A FRAMEWORK FOR INTEGRATING PHYTOREMEDIATION INTO THE LANDSCAPE ARCHITECTURAL DESIGN PROCESS

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ABSTRACT

A FRAMEWORK FOR INTEGRATING PHYTOREMEDIATION INTO THE LANDSCAPE ARCHITECTURAL DESIGN PROCESS

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The redevelopment of brownfields, sites having real or perceived contamination from previous uses, is becoming a popular method of tackling urban renewal/ infill projects. Current methods of remediating the soil on these sites are costly and damage the integrity of the soil. In the last ten to fifteen years there has been a significant surge of research done on a technique called 'phytoremediation', which involves the use of plants to extract, stabilize, or volatilize contaminants in soil, air or water. This method offers a cost effective way of controlling and/or removing contaminants *in situ,* thereby retaining the integrity of the soil. The purpose of this thesis is to integrate the scientific research into a framework that can assist a landscape architect in the design of brownfields to be remediated using phytoremediation. To create this framework the current literature on phytoremediation was reviewed and critically analyzed in order to identify the steps necessary for a successful phytoremediation program. These steps were then organized sequentially, in the form of a decision tree, to ensure that all pertinent information be integrated into the landscape architectural design process. The framework was applied to a case study to demonstrate its utility for landscape architects and implications for the use of phytoremediation in landscape architecture are discussed.

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1.0 INTRODUCTION

As industrial processes become obsolete, or more refined, industries are moving to new locations; often leaving large contaminated parcels of land behind in a state that is hazardous to human health and surrounding ecosystems. These lands are often referred to as brownfields. The U.S. EPA (www.epa.gov/brownfields) defines brownfields as abandoned, idled, or underused industrial and commercial facilities where expansion or redevelopment is complicated by real or perceived environmental contamination. Brownfields come in a variety of shapes and sizes that can include closed gas stations and dry cleaners, vacant warehouses, abandoned rail yards, or former coal plants or steel mills. With urban renewal/revitalization on the increase these lands are being reclaimed for new industries, housing, or public use; the development of which landscape architects are largely involved in.

Currently the most common method of decontamination is to remove the soil and dispose of it in a hazardous waste landfill, a practice commonly referred to as 'dig and dump'. Not only does this leave the contaminant untreated, it also shifts the land-base use to another area, destroys the integrity of the soil for further planting, and is extremely costly. In the last ten to fifteen years there has been a significant surge of research done on a decontamination technique called 'phytoremediation'. Phytoremediation involves the use of plants to extract, stabilize, or volatilize contaminants in soil, air or water. This method offers a cost effective way of controlling and/or removing contaminants *in situ*, thereby retaining the integrity of the soil and removing pressure on hazardous waste landfills.

Ensley (2000) did a cost comparison of 'dig and dump' and phytoextraction for a lead (Pb) contaminated site and estimated that using phytoremediation for the given site would be $20-80/ton of contaminated soil (including the cost of hazardous biomass disposal). In comparison to his estimate of $150-350/ton for 'dig and dump', phytoremediation is a decidedly cheaper alternative.

The only undisputed benefit 'dig and dump' remediation has over phytoremediation is the fact that phytoremediation cannot result in 100% cleanup whereas 'dig and dump' can. Phytoremediation can generally only remediate the fraction of the contamination that is most bioavailable. Although it may seem like a shortcoming, in the remediation of brownfields it is not. Removing the fraction of bioavailable contaminant is compatible with risk-based remediation approaches that allow the unleachable fraction to remain in the soil. This risk based approach is particularly suited to the remediation of brownfields where the post-clean up use may be industrial and target clean up levels may therefore be more lenient (Glass 2000).

Other than 'dig and dump' there are other engineering based technologies that are available for the treatment of contaminated soil. These engineering based technologies can be loosely categorized as either isolation/containment which involves vaults and caps, or decontamination which involves processes such as soil flushing, venting, heating, electro-osmosis, and bioremediation. These methods do not have the same popularity as 'dig and dump' because where vaults and caps are used the contaminant is still present on site and the cap presents a physical barrier to planting and underground utilities which in turn limits potential future land uses. Decontamination methods such as soil flushing, venting, heating, and electro-osmosis are costly, in part due to the fact that the soil must be taken off-site to be treated, and they also have varying degrees of success.

The terms bioremediation and phytoremediation are often used synonymously, but they are in fact two different processes which provide different results. Bioremediation deals with the degradation of organic compounds into their less toxic or nontoxic components with the use of microbial organisms, whereas phytoremediation involves the use of plants to stabilize, extract or volatilize both organic and inorganic contamination in soil, air or water. Microbial bioremediation is limited to the degradation of organic contaminants due to the fact that it has been ineffective at addressing the challenge of toxic metal contamination, particularly in soils, as some bacteria and fungi are able to accumulate heavy metals (Cunningham & Ow 1996), but these microbes are difficult to effectively remove from the soil matrix in a cost-effective manner.

In the case of organic contamination most microbes that are used in bioremediation processes live in the A horizon of the soil (Shimp et al. 1993). If the contamination is limited to this horizon only, current bioremediation methods may be sufficient, but where the contamination extends into the B and C horizons of the soil, deep rooting plants may be more appropriate. These deep extending root systems can supply and distribute limiting nutrients for microbial growth. This would suggest a possible melding of the two methods.

In order to employ current bioremediation methods specialized equipment and operators are required which increases the cost of this technique. Phytoremediation on the other hand relies on agricultural machinery and agronomic practices which are already well established and widely available.

One of phytoremediation's advantages, in addition to those mentioned above, is that it can be considerably cheaper than bioremediation. One of the factors is that it is several times cheaper to grow plants than to grow an equivalent weight of bacterial biomass. This is because plants don't require the sterile conditions or organic nutrients that bacteria need (Raskin 1996). Another advantage of using phytoremediation over bioremediation is that bioremediation methods often remove all biological activity from the soil and adversely affect its physical structure (Baker et al. 1994), as a result making it difficult to establish vegetation post-treatment.

1.1 PURPOSE OF THIS STUDY

The goal of this thesis is to develop a framework for the translation and synthesis of scientific information into a format that can be used by landscape architects to integrate phytoremediation research into the landscape architectural design process.

Therefore the purpose of this thesis is to explore the potential for the integration of phytoremediation into the landscape design process.

In order to explore this potential the objectives are as follows:

1. Critically analyze/evaluate the current literature on phytoremediation;
2. Review landscape design processes;
3. Derive a list of questions (from information in the literature review) that need to be considered in designing a phytoremediation program;
4. Organize these questions sequentially in the format of a decision making tree;
5. Illustrate the use of the framework through a case study; and
6. Discuss the implications for landscape architecture in the use of phytoremediation.

1.2 SIGNIFICANCE OF THIS STUDY

The principle of using plants to remediate polluted soils is not unfamiliar to landscape architects, as they are often involved in the construction of wastewater management ponds and the like. there is a danger though in making the assumption that phytoremediation is as easy as selecting a specific plant which absorbs a specific contaminant. The wastewater systems that landscape architects create are largely dealing with the effects of excess nutrients and a relatively limited range of toxic elements, whereas the composition of contaminants on a brownfield is often very complex, and since they are a relatively new area of study, there can be many unpredicted outcomes, often more hazardous than the original situation.

Many of the authors and academics contributing to the body of knowledge on brownfields development and phytoremediation have suggested that remediation technology and site design should be closely integrated.

> "The redevelopment of contaminated sites is an emerging area of practice that will require landscape architects and site engineers to work closer with environmental professionals than has been the case in the past. Unlike the environmental professional, the site design professional has historically taken the lead in the development of land and, as such, can embrace the requirements of the practice of brownfield redevelopment more immediately than the environmental professional can learn land planning. .Even new technologies such as phytoremediation employ some knowledge and techniques familiar to site designers. Site designers need to acquire the language of site redevelopment and gain an understanding of the methods of the environmental professional to be effective project leaders on redevelopment projects" (Russ 2000, p. vi).

> "The application of phytoremediation in the field requires some creativity as well as solid scientific, environmental, and agronomic skills. Because of the extreme variability of soil properties at contaminated site, debris, and regulatory concerns, one must be able to distinguish those tasks and sites that are difficult to manage from those that are impractical to improve the soil quality, fertility and metal uptake. Phytoextraction in the field becomes somewhat of an art that draws heavily on experience from other disciplines" (Blaylock & Huang 2000, p. 68).

Although there are landscape architects exploring this application, to date there has not been any publicly available/published process that addresses this issue.

1.3 LIMITATIONS OF THIS STUDY

The focus of this study will be on terrestrial environments, rather than aquatic, as soil is most likely to be in a landscape architects scope of work, and keeps the topic to a manageable size for this thesis. Presently the remediation of aquatic environments using plants often involves the rerouting of contaminated water across a system of suspended plant roots. These systems will require different amendment applications, planting methods, and harvesting techniques, but will have some considerations in common with soil remediation in terms of selecting appropriate plant material. Therefore the framework presented in this study should not be applied to aquatic environments directly, but may be used to indicate factors for consideration in the selection of appropriate plant material.

1.4 STRUCTURE OF THIS THESIS

The following four chapters are organized as follows:

Chapter 2 – Literature Review. This literature review is the synthesis and/or meta-analysis, of the scientific research and development, relevant to landscape architecture, which has taken place to date on the topic of phytoremediation.

Chapter 3 – Integration. This chapter aims to organize the information obtained through the literature review in the form of decision trees and guidelines that will act as a design tool for landscape architects.

Chapter 4 – Case Study. This case study acts as a vehicle for the demonstration of the use of the decision tree and guidelines developed in Chapter 3.

Chapter 5 – Discussion and Implementation. This final chapter serves to highlight the promises and limitations of phytoremediation, consider the role that landscape architecture may play its use and development, and provide recommendations for the future use of phytoremediation by landscape architects.

2.0 INTRODUCTION

The purpose of this chapter is to establish what research has been done to date in the development of phytoremediation and to determine the components of phytoremediation that would impact the work of a landscape architect or designer. This chapter will begin by giving a general introduction to phytoremediation and then will be broken down into the functions of the soil, the functions of the plants, and the general design process.

2.1 PHYTOREMEDIATION OVERVIEW

Phytoremediation is defined as the use of plants to extract, stabilize, or volatilize contaminants in soil, air or water. The use of plants in the treatment of wastewater contamination is well known and practiced. This practice is thought to be over 300 years old (Cunningham & Berti 1993). Early forms of such phytoremediation include constructed wetlands, reed beds and floating-plant systems.

