediation of Hazardous Waste*. New York: Marcel Dekker Inc. pp 779-790.
- Kumar, P.B.A., Dushenkov, V., Motto, H., Raskin, I. (1995). *Environmental Science and Technology* 29: 1232.
- Larson, B.M., Hertkorn, N., and Sandermann, Jr., H. (1999). Classification of Explosives Transformation Products in Plant Tissues. *Environmental Toxicology and Chemistry* 18: 1270-1276.
- Lellinger, D.B. (1985). *A Field Manual of the Ferns and Fern-Allies of the United States and Canada*. Washington, DC: Smithsonian Institution Press: 389 pp.
- Leyval, C., Turnau, K, and Haselwandter, K. (1997). Effect of Heavy Metal Pollution on Mycorrhizal Colonization and Function: Physiological, Ecological and Applied Aspects. *Mycorrhiza* 7(3): 139-153.
- Li, Z.M., Shea, P.J., Comfort, S.D., Zhang, T.C., and Erickson, L.E. (1996). Fenton Oxidation Of TNT in Soil Slurries as Influenced by Temperature, Dissolved Organic Matter, and Clay Minerals. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Lichvar, R., and Sprecher, S. (1999). Wetland Delineation for Fort Greely, Alaska. Final report to U.S. Army Alaska, Fort Richardson, Alaska.
- Lindemann, T., Prange, A., Dannecker, W., and Neidhart, B. (2000). Stability Studies of Arsenic, Selenium, Antimony and Tellurium Species in Water, Urine, Fish and Soil Extracts Using HPLC/ICP-MS. *Fresenius' Journal of Analytical Chemistry* 368(2/3): 214-220.
- Lipkin, R., and Murray, D.F. (1997). *Alaska Rare Plant Field Guide*. USFWS, National Park Service, BLM, Alaska Natural Heritage Program, and USFS.
- Logan, T.J., Goins, L.E., and Lindsay, B.J. Field Assessment of Trace Element Uptake by Six Vegetables from N-Viro Soil. (1997). *Water Environment Research* 69(1): 28-33.
- Lombi, E., and Gerzabek. M.H. (1998). Determination of Mobile Heavy Metal Fraction in Soil: Results of a Pot Experiment with Sewage Sludge. *Communications in Soil Science and Plant Analysis* 29(17-18): 2545-2556.

- Lucero, M.E., Mueller, W., Hubstenberger, J., Phillips, G.C., and O'Connell, M.A. (1999). Tolerance to Nitrogenous Explosives and Metabolism of TNT by Cell Suspensions of *Datura Innoxia*. In *Vitro Cellular and Developmental Biology—Plant* 35 (6): 480-486.
- Major, E.B. (1997). Testing Application of Biological Criteria in the Mining Environment, Final Report. For EPA, Environment and Natural Resources Institute, University of Alaska Anchorage.
- Makhon'ko, K.P., Vertinskii, Y.K., and Raspopova, T.G. (1987). Accumulation of Microelements by Plants on Watersheds in the Permafrost-Taiga Zone. *Soviet Journal of Ecology* 18(4): 200-204.
- Malcolm, M.J., Allen, M.S., and Slaughter, K.E. (1990). Analytical Results and Sample Locality Map of the Nonmagnetic, Heavy-mineral-concentrate Samples Collected from the Eastern Part of the Lime Hills Quadrangle, Alaska. [Denver, CO]: DOI, USGS.
- Maloney, S.W. (1994). TNT Redwater Treatment by Wet Air Oxidation. Champaign, Illinois: USACE, Construction Engineering Research Laboratories.
- Marion, G.M., and Pelton, D.K. (2000). Frozen Soil Barriers for Explosives Containment. USACE, CRREL, ERDC Technical Report ERDC/CRREL TR-00-19.
- Markert, B. (1994). Plants as Biomonitors for Heavy Metal Pollution of the Terrestrial Environment. VCH, Weinheim.
- McEldowney, S., Hardman, D.J and Waite, S. (1993). Treatment Technologies. In: S. McEldowney, J. Hardman and S. Waite (Eds.). *Pollution, Ecology and Biotreatment*, pp 48-58. Longman Singapore Publishers Pte. Ltd. Singapore.
- McFarlan, S. 2-4-6-Trinitrotoluene Pathway Map. (2000). University of Minnesota: 3 pp. http://umbbd.ahc.umn.edu/tnt/tnt_map.html. Retrieved March 17, 2001.
- McGrath, S.P., Sidoli, C.M., Baker, A.J.M, and Reeves, R.D. (1994). Using Plants to Clean Up Heavy Metals in Soils. 15th World Congress of Soil Science, Acapulco, Mexico, 10-16 July 1994. *Transactions*, Vol. 4a: Commission III symposia: 362-363.
- McKendrick, J.D. (1999). Wildlife and Vegetation Find Habitat Niches on Oil Field Gravel Pad. *Agroborealis* 31(1): 36-38.
- McLean, J.E., and Bledsoe, B.E. (1992). Behavior of Metals in Soils. EPA Ground Water Issue, EPA 540-S-92-018: 25 pp.
- McNeill, K.R. and Waring, S. (1992). Vitrification of Contaminated Soils. In: J.F. Rees (Ed.): *Contaminated Land Treatment Technologies*. Society of Chemical Industry, Elsevier Applied Science, London.
- McQueen, C.B. (1990). *Field Guide to the Peat Mosses of Boreal North America*. Hanover, New Hampshire: University Press of New England: 138 pp.
- Meeussen, J.C.L., Keizer, M.G., van Riemsdijk, W.H., and deHaan, F.A.M. (1994). *Jour. Environmental Quality* 23: 785-792.

