The Use of Soil Amendments for Remediation, Revitalization, and Reuse

Solid Waste and Emergency Response (5203P)

EPA 542-R-07-013
December 2007
www.epa.gov

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Foreword

The U.S. Environmental Protection Agency (EPA) hosted a three-day Soil Amendments for Ecological Revitalization Workshop in August 2006 to assess known problems and potential solutions related to the use of soil amendments in revitalizing ecosystems on contaminated lands. This paper is a product of that workshop. Soil amendments of interest consist of waste residuals such as municipal biosolids, animal manures and litters, sugar beet lime, wood ash, coal combustion products, log yard waste, neutralizing lime products, and a variety of composted agricultural byproducts, as well as traditional agricultural fertilizers. This *in situ* soil remediation technology can be applied to Superfund and brownfields sites, large and small mining sites, and other sites with disturbed or degraded soils. Appropriate application of this technology has the potential to protect human health and the environment by reducing contaminant bioavailability and mobility at a considerably lower cost than other available options. This, in turn, allows for revitalization and reuse of these lands.

Disclaimer

This paper was prepared by the EPA Office of Superfund Remediation and Technology Innovation (OSRTI), with support under Contract Number 68-W-03-038. Although it has undergone EPA and external review by experts in the soil amendments field, information in this paper also was derived from a variety of sources, some of which have not been peer-reviewed. This document does not reflect Agency policy, nor is it a regulation. Thus, it does not change or substitute for any legal requirements. It also is not legally enforceable, and does not confer legal rights or impose legal requirements upon any member of the public, states, or any other federal agency. For further information, contact Ellen Rubin, EPA/OSRTI, at 703-603-0141 or, by email, at rubin.ellen@epa.gov.

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Cover and document photos courtesy of Dr. Sally Brown, University of Washington; William Toffey, Philadelphia Water Department; City of Princeton, IN; City of Shoreview, MN; College of Tropical Agriculture and Human Resources, University of Hawaii at Mānoa.

Acknowledgements

EPA would like to thank all the individuals and organizations that contributed their time, thought, and effort to the development of this paper. Without their efforts, the paper would not have come to fruition. The core group includes:

Harry L. Allen, IV, U.S. EPA
Dr. Sally Brown, University of Washington
Dr. Rufus Chaney, U.S. Department of Agriculture
Dr. W. Lee Daniels, Virginia Tech
Dr. Charles L. Henry, University of Washington
Dennis R. Neuman, Montana State University
Dr. Ellen Rubin, U.S. EPA
Jim Ryan, U.S. EPA
William Toffey, Philadelphia Water Department

EPA also would like to thank all reviewers and collaborators to this work group:

Harry Compton, U.S. EPA
Susan Mooney, U.S. EPA
John Oyler, Consultant
Lakhwinder Hundal, Metropolitan Water Reclamation District of Greater Chicago
Heather Henry, National Institute of Environmental Health Sciences
Ashfaq Sajjad, U.S. EPA
Mark Sprenger, U.S. EPA

Development of this paper was supported by the U.S. EPA Technology Innovation and Field Services Division and the U.S. EPA Land Revitalization Office.

Acronyms and Abbreviations

ARARs	Applicable or Relevant and Appropriate Requirements
BMP	Best management practice
CAFO	Concentrated animal feeding operations
CCA	Chromated copper arsenate
CCE	Calcium carbonate equivalent
CCP	Coal combustion products
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)
C:N	Ratio of carbon to nitrogen
Ca:Mg	Ratio of calcium to magnesium
Cu:Mo	Ratio of copper to molybdenum
EPA	U.S. Environmental Protection Agency
FBC	Fluidized-bed combustion
FGD	Flue gas desulfurization
NA	Not applicable
NAS	National Academy of Science
OM	Organic matter
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCP	Pentachlorophenol
% solids	A weight measurement of the amount of solids and liquid in a sample
POTW	Publicly Owned Treatment Works
RCRA	Resource Conservation and Recovery Act
ppt	Parts per thousand
PWD	Philadelphia Water Department
SAR	Sodium adsorption ratio
SMCRA	Surface Mining Control and Reclamation Act of 1977
t/ac	Tons per acre
TEQ	Toxic equivalent
TPM	Technical performance measure
USACE	U.S. Army Corps of Engineers
VDMME	Virginia Department of Mines, Minerals and Energy
WTR	Water treatment residuals

TABLE OF CONTENTS

List of Tables

List of Figures

1.0 INTRODUCTION

Hundreds of thousands of acres of disturbed and contaminated land scar this country's landscape. Some of these lands are in remote locations making cleanup very difficult. Others have minimal funds for cleanup or are so large that cleanup becomes economically impractical. There is a need for cost-effective, low energy technologies that can be applied at these sites. This paper provides information on the use of soil amendments, a cost effective *in situ* process for remediation, revitalization, and reuse of many types of disturbed and contaminated landscapes.

> The purpose of this paper is to assist regulators, consultants, site owners, neighbors, and other stakeholders in understanding the principles of soil amendment application for remediating and revegetating contaminated sites and to encourage widespread use of this alternative to revitalize and reuse contaminated land.

This paper focuses on amendments that are generally residuals from other processes and have beneficial properties when added to soil. Commonly used amendments include municipal biosolids, animal manures and litters, sugar beet lime, wood ash, coal combustion products such as fly ash, log yard waste, neutralizing lime products, composted biosolids**,** and a variety of composted agricultural byproducts, as well as traditional agricultural fertilizers. Applied properly, soil amendments reduce exposure by limiting many of the exposure pathways and immobilizing contaminants to limit their bioavailability. The addition of amendments restores soil quality by balancing pH, adding organic matter, increasing water holding capacity, re-establishing microbial communities, and alleviating compaction. As such, the use of soil amendments enables site remediation, revegetation and revitalization, and reuse.

Superfund sites, large and small mining sites, landfills, and industrial sites such as refineries, smelters, foundries, milling and plating facilities, and other sites with contaminated or disturbed soils exhibit a variety of problems that often can be addressed effectively and directly through the use of soil amendments. These problems include:

- The <u>toxicity</u> of various soil contaminants, principally metals, can be harmful to plants, soil animals, and soil microbial populations.
- A <u>higher- or lower-than-normal soil pH</u> range can cause soil infertility and cause soil metals (low pH) and oxyanions (e.g., arsenate at high pH) to go into solution.
- <u>Excess sodium (Na)</u> can cause toxicity to plants, a breakdown of soil physical structure, and dispersion, which limits root growth, aeration, and water infiltration through the soil.
- <u>Excess salts</u> (e.g., sulfates and chlorides) limit plant rooting and water and nutrient uptake.
- Changes in <u>soil physical properties</u>, such as density, aggregation, and texture, can reduce water infiltration and the moisture-holding capacity of the soil and stifle efforts to revegetate a site.

- Deficiencies in essential micronutrients like Zn and Mn can lower soil fertility; however, the same elements can be toxic at higher concentrations. In some cases, soil treatments to reduce phytotoxicity of one contaminant may reduce the phytoavailability of another essential element. Adding that nutrient as a companion fertilizer can prevent the deficiency due to the soil treatment.

Although soil amendments and associated enhancements in microbial activity can be used to address volatile and semivolatile contaminants that have left sites barren of vegetation, this paper focuses on the use of amendments on sites dominated by inorganic contaminants.

1.1 Background

The bioavailability of contaminants poses a health risk to animals and humans who may be exposed to contaminated sites. Possible exposure pathways include ingestion of contaminated soil or water from the site, direct contact with contaminated soil, inhalation of contaminants adhered to dust in the air, and ingestion of food items (i.e., plants or animals) that have accumulated contaminants from exposure to contaminated soil or water. Managing the risks posed by contaminants at a site involves understanding the possible pathways and applying appropriate remedial measures to mitigate, treat, or remove sources (Ref: 46).

Figure 1 illustrates how soil amendments can help mitigate exposure to contaminants. With the addition of appropriate soil amendments, metals in the amended area are chemically precipitated and/or sequestered by complexation and sorption mechanisms within the contaminated substrate. Metal availability to plants is minimized, and metal leaching into groundwater can be reduced. In certain cases, metal availability below the treated area is also reduced.

Active plant growth is an integral part of the soil amendment process; vegetation relocates water in the root zone and can transpire several hundred thousand gallons of water per acre during the growing season. This relocation has a significant impact on the volumes of water and metals that are able to move toward the groundwater. The selection of plant species for amended soil is based on the availability of seed or seedlings, their ability to establish and grow in the newly created root zone, the species' inability to translocate (move) metals from roots into the above-ground biomass of the plant, and land use and management considerations.

> Plants stabilize the landscape from erosion, greatly reducing surface water runoff and sediment loss to receiving streams. Plants also reduce erosion caused by wind.

Because soil amendments have a wide range of uses, the knowledge presented in this paper may be applied to various situations ranging from time-critical contaminant removal actions to ecological revitalization projects. Practitioners can use soil amendments to "jump-start" ecological revitalization at significant cost savings compared to traditional alternatives. In addition to eliminating exposure pathways and/or immobilizing metals and other contaminants, recycling these residual organic byproducts, instead of disposing of them, results in significant ecological benefits for the hydrosphere and atmosphere.

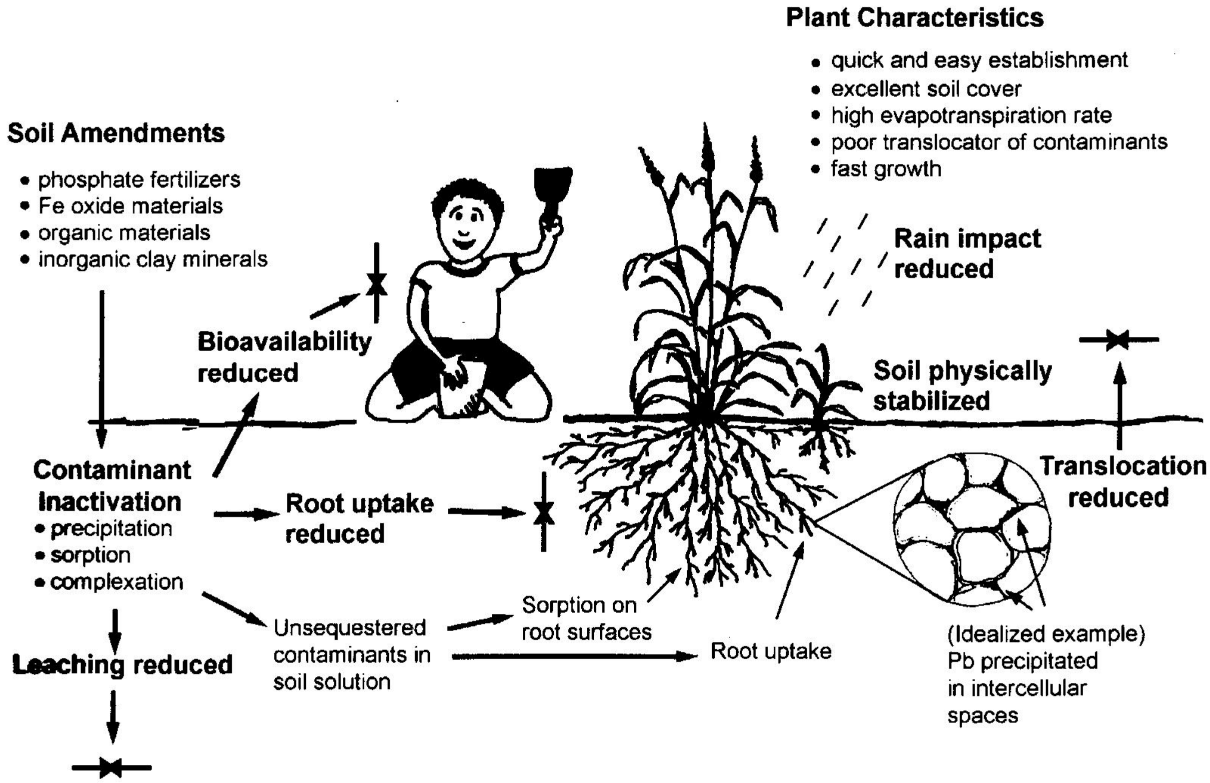


Figure 1. The Role of Soil Amendments and Plants in the Amendment of Metal-Contaminated Soil (Ref. 3)

1.2 How the Paper Is Organized

This paper is divided into the 10 sections shown below. These sections are structured to expand on information provided in the quick-reference tables that begin Sections 2, 3, 4, and 5 and present additional information about the use of amendments in a logical order. Each quick-reference table can be used independently, however, depending upon the user's primary focus.

- Section 1, Introduction, provides an overview of the soil amendments issue and describes the organization of the paper.
- Section 2, Types of Problems Addressed by Soil Amendments, describes how soil amendments can be used to address toxicity, pH, salinity (excess salts), sodicity (excess sodium), poor soil physical properties, and nutrient and fertility issues.
- Section 3, Types of Sites Where Soil Amendments Can Be Used, discusses hard rock mining sites, coal mining sites, refining and smelting sites, and construction sites and includes information on individual contaminants that may be present, the problems associated with them, and options for remediating them.
- Section 4, Types of Soil Amendments, describes soil amendments suitable for use in remediating and restoring sites, including their availability, potential uses, and issues regarding public acceptance issues, costs, advantages, and disadvantages.