The use of plants in the treatment of soil contamination is a more recent practice, the specific starting point of which is difficult to assess. Plants have historically been used as ore mining indicators due to their known ability to survive/absorb certain metals. For the most part the plants found growing on contaminated sites are not able to bioaccumulate noticeable quantities of the soil toxins in their above ground parts as their mode of survival is tolerance of the contaminants present rather than accumulation of them. However, there are plants that are known to take up appreciable amounts of these heavy metals, these plants are referred to as 'hyperaccumulators'. The amount of heavy metals a plant can take up, as a percentage of its dry weight, is what classifies it as a hyperaccumulator. Hyperaccumulators are the basis for a subcategory of phytoremediation referred to as 'phytoextraction' which will be discussed later in this chapter. The biological function of heavy metal bioaccumulation in plants is thought to be a naturally occurring defense mechanism against disease and herbivorous insects (Comis 1996, Boyd et al. 1994, Boyd and Martens 1994, Boyd and Martens 1995).

Other subcategories of phytoremediation that will be discussed are: 'phytostabilization', which is based on the use of toxin tolerant plant species; 'phytovolatilization', which is based on the use of plants which assist in volatilizing contaminants from the lithosphere to the atmosphere; 'phytodegradation' and 'rhizodegradation', which are based on the breakdown of organics in the plant and it's rhizosphere; and 'hydraulic control', which is based on the ability of plants to absorb and transpire large amounts of water. Each of these subcategories will be discussed in terms of their interaction with the contaminant, interaction with the soil, associated risks, and selection of plant material in Section 2.2.2.

2.2 SOIL MECHANISMS

2.2.1 General Soil Conditions

Industrial sites being considered for remediation have most likely been subject to a number of activities that affect the soil structure, among these are: compaction from heavy traffic, buildings, and excavations. Determining the techniques necessary to restore the land to a condition conducive to plant growth is the first step before phytoremediation can occur (Blaylock & Huang 2000). Also of importance in terms of soil are the sand and clay/loam content values, particle size distribution and percentage of organic matter. Soil conditions may not be homogeneous and therefore different levels of amendments will be required in different areas.

2.2.2 Soils Contaminated with Inorganics

Heavy metal contamination accounts for 40% of the contamination on the approximately 1000 sites identified in the EPA's 1986 National Priority List. Inorganic contaminants differ in treatment from organic contaminants in that they cannot be broken down into less harmful components, therefore it is necessary that they be extracted from the soil, or immobilized.

Metals exist in the soil as either:

1. Free metal ions and soluble complexes;
2. metal ions occupying ion exchangeable sites and specifically adsorbed on inorganic soil constituents;
3. organically bound metals;
4. precipitated or insoluble compounds, particularly of oxides, carbonates and hydroxides; or
5. metals in the structure of silicate minerals (Salt et al. 1995).

In scenarios one and two the metals are readily available for uptake by plants. In situations three and four manipulation of the soil environment is necessary to improve availability of these metals and therefore the effectiveness of phytoremediation. Situation number five is typical of background or indigenous metal levels (Salt et al. 1995).

To aid in the situations presented in three and four, chelating agents have been used to create metal-chelate complexes that prevent the precipitation or sorption of these metals (i.e. adherence to organic matter in soil), which keeps them available for plant uptake (Salt et al. 1995). The addition of these chelating agents requires careful timing as experiments done by Dushenkov et al. (1997) show that the addition of chelators to the soil during the early stages of plant growth inhibited plant development. In addition, experiments done by Blaylock et al. (1997) showed that the use of chelators was most effective when applied to established plants several days before harvest. Although the addition of chelates can help release metals for plant absorption, it can also allow leaching down the soil profile and present a risk of groundwater contamination. In addition to chelating agents, lowering the pH of the soil can also aid in increasing the availability of metals for plants (Harter 1983). A moderately acidic pH can be achieved artificially by applying fertilizers containing ammonium or soil acidifiers. Generally the lowering of soil pH by one unit will increase metal solubility by a factor of 10 (Förstner 1995). It should be noted that some plants have a natural ability to acidify their rhizoshpere by exuding protons (Salt et al. 1995), but it was found by Zhu et al. (1999) that possible leaching by this mechanism is not a concern.

According to Förstner (1995) approximately 70% of all metal contaminated sites involve two or more metals. Therefore the possibility of synergistic effects may be of considerable importance at some heavy metal contaminated sites (Ebbs et al. 1997). Examples of such synergistic effects are shown in research done by Turner (1973) where it was shown that cadmium (Cd) can increase the uptake of zinc (Zn) is some species, whereas Ebbs and Kochian (1997) showed that copper (Cu) can limit the uptake of Zn in *Brassica* spp.

Other soil constituents/amendments to consider are organic matter and phosphorous. Both organic matter and phosphorus have been shown to either increase or decrease availability of metals (Förstner 1995). Lead (Pb) has been shown to be rapidly stabilized by the addition of phosphates whereas arsenic (As) has been found to become more mobile (Berti and Cunningham 2000). Therefore care should be taken in the planning and management of soil amendments where more than one metal is being targeted. Careful planning will ensure that it does not have a negative impact by excessively increasing metal mobility or preventing its uptake by phytoremedial plants.

2.2.3 Organic Contaminated Soil

The bioavailability of organics in soil can be reduced by precipitating or binding of contaminants to soil particles. Amendments to increase the solubility of organics in soil are not discussed to a great extent in the literature as it seems that the microbial populations in the rhizosphere of the phytoremedial plants are effective at degrading and mobilizing the less soluble compounds for plant uptake (Nyer and Gatliff 1998). Therefore it is important to amend the soil for the growth and functioning of the microbial communities.

The growth of microorganisms that degrade organic contaminants at low concentration are most commonly limited by substrate/energy, and less frequently, by nitrogen, phosphorus, or trace minerals and, in the case of saturated soils, oxygen (Shimp et al. 1993). Therefore, in order to provide the ideal soil conditions for the remediation of organic contaminants the addition of nutrients and aeration of the soil should be considered.

2.2.4 Soil Sampling

When designing or evaluating a soil-sampling plan it is important to understand the stated objectives of the sampling plan, i.e. what questions does the plan expect to answer? There are three types of samples: grab, composite, and integrated. Grab samples are individual samples that are taken from a specific location where the extent and nature of the contaminant are already known. Composite samples are a combination of a number of samples that are mixed together thoroughly as a 'representative' sample. The analysis of such a sample represents an average condition, it can only determine the presence of a contaminant, not the extent or severity. It is generally used for initial assessment purposes. Integrated sampling is used to measure/monitor conditions over a period of time. A sample is taken from the same location over a period of time.

The sampling design can be categorized as either: judgmental, random, systematic, or a combination of all of these. Judgmental programs go directly to an area of suspected contamination. This is a cost-effective approach, but biased toward the worst-case scenario, not considering marginal areas. Random sample programs evaluate the entire site by randomly sampling at grid intersections across the site. The results indicate the average condition. Systematic sample programs are similar to random sample programs, the difference being that samples are taken at every grid intersection. This is a low bias, site-wide approach, but judgment is used in selecting grid frequency.

Berti et al. (1998) suggest that where phytoextraction is being considered as a remediation alternative a treatability study should be carried out prior to implementation. The treatability study would involve analyzing soil samples in a greenhouse to determine the potential effectiveness of phytoextraction with that particular soil-contamination mixture. This can be a drawback to developers as these studies are time consuming and an additional cost, but two seemingly similar sites can produce markedly different plant performance. These treatability studies can prevent a disappointing outcome on a full-scale project and prevent a damaging reputation for the technology.

2.2.5 Contaminant Characterization

There are a number of techniques available for the assessment of contaminant characteristics. These methods involve laboratory procedures that are most likely out of a landscape architects scope of work and therefore a specialist should be consulted for the chemical analysis of soil samples.

2.3 PLANT MECHANICS

To better understand how phytoremediation functions it can be helpful to consider a plant as an engineering mechanism. A green plant is a "solar-driven, pumping, and filtering system that has measurable loading, degradative, and fouling capacity" and the roots are "exploratory, liquid-phase extractors that can find, alter and/or translocate elements and compounds against large chemical gradients" (Cunningham and Berti 1993, pg. 208). Root surfaces support active bacterial biofilms and fungal extensions that significantly augment soil surface contact, metabolic capacities, and can alter most measurable soil physical and chemical parameters (Cunningham and Berti 1993).

The most significant interaction for the remediation of soil using plants is that between the soil and the root system. In order for the plants to be effective, their root systems must be in contact with the contaminated soil. This means that either the roots need to extend through the contaminated soil, or that the contaminated soil needs to be brought to the roots. The latter can be achieved by deep plowing. Deep plowing can bring soil up from a 2-3 foot depth and place it within 8-10" from the surface.

The remediation techniques employed on a contaminated site strongly depend on the nature, concentration, and physical state of the pollutants, the type of soil and specific aspects of the site itself (Rulkens et al. 1993).

2.3.1 Treatment of Inorganics

Primary sources of heavy metal pollution are the use of fossil fuels, mining and smelting of metalliferous ores, municipal wastes, fertilizers, pesticides, sewage (Kabata-Pendias and Pendias 1989), metal plating, chemical mining and smelting, battery recycling, wood treating, oil and solvent recycling, nuclear processing plants and landfills (Förstner 1995). Aside from direct dumping of metal wastes, metals enter the environment by aerial deposition from burning of fossil fuels and mining and smelting activities. Lead (Pb), copper (Cu), zinc (Zn), and arsenic (As) can be related to emissions from industrial plants, coal power plants, and refuse incineration plants (Förstner 1995). Metalliferous mining and processing, including the dumping of the associated wastes, usually produces the most severe cases of heavy metal pollution. Operations such as smelting, and effluent and waste disposal disseminate metal contaminants further from their sources of generation, by air, water and vehicular transport. The most common heavy metal contaminants are arsenic (As), cadmium (Cd), copper (Cu), mercury (Hg), lead (Pb), zinc (Zn), and radioactive strontium (Sr), cesium (Cs), and uranium

(U) (Raskin). Table 1 lists these most common contaminants and some of their likely industrial sources.