- Mench, M.J., Didier, V.L., Loffler, M., Gomez, A. and Masson, P. (1994). Journal of Environmental Quality 23: 58-63.
- Mengoni, A., Gonnelli, C., Galardi, F., Gabbriellini, R., and Bazzicalupo, M. (2000). Genetic Diversity and Heavy Metal Tolerance in Populations of *Silene paradoxa* L. (Caryophyllaceae): A Random Amplified Polymorphic DNA Analysis. Molecular Ecology 9(9): 1319-1324.
- Meyer, M.P., VandeWeb, D.A., and Shepherd, A.D. (2000). Mineral Assessment of Ahtna, Inc. Selections in the Wrangell-St. Elias National Park and Preserve, Alaska. BLM-Alaska Technical Report 34.
- Microbial Weathering Study of Composted Explosive-Contaminated Soil Obtained from the Umatilla Army Depot Activity, Umatilla, Oregon. Report No. SFIM-AEC-ET-CR-98042, October 1998. Technology Transfer Center, U.S. Army.
- Mitchell, W.W. (1965). The Status of Hybridization Between *Agropyron Sericeum* and *Elymus Sibiricus* in Alaska. Canadian Journal of Botany 43: 855-859.
- Mitchell, W.W. (1972). Red Fescue and Bluegrass Rank High in Frequent-Cut Test. *Agroborealis* 4(1) 30-31.
- Miyares, P.H., Reynolds, C.M., Pennington, J.C., Coffin, R.B., Jenkins, T.F., and Cifuentes, L. (1999). Using Stable Isotopes of Carbon and Nitrogen as In-Situ Tracers for Monitoring the Natural Attenuation of Explosives ERDC/CRREL Special Report 99-18.
- Molecular Bonding System for Heavy Metals Stabilization. (1997). Washington, DC: Solucorp Industries Ltd. For EPA, Superfund Innovative Technology Evaluation.
- Moore, B.W., Froisland, L.J., and Petersen, A.E. (1995). Rapid Separation of Heavy Rare-Earth Elements. DOI, Bureau of Mines.
- Moose and Molybdenum Don't Mix. (1996). *Current Science* 82(1): 13.
- Murray, D.M., Parker, C., and Batten, A.R. (1994). Flora of Alaska (preliminary). Northern Plant Documentation Center Report 86. Herbarium, University of Alaska Museum, Fairbanks, Alaska.
- Mushgrove, S. (1991). An Assessment of the Efficiency of Remedial Treatment for Metal Polluted Soil. In: M.C.R. Davies (Ed): Land Reclamation: an End to Dereliction. Intern Conf on Land Reclamation, April 1991, University of Wales. Essex, UK: Elsevier Science Publishers.
- Myers, T.E., and Townsend, D.M. (1996). TNT Breakthrough Curves for Aquifer Materials from the Louisiana Army Ammunition Plant, Shreveport, LA. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: <http://www.ecc.ksu.edu/HSRC/Abstracts96.html>. Retrieved April 1, 2001.
- Nam, S. (1997). On-Site Analysis of Explosives in Soil: Evaluation of Thin-Layer Chromatography for Confirmation of Analyte Identity. USACE CRREL, Special Report 97-21: 14 pp.
- Nash, J.T., et al. (1996). Geochemical Characterization of Mining Districts and Mining-related Contamination in the Prescott National Forest Area, Yavapai County. DOI, USGS.

- National Technology Transfer Center. The Cleanup Pillar. (No date). Web site: <http://www.nttc.edu/env/dod/grnbkclp.html>. Retrieved April 1, 2001.
- Nelson, M.G., Packee, E.C., and Helm, D.J. (1995). Reclaiming an Abandoned Placer Mine in Alaska. *Mining Engineering* 47: 240-242.
- No Change Expected in Part 503 Cadmium Limit. (1995). *BioCycle* 36(5): 8.
- Norman, A.G. *Advances in Agronomy*, Vol. 20. (1968). New York: Academic Press.
- Novel Cleanup of Explosives. (2000). *Environmental Science & Technology* 34(15): 354.
- NTTC. Heavy Metals Contamination Soil Project. (No date). Web site: http://www.nttc.edu/env/Heavy_Metals/heavy_metals_chap1.html. Retrieved: April 11, 2001.
- Odum, H.T., et al. (2000). *Heavy Metals in the Environment: Using Wetlands for Their Removal*. Boca Raton: Lewis Publishers.
- Ouzounidou, G., Moustakas, M., and Eleftheriou, E.P. (1997). Physiological and Ultrastructural Effects of Cadmium on Wheat (*Triticum aestivum* L.) Leaves. *Archives of Environmental Contamination and Toxicology* 32(2): 154-160.
- Palazzo, A.J., and Leggett, D.C. (1986). Effect and Disposition of TNT in a Terrestrial Plant and Validation of Analytical Methods. CRREL Special Report 86-15.
- Parker, D.R., and Pedler, J.F. Reevaluating the Free-Ion Activity Model of Trace Metal Availability to Higher Plants. (1997). *Plant and Soil* 196(2): 223-228.
- Pennington, J.C., Brannon, J.M., Gunnison, D., Harrelson, D.W., Zakikhani, M., Clarke, J. Miyares, P., Jenkins, T.F., Hayes, C., Ringleberg, D., Perkins, E., and Fredrickson, H. (2001). Monitored Natural Attenuation of Explosives. *Soil and Sediment Contamination* 10(1): 45-70.
- Peters, R.W., and Shem, L (1992). *Applied Microbiological Biotechnology* 40: 926-932.
- Peterson, P.J. (1993). Plant Adaptation to Environmental Stress: Metal Pollutant Tolerance. Paper in *Plant Adaptation to Environmental Stress*. Fowden, L, Mansfield, T., and Stoddart, J., eds. London, UK: Chapman and Hall Ltd.
- Phytoremediation of Lead-Contaminated Soil. (No date.) Environmental Center, U.S. Army. Web site: <http://aec-www.apgea.army.mil:8080/prod/usaec/et/restor/phyremld.htm>. Retrieved: March 24, 2001.
- Pilarski, J., Waller, P., and Pickering, W. (1995). Sorption of Antimony Species by Humic Acid. *Water, Air, and Soil Pollution* 84: 51-59.
- Pilon-Smits, E.A.H., Zhu, Y.L., Sears, T., and Terry, N. (2000). Overexpression of Glutathione Reductase in *Brassica juncea*: Effects on Cadmium Accumulation and Tolerance. *Physiologia Plantarum* 110(4): 455-460.
- Plant Adaptation to Mineral Stresses in Problem Soils. (1975). U.S. Department of Agriculture, Agricultural Research Service. (372) 47-55.