- Section 5, Logistical and Other Considerations, focuses on a range of issues (e.g., site characteristics and operations, issues related to the public, and cost) that may need to be addressed in using soil amendments for remediation and revitalization at a specific site.
- Section 6, Revegetation of Amended Soil, provides helpful information about planning for and implementing site revegetation efforts.
- Section 7, Permitting and Regulations, reviews the regulatory requirements and authorities that may pertain to the use of soil amendments to remediate and revitalize sites.
- Section 8, Benefits of Using Soil Amendments, summarizes the environmental, human health, economic, and other advantages of soil amendments in remediating and revitalizing sites.
- Section 9, Monitoring and Sampling Amended Sites, describes an ongoing effort to delineate technical performance measures for use in verifying the effectiveness of soil amendments.
- Section 10, Conclusions.

In addition, this paper provides references to documents and Internet resources used in the preparation of this document, other relevant references, and useful links for obtaining additional information.

2.0 TYPES OF PROBLEMS ADDRESSED BY SOIL AMENDMENTS

Soil amendments can be used to address two primary categories of problems at contaminated sites: (1) contaminant bioavailability/phytoavailability and (2) poor soil health and ecosystem function. Solutions to the specific types of problems within these categories depend on the nature of specific contaminants, known exposure pathways and adverse effects, and specific interactions involved with the various recommended soil amendments and other contaminants (see Table 1).

Table 1: Types of Problems Addressed by Soil Amendments

	Exposure Pathways and Adverse Effects	**Interactions**	**Solutions**
Contaminant Bioavailability/Phytoavailability Problems			
Toxicity (inorganic)			
Aluminum (Al)	Phytotoxicity Runoff Leaching	Low pH [2] = more toxic; Low P = more toxic; High calcium (Ca) = less toxic	Raise pH greater than 6.0, add OM and P; add gypsum or other high soluble Ca source
Arsenic (As)	Soil Ingestion Runoff Leaching	High pH [2] = more toxic; High P = more soluble	Add organic matter (OM) and adjust pH to between 5.5-6.5
Borate (BO_3^{3-})	Phytotoxicity	Low and High pH [2] = more toxic	Add iron oxide and acidify (pH between 6.0-7.0)
Cadmium-to-Zinc Ratio (Cd:Zn) [1]	Food chain	High ratio = greater bioavailability (risk) of Cd	Add Zn to reduce the Cd:Zn ratio
Chromate (CrO_4^{2-})	Phytotoxicity Runoff Leaching	High pH [2] = more toxic	Add reductants, e.g., OM, biosolids; also acidify to less than 6.5
Copper (Cu)	Phytotoxicity Runoff Leaching Aquatic receptors	Low pH [2] = more toxic; low OM = more toxic	Raise pH (6.0-7.0), add P, OM, and sorbents
Lead (Pb)	Soil ingestion	Low phosphorus (P) = more toxic	With no As present, raise pH to 6.0 or greater; with As present, raise pH to 5.5-6.5; add P, and iron oxide
Manganese (Mn)	Phytotoxicity Runoff Leaching	Low pH [2] = more toxic	Raise pH greater than 7.0
Molybdenum (Mo)	Food chain Cu:Mo ratio	High pH [2] = more toxic; Low Cu = more toxic	Acidify (pH between 5.5- 6.5) and add Cu

	Exposure Pathways and Adverse Effects	Interactions	Solutions
Nickel (Ni)	Phytotoxicity	Low pH [2] = more toxic; low P = more toxic	Raise pH (7.0-8.0), add P, OM, and sorbents
Selenium (Se)	Food chain Runoff Leaching	High pH [2] = more toxic	Acidify (pH between 5.5-6.5)
Sulfate (SO_4^{2-})	Phytotoxicity to salt effects	NA	Irrigate soil
Zinc (Zn)	Phytotoxicity	Low pH [2] = more toxic; low P = more toxic	Raise pH (7.0-8.0), OM, and sorbents[3], e.g., iron and manganese oxides, WTR[4]
Toxicity (organic)			
Polycyclic Aromatic Hydrocarbon (PAH)	Soil Ingestion	Low OM [5]= more bioavailable	Add OM and tillage
Polychlorinated Biphenyl (PCB)	Soil Ingestion	Low OM [5]= more bioavailable	Add OM and tillage
Poor Soil Health/Ecosystem Function Problems			
High or Low pH			
Active Acidity (as measured directly in a water:soil mixture)	Runoff Leaching	Controls metal solubility and microbial activity; increases metal availability [6]	Add lime and/or other alkaline soil amendments
Alkalinity	Anion solubility and metal micronutrient availability	See Mo, Se, As listed above	Add acid equivalent
Potential Acidity (total acid production capacity with time; largely from unreacted sulfides)	Runoff Leaching Metal and salt evolution and associated phytotoxicity	Similar to active acidity (above) [6]	Estimate total lime demand and add 1.25 to 1.5 times the demand
Sodicity or Salinity			
Electrical Conductivity	Phytotoxicity, plant water stress, nutrient uptake imbalances	High Na = more toxic	Irrigate; OM may help
Sodium (Na)	Phytotoxicity Sodicity[7]	High SAR = high soil dispersion	Add any Ca:Mg-rich material[1]; OM
Changes in Soil Physical Properties			
Aggregation	Rooting and moisture-holding capacity	Low OM [4]= poor aggregation	Add OM and gypsum
Bulk Density	Limits rooting and infiltration	Low OM [4]= high bulk density	Add OM and deep tillage
Texture	Moisture-holding and soil strength	High clay = poor tilth; High sand = low moisture-holding	Modify with mineral soil amendments and add OM

	Exposure Pathways and Adverse Effects	Interactions	Solutions
Nutrient Deficiencies and Low Fertility			
High Calcium-to-Magnesium Ratio (Ca:Mg)[1]	Induced Mg deficiency in plants; Can reduce growth or kill plants	Very strong acidity causes loss of exchangeable cations (Ca, K, Mg), which makes Mg deficiency more likely; Addition of only calcitic limestone to acidic site can more easily induce Mg deficiency. Dolomitic or Mg-containing calcitic limestones do not cause this Mg deficiency risk	Add Mg
High C:N [1] ratio	Limits nitrate availability to plants/limits growth	NA	Add N or high-N soil amendments, e.g., manures, biosolids
High N	Nitrate leaching; Suppresses legumes and conifers	NA	Add cellulosic carbon, e.g., sawdust, rice hulls, or wood chips
High P	Runoff of soluble P or movement of soil particles to water can cause eutrophication; Limits Pb bioavailability; Reduces Cu, Cd, Ni, Zn phytoavailability; Supports legumes	Increases As availability[9]	Add Al or Fe to acid soils or Ca to alkaline soils to bind P; Drinking Water Residuals may be an effective source of Al or Fe for this purpose
Low Carbon-to-Nitrogen Ratio (C:N) [1]	Runoff Nitrate leaching	NA	Add cellulosic C e.g., sawdust, rice hulls, or wood chips
Low Nitrogen (N)	Limits growth	High C:N [1] ratio = low N availability	Add N and/or high-nitrogen OM
Low P	Limits growth	Increases metal availability[8]	Add P or high-P organic soil amendments
Manganese (Mn) deficiency	Limits growth	NA	Add Mn or lower pH to less than 6.0

[1] Ratios:
C:N ratio = 15-40:1
Ca:Mg ratio = no greater than 20:1
Cd:Zn = <0.015 on weight basis
Cu:Mo = >2:1 for cattle and >5:1 for sheep. Recommended Cu levels in feed/forages are 8 to 11 mg/kg. This amount should provide adequate copper if the diet does not exceed 0.25 percent sulfur and 2 mg Mo/kg diet. In a Cu-deficient diet, Mo can be toxic. Sulfur status of feed and forage also is a co-factor (Ref. 30, 26). Cu deficiency in cattle and sheep is easy to correct with mineral salt licks or supplements.

[2] Low pH = <5.5; High pH = >8

[3] WTR = water treatment residuals

[4] Target OM% for soil = >2.5%; target OM% for contaminated soil = >5%

[5] The term sorbents, as used here, describes materials that can hold on to or sorb different contaminants. There are a range of these materials, with different materials better suited for absorption of different contaminants. Some examples of sorbents include charcoal for different organic contaminants, water treatment residuals for excess P and some heavy metals, and high surface area iron oxides for heavy metals including Pb and As.
(Refs. 6, 13, 14, 58)

[6] All severely acidic soil systems are detrimental to plant growth because of Al and Mn toxicity. In cases where metal contaminants are present, acidity will increase metal availability. The toxicity of Al may be corrected by adding residuals high in cations such as Mg, Ca and K, even if these are in a form that does not increase soil pH. It is important in remediating these types of systems to make sure that sufficient Mg is available for plants. In cases where metal contaminants are present, acidity will increase metal availability.

[7] A measure of the excess sodium in a soil which imparts a poor physical condition to the soil. (Ref. 31)

[8] In cases where metal contaminants are present, insufficient P increases metal availability. Metals that are critical include Pb, Zn, and Cd. Agronomic tests for P availability to crops are useful to determine P status in soil where low P is suspected.

[9] High P is a concern in cases of As contamination. Since P and As are chemically related, high P increases As availability. Tests, including water soluble P and Fe strip P, are available to determine P status in cases where high P is suspected. For more information, see http://www.sera17.ext.vt.edu.

2.1 Exposure Pathways and Adverse Effects

2.1.1 Contaminant Bioavailability/Phytoavailability Problems

Although chemicals may be present in soils, not all of them may be bioavailable or phytoavailable. Bioavailability and phytoavailability are terms used to describe the degree to which contaminants are available for absorption or uptake by and interaction with the metabolism of organisms that are exposed to them. These processes are quantifiable through the use of multiple tools (Ref. 23, 33). Several types of exposure pathways and/or adverse effects may need to be addressed to solve bioavailability and/or phytoavailability problems.

2.1.1.a Phytotoxicity

Harmful substances can accumulate in plant tissue to a level that affects its growth and development (Refs. 2, 8). Metal toxicity can occur when a metal (often a necessary plant nutrient) is present in high concentrations. Toxicity becomes more severe at acidic soil pH or when coupled with other nutrient deficiencies.

Certain metals are more toxic to plants than they are to humans. An example of this is Zn. It will kill plants in concentrations that are too low to cause any negative human health effects. Some metals are necessary nutrients for animals. Plants with elevated concentrations of these nutrient metals generally will not cause detrimental effects to the animals that ingest them. These elements, even when essential for plants, can cause plant toxicities. Other metals, such as Pb, are generally not toxic to plants but can cause negative human health effects when soil is ingested directly. Most metals that are a threat to humans and wildlife are not necessary nutrients. For the majority of these (including Cr, As, and Hg) uptake by plants is minimal. The exception is Cd, due to its chemical similarity to Zn, a necessary nutrient. Cadmium is the most important example of a metal that is toxic to plants only at very high concentrations. Plants can take up Cd into foliar tissue. Foliar concentrations of Cd can be high enough to cause harm to wildlife before plants show any toxicity symptoms. Plant tissue tests can help to determine if there is metal toxicity. Commercial labs and land grant universities can generally do plant tissue analysis. Grab samples from young leaves of several plants in a field can be combined for analysis. They should be washed in soapy water, rinsed and air-dried before being sent to a lab. While toxic concentrations of metals in the above-ground portion of plants, including leaves and stems, vary across plant species, generally Zn > 400 mg/kg, Mn > 1000 mg/kg, and Cu > 40 mg/kg are potentially toxic.

2.1.1.b Food Chain Contamination

When plant cover is restored to a site, the potential for food chain contamination should be considered. Food chain contamination refers to the potential for the soil metals to cause harm to animals that feed off of the plants and soil mesofauna (animals living among the litter and inside the microscopic crevices of the site soil). Soil particles on the plants or the soil mesofauna may result in high enough levels of contaminants that are toxic to animals that consume them. For example, if shrews at a restored site feed largely on earthworms, the shrews will be exposed to high concentrations of contaminants in the soils. This is the case because earthworms generally consist of over 50% soil by weight. Consumption of soil through earthworm ingestion has the potential to result in high body burdens for shrews. This then could lead to an increase in body burden for birds that prey on the shrews. Soil extractions, such as dilute $Ca(NO_3^{-1})_2$, have been shown to be related to earthworm available metals and offer one way to evaluate this risk.

2.1.1.c Ingestion of Contaminated Soil

Ingestion of contaminated soil may result in an increased exposure to most elements. Examples of inorganic elements that may pose a risk include fluorine (F), lead (Pb), arsenic (As), and cadmium (Cd). Direct ingestion of soil by humans is generally not a risk for adults. Consumption of soil on an empty stomach will also result in greater contaminant adsorption due to the acidic gastric environment and a lack of competing ions. For wildlife, the situation is different. As stated earlier, some animals normally ingest high volumes of soil. Examples include worms and some water fowl. If the area that is being restored is expected to provide habitat to water fowl that dive into and feed on food, such as worms, in the sediment, the potential for contaminants to enter the food chain or to harm animals through direct ingestion is increased.