Table 1. Sources of Inorganic Pollution

Pollutant	Industrial Sources
As	Production by metal smelters, use as a herbicide, and refuse incineration plants
Cd	Production by metal smelters
Cs	Consequence of nuclear spills and accidents
Cr	Production by metal smelters
Cu	Emissions from industrial plants, coal power plants, and refuse incineration plants
Hg	Industrial bleaching, dredging of waterways containing Hg, past agricultural use as a pesticide, mining of gold. Fossil fuel and medical waste incineration account for >80% of atmospheric emissions.
Ni	Production by metal smelters
Pb	Emissions from industrial plants, coal power plants, and refuse incineration plants
Se	Agricultural irrigation, wastewater of oil refineries, electric power plants and other industries.
Sr	Consequence of nuclear spills and accidents
Tl	Emissions around cement works using pyretic smelting residues which contain thallium, smelting and metallurgical industries
U	Development of the nuclear industry involving mining, milling, and fabrication of various U products.
Zn	Production by metal smelters

Sources: Brooks (1998); Russ (2000); Blaylock and Huang (2000); and Förstner (1995)

2.3.1.1 *Phytoextraction*

Phytoextraction involves the use of plants that bioaccumulate metals from the soil and store them in their aerial tissues which are then harvested (Fig. 1). Plants naturally absorb heavy metals from the soil which are necessary for their development (Fe, Mn, Zn, Cu, Mg, Mo and sometimes Ni), but some plants exist which do not restrict other heavy metals from accumulating, metals which have no known biological function (Cd, Cr, Pb, Co, Ag, Se and Hg). The excessive uptake of these metals would be toxic to most plants, but not to plants now known as hyperaccumulators.

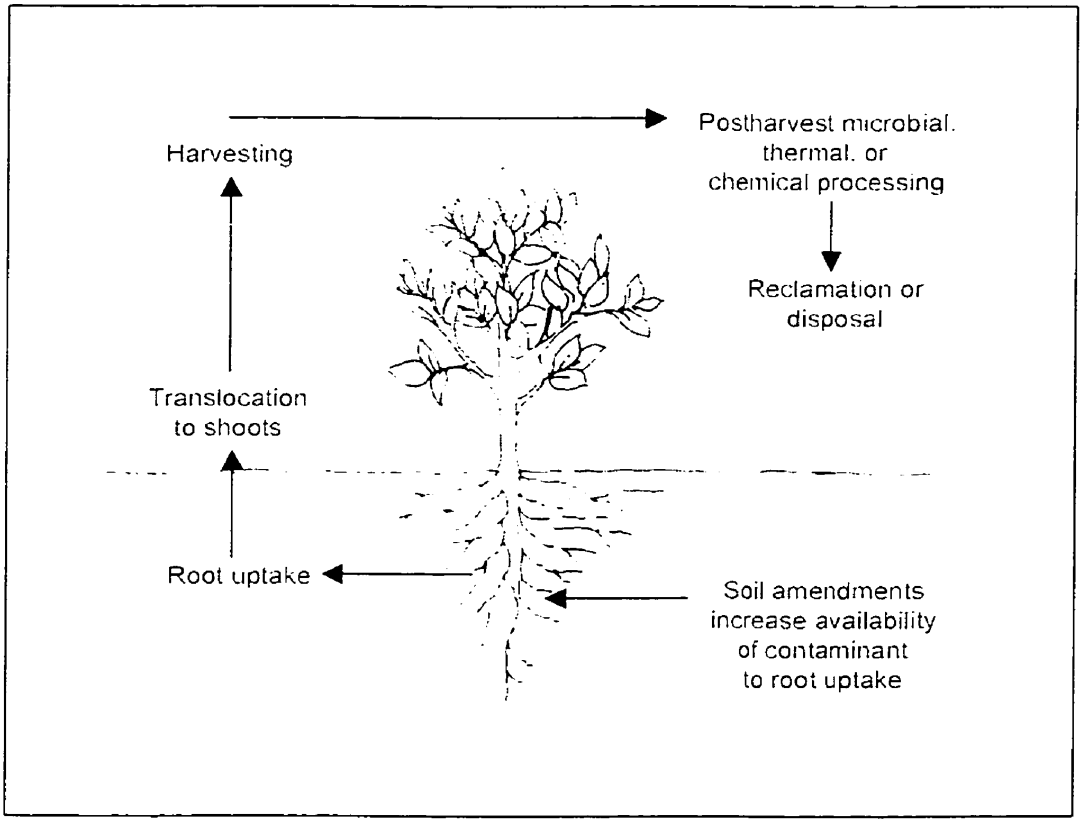

FIGURE 1. Phytoextraction (After Cunningham et al. 1995)

The level of metals in 'indicator' species (species which indicate the presence of metalliferous parent material) generally reflects the metal levels in the soil whereas the levels in hyperaccumulating species can far exceed the concentrations present in the soil (Raskin et al. 1994).

The uptake of metals from the soil by hyperaccumulators does not appear to be a passive phenomenon. The metal contents do not increase linearly as the metal concentration of the soil increases. Morrison et al. (1980) showed that accumulation even happens when the concentrations in the soil are low, which suggests an active uptake and sequestration process (Brooks 1998).

Hyperaccumulating species have been found all over the world. Places include: the United Kingdom, Germany, Switzerland, Spain, France, Italy, Bulgaria, Greece, Czechoslovakia, Zaire, The Philippines, North Caledonia, New Zealand, Japan and the United States (Cunningham & Berti 1995). For a list of these species please see Appendix A. Below is a list of the eight most common heavy metal contaminants and the corresponding plant families that have been found to have hyperaccumulating species.

Table 2. Metals and the associated hyperaccumulating families

Element	No. of Species	Families
Cadmium	1	Brassicaceae
Cobalt	26	Lamiaceae, Scrophulariaceae
Copper	24	Cyperaceae, Lamiacaeae, Poaceae, Scrophulariaceae
Manganese	11	Apocynaceae, Cunoniaceae, Proteaceae
Nickel	290	Brassicaceae, Cunoniaceae, Euphorbiaceae, Flacourtiaceae, Violaceae
Selenium	19	Fabaceae
Thallium*	1	Brassicaceae
Zinc	16	Brassicaceae, Violaceae

* Leblanc et al. (1997)

Source: Brooks 1998

It is difficult to find consensus on what defines a plant as a hyperaccumulator. Baker and Brooks (1989) defined hyperaccumulators as plants that contain more than 1000 mg/g (0.1%) of cobalt (Co), copper (Cu), chromium (Cr), lead (Pb), or nickel (Ni); or 10,000 mg/g (1%) magnesium (Mn) or zinc (Zn) in dry matter and these parameters are the basis for the plants listed in Table 2 and Appendix A. According to Comis (1996) a plant's capacity to take up more than 2.5% of its dry weight in heavy metals without a reduction in yield qualifies it as a hyperaccumulator. Cunningham and Ow (1996) consider an accumulation of 1-3% dry weight optimal hyperaccumulation. Baker et al. (1994) considered plants native to metalliferous soils with a capacity to bioaccumulate metals to concentrations greater than 2% in the aerial dry matter as plants suitable for phytoremediation.

The rate of heavy metal removal in phytoextraction is dependent on biomass gathered during harvest, metal concentration in the harvested parts, and the number of harvest per year (Cunningham and Ow 1996). Remediation programs will most likely have a time limit and therefore it will be necessary to choose plants that can accumulate the contaminant as quickly as possible.

Naturally occurring hyperaccumulating plants generally do not have a far-reaching root network or high biomass which limits their effectiveness in an aggressive phytoremediation program. This being said, these plants do contain a valuable store of genetic and physiologic information (Cunningham & Berti 1993) and therefore care should be taken to protect the indigenous ecosystems in order not to lose this promising resource.

Experiments carried out by Baker et al. (1994) showed that a higher biomass could be achieved in hyperaccumulating plants, in comparison to their natural environment biomass, using agronomic practices. The method included propagating the seedlings (a variety of species from the Brassicaceae family) under glass, planting them directly into freshly cultivated soil (contaminated with Zn, Cd, Ni, Cu, Pb and Cr) in early spring, at a density of 90 plants/m2, a light application of fertilizer, and harvesting at peak biomass (approximately 6 months after planting).

Huang & Cunningham (1996) have proposed that it may not be necessary to only investigate hyperaccumulating species. In an experiment using *Zea mays* (corn) they applied a chelator just as the plants reached maximum biomass in order to force lead (Pb) uptake. This of course is toxic to the plants but the plant material was harvested promptly and the lead (Pb) content increased from 0.004 to 1.06% in the dry matter. The advantages of using a plant such as corn is that the optimal agricultural practices have already been developed, the disadvantage is that it may be difficult to harvest the dead plant material and there may be a greater chance of grazing/herbivory by animals used for human consumption. In addition it is currently unclear what will happen to the residual chelating agent, it may simply be substituting one pollutant for another and affect future crops.

There is a caution to be aware of when considering the employment of phytoextraction. The heavy metal loadings that have been transferred from the soil to the plant may subsequently be transferred to grazing animals and there may be a further chance of the metals moving up the animal food chain to humans. Although naturally occurring heavy metal loading in plants is thought to be a function of protection against herbivory by pests scientists fear that the insects will be able to adapt and tolerate the presence of heavy metals plant tissue. If these insects are able to survive the heavy metal consumed, these insects could be consumed by birds and metals will be bioaccumulated in the food chain rapidly.

In terms of assessing the risk of metals entering the food chain, "passage poisons" (such as Zn, Cu, Ni) in food chains are more toxic to the plants themselves than to humans and animals which may eat them, as a result the plants will most likely die before being consumed by an animal. "Accumulation poisons" (such as Pb, Cd and Tl) on the other hand, are usually tolerated by plants in greater amounts than what is recommended for food and feed. Elements such as Cr and Hg are translocated to the shoots in such small fractions that they are not expected to be a problem (Förstner 1995). This can be less than straightforward because elements often occur together, such as Zn and Cd. Zn is phytotoxic and usually results in a decrease in crop yield before it can enter the food chain. Cd on the other hand is a food chain toxin which rarely inhibits plant growth (Brooks 1998). The risk is dependent on which metal is able to act first. It is likely that the Zn will kill the plant before the Cd is consumed by fauna.

As can be seen from the situation above plants which cannot survive certain soil conditions may not necessarily be sensitive to the target contaminant but may rather be sensitive to the presence of other toxins in the soil, these 'other toxins' become the limiting factor (Cunningham et al. 1995).