- Plant Uptake and Compost Weather Studies. (No date.) USAEC. Web site:
<http://aec.army.mil/prod/usaec/et/restor/plantupt.htm>. Retrieved: March 24, 2001.
- Plants of Alaska, Alphabetical Listing. (1994). U.S. Department of Agriculture, U.S. Soil Conservation Service, Anchorage, Alaska.
- Poulsen, I.F., and Bruun Hansen, H.C. (2000). Soil Sorption of Nickel in presence of Citrate or Arginine. *Water, Air, & Soil Pollution* 120(3/4): 249-259.
- Preliminary Characterization, Silver Crescent Mill Tailings and Mine Site, East Fork Moon Creek, Shoshone County, Idaho. (1996). Prepared by the Western Field Operations Center and Spokane Research Center, U.S. Bureau of Mines, Spokane, Washington. DOI, Bureau of Mines.
- Price, C.B., Brannon, J.M., Yost, S.L., and Hayes, C.A. (2001). Relationship Between Redox Potential and pH on RDX Transformation in Soil-Water Slurries. *Journal of Environmental Engineering* 127(1): 26-31.
- Price, L.C., Dewitt, E., and Desborough, G. (1998). Implications of Hydrocarbons in Carbonaceous Metamorphic and Hydrothermal Ore-deposit Rocks as Related to the Hydrolytic Disproportionation of Organic Matter. DOI, USGS.
- Public Health Assessment, Iowa Army Ammunition Plant, Middletown, Iowa. (1999). CERCLIS No. IA7213820445. Federal Facilities Assessment Branch, Division of Health Assessment and Consultation, Agency for Toxic Substances and Disease Registry. Web site:
http://www.atsdr.cdc.gov/HAC/pha/iowaarmy/iaa_toc.html. Retrieved April 8, 2001.
- Racine, C., Lichvar, R., and Duffy, M. (2001). An Inventory of the Vascular Flora of Fort Greely, Interior Alaska. USACE, CRREL TR-10-5: 44 pp.
- Racine, C., Lichvar, R., and Duffy, M. (February 2001). An Inventory of the Vascular Flora of Fort Greely, Interior Alaska. USACE CRREL: 44 pp.vice.
- Rao, K.J., and Shantaram, M.V. (1995). Effect of the Application of Garbage on the Soil-Plant System: A Review. *Agricultural Reviews—Agricultural Research Communication Centre* 16(3): 105-116.
- Rao, P.S.C., Davis, G.B., and Johnston, C.D. (1996). Technologies for Enhanced Remediation of Contaminated Soils and Aquifers: an Overview, Analysis and Case Studies. In: R. Naidu, R.S. Kookana, D.P. Oliver, S. Rogers and M.J. McLaughlin (Eds): *Contaminants and the Soils Environment in the Australasia-Pacific Region*. P3610410. Kluwer Academic Pub. London.
- Raskin, I., Kumar, N., Dushenkov, S., and Salt, D.E. (1994). Bioconcentration of Heavy Metals by Plants. *Current Opinion in Biotechnology* 5:285-290.
- Raskin, I., Nanda Kumar, P.B.A., Dushenkov, V. and Salt, D.E (1994). *Current Opinion in Biotechnology*, 5: 285.