> Children, who are growing will absorb a greater portion of the ingested contaminant (particularly true for Pb) than adults.

2.1.1.d Runoff and Leaching

Soils devoid of vegetation are especially prone to water and wind erosion. Runoff refers to the movement of materials over the soil surface. Actual particles of soil can erode off of the surface. In addition, contaminants can come into solution and flow over the surface soils and off site. Leaching refers to the movement of contaminants through the soil profile. Although it is possible for contaminated particles to move through the soil though large pores, it is much more common for contaminants to come into solution and travel downwards through the soil with soil water. Runoff from these barren landscapes may contain contaminants, for example, copper (Cu) and Zn, at concentrations that may be lethal to aquatic resources in receiving streams. This problem is exacerbated if the runoff water is acidic.

At many mine sites, the formation of acid rock or acid mine drainage is common. During mining, uncovered rock may be exposed to oxidation processes, and this rock can remain exposed after the mine is abandoned. The oxidation of sulfide minerals in the rock, especially iron sulfide (FeS_2) produces acid that can solubilize metals. These low pH waters with elevated bioavailable metals can adversely impact receiving streams and aquatic receptors. Mine wastes and contaminated soil can be amended and vegetated to limit the loss of acidic, metal-rich runoff water to adjacent receiving streams. Studies compared 26 runoff events involving non-amended and contaminated soil to one event from lime-amended soil at a large Superfund site in Montana. The pH of runoff water from the untreated areas typically ranged from 3.8 to 5.3, while pH from the remediated soil was 6.2 during the single runoff event. Copper (Cu) and Zn levels in runoff water from the non-amended soil were several orders of magnitude higher than those observed from the treated site (Ref. 1).

2.1.2 Poor Soil Health/Ecosystem Function Problems

It is critical to revitalize soil health following drastic disturbance of a site through mining or other industrial activity. In most cases, appropriate organic and/or inorganic soil amendments can be used to revitalize soil by increasing water holding capacity, re-establishing microbial communities, and alleviating compaction**.** Refer to *The Nature and Property of Soil* by Brady and Weil for more details on soils (Ref. 4).

> All components of an ecosystem are dependent on healthy soil for the system to function optimally.

2.1.2.a High or Low pH

A higher- or lower-than-normal pH range (typically <5.5 or >8.5) in the soil, which could result from the runoff or leaching of industrial contaminants, acidic deposition, or exposure of acid- or alkaline-reactive geologic materials, can cause soil infertility and limit the microbial activity. Phytotoxicity is more likely with strongly acidic soil, such as soil where pyritic (containing sulfides) ores or acidic smelter emissions have caused local contamination. Pyrite and other sulfides in soil generate large amounts of sulfuric acid when they are oxidized. For example, in Butte, MT, and Leadville, CO, mine wastes reached a pH < 3.5 due to oxidation of pyrite in the soil. When soil is high in Zn, Cu, or nickel (Ni) contamination, soil pH may have to be raised to above 7.0 to reduce metal solubility enough to protect plant health and ensure food-chain safety. On the other hand, exposure of high Na subsoil or mine spoils can generate very high pH conditions that drastically limit phosphorus (P) availability and may induce high As, selenium (Se), and molybdenum (Mo) solubility. Similar problems may be found where waste limes (burnt lime and hydrolysis products) are found at elevated levels.

2.1.2.b Sodicity

Sodicity (high concentrations of Na) and/or high levels of exchangeable Na+ in soil has a detrimental affect on plants and, therefore, limit the use of salt-affected soils. Detrimental effects of sodicity or sodic soils are due to toxicity of Na+, HCO_3-, and OH- ions and to reduced water infiltration and aeration. Excess Na can cause soil dispersion, which inhibits plant growth by hardening soil and blocking water infiltration, reducing soil hydraulic conductivity, and creating a cement-like surface layer that blocks growth of root systems and water infiltration through the soil (Ref. 22). Soil with an accumulation of exchangeable sodium is often characterized by poor tilth (physical condition of soil related to its ease of tillage, fitness as a seedbed, and its favorability to seedling emergence and root penetration) and low permeability making it unfavorable for plant growth (Ref. 21).

2.1.2.c Salinity

Salinity, or excess salts, such as chlorides and sulfates in the root zone limits the ability of plants to withdraw water and nutrients from the soil. In this hypertonic micro-environment, water is lost from the roots to achieve osmotic equilibrium with the surrounding environment. In effect, the salts physically draw out water from the plant root leading to desiccation. Salts also interfere with active ion uptake mechanisms at the root interface requiring plants to exert more energy to extract water and nutrients. This decrease in plant-available water and nutrients in saline environments causes plant stress.

2.1.2.d Soil Physical Properties

Soil physical properties refer to the physical characteristics of the soil including, increased bulk density, poor aggregation, and textures that are too sandy or clayey. If a soil has a high bulk density (high weight per unit volume), it is generally too dense to contain enough pore space to allow oxygen to diffuse through a soil and keep it well aerated. In addition, pore space allows water to enter and move through a soil, helping avoid waterlogged conditions. A soil with high bulk density generally will have high clay content. Soils that consist of rocks and coarse fragments can have too much pore space, which allows water to flow through the soil very quickly. Roots have difficulty anchoring, and there is no habitat for soil microorganisms. Another important property is water infiltration capacity. If the soil surface is too crusted, water will pond or run off the surface. This increases the potential for the soil to be droughty.

> In order for the soil to support a healthy vegetative cover and microbial community, the soil must be able to maintain a sufficient amount of oxygen when wet and hold onto a sufficient amount of water during a dry spell.

2.1.2.e Nutrient Deficiencies/Low Soil Fertility

Striking the appropriate balance in metal concentrations is essential, since many of these metals also are toxic in high concentrations. Deficiencies in phosphorus (P) and nitrogen (N) limit growth. It is important to maintain sufficient available or labile N, P and K for the species of interest based on local (state) soil testing laboratory guidance. Deficiencies in Zn, Cu, manganese (Mn), and other metals that are necessary micronutrients also can lower soil fertility. In addition, proper ratios of Ca to Mg and carbon (C) to N are necessary for plant growth. As a rule-of-thumb, the C:N ratio is 15-40:1; the ideal Ca:Mg ratio is no greater than 20:1 (Ref. 5). Higher

C:N ratios will lead to immobilization of N. Soil microbes will scavenge for nitrogen and limit its availability for plants. In the case of lower C:N ratios, N will be in excess. This can lead to N leaching through the soil. While a wider range for acceptable C:N ratios is shown above, an optimal range would be 20-30:1. Refer to *Soil Fertility and Fertilizers* by Havlin and Tisdale for more details (Ref. 18).

2.2 Interactions

Contaminants can be, and generally are, co-occurring. For example, Pb and Zn commonly occur together in sulfide ores, and there may be significant As and Se in the material as well.

When two or more contaminants are present, the more protective solution should be applied. For example, Cd is almost always present at Zn-contaminated sites. Solutions to elevated Zn include raising soil pH. Adding sufficient P fertilizer also will reduce the bioavailability of Cd. Sometimes two solutions may be antagonistic or contradictory. In such cases, one should proceed based on the primary driver for ecosystem health. A good example would be a site that is co-contaminated with Pb and As. If the site were contaminated by Pb alone, addition of high rates of P would reduce Pb bioavailability. However, where As is a co-contaminant, adding high rates of P may increase As solubility. Here, if Pb is the primary driver and As concentrations are relatively low in comparison, P addition should be the preferred solution. When both Pb and As concentrations are high and both contaminants are risk drivers, an alternative solution, such as addition of a high-surface-area iron (Fe) oxide, such as ferrihydrite or high Fe biosolids compost, which is effective for both contaminants, would be the preferred alternative.

2.3 Solutions

Most of the solutions to the various problems presented in Table 1 include raising or lowering the pH of the soil; adding organic matter, phosphate and /or sorbents; tillage; and other listed management alternatives. Table 3 lists soil amendments that can be used to adjust the pH, add organic material, and act as a sorbent. Sorbents are a subset of amendments and have desirable chemical properties for reducing the solubility and bioavailability of various toxic elements or compounds.

3.0 TYPES OF SITES WHERE AMENDMENTS CAN BE USED

Many contaminated sites that would benefit from revitalization fall into four broad categories—hard rock mining sites, abandoned coal mines, refining and smelting sites, and construction sites. Some of these categories can be further divided into specific site types. For each site type, Table 2 shows the contaminants and problems that are likely to be found and suggests soil amendments to solve the problems. For example, all types of sites within the hard rock category potentially will have mine wastes onsite or nearby. They also may have tailings present. Soils at these sites generally are infertile with poor physical properties. The general solution for revitalization of these sites is to add an organic soil amendment mixture rich in N and P, adjust the pH using neutralizing lime, followed by seeding and planting of vegetation species appropriate for the land use.

3.1 Hard Rock Mining Sites

Hard rock mining sites are sites where the desired mineral must be extracted from rock hosts. Examples of common hard-rock derived metals include Fe, Zn, Pb, cobalt (Co), Cu, gold (Au), and Mo, although some of these are mined from sedimentary deposits as well. The desired metal is present at an elevated concentration in a mineral matrix (ore) that is sufficiently above background to make extraction of the metal economically viable. In addition to the mined ore, hard rock mining sites must move large amounts of non-mineralized rock (overburden) to get to and remove the ore. These sites can include open pit and underground mining operations. In both cases, overburden or waste rock with low mineral concentration frequently makes up a large portion of the waste material onsite. Tailings, created when the ore-rich rock is ground up and the economic mineral is extracted via flotation or screening, also can be present onsite or in adjacent tailing disposal facilities. Adjacent soil also may be contaminated from fluvial deposition or, in some instances, the use of historical irrigation practices. For most of these sites, overburden or waste rock, which often is acidic and has elevated contaminant concentrations, is the material left that needs to be revegetated.

Since many hard rock mining sites generate acidic soil conditions in their overburden and waste rock, addition of liming materials is usually an essential first step to site remediation. However, there are limitations associated with lime treatment of acid-forming mine waste. Problems achieving adequate mixing are commonly encountered in excessively rocky materials.
Lime is not well mixed into the full depth of the profile, and tillage equipment tends to create a rock pavement veneer with repeated incorporation passes of soil with more than 40% rock. A second limitation encountered with lime treatment relates to contamination levels. When levels of trace metals are modest, bulk alkaline addition can neutralize pH enough to precipitate toxic metals and control phytotoxicity. However, when high levels of metals are present in the neutralized root zone following treatment, residual phytotoxicity has caused apparent vegetation failure. No rigid criteria have been developed to address this issue. Progressively more intensive treatments, adding more organic matter and fertilizer, have been employed with modest success.

At the highest levels of total metals in the treated soil profile, very few plants will survive (Ref. 29).

3.2 Coal Mining Sites

This category includes both eastern (dominantly acid-forming) and western (high salt and sodium) coal mining sites. It also includes piles of coal processing waste piles and fills, which tend to be much more difficult to reclaim and revegetate than the mine sites.

Sand and gravel mining sites are included within this category, because vegetation challenges are similar to those at coal mining sites. For most of the sites within this category, contaminant concentrations are low. Obstacles to ecosystem revitalization are related to undesirable pH levels, low fertility, and poor soil physical properties.

3.3 Smelting and Refining Sites

Smelting and refining sites are facilities where different ores or fuels have been processed. Contaminated waste materials at these sites are confined to a smaller area than at hard-rock mining sites or coal mining sites; however, aerial deposition of contaminants at the processing facility can spread contamination over a very wide area. Localized and aerially dispersed contaminants or wastes are the two broad categories within this category of sites. Complex organic compounds are common contaminants at refining sites and these issues are not specifically addressed in this paper.

3.4 Construction and Mixed-Contaminant Sites

Construction sites are very common and include urbanized and industrialized areas, highway and utility corridors, and airports. Revitalization of these sites is significantly improved when soil amendments are used. Mixed-contaminant sites are those with elevated but relatively low concentrations of multiple metals and organics. Common examples include urban brownfields sites.

3.5 Other Sites

While the range of soil amendments listed in Table 2 can restore ecosystem function and a self-sustaining plant cover on the majority of sites, some disturbed sites do not respond to the addition of amendments. Sites with excess amounts of soluble salts or pyretic materials are examples. In both cases, the recommended approach is to cap the disturbed site and create a new soil horizon above the cap. This approach was used at a smelter waste site in Poland where excessive salts prevented plant establishment despite high application rates of biosolids and a high calcium carbonate residual (Ref. 11). As an alternative, the site was capped with 10 inches of the high lime material, and a new soil horizon was created with biosolids incorporated into the upper portion of the lime cap. For such highly contaminated sites, residuals and soil amendments are excellent alternatives to clean fill for building a new soil above the barrier to the damaged soil.