Aside from herbivory that may take place directly on site, it will also be important to minimize the dispersal of seed, pollen, or leaves off site. This could be achieved by harvesting before flowering occurs, but at a high biomass yield. Harvesting is also important because the senescence of old leaves returns elements to the soil in a bioavailable form (Brooks 1998). This can particularly be a problem with the use of trees on a metal contaminated site. The use of trees for phytoextraction in particular should be done with caution as there is still very limited knowledge relating to the uptake patterns of heavy metals in trees. Research to date shows that metals tend to remain in roots rather than being transported to aerial tissues (Borgegard and Rydin

1989; Arduini et al. 1994) but it is not certain whether this is true for all species and situations.

The harvested material containing heavy metals can later be reduced off-site by ashing, and in some cases, where economically feasible, the ash can be further processed to reclaim the metals for further commercial use. Where the remaining metals have no significant commercial value the resulting ash will need to be disposed of in a hazardous waste landfill. This method results in a volume of material less than 10% of that which would be created if the contaminated soil itself were dug up for treatment (U.S. EPA 1998).

In order to determine the rate of uptake that will be required by a crop to achieve the desired level of decontamination within a given time period the following equation proposed by Dushenkov (1997) can be used:

$mME=a[Me]^{*}m_{pl}$

where mME is the total amount of metal to be removed every year, *a* is the coefficient of units conversion, [Me] is the metal concentration based on dry weight, and m_{pl} plants dry weight accumulated during the growing period. By using this equation you can see the relationship between crop yields and the expected metal concentrations that are required to clean a site within a given number of years and use this as guide to selecting/creating the ideal hyperaccumulating species.

The largest number of hyperaccumulating species in the temperate zone belong to Brassicaceae (Baker and Brooks 1989), and in the tropics Euphorbiacaea (Spurge family) is best represented (Raskin et al. 1994). See Appendix A for an exact geographic representation.

2.3.1.2 *Phytostabilization*

Phytostabilization involves the use of plants to immobilize soil contaminants through absorption and accumulation by roots, adsorption onto roots, or precipitation within the root zone of plants (Fig. 2). Phytostabilization is appropriate when the level of contamination is low and surficial, and the possibility of exposure to the public is limited.

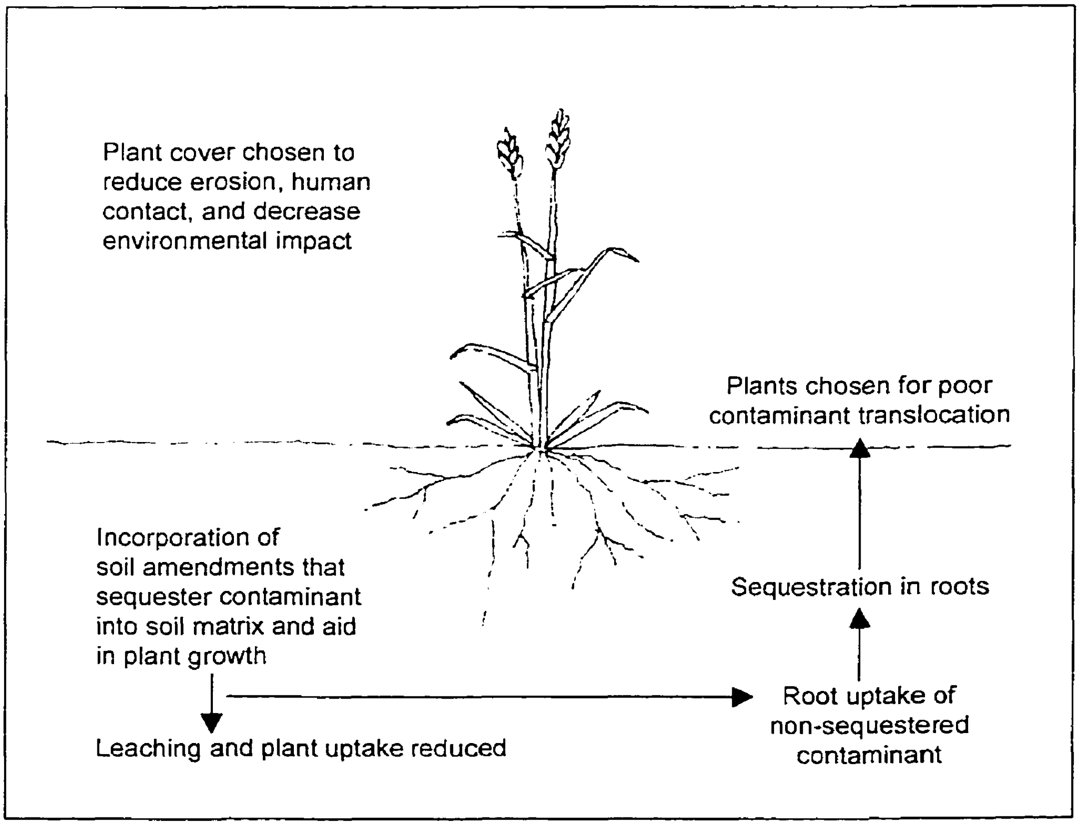

FIGURE 2. Phytostabilization (After Cunningham et al. 1995)

Plants involved in phytostabilization either tolerate the presence of heavy metals in the soil, rather than accumulate them, or limit the uptake of heavy metals to their root system, which is difficult to harvest or graze. The presence of groundcover, regardless of metal uptake in roots, can prevent the contaminated soil from drifting off-site by wind and water erosion as well as preventing excessive leaching to the groundwater table. Therefore the role of plants in phytostabilization is threefold. Plants are used to alter the water flux through the soil profile in order to keep contaminants sequestered, to incorporate residual free contaminants into the roots, and prevent erosion.

This technique is founded on the practice of revegetation of decommissioned mine spoils and smelter facilities, in which chemical amendments were often necessary to establish plant growth. Metalliferous substrates, particularly deposits of waste products of mining and smelting, are also often poor in major nutrients, such as nitrogen, phosphorus and potassium, and have a very low water holding capacity, mainly because they are almost devoid of organic matter (Schat and Verkleij 1998).

In the case of phytostabilization there is interest in immobilizing contaminants as much as possible in terms of plant uptake as well as leaching down the soil profile. Possible amendments to achieve immobilization include alkalizing agents, phosphates, and organic materials (Cunningham & Lee 1995). Depending on the depth of contamination plowing under of amendment may be necessary. Equipment is available for depths of 30 cm, to a maximum of 90cm, for a depth greater than 90cm specialized equipment will be required. Therefore the depth of contamination should be considered with the addition of amendments as there will be an increase in the cost for specialized equipment the deeper the contaminant reaches.

Subsequent application of lime or fertilizer may be required after application of amendment due to the possible decreased availability of nutrients and the possible increase in salinity. Research suggests that a stabilization crop can best be established with the use of fertilizers. Brooks (1998) pointed out that this may require further research as the application of fertilizers to stabilizing communities may decrease plant diversity by eliminating rarer species and encouraging the appearance of weeds that would not normally tolerate the original conditions.

Careful coordination of soil amendment and fertilizer application and planting should be considered because where amendments are applied to soil and then left bare for a considerable amount of time will allow the establishment of invasive weed species. These weed species may then provide competition for nutrients and other resources necessary for growth to the intended/planted species. Of course, not planting soon enough after soil amendments will also allow the erosion and leaching of the soil with amendments and fertilizers. Once plants are established, the periodic reapplication of fertilizer or re-seeding of poor stands may be necessary, but the application of pesticides is not likely necessary if the plants have been chosen wisely and properly established.

Where phytostabilization is the remediation method selected, the soil and contaminant characterization will help define the selection of soil amendment type and rate. Applying amendments on sites with mixed metals may immobilize some and increase the mobility of others. The method will become murkier yet where organics and inorganics occur together, such a situation will require an innovative approach.

Recent research has shown that root-microbial symbioses such as mycorrhizal fungi can reduce the mobility of heavy metals in soils and significantly increase plant growth and density for site revegetation. Mycorrihizal fungi are often not present in heavily polluted soils. Presently this application is hindered by the difficulties in inoculating plants or the soil with the appropriate fungi (Colpaert 1998).

The final destination of phytostabilized areas may be nature conservation, especially if the area has a high degree of endemic metal-resistant species (Ernst 1998). Soil contaminant levels at these sites are not reduced so human activities may need to be restricted or limited. Where metal solubility is controlled so that the plant cannot take up metal, these sites may be considered for silvicultural practices. Animal grazing on such sites is normally limited to short time periods and animals are rotated to non-contaminated land for the rest of their feeding requirements (Cunningham & Lee 1995). However, the possibility of heavy metal dust particles being present on the plant surface should not be overlooked when considering excessive grazing.

The type of vegetation that is most commonly considered for phytostabilization are grasses. Studies have shown that a grass species may survive better on a contaminated soil when accompanied by the other grass species that were present in their original habitat (Turkington and Harper 1979, Silvertown 1987). Therefore it may be important to consider the plant material in terms of communities rather than on an individual basis.

Plants selected for phytostabilization should grow quickly in order to establish groundcover, have dense rooting systems and canopies, and have relatively high transpiration rates to effectively dewater the soil. In addition it is desirable to select plants that are easy to care for, have a long life or are able to self-propagate (Berti and Cunningham 2000).

2.3.2 Treatment of Organics

Primary sources of organic contaminants are the agricultural use of pesticides and herbicides, and byproducts of chemical processes in the manufacturing of plastics, synthetics and petroleum products. Aside from direct agricultural application these contaminants enter the environment by hazardous waste dumping, landfill leachate, industrial wastewater and accidental spills. Many organic contaminants are extremely persistent in the environment, and although some, such as PCB's, have been banned since 1977, one can still expect to find them on most contaminated sites. Table 3 lists the most common organic pollutant types and some of their possible industrial sources.