- RDX. (1996). Agency for Toxic Substances and Disease Registry, Public Health Service, U.S. Department of Health and Human Services. Web site: www.atsdr.cdc.gov/tfacts78.html. Retrieved March 17, 2001.
- Reed, D.T., Tasker, I.R., Cunnane, J.C. and Vandegrift, G.F (1992). Environmental Restoration and Separation Science. In: G.F. Vandegrift, D.T. Reed and I.R. Tasker (Eds): Environmental Remediation. Removing Organic and Metal Ion Pollutants. American Chemical Society, Washington, DC.
- Report of the NATO Advanced Research Works on Destruction of Military Toxic Waste. 22-27 May 1994. Modified 29 April 1997. Naaldwijk, The Netherlands: <http://www.opcw.nl/chemhaz/arwnaal1.htm>. Retrieved March 17, 2001.
- Results of a Study Investigating the Plant Uptake for the Umatilla Army Depot Activity, Umatilla, Oregon. Report No. SFIM-AEC-ET-CR-98043. November 1998. U.S. Army. Technology Transfer Center, U.S. Army.
- Roberts, D.J., Ahmad, F., and Pendharkar, S. (1996). Optimization of an Aerobic Polishing State to Complete the Anaerobic Treatment of Munitions-Contaminated Soils. *Environmental Science and Technology* 30(6): 2021-2026.
- Roberts, Jeff. (2000). Hexahydro-1,3,5-Trinitro-1,3,5-Triazine Pathway Map. University of Minnesota. Web site: http://wwwdev.engineering.labs.com/project/rdx/rdx_map.htm. Retrieved March 17, 2001.
- Ross, S.M., ed. (1994). *Toxic Metals in Soil-Plant Systems*. Chichester, UK: John Wiley & Sons.
- Salt, D.E., Smith, R.D., and Raskin, I. (1998). Phytoremediation. *Annual Review of Plant Physiology & Plant Molecular Biology* 49: 643-668.
- Samantaray, S., Rout, G.R., and Das, P. (1998). Role of Chromium on Plant Growth and Metabolism. *Acta Physiologiae Plantarum* 20(2): 201-212.
- Samantaray, S., Rout, G.R., and Das, P. (1999). Studies on the Uptake of Heavy Metals by Various Plant Species on Chromite Minespoils in Sub-tropical Regions of India. *Environmental Monitoring and Assessment* 55(3): 389-399.
- Sauve, S.; Hendershot, W.; Allen, H. E. (2000). Solid-Solution Partitioning of Metals in Contaminated Soils: Dependence on pH, Total Metal Burden, and Organic Matter. *Environmental Science and Technology* 34(7): 1125-1131.
- Schnoor, J.L., et al. (1987). Processes, Coefficients, and Models for Simulating Toxic Organics and Heavy Metals in Surface Waters. Environmental Research Laboratory, Office of Research and Development, EPA.
- Selim, H.M., and Iskandar, I.K. (1994). Sorption-Desorption and Transport of TNT and RDX in Soils. Prepared for Office of the Chief of Engineers, USACE, CRREL.
- Shaw, A.J. ed. (1990). *Heavy Metal Tolerance in Plants: Evolutionary Aspects*. Boca Raton, Florida: CRC Press.

- Shaw, A.J., ed. (1990). *Colonization and Establishment of Plants in Contaminated Sites*. Boca Raton, Florida: CRC Press.
- Sheremata, T.W., and Hawari, J. (2000). Cyclodextrins for Desorption and Solubilization of 2,4,6-Trinitrotoluene and Its Metabolites in Soil. *Environmental Science and Technology* 34(16): 3462-3468.
- Sheremata, T.W., and Hawari, J. (2000). Cyclodextrins for Desorption and Solubilization of 2,4,6-Trinitrotoluene and Its Metabolites from Soil. *Environmental Science and Technology* 34(15): 3224-3228.
- Sheremata, T.W., Halasz, A., Paquet, L., Thiboutot, S., Ampleman, G., and Hawari, J. (March 2001). The Fate of the Cyclic Nitramine Explosive RDX in Natural Soil. *Environmental Science and Technology* 35(6): 1037-1040.
- Shetty, K.G., Hetrick, B.A.D., and Schwab, A.P. (1995). *Environmental Pollution* 88: 307
- Shoebridge, L. (1993). A Review of Soil Remediation Practices in Australia. In: A. Langley and M. vanAlpen (eds.) *The Health Risk Assessment and Management of Contaminant Sites*. Proc. 2nd National Workshop on the Health Risk Assessment and Management of Contaminated Sites, Canberra 5-7 April, 1993. South Australian Health Commission, Adelaide, S.A.
- Shuman, L.M., and McCracken, D.V. (1999). Tillage, Lime, and Poultry Litter Effects on Plant Concentrations of Zinc, Manganese, and Copper. *Journal of Plant Nutrition* 22(3): 609-620.
- Simini, M., Wentsel, R.S, Checkai, R.T., Phillips, C.T., Chester, N.A., Majors, M.A., and Amos, J.C. (1995). Evaluation of Soil Toxicity at Joliet Army Ammunition Plant. *Environmental Toxicology and Chemistry* 14: 623, 630.
- Singh, J., and Comfort, S.D. (1999). Iron-Mediated Remediation of RDX Contaminated Water and Soil Under Controlled Eh/pH. *Environmental Science & Technology* 33(9), 1488+ (7 pp.)
- Smith, B. (1993). *Waste Management Environment* 4: 24-30.
- Snyder-Conn, E., et al. (1988). *Persistence of Heavy Metals in Shallow Arctic Marine Sediments Contaminated by Drilling Effluents: Draft*. Fairbanks, Alaska: USFWS Fairbanks Fish and Wildlife Enhancement Office.
- Sposito, G. (1989). *The Chemistry of Soils*. New York: Oxford University Press.
- Stairs, N. (1998). Powerful pH. *Landscape Management* 37(7): 54 (3 pp).
- Stroinski, A. (1999). Some Physiological and Biochemical Aspects of Plant Resistance to Cadmium Effect. *Acta Physiologiae Plantarum* 21(2): 175-188.
- Taylor, R.L. 1970. Red Fescue—A Valuable Species. *Agroborealis* 2(1):8,10.
- The Clean-Up Pillar. (No date). Joint Service Pollution Prevention Technical Library, Naval Facilities Engineering Service Center. Web site: <http://enviro.nfesc.navy.mil/p2library>. Retrieved: March 17, 2001.
- The Gene that Keeps Plants off Geritol. (1996). *Science News* 149(25): 399 (5 pp.).