Table 2: Types of Sites Where Soil Amendments Can Be Used

Site	Contaminant	Problem	Solution
Mining			
Hard Rock (Ferrous and non-ferrous)	There are some common mixtures of contaminants at these sites. See below for specific combinations.	Metal contamination; Soil generally is highly infertile; Acid mine drainage possibility; Poor physical properties[1] .	Commonly requires nitrogen (N) and phosphorus (P) rich organic soil amendment at high rate to improve soil physical properties and nutrient status; Neutralizing soil amendments may be necessary to raise pH.
	Copper (Cu)/Arsenic(As)/Pb/ Molybdenum (Mo)	Existing and potential acidity; Soil ingestion risk from As and Pb; Possible food chain risk from Mo; Aquatic risk from Cu	Add lime to correct potential and existing acidity; Final target pH is 5.5 to 6.5 to limit As bioavailability. In cases where Mo is primary concern, final pH is <5.5.
	Cyanide (CN)	Groundwater contamination and residual CN from leaching of gold (Au) using cyanide solutions	Oxidation of cyanide solutions; Cover or cap waste piles with cover soils.
	Lead (Pb)/Zinc (Zn)/ Cadmium (Cd)	Zn induced phytotoxicity; P deficiency; Low pH acid generating potential; Soil ingestion Pb risk; Cd food chain risk	Add lime to correct potential and active acidity plus additional 25 to 50% reserve factor; ensure sufficient P to inactivate Pb and provide fertility to support legumes.
	Mercury (Hg)/As	Food chain (aquatic) risk from Hg; Soil ingestion risk from As; Concerns about volatilization of Hg.	Surface apply organic or organic-mineral soil amendments without incorporation to eliminate volatilization potential and provide a barrier against soil ingestion.
	Nickel(Ni)/Cobalt(Co)	Ni induced phytotoxicity; P deficiency; Existing and potential acidity	Add lime to correct potential and active acidity plus additional 25 to 50% reserve factor; Ensure sufficient P to provide fertility to support legumes.
	Pyrite (FeS2)/As/Selenium (Se)/Ni/Cu	Existing and potential acidity; Soil ingestion risk from As; Se leachability and food chain risk; Wide range of other metals possible	Add lime to correct active and potential acidity plus 25 to 50% reserve factor (this will also reduce availability of other metals); If high As, lower target pH to less than 6.5.
	Selenium (Se)	Increased Se solubility and bioavailability at phosphate mines due to changes in oxidation state of Se	Achieve reducing conditions; Cover and cap waste piles.
Coal	Pyrite-based acidity and exchangeable Sodium (Na) and salts, soluble Se	Metal contamination; Rocky, compacted and infertile soil	See below
Coal waste piles	Pyrite-based acidity	Existing and potential acidity; physical problems; acid mine drainage; Dark color (which causes heat kill of seedlings); low moisture-holding	Add lime to correct existing and potential acidity plus additional safety factor of 20 to 30% is sufficient; Add organic soil amendments to revitalize soil; Modify surface texture by adding OM or adding amendment with sand or clays, such as biosolids; Lighten surface color of pile to prevent heat-kill of seedlings.

Site	Contaminant	Problem	Solution
Eastern (acid-forming)	Pyrite and associated metals	Existing and potential acidity; Physical problems; Acid mine drainage	Add lime to correct existing and potential acidity plus additional 25 to 50% safety factor is sufficient; Add organic soil amendments to revitalize soil; Modify surface texture where possible.
Sand/Gravel mines	In Eastern sites, may have associated acidity problems	Coarse texture or rocky and very infertile; Heavy soil compaction and low water retention and/or rooting depth	Add lime and organic soil amendment (generally high application rate beneficial) with appropriate C:N ratio to minimize nitrate leaching.
Western (Na and salts)	Na, salts, Se	Salinity, sodicity, and physical problems; Se leaching and aquatic biomagnification	Add OM and Ca-rich soil amendments; Irrigate to remove salts where possible; Segregate Se bearing materials and avoid Se accumulating plant species for revegetation.
Refineries/Smelters			
Aerial Deposition	Metals (see mining sites above)	Metal toxicity; Acidity, Possible infertility; In urban environment, soil ingestion may be dominant risk	See metals-specific remedies above.
Smelter Process Waste/Slag		Metal acidity; Salts; Dark color (which causes heat kill of seedlings); Cementation	See metals-specific remedies above; For color, surface mulch to modify temperature or surface apply light-colored mixtures of alkaline fly ash and biosolids; For cementation, modify physical properties; For salts, irrigate and if electrical conductivity (EC) is excessive, capping may be necessary.
Tailings	Metals (see mine sites above); Cyanide	Metal toxicity; Acidity (associated acid drainage) or alkalinity; Infertility; Physical properties; Cyanide in gold (Au) tailings	See metals-specific remedies above; modify physical properties. [1]
Construction Sites	See sand and gravel; urban contaminants	See sand and gravel; Compaction, mixed soil and geologic materials, imbalanced pH and low fertility all common	Site-specific remedies based on contaminants.
Mixed Contaminants	Low levels of metals and organics	Often former industrial sites will have soil physical and nutrient problems	Soil amendments to improve nutrient and physical characteristics and pH adjustment as needed can often reduce contaminant availability; Site-specific evaluation necessary.

[1] Poor soil physical properties, such as density, aggregation, and texture, can reduce water infiltration and the moisture-holding capacity of the soil and stifle efforts to revegetate a site.

[2] Modify Physical Properties = If the soil is too coarse, add fines, sand or silt. If the soil is too fine, add OM or a course material.

4.0
TYPES OF SOIL AMENDMENTS

This section briefly describes soil amendments and organizes them by use: organic soil amendment, pH soil amendment, and mineral soil amendment. Table 3 lists the various soil amendments along with their availability, uses, public acceptance, cost, advantages, and disadvantages. Note that specific regulatory or permitting requirements for various types of amendments are addressed in Section 7 of this document.

The type, mix, and amounts of soil amendments will vary from site to site in response to the local mix of site contaminants, soil conditions, and type of desired vegetation. The first and most essential components of any soil amendment strategy are an accurate assessment of existing site-soil conditions and knowledge of the range of target soil conditions appropriate for the revegetation species of interest. Post-revitalization land use also is an important consideration in choosing soil amendments and remedial strategies. Additionally, it is essential that potential soil amendments be carefully characterized for all important physical, chemical and microbiological properties.

4.1 Organic Soil Amendments

A wide array of organic soil amendments, with varying levels of processing and characterization is available in most regions. Organic amendments most frequently are used to provide essential nutrients (such as N and P), to rebuild soil organic matter content, and re-establish microbial populations. Benefits directly associated with improved organic matter content are: enhanced water infiltration and moisture-holding, aggregation, aeration, nutrient supply for plant growth, and microbial activity (Refs. 44, 56, 57).

Biosolids. Biosolids are the primary organic solid byproduct produced by municipal wastewater treatment processes that have been treated to meet federal and state land-application standards (Refs. 25, 53). Over 7 million tons of biosolids are generated annually by municipal wastewater treatment plants in the United States, and about 55% of this material is land applied in one form or another, primarily to agricultural land (Ref. 32). Compared to many other organic soil amendments, biosolids are highly characterized and often are readily available at low cost for use as a soil amendment on disturbed lands (Ref. 17). Biosolids characteristics can be quite variable between sources, but are very predictable from any one source. In addition to available nutrient and organic soil amendment benefits, biosolids often possess significant liming and sorbent properties as well. Use of biosolids may be limited by excessive nutrient loading concerns at higher loading rates, and odors occasionally cause public acceptance issues. The nitrogen content of biosolids is generally of the "slow-release" type and becomes available to vegetation slowly over several years following application. For more information on biosolids, go to http://www.epa.gov/waterscience/biosolids/.

Because of advancements in industrial pretreatment programs over the years, biosolids tend to have metal concentrations much lower than regulations require.

Table 3: Types of Soil Amendments

Amendment	Availability	Uses	Public Acceptance	Cost	Advantages	Disadvantages	Links
Organics							
Biosolids	Sustainable supply; Higher quantities in urban areas	Nutrient source; Organic matter (OM) source; Sorbent[1] properties increase with increasing iron content.	Largely odor-driven; Pathogen concerns; Concerns largely driven by perception.	Materials generally free; Municipalities may pay for transport and use.	Multi-purpose, multi-benefit soil amendment; highly cost-effective; EPA regulated[2]; well characterized consistent quality.	Public concern/public perceptions; High nutrient loadings in some settings; Some sources have high moisture content.	National Biosolids Partnership (http://www.biosolids.org/index.asp)
Manures	Sustainable supply; Higher quantities near CAFOs	Nutrient source; OM source.	Well accepted.	Materials generally free; Transport and application fee.	Widespread and readily available.	Not consistently regulated[2]; Variable quality; Not routinely treated for pathogen reduction; Generally uncharacterized.	Industry Residuals: How They Are Collected, Treated and Applied (http://www.clu-in.org/studentpapers/)
Compost	Location-dependent; Volumes limited; Competing users	Nutrient source; OM source.	Readily accepted.	Product and transport costs can be high.	Readily accepted; Stable product; Can be used in or near water.	High cost; Limited availability; N quantity usually significantly lower than non-composted materials.	U.S. Composting Council (http://www.compostingcouncil.org/section.cfm?id=37) Association of Compost Producers
Digestates[3]	New material; Very location dependent	Nutrient source; OM source.	May have odor problems.	To be determined; Transport and application fee.		New enough so that not regulated[2]; Variable quality; Not routinely treated for pathogen reduction; Generally uncharacterized.	

Amendment	Availability	Uses	Public Acceptance	Cost	Advantages	Disadvantages	Links
Pulp Sludges	Material available locally (Northwest and East)	OM source; Slope stabilizer.	May have odor problems; May have dioxins; May be nutrient limiting.	Materials generally free; Transport and application fee.	High C content; Large volumes; Locally available.	Highly variable quality; May contain other residuals, e.g., fly ash, waste lime, clay, which can be benefit or detriment for intended use. Total C may not reflect available C. Very low nutrient value.	American Forest and Paper Association (http://www.afandpa.org/Template.cfm?section=Pulp_and_Paper)
Yard/Wood Waste	Material available locally	OM source; Can be high C; Can be used for bulking and structure.	Yard waste can be odorous.	Materials may be free; Transport may be partially covered.	May be used to control erosion; Variable sizes available.	Large category; High variability; May be hard to obtain; Can contain herbicides.	
Ethanol Production Byproducts	New material; Very location dependent	Nutrient source; OM source.	May have odor problems.	To be determined; Transport and application fee.		New, not regulated[2]; Variable quality; Not routinely treated for pathogen reduction; Generally uncharacterized.	
pH							
Lime	Widespread	Increase pH; Increase Ca.	Highly accepted.	Product, transport and application is $8-30/ton based on transport distances.	Regulated[2]; Well characterized; Very uniform; soil aggregation.	Agricultural limestone has low solubility and can become coated and ineffective at severely acidic sites. Can be source of fugitive dust.	National Lime Association (http://www.lime.org/ENV02/ENV802.htm#BioS)

Amendment	Availability	Uses	Public Acceptance	Cost	Advantages	Disadvantages	Links
Wood Ash	Locally available	Increase pH; Source of mineral nutrients, Ca, Mg, K; Can work for odor control.	Accepted.	Materials generally free; Locally variable cover and transport costs.	Acceptance; Cost; Multi-purpose; Can limit odor of organic soil amendments.	Highly variable; Lime equivalent will vary by burn temperature and age of material; Dioxins should not be a problem but tests should be conducted to verify.	
Coal Combustion Products	Most available in eastern U.S.	Increase pH; Source of mineral nutrients (e.g., Ca).	Variable.	Materials generally free; Transport and application fee.	Regulated[2]; Well characterized; Soil aggregation; Light color reduces surface temperature for seedlings; Increases moisture-holding capacity; Reduces odor of organic soil amendments.	Varies plant to plant; can be high B and salts; can leach Se and As.	American Coal Ash Association (http://fp.acaa-usa.org/CCP.htm) The Fly Ash Resource Center (http://www.geocities.com/capecanaveral/launchpad/2095/mar_index.html)
Sugar Beet Lime	Locally available - primarily in west	Increase pH.	Accepted.	Materials generally free; Transport and application fee.	More reactive than agricultural limestone.	Potential fugitive dust.	
Cement Kiln; Lime Kiln	Locally available	Increase pH; High Ca.	Variable.	Materials can have associated cost; Transport and application fee.	Highly soluble and reactive.	Potential fugitive dust; Highly caustic; Variable content; May contain contaminants.	

Amendment	Availability	Uses	Public Acceptance	Cost	Advantages	Disadvantages	Links
Red Mud	Locally available in TX and AR in U.S.	Increase pH; Sorbent.	Variable.	Commercial product from a residual under development.	Demonstrated effective in limited testing in Australia and other sites at moderating pH and sorbing metals.	Potentially costly, High salt content; Variable CCE.	I-99 ARD Remediation Status, June 8, 2005 (http://www.dep.state.pa.us/dep/deputate/fieldops/nc/I_99/Reports_Documentation/5_PennDOT_Acid_Rock_Remediation_Plan/I-99_ARD_Pres._Tran_Sub_Final.ppt#274 ,8,Interim Remediation Measures) International Aluminum Institute (http://www.world-aluminium.org/environment/challenges/residue.html) Red Mud Project (http://www.redmud.org/home.html)
Lime-stabilized Biosolids	Locally available	Increase pH; OM and nutrient source; Potential sorbent.	See biosolids.	See biosolids.	See biosolids; Potential multi-purpose soil amendment.	Can have high odor; Lower N content than conventional biosolids; Variable lime content.	National Lime Association (http://www.lime.org/ENV02/ENV802.htm#BioS)
Mineral							
Foundry Sand	Large quantities locally available	Modifies texture; Sorbent.	Variable.	Materials generally free; transport and handling fee.	Good filler; Sand replacement.	Can have trace metals, Significant Na; Only Fe and steel sands currently acceptable.	