Table 3. Sources of Organic Pollution

Pollutant	Industrial Sources
Semivolatile organic compound (SVOC)	A broad category of chemicals that includes benzo(a)pyrene, benzo(b)flouranthene, dibenz[a,h]anthrancene, and hexachlorobutadiene.
Volatile organic compound (VOC)	Example: Benzene; associated with gasoline stations, undergroung storage tanks, landfill leachate, and industries that produce or use benzene. Such facilities include plastics factories, petroleum refineries, and chemical plants.
PCB	Were at one time commercially produced as coolants and lubricants in transformers, capacitors, and other electrical equipment.
PAH	PAHs are byproducts of incomplete combustion or degradation of organic substances. Elevated levels are associated with oil and gas use, asphalt plants, coal-tar production, aluminum production, trash incinerators, sites of fires, and anywhere coal or petroleum products are used or where wood or other organic materials are burned.
Pesticide	Pesticides are commonly used in agricultural applications and have a wide distribution and persistence in the environment.

Sources: Russ (2000); Blaylock & Huang (2000)

2.3.2.1 Phytodegradation

Phytodegradation is the breakdown of organic contaminants taken up by plants through metabolic processes within the plant, or the breakdown of contaminants external to the plant by compounds exuded by the plant. The simpler molecules created by the interaction with the root exudates are then taken up by the plant (Fig. 3). The simpler molecules are then incorporated into the plant tissues to help the plant grow faster (U.S. EPA 1998).

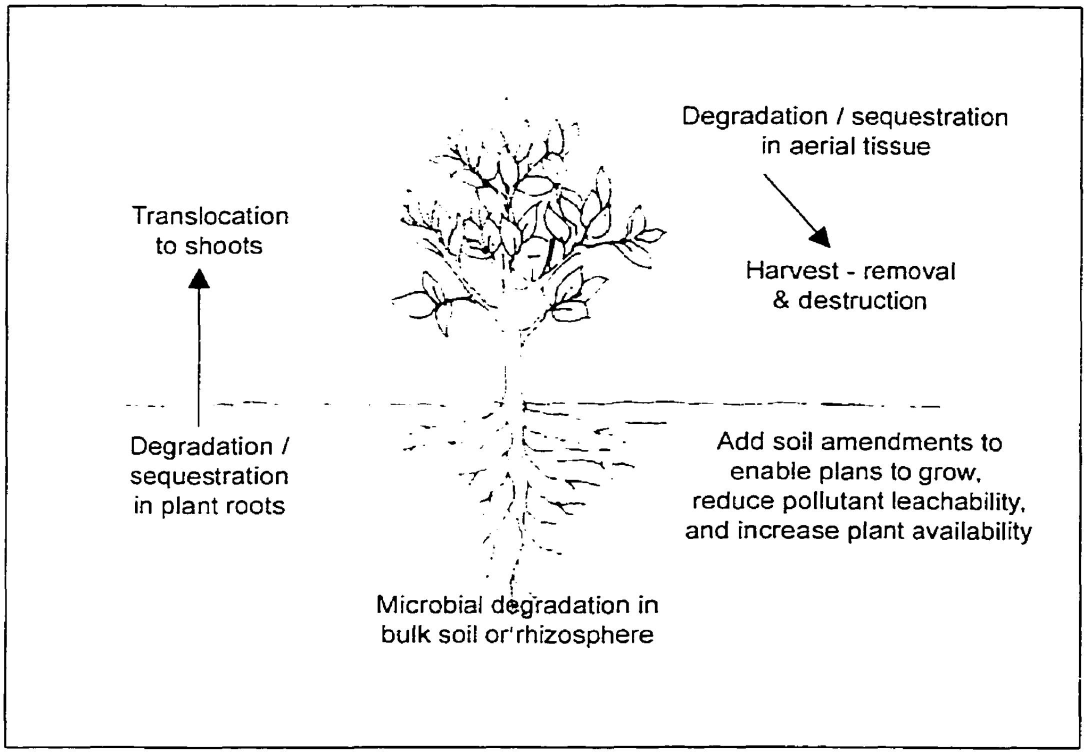

FIGURE 3. Phytodegradation (Modified after Cunningham & Lee 1995)

Studies done on the metabolism of nonagricultural xenobiotics such as trichloroethylene (TCE), TNT, glyceroltrinitrate (GTN), polyaromatic hydrocarbons (PAHs), PCBs (Pradhan et al. 1998, Nichols et al. 1997, Yateem et al. 1999, Mackova et al. 1998, and Brigmon et al. 1998) and other chlorinated compounds (Salt et al. 1998, and Langebartels and Harms 1984) showed that although most of these compounds can be metabolized, only a few chemicals appear to be fully mineralized. Some plant metabolites of pollutants may be more toxic than the original compounds, making plants less attractive compared with bacteria, which have the ability to completely degrade organic pollutants (Macek et al. 2000).

In comparison to microbial metabolisms for remediation of organics, plants act on a narrower range of substrates, perform simpler degradative steps, and generally do not reduce the xenobiotic to a molecularly simple endpoint (Cunningham and Lee 1995). Therefore a careful assessment needs to be made whether it would be safer to use bioremediation, or if the possibility exists to combine the two methods.

Predicting the capability of a plant in the remediation of organics can be assisted by looking at the K_{ow} (octanol-water portioning coefficient), a method used in the pesticide industry to predict the fate and effect of a pesticide. Cunningham and Lee (1995) state that contaminants with a log K_{ow}:

- ≤ 1 are very water-soluble and would be predicted to cause groundwater contamination without the presence of a hydrological containment system. In addition plants do not accumulate water-soluble compounds at a rate surpassing the passive influx in the transpiration stream.
- 1 – 4 are slightly more lipophilic and are taken up by roots and mobile in xylem. These are considered good targets for phytoremediation and many priority pollutants are found in this range. At the low end it would be more dependent on soil type, rainfall and how the material entered the environment.

Assessment of whether a plant is appropriate for the phytodegradation of an organic contaminant will require considerable scientific research. The above calculation is mentioned in order to provide a means of determining whether phytodegradation may be a possibility for the site in question, using information that may be available in the environmental site assessment.

2.3.2.2 *Rhizodegradation*

Rhizodegradation is the breakdown of organic contaminants in the soil through microbial activity that is enhanced by the presence of the root zone (rhizosphere) (Fig. 4).

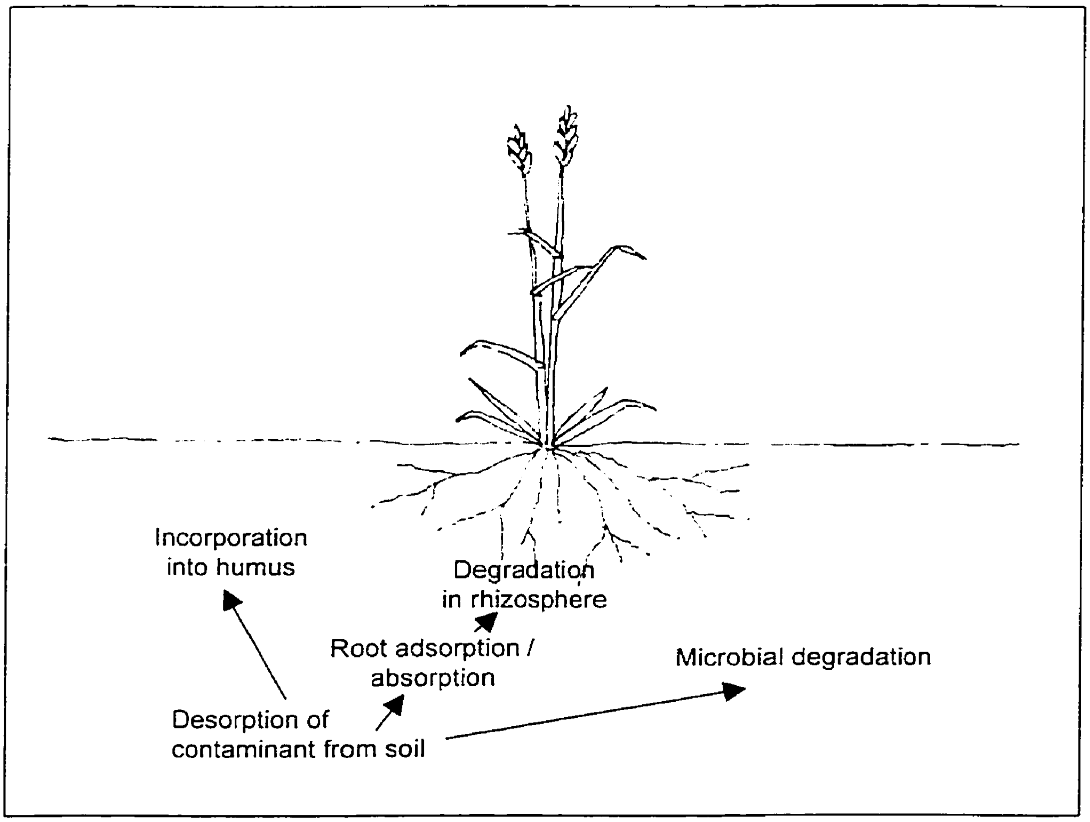

FIGURE 4. Rhizodegradation (Modified after Cunningham et al. 1995)

The ability of plants to remediate soils contaminated with organic chemicals is greatly enhanced by the presence of microbes in the soil. Microbes are good at 'degradation' of organic chemical compounds and therefore help break down organics into more environmentally acceptable endpoints. "The plant provides water, pollutant, and photosynthate flux. The microbe, mycoplasms, virus, or other provides the degradative capacity" (Cunningham & Beri 1993, pg. 211). Therefore it is important to provide a healthy rhizosphere which will serve as an enrichment zone for the increased growth of certain bacteria. The surfaces and surroundings of plant roots provide specialized habitats for soil microorganisms (Shimp et al. 1993). It should be noted that in the case of remediating heavy metals from soil such root fungi and mycorrhiza are suspected of hindering metal uptake (Comis 1996). This may pose a problem where both organics and inorganics are being treated in the same soil.

According to Shimp et al. (1993) plant-aided biodegradation is dependent on: the composition of the rhizosphere microbial communities; root exudates that act as supplemental substrates; nitrogen present in water, supplied by decaying roots, or fixed by symbiotic or free-living bacteria; oxygen transfer to the soil; and the kinetics of microbial degradation (dependent on temperature, nutrient concentrations, and water availability).

When choosing a plant for remediation of organic contaminants it is important to keep in mind that the plants must be able to support the appropriate microbial communities in their rhizoshphere (Shimp et al. 1993). For example plants that support nitrogen fixing bacteria can be helpful in the remediation of petroleum products.