- Thompson, P.L., Ramer, L.A., and Schnoor, J.L. (1998). Uptake and Transformation of TNT by Hybrid Poplar Trees. *Environmental Science and Technology* 32: 975-980.
- Thompson-Eagle, E.T., and Frankenburger Jr., W.T. (1992). Bioremediation of Soils Contaminated with Selenium. In; R. Lal and B.A Stewart (Eds). *Advances in Soil Science*, 17: 261-310. Springer-Verlag, NY.
- Thomson, J.W. (1979). *Lichens of the Alaskan Arctic Slope*. Toronto, Ontario, Canada: University of Toronto Press: 314 pp.
- Thorne, K.A. NMR Studies on the Covalent Binding of the Reductive Degradative Products of TNT to Humic Substances, Model Compounds and Peat. In *Explosives Conjugation Products in Remediation Matrices: Interim Report 2* (Pennington, J.C., et al., eds.). USACE Technical Report SERDP-98-12: 7-37.
- Thorne, P.G. Fate of Explosives in Plant Tissues Contaminated During Phytoremediation. (1999). CRREL Special Report 99-19.
- Thorne, P.G., and Leggett, D.C. (1999). Investigations of Explosives and Their Conjugated Transformation Products in Biotreatment Matrices. ERDC/CRREL Special Report 99-3.
- Thorne, P.G., and Leggett, D.C. (1999). Investigations of Explosives and Their Conjugated Transformation Products in Biotreatment Matrices. USACE CRREL, Technical Report 99-3.
- Thorne, P.G., and Myers, K.F. (1997). Evaluation of Commercial Enzyme Immunoassays for the Field Screening of TNT and RDX in Water. ERDC/CRREL Special Report 97-32.
- Tomati, U., Galli, E., and Pasetti, L. (1996). Effect of Earthworms on Molybdenum-dependending Activities. *Biology and Fertility of Soils* 23(4): 359-361.
- Toxicity Studies for Biotreatment of Explosives-Contaminated Soils. (No date.) USAEC: 3 pp. Web site: <http://aec-www.apgea.army.mil:8080/prod/usaec/et/restor/bioreem.htm>. Retrieved March 24, 2001.
- Trett, M.W., Calvo Urbano, B., Forster, S.J., Hutchingson, J.D., Feil, R.L., Trett, S.P., and Best, J.G. (2000). Terrestrial Meiofauna and Contaminated Land Assessment. *Environmental Science and Technology* 34(8): 1594-1602.
- Tsai, K., Hsu, C., and Rosen, B.P. (1997). Efflux Mechanisms of Resistance to Cadmium, Arsenic, and Antimony in Prokaryotes and Eukaryotes. *Zoological Studies* 36(1): 1-16.
- Tuin, B.J.W., and Tels, M. (1991). *Environmental Technology*, 12, 178-190.
- U.S. Geological Survey Heavy Metals Program Progress Report 1968 – Topical Studies. (1969). Washington: DOI, USGS.
- USACE, Huntsville Center. (12 February 2001). Gerstle River FUD Fact Sheet. Formerly Used Defense Sites Project Fact Sheets. Web site: <http://www.hnd.usace.army.mil/owe/factshts/factshts/gr197.html>. Retrieved: April 2, 2001.

- USAEC. (No date). Cost and Design for Application of Biotreatment Technologies for Explosives-Contaminated Soil. Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.
- USAEC. (No date). Field Demonstration: Soil Slurry Reactor. Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.
- USAEC. Bioremediation of Explosives-Contaminated Soil. Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.
- USAEC. Field Demonstration: Soil Slurry Reactor. (No date.) Web site: <http://www.aec.army.mil:8080/prod/usaec/et/restor/soil.html>. Retrieved March 24, 2001.
- Valsaraj, K. T., Qaisi, K. M., and Constant, W. D. (1998). Diffusive Transport of 2,4,6-trinitrotoluene (TNT) from Contaminated Soil to Overlying Water. *Journal of Hazardous Materials* 59(1): 1-12.
- Van Bergen, S.K., Balkalcheva, I.B., Lundgren, J.S., and Shriver-Lake, L.C. (2000). On-Site Detection of Explosives in Groundwater with a Fiber Optic Biosensor. *Environmental Science and Technology* 34(4): 704-708.
- Van Lune, P., and Zwart, K.B. Cadmium Uptake by Crops from the Subsoil. (1997). *Plant and Soil* 189(2): 231-237.
- Vernet, J.P., ed. (1992). *Impact of Heavy Metals on the Environment*. New York: Elsevier.
- Viereck, L.A., and Little, Jr., E.L. (1972). *Alaska Trees and Shrubs*. Agriculture Handbook No. 410, U.S. Forest Service.
- Waldron, H.A., ed. (1980). *Metals in the environment*. London: Academic Press.
- Wallenborn, S.R., and Bailey, C.G. (2000). Separation and Detection of Explosives on a Microchip Using Micellar Electrokinetic Chromatography and Indirect Laser-Induced Fluorescence. *Analytical Chemistry* 72(8): 1872-1878.
- Walsh, M.E., and Ranney, T.A. (1998). Determination of Nitroaromatic, Nitramine, and Nitrate Ester Explosives in Water Using SPE and GC-ECD: Comparison with HPLC. USACE CRREL Technical Report 98-2.
- Walsh, M.E., and Ranney, T.A. (1999). Determination of Nitroaromatic, Nitramine, and Nitrate Ester Explosives in Soils Using GC-ECD. USACE CRREL Technical Report 99-12.
- Walsh, M.E., Collins, C.M., Racine, C.H., Jenkins, T.F., Gelvin, A.B., and Ranney, T.A. (2001). Sampling for Explosives Residues at Fort Greely, Alaska: Reconnaissance Visit July 2000. ERDC/CRREL Technical Report (in review).
- Wareing, P.F., and Phillips, I.D.J. (1981). *Growth and Differentiation in Plants*, 3rd ed. Oxford: Pergamon Press: 343 pp.
- Welsh, S.L. (1974). *Anderson's Flora of Alaska and Adjacent Parts of Canada*. Provo, Utah: Brigham Young University Press: 724 pp.