Amendment	Availability	Uses	Public Acceptance	Cost	Advantages	Disadvantages	Links
Steel Slag	Locally available	CCE, sorbent, and Mn fertilizer.	Accepted.	Materials generally free; Transport and grinding fee.	Combination of CCE and sorbent, including Mn.	May volatilize ammonia.	National Slag Association (http://www.nationalslag.org/slagsites.htm)
Dredged Material	Large quantities locally available	Modifies texture; Top soil substitute useful for covering sites.	Variable.	Materials generally free; Transport may be paid by generator.	Can be top soil substitute; Ideal for blending with other residuals.	Needs dewatering; Can have wide range of contaminants; Can have Na.	
Gypsum	Large quantities locally available	Good for sodic soil; Good for low pH soil; Good for soil structure.	Variable.	Materials generally free; Transport fee.	Improves aggregation; Offsets aluminum toxicity.	Different sources of waste gypsum and wide range of potential contaminants, many of which are regulated[2].	
Water Treatment Residuals (WTR)	Available wherever water is treated	Good for binding P; Potential sorbent.	Accepted.	Materials generally free; Transport costs may be covered by generator.	Moderates P availability when mixed with high P soil amendments.	Different materials have variable reactivities; May contain As and radioactive isotopes.	
Coal Combustion Products (CCP)	Available where coal is burned	Sorbent; Improve water-holding capacity; Excellent mix for biosolids; Compost to create cover soil.	Variable.	Materials generally free; Transport and application fee.	May have CCE value; Large volumes available.	Large quantities generally necessary to achieve benefits; Can have contaminants including Se, B, As and metals.	

[1] The term sorbents, as used here, describes materials that can hold on to or absorb different contaminants. There are a range of these materials, with different materials better suited to absorption of different contaminants. Some examples of sorbents include charcoal for different organic contaminants, water treatment residuals for excess P and some heavy metals and high surface area iron oxides for heavy metals including Pb and As (Refs. 6, 13, 14, 58).

[2] See Table 6. Regulatory Requirements for Sites Using Selected Soil Amendments

[3] Digestate, as used here, is defined as a general category for organic wastes that have been partially treated through anaerobic digestion.

Manures. Over 25 million tons of animal manures are generated annually in the United States (Ref. 57). Manures vary widely in moisture, nutrient content, and relative stability. Some manures are dewatered or otherwise stabilized for beneficial use, but most are applied “as is” on nearby agricultural lands as nutrient and organic matter amendments. The nitrogen content of manures is usually readily available to vegetation and does not persist in the soil as long as the nitrogen from biosolids or other types of manures.

Composts. Compost is the stable soil conditioning product that results from aerobically decomposing raw organic materials, such as yard trimmings, food residuals, or animal byproducts (http://www.epa.gov/compost/). The composting process involves a proper carbon-to-nitrogen ratio, a favorable temperature regime, water, and air to yield the compost end-product that is less in volume than the original material and free from offensive odors. Composting is used frequently to significantly reduce pathogens in organic waste streams since the process generates temperature hot enough to achieve this reduction. Compost availability and composition varies widely, but in general, compost is generated in much smaller volumes nationally than manures or biosolids. Composts generally have a lower N content than biosolids or manures.

Digestates. The term “digestates” is used in this paper as a general category for organic wastes that have been partially treated through anaerobic digestion. Anaerobic digestion of organics is a way to reduce volume, destroy pathogens, and generate methane for energy recovery. This type of digestion is *status quo* for many municipal biosolids and is becoming increasingly common for animal manures and food residuals. The material that comes out of digesters typically is a high-organic-matter semi-solid that can have a relatively high nutrient content. This type of treatment is commonplace for municipal biosolids; however, biosolids are considered separately from digestates in this paper, even though their properties and potential uses are likely to be similar.

Papermill Sludges. Papermill (pulp) sludges also are available for use as soil amendments on disturbed lands (Refs. 16, 40), but tend to vary from source to source. In general, papermill sludges are much lower in N and P than biosolids and composts, but can provide large amounts of organic matter. Many papermills also combine other residuals such as waste lime, fly ash, or kaolin with their pulp sludges, which may greatly enhance their soil amendment potential (Ref. 20).

Yard and Wood Waste. Many localities collect yard waste (lawn, garden, shrub/tree trimmings, etc.) and make it available for local reuse. Similarly, large amounts of wood waste (bark chips, sawdust, whole tree chips, etc.) may be available from wood processing facilities or from right-of-way maintenance activities. Collectively, these materials tend to vary greatly in composition, size, and relative decomposition/stability, but can serve as significant and beneficial organic matter amendments or mulching materials. In recent years, wood products have been increasingly utilized as fuel in industrial boilers and, therefore, are not as readily available.

Ethanol Production Byproducts. Because this is a relatively new source of soil amendments, its availability is very location specific. It is generally uncharacterized and there is very little information available about it.

4.2 Soil Acidity/pH Soil Amendments

Many degraded sites are plagued by low soil pH conditions and associated problems, including heavy metal bioavailability and direct toxicity to microbes. Fortunately, a wide array of alkaline soil amendments is available. All liming/alkaline soil amendments should be tested for their net neutralizing power. This is commonly expressed on a calcium-carbonate-equivalent (CCE) basis. The particle size of liming materials also is very important in that sand-sized or larger ($\geq$ 0.05 mm) particles are much slower to react than finer-textured materials.

> Many soil amendments (e.g., lime) have important positive effects on runoff and leachate water quality in addition to ameliorating adverse plant growth conditions.

Lime. pH-neutralizing soil amendments include ground calcium carbonate ($CaCO_3$), or limestone; calcium oxide (CaO), or burnt lime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; and industrial waste products, such as cement kiln dust and sugar beet precipitated calcium carbonate, are widely available. The applicability of each soil amendment is subject to chemical analysis of CCE, moisture content, and particle size. Additionally, lime amendments should not contain phytotoxic characteristics. Phytotoxicity effects of industrial waste products can be determined by greenhouse testing, and should not be determined by chemical analysis alone. Pure alkaline products such as ground limestone, calcium oxide, and calcium hydroxide do not need independent greenhouse evaluation prior to field use (Ref. 29). Liming is commonly used to reverse phytotoxicity of Zn, Cu, or Ni. However, excessive liming may reduce phytoavailability of soil Mn and other essential micronutrients, and induce Mn deficiency depending on Mn levels present in the contaminated soil.

Wood Ash. Wood ash is locally available in small to moderate amounts from wood-fired utilities. Wood ash provides K and certain micronutrients to the treated soil/plant system. CCE varies by source and the degree to which the ash product has been weathered and hydrated. Wood ash may contain contaminants if other fuels, such as tires or waste oil, have been co-combusted with the wood. The ash of wood treated with chromated copper arsenate (CCA) or pentachlorophenol (PCP) is not acceptable for use on land because of the contaminants present in these materials.

Coal Combustion Products (CCPs). Over 100 million tons of coal fly ash and flue gas desulfurization (FGD) lime sludge are produced annually in the United States (Ref. 24). These products can provide a low-cost alkaline alternative to conventional lime sources. The CCE of fly ash can vary from 0 to > 50%, so appropriate testing of all land-applied materials is essential. FGD materials typically are higher in CCE than fly ashes, and the two are commonly co-mingled at generating facilities. Gypsum also is commonly a major component of FGD. High levels of soluble salts and boron (B) in both products may limit the application rate. Boron and soluble salt levels are reduced in weathered material, if this is locally available. Heavy metal concentrations should be determined in these materials prior to use. Metals levels can vary considerably between sources.

Sugar Beet Lime. During purification of sugar from sugar beets or cane, lime is added to neutralize organic acids present in the plant materials along with sugar. Sugar beet lime, the limestone byproduct of this process, is available wherever sugar is produced or packaged. It usually has a fine particle size, and may include byproduct organic matter needing application. These byproduct limestones contain organic matter and have relatively high CCE values. They are an underutilized resource mainly because of additional transportation costs resulting from remote locations and relatively high water content.

Cement Kiln Dust. A highly soluble and reactive byproduct of the cement industry, kiln dust is also locally available in moderate quantities. This product may contain higher than desirable concentrations of contaminants. Like all lime substitutes, these materials should be carefully characterized before use. This material can vary considerably between sources.

Red Mud. Red mud is a highly alkaline byproduct of the aluminum industry found in very large quantities near active refineries in Arkansas, Texas, and other states. Several commercial products (e.g. Bauxsol™), based on processed red mud, are currently available. Bauxsol™ has been pilot tested on three acid rock drainage (ARD) sites in Pennsylvania (Ref. 38).

> Red mud is known for its combined liming and sorbent properties.

Lime-stabilized Biosolids. This is a product of secondary treatment of biosolids via addition of CaO or other lime (alkaline)-based reactive products. Lime-stabilized biosolids have a variable CCE (10 to > 50%) but also contribute significant nutrient and organic-matter benefits. Lime-stabilized biosolids may be available in large quantities near cities that use lime stabilization in their wastewater treatment facilities.

4.3 Mineral Soil Amendments and Conditioners

While organic matter and lime/alkaline soil amendments are used most often, a wide range of mineral byproduct materials with significant soil amendment, conditioning, or even soil substitute properties may be available locally (Ref. 56). All materials should be characterized prior to use.

Foundry Sand. A byproduct of the metal casting industry, foundry sand is available locally in moderate amounts. It is used primarily as a soil conditioner to improve texture but may contain various heavy-metal residues from the casting process.

Steel Slag. Steel slag is available locally in moderate quantities. It often is used as a combined alkaline soil amendment, sorbent, and micronutrient source.

Dredged Materials. Available in very large quantities near commercial waterways and estuaries, dredged materials may be used to modify surface soil texture or, in thicker lifts, to form an entire soil profile. Dredged materials can be highly variable in physical and chemical properties and may contain organic contaminants, including herbicides.

Gypsum. Very large amounts of gypsum are produced in the manufacturing of P fertilizers, titanium pigment production, and a range of other industries that neutralize sulfuric acid extracts in their processes. Gypsum is used to enhance soil aggregation, offset aluminum (Al) toxicity, and ameliorate sodic soil conditions. The product varies by industrial process and location and can contain trace contaminants of concern, such as Cd, F, and uranium (U).

Water Treatment Residuals (WTR). Alum and other compounds are used in drinking water plants to flocculate or precipitate P, fine clays, silts, and organics from the raw water feed. The resultant water treatment sludges can be used as a soil conditioner to improve texture, or as a sorbent for excess P or other contaminants of concern.

Coal Combustion Products (CCPs). CCPs are generated in large volumes nationwide and are frequently employed as liming alternatives for ameliorating acidic soil. However, CCPs also are used for their metal-sorption ability, as soil conditioners to modify soil texture and improve water-holding, or as simple dry-bulking agents to improve the handling properties of wetter byproducts such as biosolids.

4.4 Application Rates

There are several approaches that can be used to determine the appropriate application rate for the soil amendments to be used.

> Appropriate application rates depend on the specific concern to be addressed.

One approach is to look at healthy soil in the environment at the site. The total organic matter of such soil can be used as a target value for the target site. If this approach is taken, a significant portion of the organic matter applied will decompose to carbon dioxide (CO_2) and water in a relatively short time frame. If a nearby soil has 2% organic matter, adding 4% to the site is a way to compensate for the initial rapid decomposition. Another approach is to look at rates that have been used at similar sites. For example, coal mining sites have been successfully restored with a range of biosolids products added at 22 to about 100 dry tons per acre (Ref. 17). Metal-contaminated sites (primarily hard rock mining sites) have been restored with mixtures of biosolids and lime, with biosolids added at rates of about 25-100 tons per acre and higher. The appropriate rates at other hard rock sites with low probability of metal toxicities where soil fertility and poor physical properties are the primary impediments to plant growth will be similar to those for coal sites.

A heavily contaminated, barren mountainside adjacent to a large smelting complex in Palmerton, PA. was revegetated using a blend of 105 wet tons/acre anaerobically digested biosolids (21 dry tons/acre), 52.5 tons/acre fly ash and 10 tons/acre agricultural limestone (Ref. 37). In this case, the application rates were determined primarily based on the organic nitrogen content of the biosolids, then using half that amount of fly ash and twice the required amount of limestone needed to neutralize the soil (pH 7.0). The blend, 167.5 dry tons/acre, was surface applied with seed mixed in. It provided a uniform cover about 2 inches in depth and was very successful. The organic nitrogen content of the biosolids was used as a determining factor because that nitrogen component would provide the slow-release nitrogen needed by the vegetation. The 2000 lbs/acre applied would be slowly mineralized by soil bacteria to plant-available nitrate and ammonia, providing an annual amount of 100 – 200 lbs/acre for a five to seven year period. This was the amount of nitrogen required by the grass/legume vegetation that was seeded, preventing a loss of nitrogen from the site. The fly ash amount was determined based on lab, greenhouse and field trials, and supplied numerous benefits to the blend. The heavy metal content of the fly ash was added to the metals content of the biosolids for the metals loading calculations for the project and none exceeded the amounts allowed by Pennsylvania regulations (Ref. 35).