Classes of organic compounds that are more rapidly degraded in the rhizosphere than in bulk soil include polycyclic aromatic hydrocarbons, total petroleum hydrocarbons, chlorinated pesticides (PCP, 2.4-D), other chlorinated compounds like polychlorinated biphenyls (PCBs), TCE, explosives (2,4,6,-trinitrotoluene [TNT], hexahydro-1,3,5-trinitro-1,3,5-triazine [RDX], dinitrotoluene [DNT]), organophosphate insecticides (diazinon, parathion), and surfactants (detergents) (Macek et al. 2000).

2.3.3 Treatment of Inorganics and/or Organics

2.3.3.1 Phytovolatilization

Phytovolatilization involves the use of plants to extract volatile contaminants from the soil and volatilize them from their foliage (Fig. 5). Phytovolatilization is a method that has been most widely explored for the extraction of mercury (Hg) from polluted soils using transgenic plants. The results have been extremely positive, but there are definite drawbacks. Once the mercury (Hg) has been volatilized from the plants leaf surface it is expelled into the atmosphere where the potential complications of airborne mercury (Hg) are yet unknown (Salt 1998).

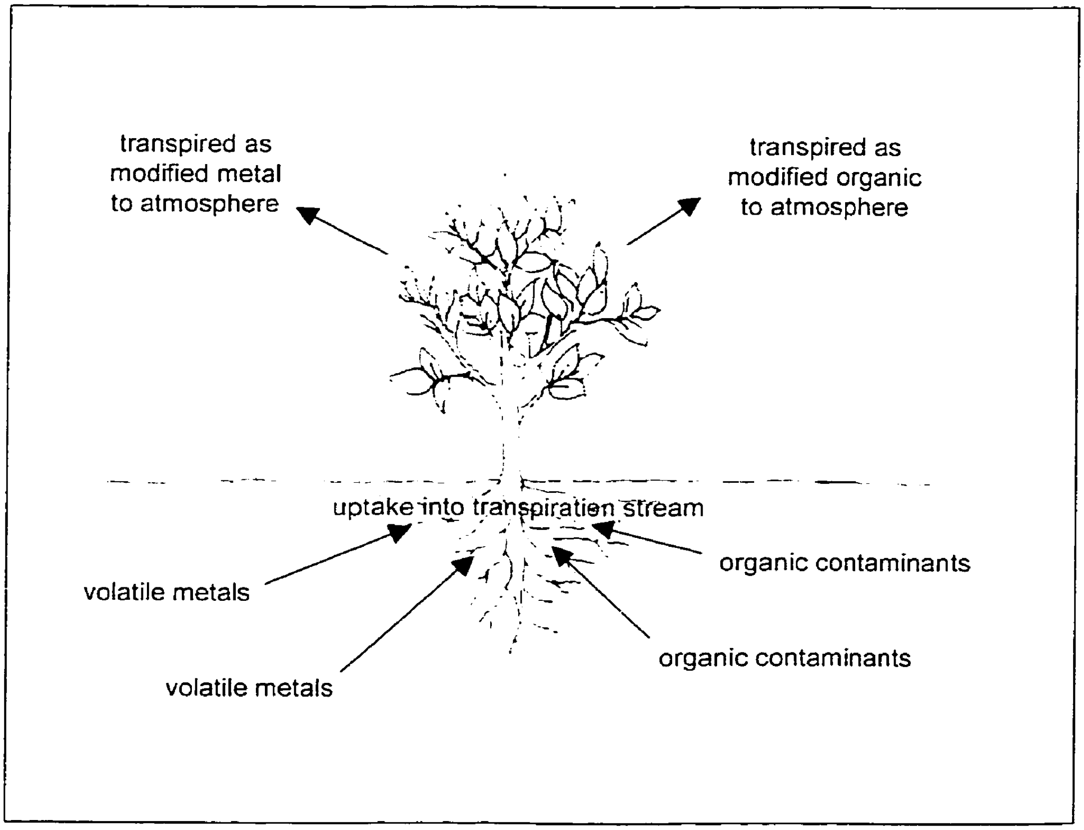

FIGURE 5. Phytovolatilization Processes

In the case of organics a study done by Aitchison et al. (2000) used poplars for the remediation of dioxane. This study found that 76-83% of the dioxane was volatilized into the atmosphere. This study stated that the "worst case" conditions of atmospheric dioxane and it's potential by-products pose little threat to public health.

In many ways the end result of phytovolatization of organics is much like the end result of bioremediation. The soil has been remediated and the pollutant has been transferred from the lithosphere into the atmosphere without the need for harvesting, possible combustion, and physical removal of the resulting ash or dry biomass for storage (Brooks 1998). The use of phytovolatilization may be dependent upon whether microbes for the break down of a given contaminant already exist and which is the cheaper alternative.

It appears that more research is required in the risks associated with translation of soil toxins to the atmosphere before this will become a widely used practice.

2.3.3.2 *Hydraulic Control of Contaminants*

Plants that have extensive root systems that reach down toward the water table and have a dense root mass that takes up large quantities of water, can act as hydraulic pumps preventing or controlling the migration of subsurface water (fig. 6). Specific applications using plants for hydraulic control are riparian buffer strips, vegetative caps, and plume control (U.S. EPA 1998).

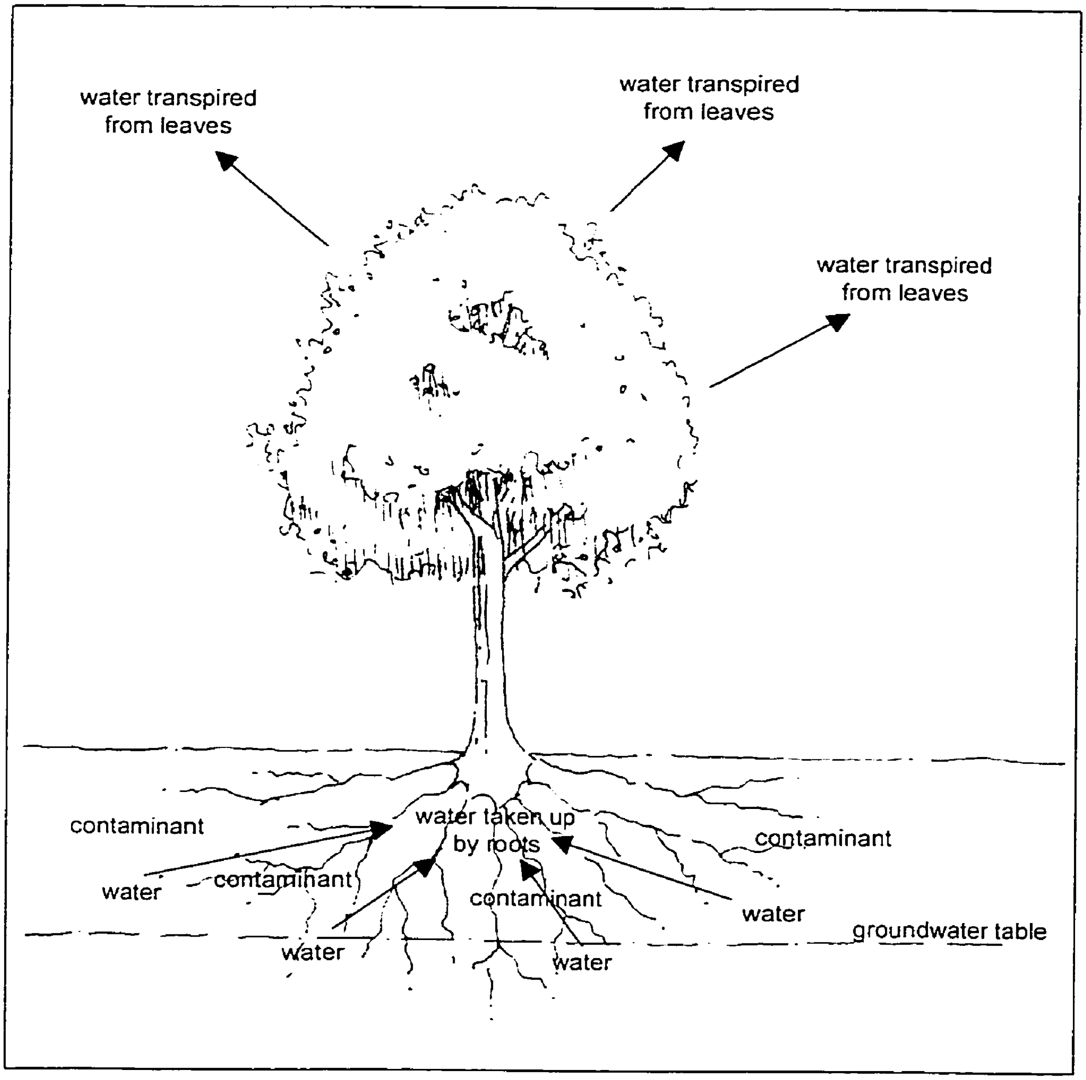

FIGURE 6. Hydraulic Control Processes

A plant's transpiration characteristic has been used extensively to concentrate solutions and control groundwater seepage. Poplars are commonly used to control the flux of water through the soil as they are phreatophytes (roots extend to the water table) they can withdraw water from a depth of 3m (15ft). This extensive root system also provides the ability to transfer oxygen to the rootzone for potential aerobic mineralization of organics, and build up of organic carbon in the rhizosphere due to root necromass, which retards the movement of hydrophobic organics (Jordahl et al. 1997). The webbing of the root systems of plants also makes them a valuable soil stabilizer and erosion prevention tool.

The success of hydraulic control depends on the rooting depth and density, the hydraulic conductivity of the waste and soil, growth rate of the trees, and climatological factors such as humidity, sunlight, wind speed, and rainfall. In the winter months when deciduous trees are dormant the success of this treatment will depend on the moisture holding capacity of the soil.

2.3 RISK BASED ASSESSMENT

The three most common options for soil cleanup are: cleanup to background conditions; cleanup to generic, statewide, numeric standards; or site-specific, risk-based, and use-based standards (Dinsmore 1996). Cleaning up to generic, numeric standards is problematic in that it may not take into account that in some areas the natural background concentrations of heavy metals in soils exceed those that are considered safe by the regulatory agencies (Runnels et al. 1992). In a similar manner, cleaning up to background conditions may be unreasonable as some metals that are essential plant nutrients may not have been present before. Popular opinion is that using a site-specific, risk-based, use-based level of standards provides the most efficient and effective design both in terms of quality of remediation and cost.