- West, R.L. (1982). Kantishna Hills Heavy Metals Investigations, Denali National Park. Fairbanks, Alaska: USFWS.
- West, R.L., and Deschu, N.A. (1984). Kantishna Hills Heavy Metals Investigations: Denali National Park 1983. Fairbanks, Alaska: USFWS.
- Wheeler, M (1994). Site Remediation: An Australian Perspective on "Best Practice." In Cole, J. (ed.) Environmental Management Industry Association of Australia Yearbook 1994. Waterloo, NSW, Australia: Executive Media, 156-160.
- Wild Edible and Poisonous Plants of Alaska. (1993). University of Alaska Fairbanks: Cooperative Extension Service, Bulletin 300C-0028.
- Wild, A. (1993). Soils and the Environment: An Introduction. Cambridge: Cambridge University Press.
- Williams, G.M. (1988). Integrated Studies into Ground Water Pollution by Hazardous Waste. In: J.R. Gronow, A.N. Schofield and R.K. Jain (Eds.). Land Disposal of Hazardous Waste, Engineering and Environmental Issues. Chichester, Sussex, UK: Ellis Horwood Ltd., 37-48.
- Williams, L.E., Pittman, J.K., and Hall, J.L. (2000). Emerging Mechanisms for Heavy Metal Transport in Plants. *Biochim Biophys Acta* 1465(1-2): 104-126.
- Williams, R.T., Ziegenfuss, P.S., and Sisk, W.E. (No date). Composting of Explosives and Propellant Contaminated Soils Under Thermophilic and Mesophilic Conditions.
- Wills, B. (1988). Mineral Processing Technology. 4th Ed. Oxford: Pergamon Press,.
- Wollin, K.M., and Levsen, K. (1999). Field Screening Methods for Explosives from Military Contaminated Sites. *Umweltwiss. Schadst.-Forsch* 11(6): 353-364. (Written in German.)
- Xiong, Z.T. (1998). Lead Uptake and Effects on Seed Germination and Plant Growth in a Pb Hyperaccumulator *Bassica Pekinensis* Rupr. *Bulletin of Environmental Contamination and Toxicology* 60: 285-91.
- Yaman, M. (2000). Nickel Speciation in Soil and the Relationship with Its Concentration in Fruits. *Bulletin of Environmental Contamination and Toxicology* 65(4): 545-552.
- Yland, M.W.F., and Wachem, E.G. (1988). Soil Covering Systems as Remedial Action in Contaminated Housing Areas in The Netherlands. In: K. Wolf, W.J. van den Brink and F.J. Colon (Eds.) Contaminated Soil 88. Pp 597-599. Second Intern. TNO/BMFT Conference on Contaminated Soil, 11-15 April, 1988.
- Ylaranta, T. (1996). Uptake of Heavy Metals by Plants from Airborne Deposition and Polluted Soils. *Agricultural & Food Science in Finland* 5(4): 431-447.
- Zhang, X., Yi, C., and Zhang, F. (1999) Iron Accumulation in Root Apoplasm of Dicotyledonous and Gramineous Species Grown on Calcareous Soil. *The New Phytologist* 141(1): 27-31.
- Zhu, D., Schwab, A.P., Banks, M.K., and Wang, E.X. (1996). The Impact Of Vegetation On Heavy Metal Movement. Conference Paper. HSRC/WER Joint Conference on the Environment. Web site: [http:// www.ecc.ksu.edu/HSRC/Abstracts96.html](http://www.ecc.ksu.edu/HSRC/Abstracts96.html). Retrieved April 1, 2001.

Zohlen, A., and Tyler, G. (2000). Immobilization of Tissue Iron on Calcareous Soil: Differences Between Calcicole and Calcifuge Plants. *Oikos* 89(1): 95-106.

9.1 Web Pages Consulted

Alaska Natural Heritage Program

Alaska Department of Environmental Conservations

USACE

US Army

CRREL

EPA

EPA Region 3

EPA Region 10

Fort Greely

CRREL

U.S. Army Corps of Engineers

USDA

WES

9.2 Telephone Consultations and Personal Interviews

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10.0 GLOSSARY

Absorption – the process of absorbing or of being absorbed

Adsorption – the adhesion in an extremely thin layer of molecules (as of gases, solutes, or liquids) to the surfaces of solid bodies or liquids with which they are in contact

Aerobic – living, active, or occurring only in the presence of oxygen

Anaerobic – living, active, or occurring in the absence of free oxygen

Bioremediation – Boosting the activity of naturally occurring microorganisms. Two methods are bioslurry and composting.