Another approach is to follow laboratory protocols. For example, laboratory protocols for calculating the acid-base account from field soil samples; determining lime-quality CCE, moisture content, and particle size; and delineation of spatial variation in the lime rate observed in the field, are used for determining the application rate for neutralizing acid-forming mine waste to ensure that appropriate amounts of soil amendments are applied spatially at proper depths. Analytical tests that measure active and potential acidity have been documented (Refs. 42, 43).

In other cases, however, the amount of amendments added to the soil can be a qualitative rather than a quantitative decision. This is generally the case for amendments used to increase soil organic matter or to rebuild soil.

Some states regulate the use of different soil amendments. These regulations often are formulated to protect against excessive leaching of N to groundwater while still allowing application of soil amendments at high enough rates to assure success of the revegetation effort. For example, Virginia Department of Mines Minerals and Energy (VDMME) developed guidelines limiting application of biosolids for revitalization to 33 tons per acre for class B biosolids or 51 tons per acre if the C:N ratio of the soil amendment was 25:1 or greater (Ref. 55). Similar maximum rates are in place for reclamation of mined land in Maryland and Pennsylvania.

> Higher application rates of soil amendments are required when rebuilding soil rather than simply enhancing damaged soil.

In rebuilding soil, it is important to include a mixture of N-rich materials with C-rich materials to reduce the potential for N leaching while providing sufficient organic matter. In general, a bulk amendment C:N ratio between 20:1 and 40:1 is recommended, but higher C additions may be viable in certain scenarios. It also may be appropriate to include a mineral soil amendment like foundry sand or wood ash as part of the amendment mixture respectively for inorganic bulk and plant nutrients. Here, operational considerations and budget often can be the limiting factors in determining appropriate application rates. The functional A horizon, also called topsoil, is where seeds germinate and plant roots grow. It is made up of a mineral particle matrix with a significant (1 to 10%) humus (decomposed organic matter) content. This layer is generally > 4 inches. The goal should be to create a surface layer (A horizon) that is close to or greater than this depth.

5.0 LOGISTICS AND OTHER CONSIDERATIONS

Availability, transportation, storage, and blending are the key logistical issues to evaluate when using soil amendments for site remediation and revitalization (see Table 4). Other essential concerns discussed in this section are public acceptance and cost.

5.1 Availability

Soil amendment materials are available almost everywhere. Sources include Publicly Owned Treatment Works (POTWs), concentrated animal feeding operations (CAFOs), coal-fired power plants, and pulp and paper mills, as well as retail sources. A limited list of sources for various types of soil amendment materials is available on U.S. EPA's Clean-Up Information System website at www.clu-in.org (Ref. 9). Also see the links to sources of information on the various types of amendments in Table 3.

5.2 Transportation

Truck-delivery of residuals to a project site requires good access including roads kept clear of snow and ice during periods of delivery, roads built to withstand heavy truck weights, bridges that legally can carry truck weights, and sites with unloading areas that are level and firm for safe truck dumping. Other project-specific considerations may include the need for a truck scale, sampling apparatus and an on-site lab for rapid field characterization of material. Specialized transport vehicles may be needed for soil amendments that are highly hydroscopic (have high moisture content), caustic, or have other special characteristics. This can translate to high unit costs for transportation. Liners should be considered for loads of high-moisture materials for safer dumping.

> Transport logistics (identifying sources and delivery costs) should be considered first when planning for the use of soil amendments for remediation, revitalization, and reuse of disturbed sites.

Where sources of soil amendments are within 200 miles of a project site, dump trailers or dump-truck delivery of amendments is economically viable. Longer distances make rail hauling practical, but development of short-line rail service, or rail-to-truck transfer, can be costly. The potential impact of concentrated truck traffic on homeowners directly adjacent to the haulage route, including access, also should be considered.

Table 4: Logistics and Other Considerations in Using Soil Amendments

Amendment	Transport	On-site Storage	Blending	Application	Application Equipment
Organics					
Biosolids	Can be costly due to high moisture content for some materials; High potential for cost-share with municipality; Rail haul is possible; Intra-modal transport containers (rail/truck) may simplify transfers from rail to truck.	Extended storage of high moisture materials can generate offensive odors. Can use storage as treatment with onsite processing to compost or stabilize with lime. Blending with fly ash prior to storage can reduce odors.	Can be mixed with high C material to reduce N leaching potential. Can also be mixed with lime materials for complete amendment or CCPs.	Industrial disks will be needed for surface or incorporated high moisture content of some materials, chisel plow or rippers; Material can be surface applied and allowed to dry before incorporation; If blended with dry mineral materials, e.g., fly ash, the moisture content is similar to topsoil (50-55%) and can be surface applied without incorporation.	Range of options available. Generators may have expertise. Options include dump truck + dozer, side cast spreader, aerospreader™, and custom biosolids application vehicles including terragators. May also be bulldozed down steep slopes.
Manures	See biosolids.	See biosolids.	See biosolids; less stable than biosolids.	See biosolids; less stable than biosolids.	See biosolids; less stable than biosolids.
Compost	Due to low bulk density and high water content, high transport costs.			See biosolids.	Blowers, pneumatic spreaders, manure spreaders, aerospreader™, etc.
Digestates[1]		See biosolids.	See biosolids.	See biosolids.	See biosolids.
Pulp Sludges	See compost.	Can become anaerobic and odorous.	Can have very high C:N ratio[2] which may necessitate blending with N-rich material for plant growth.	See biosolids.	See biosolids.
Yard/Wood Waste	See biosolids.	See pulp sludges.	Check C:N ratio. If >30:1, will necessitate mixing with a high N material like manure or biosolids.		See compost; Standard agricultural tillage to12 inches.
Ethanol Production Byproducts		See pulp sludges.	Too new.		

Amendment	Transport	On-site Storage	Blending	Application	Application Equipment
pH					
Lime	Cost varies with distance and water content; Usually by truck or rail.	Lime pile should be covered to avoid dusts and precipitation.	Can be blended with an organic soil amendment.	Lime spreader.	Lime spreader; aerospreader™; hydro-mulcher; Rip prior to incorporation; Incorporation equipment may include tillage to 12 inches, rotary mixers (24 inches), or specialized plows (up to 47 inches).
Wood Ash		pH will decrease to 8.3 as material is exposed to air; Will be slower reacting and less soluble; This process will occur quickly if lime material is mixed with an organic residual for storage.	Can also be a source of K and P; If pH is > 8.3 can drive off N from manures or biosolids and decrease nutrient value; If blended with manures or biosolids and seeded immediately, the ammonia generated can kill the seed.		See lime.
Fly Ash		See wood ash.	Can be source of K.		
Sugar Beet	See compost.	See wood ash.			See lime.
Cement Kiln Dust	See lime.	See wood ash; In addition nutrient value, N can decrease with volatilization over time.	Can also be a source of K and P; If pH is > 8.3 can drive off N from manures or biosolids and decrease nutrient value.	Can be caustic.	See lime.
Red Mud				Can be salty.	
Lime-stabilized Biosolids	See biosolids.			See biosolids.	
Mineral					
Foundry Sand	Generally high application rates will involve high cost; Cost may be covered by generator.			High volume soil amendments; Should be handled in bulk.	Loaders, haulers, pans, dozers.

Amendment	Transport	On-site Storage	Blending	Application	Application Equipment
Dredged Material	See foundry sand.			See foundry sand.	See foundry sand.
Gypsum	See foundry sand.			See lime.	See lime.
Water Treatment Residuals				See lime.	

[1] Digestate, as used here, is defined as a general category for organic wastes that have been partially treated through anaerobic digestion.

[2] Ratio of carbon to nitrogen; C:N ratio is 15-40:1

5.3 Storage

Temporary stockpiling of soil amendments in advance of application is often necessary. The stability of a soil amendment is an important factor in planning for on-site storage. Exposure to rainfall while in storage may affect the quality of some soil amendments. Other amendments are biologically active, and their nutrient properties or odor characteristics may change while in storage. Some materials may be composted at an on-site storage facility, but regulatory restrictions may apply. In some states, on-site storage for any protracted period of time (e.g., > 14 days or over winter) may require a compacted pad below and low berms around the base of the stockpile to retain leachates and seepage. In some instances, blending two soil amendments prior to storage (e.g., biosolids and fly ash) can overcome odor problems and alleviate reduced usability due to rainfall exposure while being stored. Other admixtures likely will show similar characteristics if the soil amendments are paired to be synergistic, i.e., each overcoming negative aspects of the other.

5.4 Application

For some materials, such as biosolids, regulatory requirements may limit the steepness of a site that can be approved for reclamation. In other cases, using soil amendments on sites with unusually steep gradients may have advantages. For example, a blend of fly ash and biosolids has been shown to become partially cemented onto a hillside at slopes approaching 1:1 (100%) and, hence, highly resistant to movement. Many of the state regulatory requirements for maximum slope on a project site were developed with equipment limitations and runoff considerations in mind. If a project can be designed to allow the equipment to remain on fairly moderately sloping access roads on an otherwise steep site and limit surface water impacts, it may be possible to obtain regulatory approval.

The gradient or slope of a project site influences selection of soil amendments.

Project plans should reflect seasonal differences in potential adverse impacts from soil amendment use. For example, excessive nitrate-N loss in winter may occur if nutrient-rich soil amendments are applied after the growing season. The workability of the land surface may degrade if soil amendments are applied during a rainy season, and seedling germination may be inhibited by excessive drought if applied in the dry season. In addition, temperature may impact the feasibility of onsite composting.

The amount of moisture in the soil amendment, commonly reported as % solids, is the predominant characteristic that dictates application procedures and timing. Typical ranges of solids content of biosolids applied to revitalization sites have included liquid sludge at 2-8% solids, which can be pumped easily; semi-solid biosolids at 8-18% solids, which also can be pumped (though less efficiently than liquids); and solid biosolids cake at 20-40% solids, which may be flung from a manure-type spreader or end-dumped (Ref. 5).

Application rates typically are calculated on a dry-weight basis. This means that, for an average dewatered biosolids (20% solids), application of 90 dry tons per acre would involve applying 450 tons per acre of material. This is a significant amount of material that can complicate incorporation efforts. A variety of equipment technologies are available to perform direct spreading, including farm manure wagons, all-terrain vehicles with rear tanks, and dump trucks. Heavy applications like these can be accomplished using two basic techniques, both of which are relatively easy and relatively inexpensive.

- **Single application**. The fastest and most cost-effective method is to make the total application in a single "lift" (an application that is immediately incorporated into the soil). Depending upon the application rate and % solids, this may be as little as 1 to 30 inches in depth. Soil amendment mixtures can be allowed to dry on the surface before incorporation. This may take a complete summer period. Drying can be enhanced by seeding with a grass that can germinate and withstand the anaerobic conditions of the soil amendments. A cereal grass such as annual rye or wheat generally is very effective for this purpose. Once the soil amendment has dried, normal farm disks or chisel plows can be used to incorporate the mixture into the subsoil. If the amendments are incorporated into the soil when wet, high moisture materials added at high application rates will involve use of heavy duty equipment (e.g., mine disks) capable of deep mixing and incorporation.

- **Multiple lifts**. Soil amendment applications also can be made in smaller or partial lifts. In fact, some states require incorporation of biosolids within a certain time period. When multiple heavy applications are needed within a short period of time, working the soil becomes a challenge, because repeated applications followed by mixing without drying will turn the soil into a deep quagmire (potentially far deeper than the actual depth of amendment added). Costs will be significantly higher, because the soil is worked many more times in this method.

There are several technologies that are effective for applying and incorporating materials at these rates. Site topography, soil strength, evenness (including debris), and proximity to waterways are the physical features that affect equipment selection. Easy access, stable soil, and a clear site favor the simple methods, while rockiness, obstructions, or steep slopes necessitate special equipment. The application rate also is important, as light applications need a more precise method. Table 5 summarizes the common types of equipment available to make applications to disturbed soil (Ref. 5).

- **Incorporation**. Incorporation of high rates of biosolids mixtures similarly require the proper equipment and equipment operators. The low % solids of the biosolids means that when making a 100 dry t/ac application, more than 500 wet t/ac of material may actually be applied. Generally a large track bulldozer pulling a 36-inch disk is required. Smaller equipment will just float on the surface of the biosolids mixture. Large chisel plows also are capable of incorporating amendments. Achieving a completely homogenous mixture is not possible when incorporating high rates of amendments. Although not always necessary, maximizing soil-amendment contact whenever possible can increase the effectiveness of the amendment.