Risk assessments will need to be done by a certified professional, but the resulting information will be valuable to the landscape architect in understanding the potential impacts of contamination on aquifers, soils, contributing watersheds, air quality, and surrounding landuse. The result of the risk assessment will also determine the level of cleanup required and thus help determine which remediation methods will be viable alternatives.

2.5 DESIGN PROCESS

Lyle (1999) defines design processes as the vehicles for creative participation in natural processes. He also goes on to say that the way we go about design varies with the scale of concern and the situation at hand. In this respect phytoremediation can be seen as a natural process in which designers creatively participate and/or manipulate in order to obtain a site-specific level of decontamination.

Discussing a design process for phytoremediation is difficult as there are many generalized design processes to choose from, but as of yet, none are specialized towards accounting for contamination. This is in part due to the fact that landscape architects have not had to deal with the issue of contamination on a site until recently. Traditionally the contamination would have been dealt with prior to introducing the landscape architect to the project. It is the use of plants in the process of phytoremediation that now opens the field of decontamination to the profession.

The use of phytoremediation has concerns that are not addressed in the traditional design approaches which focus on human use and aesthetics, nor can the more recent ecological design processes completely embrace it.

Although the proper use of phytoremediation will involve an understanding and respect of ecological systems, this understanding will be required in order to keep the phytoremediation system closed from greater ecological processes, rather than to enhance or integrate them long-term.

Design involving phytoremediation can get very complicated as it combines two different modes of thought: analytical use of scientific information and creative exploration. Lyle (1999) states that science and design can work together as long as the roles of each are clearly established. In the case of phytoremediation the scientific aspect will most likely take the lead as the implications of not doing so can have a great effect on public health and the environment.

Due to the fact that there is not presently a set design process for contaminated sites available, it is desirable to identify the most basic and common steps involved in site design to provide a basis for the framework to be developed in Chapter 3.

Motloch (2000) states that there are as many design processes as there are designers, but that these processes share some characteristics. According to Motloch (2000) these processes all identify some issue to be resolved or problem to be solved. Ideas for solution are implemented and then evaluated, which usually leads to a greater understanding of the problem (Fig. 7). Motloch also states that these characteristics rarely occur as discrete entities, but more often occur intuitively and without apparent organization. Therefore these design processes are not linear in character, but rather cyclical and ongoing.

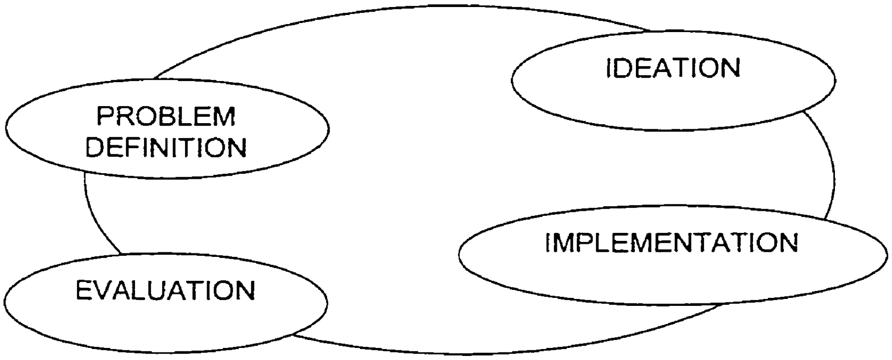

FIGURE 7. Commonality of Design Processes (after Motloch 2000).

Supporting the commonality of design processes outlined by Motloch (2000) is the site design process proposed by Rutledge (1986) which is outlined in three phases beginning with a 'survey', or an assembling of facts and data. The second step is 'analysis', or the making of value judgments about the effects of one fact upon another. The third step is 'synthesis', or the weaving of the results of analysis into a comprehensive solution to the problem. Rutledge (1986) points out that the steps may not be done strictly according to this chronology, for there is much feedback and interplay among them. Although evaluation is not included in the three phases it is the next topic to be discussed in his book 'Anatomy of a Park' and is discussed as a part of the design process. The stages 'survey', 'analysis' and 'synthesis' described by Rutledge (1986) are analogous to the 'problem definition', 'ideation', and 'implementation' stages described by Motloch (2000), thus indicating that it is a good representation of a common core design process.

The process that Lyle (1999) discusses is somewhat similar to those described by Motloch (2000) and Rutledge (1986), with the following most marked exception. Lyle (1999) states that feedback from later to earlier stages is a basic part of every design process and since management usually involves periodic redesign, the feedback loop can be the critical, permanent linkage between management and design (Fig. 8). Therefore management will be added as the fifth stage of the design process to be discussed in this thesis.

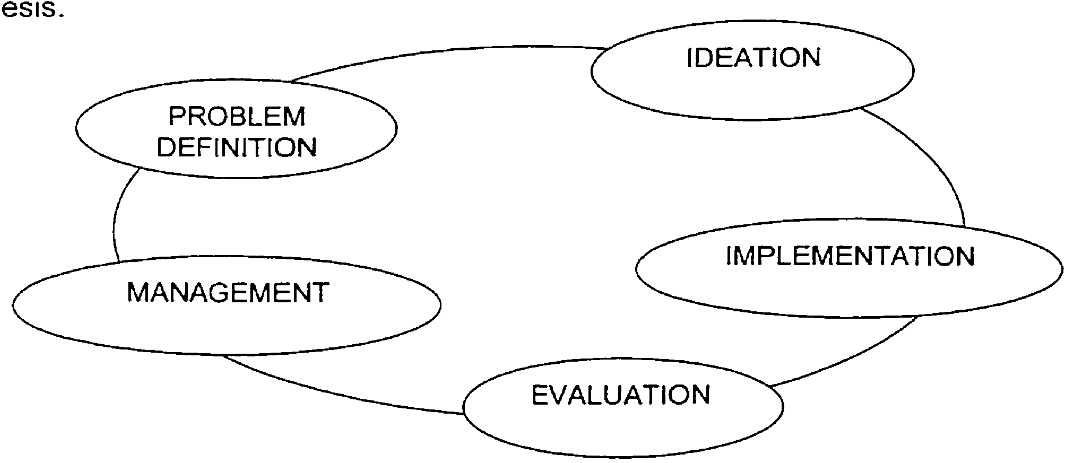

FIGURE 8. Revised Commonality of Design Processes

The five stages of design to be used in the framework are discussed briefly below.

2.5.1 Problem Definition

Problem definition involves analyzing the site in terms of the requirements and goals of the future use of the site. Programming and site analysis are tools that can be used in defining the problem. Programming can involve the development of matrices and functional relationship diagrams to determine priorities. The site analysis involves inventories, site visits or reconnaissance, and communication with other professionals on the project.

2.5.2 Ideation

According to Motloch (2000) the generation of design ideas or design concepts is largely an intuitive integration of the program and site analysis. This may require a different interpretation with phytoremediation, as science will take a lead in order of importance, and therefore drive much of the design. Where design concepts may vary are in the choice of implementation strategies, i.e. choosing a variety of plant options, soil amendments, and machinery.

2.5.3 Implementation

In the implementation stage schematic designs are drawn up in order to specify forms, circulation patterns and materials.

2.5.4 Evaluation

At the stage of evaluation the various schematic designs of the concept are compared to the program developed in the definition of the problem and are evaluated as to whether or not they satisfy all of the requirements set out at the beginning of the project. During this evaluation consideration should be given to whether or not the designs have brought about any new problems or areas of concern. In which case the designer would cycle back to the beginning of the process to address this new issue.

2.5.5 Management

The inclusion of management is particularly important in ecosystem design because of the variable future that is a fact of life for any organic entity (Lyle 1999). Although phytoremediation is not ecosystem design in the traditional sense, it certainly can have an impact on them.

Monitoring is a fundamental activity in environmental management, much in the same sense that taking of temperature readings or blood pressure are to measure the health of a human body (Lyle 1999). Without knowing the vitality of the system, meaningful decisions are not possible. It is also impossible to measure everything in an environmental system, therefore it is equally important to know the variables that are capable of indicating the health of a system (Lyle 1999).

2.6 SUMMARY OF THE LITERATURE REVIEW

In summary the literature review has illustrated that there has been much activity in the scientific research of phytoremediation. Although, due to the relatively young age of this research database, it appears there are many more questions at this point than there are definitive answers. These unanswered questions will limit the immediate applicability of phytoremediation in many situations.

From the literature review it can be seen that phytoremediation is a technique that is highly sensitive to the environment in which it occurs. Overcoming or mitigating these sensitivities will require that the users of this technology understand where inadvertent results could occur, and possible ways to mitigate them.

The next chapter attempts to translate the complex scientific information presented in this chapter into a format that will aid a landscape architect in the decision to use phytoremediation and provide a tool to aid in the design of a phytoremediation program.

3.0 INTRODUCTION

The goal of this chapter is to organize the information from the literature review in such a way that a landscape architect with limited scientific knowledge can determine whether phytoremediation is appropriate for a given site and aid them in identifying important factors that will have to be considered in its implementation. In order to present this information in an easy to use format, a decision tree with a series of loops will be developed. This decision tree maps the information presented in the literature review and will eventually lead the user to explore another remediation technology, or lead the user to a series of guidelines to aid in the implementation, evaluation and management of a phytoremediation program.

3.1 DECISION TREE

The information collected during the literature review was integrated to create a decision tree with a series of loops. Through the literature review basic categories of information essential to the efficient and effective use of phytoremediation were identified (e.g. soil amelioration, soil amendments, harvesting, contaminant end-points). These categories of information were then transformed into a series of questions posed in the decision tree.

The decision tree can be easily used by a non-expert in order to ensure that they are aware of all the impacts that phytoremediation can have on the environment. In addition, the decision tree can help highlight where the designer has the opportunity to mitigate possible problems.

The decision tree should be viewed as a tool for responsible decision-making by landscape architects, and should in no way be viewed as a substitute for qualified environmental assessments or public health measures.

The decision tree is based on one developed by Brace (1984) for the purpose of identifying the potential impacts of a project on archaeological resources. The decision tree in this study goes to a greater level of detail than Brace's (1984), as its purpose is to guide the starting blocks of design, in addition to determining the potential impacts of phytoremediation.