Bioslurry – a bioremediation technique wherein the contaminated materials are mixed into a slurry to allow contact between the microorganisms and the contaminants. The treated slurry is then suitable for direct land application.

Cation Exchange Capacity – The total amount of exchangeable cations that a soil can adsorb. It is sometimes called "total exchange capacity" "base exchange capacity," or "cation adsorption capacity." It is expressed in milliequivalents per 100 g of soil or of other adsorbing materials such as clay.

Composting – uses naturally occurring microorganisms to degrade organic wastes (such as to degrade hazardous substances in soil into nontoxic materials). Increased temperatures from heat produced by microorganisms speed their metabolism and degradation of the organic materials in the waste.

Degradation – the reduction of the complexity of a chemical compound

Denitrification – an act or process of denitrifying, specifically the reduction of

nitrates or nitrites commonly by bacteria and usually resulting in the escape of nitrogen into the air

Denitrify – to remove nitrogen or its compound from.

Explosive – An explosive is a compound or mixture susceptible (by heat, shock, friction or other impulse) to a rapid chemical reaction, decomposition or combustion with the rapid generation of heat and gases with a combined volume much larger than the original substance (Source: ILPI, <http://www.ilpi.com/msds/ref/explosive.html>).

Forbs – herbs other than grasses. Herbaceous plant other than those in the Gramineae (true grasses), Cyperaceae (sedges), and Juncaceae (rushes) families, i.e., any nongrass-like plant having little or no woody material

Grasses – "Grass" refers to "any plant of the family Gramineae, an important and widely distributed group of vascular plants, having an extraordinary range of adaptation. Numbering approximately 600 genera and 9,000 species, the grasses form the climax vegetation (see ecology) in great areas of low rainfall throughout the world. Most grasses are annual or perennial herbs with fibrous roots and, often, rhizomes. The stems are always noded and are typically hollow and swollen at the nodes, although many genera have solid stems. The leaves have two parts: a sheath surrounding the stem (called the culm in grasses); and a blade, usually flat and linear. The flowers are of a unique form, the inflorescence being subdivided into spikelets each containing one or more tiny florets. (In other flowering plants the inflorescences are clusters of separate flowers, never spikelets.) The dry seedlike fruit is called a caryopsis, or grain" (www.infoplease.com).

In-Situ – In-situ, or unexcavated, methods of soil treatments can include venting the soil with perforated underground piping or simply monitoring the natural breakdown of the contamination.

Phytodegradation, also called phytotransformation – the breakdown of contaminants taken up by plants through metabolic processes within the plant, or the breakdown of contaminants external to the plant through the effect of compounds (such as enzymes) produced by the plants (EPA, “Citizen’s,” 1998)

Phytoextraction – the direct uptake into plant tissue of metals, radionuclids, and certain organic compounds from soil

Phytoremediation – applies to a group of technologies that use plants and their associated rhizospheric microorganisms to remove, degrade, or contain chemical contaminants found in soil, sediments, groundwater, surface water, and even the atmosphere (Myers, Bryan, and Gilland, 2000). The EPA defines phytoremediation as the direct use of living green plants for in situ, or in place, risk reduction for contaminated soil, sludges, sediments, and groundwater, through contaminant removal, degradation, or containment.

Phytostabilization – the use of certain plant species to immobilize contaminants in the soil and groundwater through absorption and accumulation by roots, absorption onto roots, or precipitation within the root zone of plants (EPA, “Citizen’s,” 1998).

Phytotransformation – involves the degradation of contaminants through plant metabolism.

RDX – hexahydro-1,3,5-trinitro-1,3,5-triazine, commonly known as RDX (Royal Demolition explosive) is a white, crystalline, water-insoluble, powerful high explosive

(infoplease.com). It “is a hexacyclic ring containing six nitrogen atoms” (Roberts, 2000). Also known as cyclonite, hexagen, and cyclotrimethylemetrinitramine, RDX is a synthetic product that is used widely by the military in bombs and shells.

Rhizofiltration – the adsorption or precipitation onto plant roots or absorption into the roots of contaminants that are in solution surrounding the root zone; used primarily to address contaminated groundwater rather than soil (EPA, “Citizen’s,” 1998).

TNT – 2,4,6-Trinitrotoluene is “a yellow, odorless solid that does not occur naturally in the environment” (McFarlan, 2001). “It is commonly known as TNT and is an explosive used in military shells, bombs, and grenades, in industrial uses, and in underwater blasting.”

TNT – (from infoplease.com dictionary) - 1. Chem. a yellow, crystalline, water-insoluble, flammable solid, $C_7H_5N_3O_6$, derived from toluene by nitration, a high explosive unaffected by ordinary friction or shock: used chiefly in military and other explosive devices, and as an intermediate in the preparation of dye-stuffs and photographic chemicals. Also, T.N.T. Also called trinitrotoluene, trinitrotoluol, methyltrinitrobenzene, trotyl.

trinitrotoluene or TNT (- from infoplease.com encyclopedia) $CH_3C_6H_2(NO_2)_3$, crystalline, aromatic compound that melts at $81^\circ C$. It is prepared by the nitration of toluene. Trinitrotoluene is a high explosive, but, unlike nitroglycerin, it is unaffected by ordinary shocks and jarring, and must be set off by a detonator. Because it does not react with metals, it can be used in filling metal shells. It is often mixed with other explosives, e.g., with ammonium nitrate to form amatol.