In most cases, the municipality or private contractor that has applied the soil amendments for a municipality or generator will have appropriate application equipment and operators. Arranging for application and incorporation as part of the agreement to use biosolids from a municipality may be the best way to ensure appropriate and cost effective application of the materials. If the particular municipality does not have the appropriate equipment, others will. Examples of municipalities and states that have large scale application equipment include: Chicago (contact Thomas Granato, (708)222-4063); Virginia (contact Lee Daniels, wdaniels@vt.edu); Denver (contact Bob Brobst, brobst.bob@epamail.epa.gov); and Philadelphia (contact Bill Toffey, William.Toffey@phila.gov). Bob Bastian (U.S. EPA Washington, DC, bastian.robert@epamail.epa.gov) also has information on application equipment across the country. For more information on application equipment go to http://faculty.washington.edu/clh/whitepapers/biosolidswhite.pdf.

5.5 Blending

Individual soil amendments can be combined with other residuals to produce characteristics optimal for revitalization of a particular type of site. For example, the target may be to produce a blend containing a full range of nutrients with optimal soil pH and texture, or to moderate the pH of an amendment mix or achieve a desired balance of C and N in order to reduce the risk of nitrate leaching. Blending equipment may be required to achieve proper soil conditions when using amendments. Two basic approaches are *in situ* mixing of soil amendments into the receiving surface or *a priori* blending of a soil mix made from amendments followed by emplacement onto the receiving surface. Both operations involve large-scale equipment. The former requires large fixed pieces, such as pug mills or tub grinders, which may be movable around the site but essentially blend and shred from a designated location that has a power source. The use of tracked or wheeled vehicles to pull farm-like equipment for spreading and plowing also can be used for *in situ* blending of amendments and soil. In either case, care should be taken to avoid over mixing, particularly with biosolids, as this can result in a loss of flocculent structure that makes the material difficult to apply. Operators also should monitor closely to verify that proper ratios of materials are maintained. Experience with one large-scale remedial action using blends of biosolids and fly ash in Pennsylvania revealed that the use of a large, fixed mixing station was detrimental to the vegetation process, because the material was over-blended. The resulting mix was difficult to apply and crusted after application, which slowed vegetation emergence significantly. This was overcome by using a front-end loader to do much reduced blending and by placing alternating buckets of amendments into the spreader truck. The action of being thrown from the spreader achieved a uniform mixing of the amendments when applied (Ref. 37).

Table 5. Comparison of Different Application Systems Used in Remediation (Ref. 5)

System	Range *	% Solids**	Relative Costs	Advantages	Disadvantages
Biosolids dump truck discharge, spreading with dozer	10-15’	> 12%	Low capital, low O&M	Simple to operate, fast for high application rates.	Need cleared, relatively flat site, acceptable to heavy equipment, difficult to get even applications for low application rates.
Application vehicle with mounted cannon	Up to 125’	< 12%	Moderate capital, high O&M	Can make even applications for low rates, any terrain.	May need special trails with strength for repeated trips, slow.
Application vehicle with rear splash plate	10’	15-35%	Moderate capital, moderate O&M	Can make even applications for low rates, moderate terrain.	May need special trails with strength for repeated trips, slow.
Application vehicle with side discharge	Up to 200’	15-90%	Moderate capital, moderate O&M	Can make even applications on any terrain and at any rate, including low rates.	May need special trails with strength for repeated trips, moderate speed.
Manure-type spreader - rear discharge	10’-30’	> 25%	Low capital, low O&M	Can make even applications for low rates, moderate terrain.	Limited to high % solids, trails may need to be close together, moderate speed.

* Range is defined as the distance away from the equipment that the amendment material can be thrown.
** It is best to check with POTW about the equipment they use, because % solids may vary for different equipment.

NOTE: Injection may be applicable in particular situations, and should be evaluated on a case-by-case basis.

5.6 Public Considerations

Issues affecting the community living near or affected by a site where soil amendments will be used should be taken into account when planning and implementing remediation and revitalization plans. These include:

> The involvement of community stakeholders in the decision-making process is a key element in projects to remediate and revitalize a site using soil amendments.

Public outreach. Public outreach in projects involving the use of soil amendments should include two-way communication—communicating with/informing affected stakeholders about plans and soliciting/listening to input from the community on project plans. This is particularly important when remedial or revitalization work is to be done on private property. Effective public outreach can include the use of site tours, fact sheets, public meetings, media tours of project sites, websites, and telephone hotlines. Public outreach is very important for projects with significant potential for community impact, where health and environmental concern is high, where costs and complexity are extraordinary, and where the final use of the site is a matter of community concern.

Odor. Odor emissions can be a major cause of public dissatisfaction with projects using soil amendments. Selection of amendments should take into account the potential for release of odorants at malodorous intensities beyond the project boundary. Odor management, including applying well stabilized material, avoiding land application when wind conditions favor transport of odors to residential areas, minimizing the length of time that amendment materials are stored, reducing visibility, maximizing the distance of the storage area from occupied dwellings, and training all staff to identify and mitigate odors, should be a high priority throughout the project if odorous soil amendments are used. More information on the causes of odor and a comparison of various odor treatments can be found in EPA's *Biosolids and Residuals Management Fact Sheet: Odor Control in Biosolids Management* (Ref. 51).

Demonstrations. Because revitalization projects frequently focus on sites of heightened community or regulatory concern, and project managers may be held to a high standard of proof when selecting amendments for *in situ* treatment, demonstrations of different residuals and different ratios of residual mixtures may be warranted. Reviewing demonstration projects or pilot studies in which various types of soil amendments have been used also may be helpful in determining whether a particular type of amendment is appropriate for a similar site.

5.7 Costs

The volume of soil amendments needed, their availability, transportation, and onsite storage issues are among the most important factors in determining per-acre costs of using soil amendments to remediate and revitalize a site. These costs can vary widely. A project in which amendments suitable for revitalization are already on site may cost up to $1,000 per acre treated; a project requiring organic material alone to be delivered may cost $10,000 per acre treated; and a site requiring a variety of soil amendments to cover and treat may exceed $100,000 per acre treated.

One of the first large-scale demonstration of biosolids and lime addition at a Superfund site was conducted in 2005 on about 40 acres at the California Gulch Superfund Site, Operable Unit 11, in Leadville, CO (Ref. 49). The cost of the one-year field demonstration was estimated at about $100,000 per acre. This cost included road construction through remote areas and extensive hard engineering with rip-rap boulders, root wads, and bend-way weirs in areas that were treated. As with many large demonstration projects, the cost of this demonstration included the capital expended learning the best management practices (BMPs) that would serve to bring costs down in future projects.

The Philadelphia Water Department (PWD) has used at least some of its biosolids for reclaiming coal mines in Pennsylvania for over 25 years. Reclamation project sites receive approximately 200 tons (60 dry tons) of biosolids per acre. PWD uses contracted services on behalf of the landowner, and these services include transporting biosolids to the site, final grading, liming, temporary product storage, spreading, disking, seeding, and other services. Environmental monitoring is not usually required, although the contractor should ensure that an adequate vegetative cover is achieved across the entire treatment area and that soil pH is maintained for two years after treatment. This bundle of services is charged to the city on the basis of the unit cost of biosolids handled. The range in prices over the past ten years has been $40 to $50 per ton of biosolids. At typical application rates, this converts to a cost of $8,000 to $10,000 per acre (Ref. 45).

Similarly, costs for in-place treatment of acid metalliferous mine wastes using lime and compost at the Clark Fork Superfund site in Missoula County, MT, are estimated to be in the range of $6,000 to $10,000 per acre (Ref. 28). Costs for using soil amendments to reclaim approximately 1,000 acres of the Blue Mountain Operable Unit at the Palmerton Zinc Superfund Site in Palmerton, PA, in the 1990s, ranged from $4,500 to $5,500 per acre (Refs. 36, 41).

In some cases, the cost of treatment can be reduced significantly if soil amendments can be obtained without cost. For example, construction of the Stafford Regional Airport between 1998 and 2000 disturbed over 400 acres of land. Approximately 300 of these acres were contaminated by sulfidic Coastal Plain sediments, which were intentionally spread across the final surface due to their dark “organic-like” color. These materials contained approximately 1% reactive iron sulfides with virtually no inherent neutralizing capacity (Refs. 34, 15). By the fall of 2001, the average soil pH across the site was around 3.0 with many locations having a pH of less than 2.0. The main stem of the Potomac Creek, the second-order stream draining the airport’s watershed, was high in Fe and S and had an in-stream pH of 3.7.

Over the fall and winter of 2001, three rehabilitation alternatives were considered for this site. In all cases, it was estimated that seed and mulch would add no cost. Alternative 1 involved the use of lime stabilized biosolids. The biosolids sources bore the cost of the biosolids utilization through biosolids management, transportation, and utilization contractual arrangements already in place, resulting in a net price per acre of this option of $0 (Ref. 39). Alternative 2 involved the use of agricultural lime and compost (Ref. 12). Studies on revegetation of sulfidic materials indicated that these materials could be successfully revegetated/remediated via the application and incorporation of 15 tons per acre of lime plus 35 tons per acre of yard waste compost (or similar high quality organic soil amendment), plus minimal additional N-P-K fertilizer. Estimated costs for these combined soil amendments (based on Virginia Tech Extension Service Farm Budgets and proprietary information from the contractor would be $330,000, or about $1,100 per acre. Alternative 3 involved use of an agricultural lime (applied at 100% of potential acidity) treated/barrier layer in the surface of the acid-forming materials under a reduced thickness (6 inch) soil cover for revegetation. Such covers are now routinely used in the coalfields of southwestern Virginia on similar materials and have been quite successful. The estimated cost for this conventional option would be $6,793,500, or $22,645 per acre (Ref. 10).

The utilization of lime-stabilized biosolids was elected as the optimal remedy due to obvious economies, the presence of able and willing contractors, and the willingness of regulatory agencies to allow Virginia Tech to monitor the site remediation as a research project. In the spring of 2002, lime-stabilized biosolids from Blue Plains (Washington, D.C.), Upper Occoquan (VA), and several smaller plants in Maryland were applied to various areas of the site according to predicted potential acidity/lime demand of the upper 6 inches of the soil (Ref. 35). Due to biosolids management and utilization arrangements with the contractors, all land application and incorporation costs were borne by the biosolids sources (Ref. 10).

Even in cases where soil amendments themselves are donated, other costs may be incurred. Daily cost for hiring a tractor trailer is about $600 (2006). The typical load capacity for a trailer over the highway is about 23 tons. The number of daily delivery trips and the possibility of splitting costs with back-hauled deliveries are factors that influence the unit charge for residual delivery to a reclamation project. Distances of over 150 miles between the origin of the residual and its destination make two deliveries per day unlikely; distances less than 50 miles make three deliveries daily a possibility. As a result, unit costs may range from $10 per ton for short haul, to $20 per ton for medium range, and $30 or more per ton for long haul. Congestion in urban areas, tolls, traffic restrictions, and special truck equipment needs may add a premium to vehicular costs (Ref. 45).

> The cost of transporting residual amendments may be the largest budget item in a remediation project.

Costs for handling residuals at an application site will depend on the size of the field crew and the number of pieces of equipment. An operator with a piece of field equipment (e.g., spreader or front-end loader) may cost about $1,000 per day. Depending on the complexity of a field operation (e.g., the extent of final grading and the number of passes with incorporation equipment), a team of three operators may complete work at a rate of between 1 and 10 acres a day. As a result, the cost per acre for equipment operation has a wide range of costs, from $300 to $3,000 per acre, with higher costs reflecting sites with extreme conditions of slope, poor soil cover, or inadequate drainage (Ref. 45).

Costs for administrative and monitoring tasks also should be considered. These expenses will vary considerably. At sites where contamination is not the primary issue, little environmental monitoring is needed. At sites where daily testing is undertaken, as may be the case where regulated residuals are used, the costs of monitoring may be significant, and the cost of monitoring and administration may be $100 to $500 per acre (Ref. 45).

6.0 REVEGETATION OF AMENDED SOIL

While ecological function should be considered early in the site remediation process to ensure it is properly implemented, revegetation is one of the final actions taken at a site. All site revegetation involves careful planning that considers soil conditions, plant species, and past experiences. Plans should address land uses that affect plant establishment. In addition, the post-revitalization land use will have a significant influence on designs, implementation, and costs.