Windrow composting – mixes the soil with compost in long piles known as windrows. Wood chips, manure, straw, alfalfa, and other

agricultural products are added to facilitate microbial growth.

10.1 Government Agencies

DEPARTMENT OF ENERGY—Manages and dismantles excess nuclear weapons, disposes of surplus fissile nuclear materials, and ensures the security of nuclear assets. Most common type of contamination: Radioactive waste, hazardous waste, mixed waste, fissile material. Major source: Former weapons production facilities. (Source: The Boston Globe).

DEPARTMENT OF DEFENSE—The nation's largest employer, the DOD provides the military forces needed to deter war and to protect the security of the United States. The DOD operates in more than 140 countries. Most common type of contamination: Fuels, solvents, industrial waste, unexploded ordnance. Major source: Underground storage tanks, landfills. (Source: The Boston Globe).

DEPARTMENT OF THE INTERIOR—As the nation's principal conservation agency, the DOI has jurisdiction over about 450 million acres of federal lands and has employees who work at more than 4,000 sites across the country. Most common type of contamination: Mining waste, municipal waste, industrial waste. Major source: Abandoned mines, oil and gas production. (Source: The Boston Globe).

DEPARTMENT OF AGRICULTURE—The department supports agriculture production,

manages the food supply, and provides economic opportunities for farm and rural residents. Most common type of contamination: Hazardous waste, mining waste, chemical waste Major source: Abandoned mines, landfills. (Source: The Boston Globe).

NATIONAL TECHNOLOGY TRANSFER CENTER—NTTC was established in 1989 by Congress to provide American companies and individuals with access to federal research and development to better enable them to compete in the international marketplace.

DEFENSE ENVIRONMENTAL RESTORATION PROGRAM—Formerly Used Defense Sites (DERP-FUDS). A DERP-FUDS project is a site that has been owned by, leased to, possessed by, or otherwise under the jurisdiction of Department of Defense (DoD). The DERP-FUDS program does not apply to those sites outside the U.S. jurisdiction. (Source: DOD Web site)

THE WATERWAYS EXPERIMENT STATION—WES is headquarters for the U.S. Army Engineer Research and Development Center (ERDC). Part of the Department of Defense laboratory system, the ERDC has as its mission to conceive, plan, study and execute engineering investigations and research and development studies in support of the civil and military missions of the Corps of Engineers and other federal agencies. (Source: WES Web site.)

11.0 ACRONYMS AND ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ADA	Ammunition Demolition Activity
ATSDR	Agency for Toxic Substances and Disease Registry
BL	Baseline
BLM	Bureau of Land Management
BRAC	Base Realignment and Closure
BTC	Breakthrough curve
Cd	Cadmium
CD	Cyclodextrin
CE	Capillary electrophoresis
CFI	Continuous-flow immunosensor
cm	Centimeter
CO₂	Carbon dioxide
Cr	Chromium
CRREL	Cold Regions Research and Engineering Laboratory
CRTC	Cold Regions Test Center
Cu	Copper
cy	Cubic yard
DA	U.S. Department of the Army
DCB	1,4-dichlorobenzene
DDE	dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DERP	Defense Environmental Restoration Program
DNT	Dinitrotoluene
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOM	Dissolved organic matter
DOT	U.S. Department of Transportation
DTIC	Defense Technical Information Center
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ERDC	U.S. Army Engineering Research Development Center
Fe	Iron
FOB	Fiber-optic biosensor
FUDS	Formerly Used Defense Sites
g	Gram
GAC	Granular activated carbon
g/L	Grams per liter
GREA	Gerstle River Expansion Area
GREATS	Gerstle River Expansion Area and Test Site
GRTS	Gerstle River Test Site

HMX	Octahydro-1,3,5,7-tetranitro-1,3,5,6-tetrazacine
HPLC	High-performance liquid chromatography
H₂S	Hydrogen sulfide
LAAP	Louisiana Army Ammunition Plant
µg	Microgram
µg/L	Micrograms per liter
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
mg/m³	Milligrams per cubic meter
mL	Milliliter
mM	Millimole
mV	Millivolt
N₂O	Nitrous oxide
Ni	Nickel
NIOSH	National Institute of Occupational Safety and Health
NMR	Nuclear magnetic resonance
NPD	Nitrogen-phosphorus detector
NRL	Naval Research Laboratory
NWTC	Northern Warfare Training Center
OB/OD	Open burning and open detonation
OE	Ordnance and explosives
Pb	Lead
PC	Phytochelatin
PCA	Principal components analysis
POL	Petroleum, oil, and lubricants
(P)NAC	Polynitroaromatic compounds
ppb	parts per billion
ppm	Parts per million
RA	Redundancy analysis
RAPD	Random amplified polymorphic DNA
RCRA	Resource Conservation and Recovery Act
RDX	Cyclonite/Hexahydro-1,3,5-trinitro,1,3,4-triazine
RPD	Relative percent difference
Sb	Antimony
SOM	Soil organic matter
S/S	Solidification/stabilization
TCLP	Toxicity characteristic leaching procedure
TNB	Trinitrobenzene
TNT	Trinitrotoluene
UMDA	Umatilla Army Depot Activity
USACE	U.S. Army Corps of Engineers
USAEC	U.S. Army Environmental Center
USAF	U.S. Air Force
USARAK	U.S. Army Alaska

USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UST	Underground Storage Tank
UV	Ultraviolet
UXO	Unexploded Ordnance
WES	Waterways Experiment Station
Zn	Zinc