6.1 Considerations with Site Revegetation

A variety of issues should be considered when revegetating sites where soil amendments have been used. These include:

- Seedbed preparation is necessary to facilitate seeding and improve the probability of seeding success. This includes leveling, breaking up large clods, and reducing soil seedbank and competitive plants.
- Obtaining plants, from seed or growing stock, is best done with as much lead time as possible. The availability of native plant materials from reliable sources is often limited. Also, plants should be planted at the most opportune time. The Natural Resources Conservation Service (NRCS) has Plant Material Centers which can augment commercial nurseries, but need advance notice (Ref. 27). The Lady Bird Johnson Wildflower Center (Ref. 19) and NRCS both maintain a list of native plant suppliers.
- Seeding of vegetation without supplemental irrigation should be done either in the spring, in advance of wet weather, or in the fall after the growing season. Three principal seeding methods—drilling, broadcasting, and hydraulic seeding—can be used. Certified weed-free seed with known germination rates should be used to avoid introduction of weeds or invasive species that are difficult to eliminate after the fact. The seed source and quality should be reported in post construction documentation.
- Including legumes in the seeding mixtures can prevent N deficiency. Legume species are adapted to different soil conditions, so regional and soil-specific characteristics may have to be taken into consideration in selecting legumes for the seeding mixture. Legumes should be inoculated with their specific *Rhizobium* symbiont prior to application.
- Mulch can be used to stabilize reseeded areas prior to establishment of the seeded vegetation. Mulch serves to decrease water erosion, reduce wind velocity, reduce soil crusting, decrease rainfall impact, and decrease soil surface temperature and evaporation.
- Irrigation may need to be considered in planning for revegetation in some regions to ensure successful plant establishment and avoid the potential for replanting in case of drought.
- Weed species represent one of the greatest threats to long-term success of soil-based revitalization efforts. Close monitoring of the habitat during establishment and control of invasive species is important because weeds and other invasive species can quickly disperse and invade disturbed land, causing problems ranging from destruction of habitat for animals native to the area, to pushing out native plants that help control erosion, to impacting land value by limiting its use (Ref. 47, 48). Developing a weed management plan is recommended.

- Managing wildlife, such as deer and beavers, is often overlooked but can be an issue. Wildlife can over-browse a newly planted site and leave it vulnerable to invasive species. Control options should be identified and explored with the local community to ensure they are acceptable.

6.2 Native Plants

An Executive Order signed April 12, 1994, recognizes the need to conserve the biodiversity and health of native plants to sustain the natural resource base in the United States. The reestablishment of native species and plant communities should be emphasized where appropriate and if commensurate with post-revitalization land use. However, for landscapes that have been severely disturbed, it is ecologically unrealistic to expect a return to baseline biological conditions. In some situations, use of native plants in revitalizing a site may not be possible. One example is a site that had heavy metal contamination of the soil. The native soil was very acidic, with a pH of 3.5 to 4.5. Following remediation, a soil pH of 6.5 or higher had to be maintained to prevent the metals from going into solution. Even though the site was revegetated, the species that previously existed there could not remain due to the dramatic soil pH change. The objective of *in situ* treatment of contaminated lands using soil amendments is to establish a self-sustaining system that does not rely on artificial inputs and, ideally, is similar to and provides nearly equal ecological value as the undisturbed adjacent landscape. The production of native plant materials for use in revitalizing lands is a rapidly expanding industry (Refs: 7, 47, 48).

Native plant communities are best in providing the ecological diversity and long-term sustainability of the landscape.

The U.S. Department of Agriculture's Natural Resource Conservation Service Plant Material Centers (http://www.nrcs.usda.gov/programs/plantmaterials/) provide native plants that can be used in many revitalization projects (Ref. 27). Scientists at the centers seek out and test the performance of plants that show promise for meeting an identified conservation need. After species are proven, they are released to the private sector for commercial production. The work at the 26 centers is carried out cooperatively with state and federal agencies, commercial businesses, and seed and nursery associations.

7.0
PERMITTING AND REGULATIONS

A variety of regulatory requirements may pertain to the use of soil amendments for ecological revitalization (see Table 6). The type of amendment chosen will determine the pertinent regulatory authorities. For example, biosolids are regulated under a "self implementing" rule issued by U.S. EPA (40 CFR Part 503) under the joint authority of the Clean Water Act (CWA), the Resources Conservation and Recovery Act (RCRA), and the Clean Air Act (CAA). At the federal level, regulations are implemented by the EPA's Water Program, while the states regulate and implement biosolids management programs through their water and/or solid waste management programs. The federal biosolids rule (40 CFR Part 503) requires that land-applied biosolids meet these strict regulations and quality standards (Refs. 50, 54). The 503 rule governs the use and disposal of biosolids. It also specifies numerical limits for metals in biosolids and pathogen reduction standards, site restrictions, crop harvesting restrictions and monitoring, and record-keeping and reporting requirements for land applied biosolids, as well as similar requirements for biosolids that are surface disposed or incinerated.

Soil amendments, such as foundry sand, may be regulated as hazardous wastes under the Resource Conservation and Recovery Act (RCRA), but are exempt from Subtitle C restrictions if they pass certain screening tests such as the Toxicity Characteristic Leaching Procedure (TCLP). Regulations for these types of nonhazardous soil amendments are implemented primarily by state solid waste programs. While federal RCRA regulations do not address using these materials as soil amendments for revitalization, many states do regulate land application or beneficial utilization of these products. In addition, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund, or state cleanup requirements should be addressed.

Beware of regulatory situations when two or more soil amendments are blended for use as a remedial material. For example, when blending biosolids with fly ash, the biosolids are regulated under the Clean Water Act self-implementing Part 503 rule as well as state water and/or solid waste programs, and the fly ash is regulated as a solid waste under RCRA. If these types of blends are envisioned, regulatory issues should be identified early in the project. At the Palmerton, PA Zinc Smelter Superfund Project, which revegetated approximately 1,000 acres of the nearby Blue Mountain, issues were identified concerning the blending of not only biosolids and fly ash, but also blending the regulatory impact due to the biosolids being regulated under the Clean Water Part 503 regulations, fly ash being regulated under RCRA, and the entire project being regulated under Superfund. This site was on the Superfund list for excessive zinc, lead and cadmium contamination of the soil. All biosolids and fly ash contain zinc, lead and cadmium. The final resolution of the regulatory dilemma was to count the metals concentration contributed by the fly ash added to the metals in the biosolids, and require that the total metals loading of the blend could not exceed the maximum amount of metals allowed under the Part 503 biosolids regulations for land application. It was also important to have this codified in a Consent Decree to protect all parties involved (Ref.36).

Table 6: Regulatory Requirements for Sites Using Selected Soil Amendments

Organics	
Biosolids	Clean Water Act (40 CFR Part 503) Class B permit required (site restrictions); may be possible to compost or otherwise treat the biosolids on site to reach Class A quality (with no site restrictions); For CERCLA actions, no permit required, but should adhere to spirit of state and local permit requirements (ARARs) when possible; State-specific regulations also may apply.
Manures	Federal and state BMP nutrient management; CAFOS may have bookkeeping requirements.
Pulp Sludges	Dioxin concentrations restricted - voluntary or required by state standard 10 ppt TEQ (toxic equivalent) for dioxin incorporated; may have high sodium which can limit applications.
pH	
Lime	State-specific lime labeling requirements.
Wood Ash	May be regulated as a caustic material; pH will decrease to 8.3 with exposure to air; state-specific soil amendment or liming material regulations.
Coal Combustion Products	State-specific regulations; NAS recommended increased study; coal mining site regulation under SMCRA expected by 2008.
Red Mud	Regulated as mining waste *in situ*, but labeled for application as soil amendment by many states/localities.
Mineral	
Foundry Sand and Steel Slag	State-specific; different states may have restriction by grade.
Dredged Materials	USACE regulations (to pull out of waterway) as well as State-specific (to land apply).
WTR	State solid waste permits may be required to land apply.

8.0 BENEFITS OF USING SOIL AMENDMENTS

The use of soil amendments has the potential to protect human health and the environment and allows remediation, revitalization, and reuse of disturbed sites by reducing contaminant bioavailability at lower cost than other available options. At many sites, this technology may be the only economically viable treatment option. In addition, this approach offers the benefit of recycling municipal and industrial residuals to reclaim damaged or disturbed land rather than disposing of what is generally considered to be waste in landfills or by incineration.

The benefits of restoring contaminated land to natural habitats include: creating green space such as wildlife sanctuaries; improving the aesthetic beauty and cultural stimulation for communities; improving economic value; cleansing air and water; mitigating flooding; reducing wind and water erosion of contaminated soil; generating and preserving soil; increasing evapotranspiration of water from a site and reducing the amount of potentially contaminated water recharging aquifers; cycling and moving nutrients; and partially stabilizing climate (carbon sequestration).

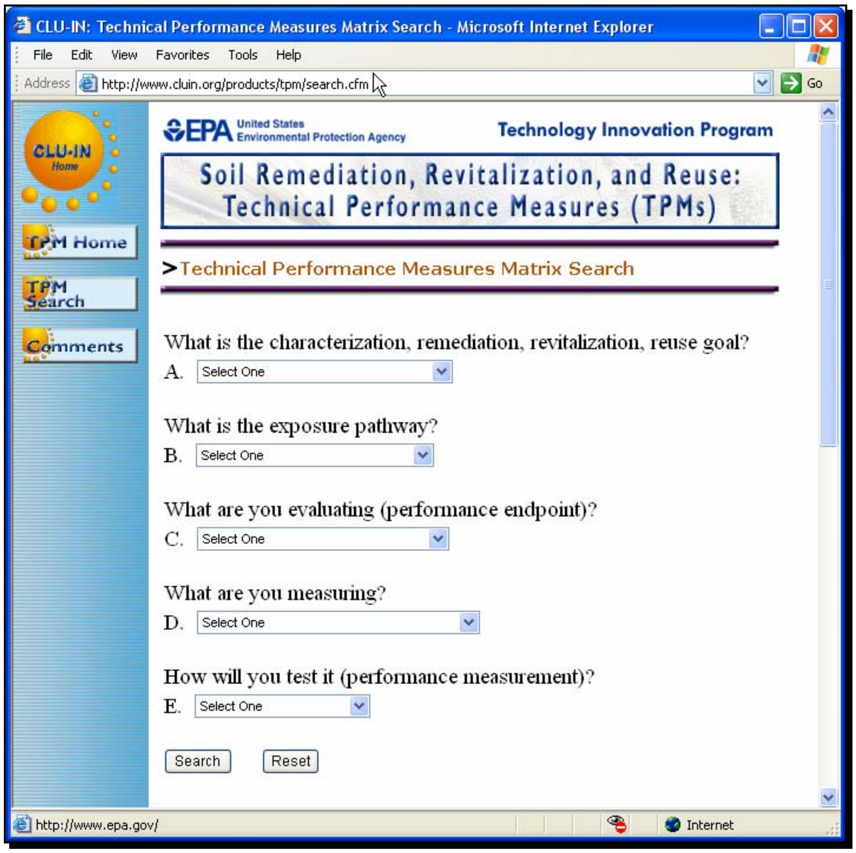
Benefits of Revitalized Land

- Provides wildlife habitat
- Provides improved water quality in receiving streams
- Sequesters carbon
- Reuses of devoid and damaged lands
- Improves property values
- Reduces wind- and water-borne contaminants leaving the site
- Increases evapotranspiration
- Reduces the amount of possibly contaminated water recharging local aquifers

Benefits of Amendments

- Restore soil health and structure allowing establishment of vegetation
- Recreate ecological function of soils
- Decrease bioavailability of toxic pollutants
- Decrease leachability and mobility of contaminants
- Decrease erosion and improve soil drainage
- Reduce costs compared to traditional remediation techniques
- May abate acid mine drainage

9.0 MONITORING AND SAMPLING AMENDED SITES



EPA has developed a Web-based tool to help site project managers select appropriate technical performance measures (TPMs) for use in demonstrating whether soil amendments are functioning as designed to reduce contaminant mobility and/or bioavailability. Remediation, Revitalization, and Reuse: Technical Performance Measures contains a range of potentially applicable TPMs. These measures draw on the collective knowledge and experience of experts to identify and document a core set of commercially available, cost effective, and proven measures that are consistent from region to region, state to state, and site to site. The range of TPMs provides site managers the flexibility they need to design the most appropriate testing for their sites while providing consistency and comparability between sites. Users can search a database of TPMs by using criteria relevant for their particular sites. The search results provide information about each TPM method that matches the selection criteria and provides comments on issues to consider when using the method and references for additional information. These TPMs will help site managers and other stakeholders assess if and when sites, where soil amendments have been used for remediation, are ready for reuse—that is, to determine when contaminant bioavailability and or mobility are reduced such that the remediation is protective of human health and the environment. To view or use the TPM tool, visit http://www.clu-in.org/products/tpm/.

10.0 CONCLUSIONS

Many soils, particularly those found in urban, industrial, mining, and other disturbed areas suffer from a range of physical, chemical, and biological limitations. These include soil toxicity, too high or too low pH, lack of sufficient organic matter, reduced water-holding capacity, reduced microbial communities, and compaction. Appropriate soil amendments may be inorganic (e.g., liming materials), organic (e.g., composts) or mixtures (e.g., lime-stabilized biosolids). When specified and applied properly, these beneficial soil amendments limit many of the exposure pathways and reduce soil phytotoxicity. Soil amendments also can restore appropriate soil conditions for plant growth by balancing pH, adding organic matter, restoring soil microbial activity, increasing moisture retention, and reducing compaction. However, the appropriate use of soil amendments is completely dependent upon appropriate characterization of both the site and the residual materials to be employed.

Soil amendments can reduce the bioavailability of a wide range of contaminants while simultaneously enhancing revegetation success and, thereby, protecting against offsite movement of contaminants by wind and water. As such, they can be used in situations ranging from time-critical contaminant removal actions to long-term ecological revitalization projects. Using these residual materials (industrial byproducts) offers the potential for significant cost savings compared to traditional alternatives. In addition, land revitalization using soil amendments has significant ecological benefits including benefits for the hydrosphere and atmosphere.

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