The steps taken in the decision trees are best encapsulated in the problem definition and ideation stages of design, as they are dependent on the systematic analysis of the information obtained through the site inventory/survey. The implementation and management stages of design are best encapsulated in the guidelines as these stages of design will become more site dependent and require the intuitive integration of the designer. Evaluation is a design stage that will occur repeatedly throughout the decision trees and guidelines as it is an integral part of making appropriate decisions at all stages of design.

The decision tree helps the designer define the problem and select the most appropriate method of phytoremediation to solve the problem and/or evaluate whether phytoremediation is appropriate or not. The decision trees are not meant to empower the user to select plant material and amendments without scientific understanding of the method or without the consultation of a professional. Rather it is meant to educate the user on the necessity of selecting appropriate plant material and highlight the impact their design decisions can have on the success of phytoremediation. The designer/user may use this tree as a tool to identify viable plant choices which should be then further researched and followed up by consultation with a professional/research specialist.

The decision tree begins with Loop 1 (Fig. 9). Loop 1 guides the user to determine the most appropriate method of phytoremediation given the results of the site analysis and programming. From Loop 1 the user will determine whether or not to use phytoremediation and if so, whether phytostabilization (Loop 2, Fig. 10), phytoextraction (Loop 3, Fig. 11), or phytodegradation or rhizodegradation (Loop 4, Fig. 12) would be most appropriate.

From Loop 2 (Fig. 10) it is possible that the user will be sent to Loop 5 (Fig. 13) to consider the use of phreatophytic plants in hydraulic control. If phytostabilization is found to be an acceptable choice the user will move on to Loop 6 (Fig. 14) to determine whether multiple contaminants will cause synergistic effects on the plants available.

Completion of Loop 3 (Fig. 11) will also lead the user to Loop 6 (Fig. 14), but more likely the user will have to go through Loop 2 beforehand in order to determine what type of groundcover may be available to tolerate the contamination over the winter as phytoextraction will result in the harvesting of the plant material at the end of each growing season.

At many points in this decision tree the user can be led out of the Loops to consider other methods of remediation that would be more effective or appropriate for the given site conditions and programming. With more time and research the necessity of some of these exit points will diminish as a wider variety of plants become available to treat contaminants and thereby the time required for phytoremediation of a site becomes shorter.

To guide the user to locate research that may aid in answering the questions posed in the tree, and determine possible plant material to use, a 'Research Guide' has been provided in Appendix C. This 'Research Guide' is not an exhaustive list of the research that has been done, but is rather a list that can act as a springboard for the user to find more information. The 'Research Guide' is organized by inorganic and organic contaminants with a list of references provided for each researched contaminant.

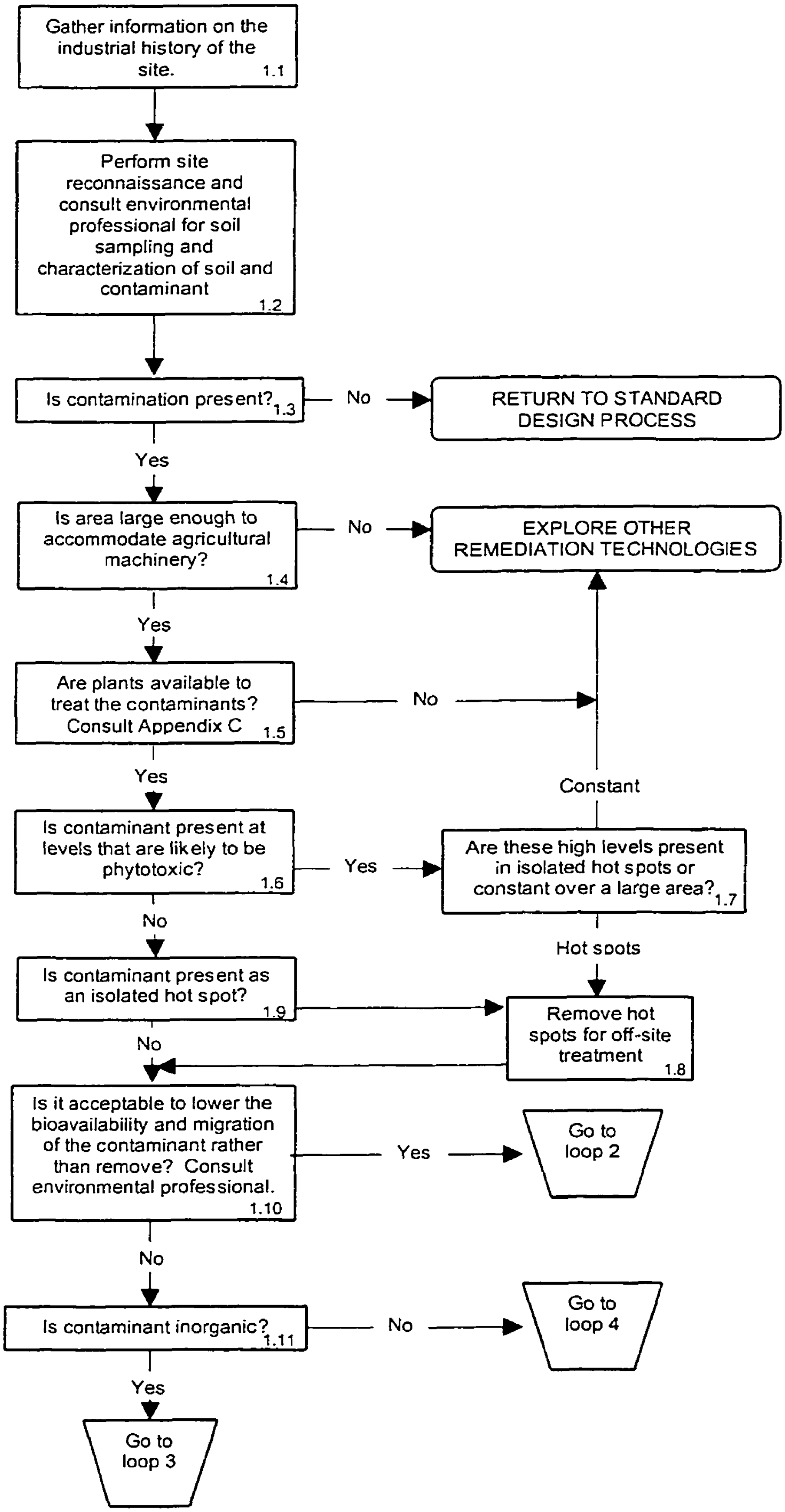

Figure 9: Decision Tree, Loop 1 – Problem Definition

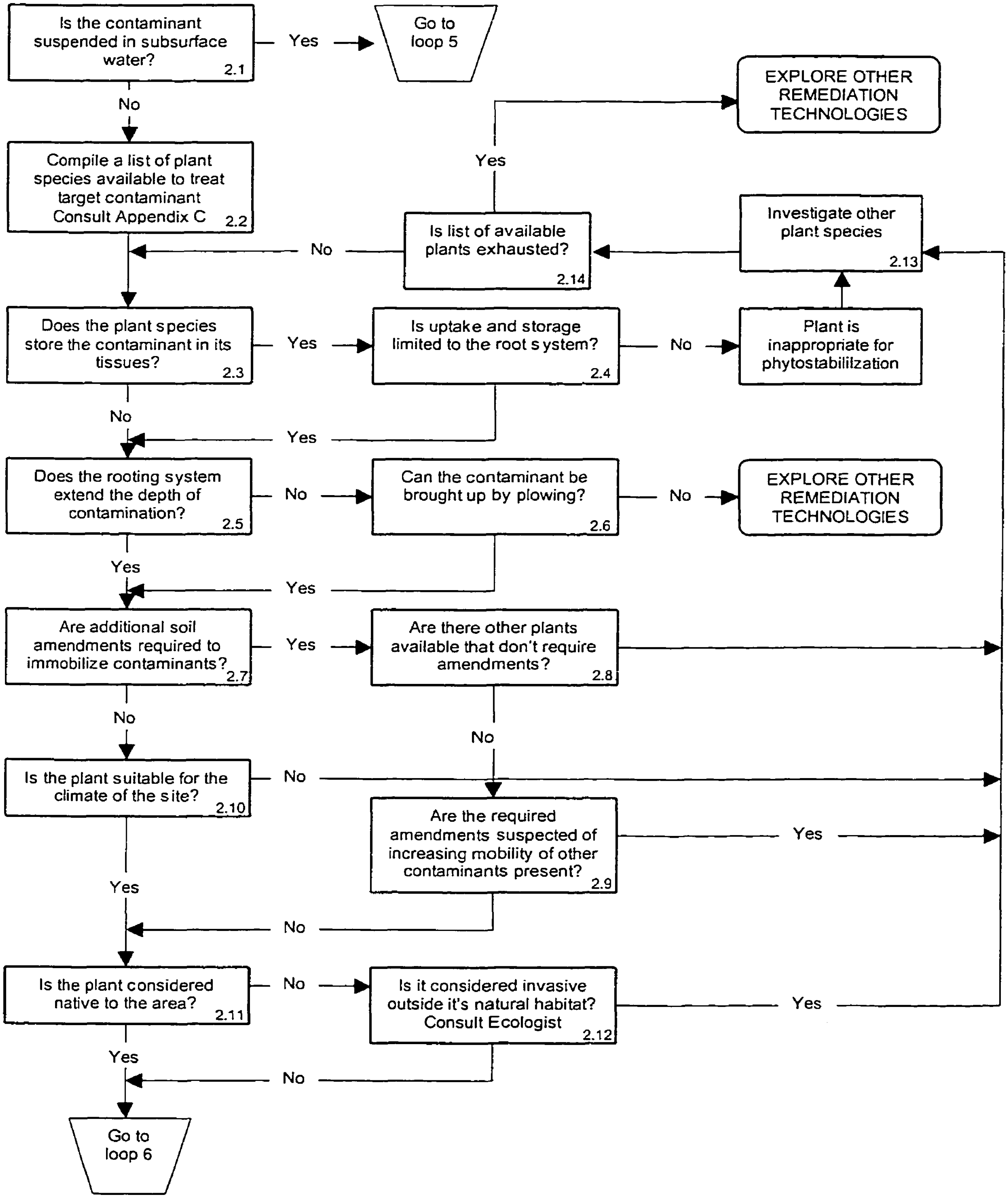

Figure 10: Decision Tree, Loop 2 – Phytostabilization

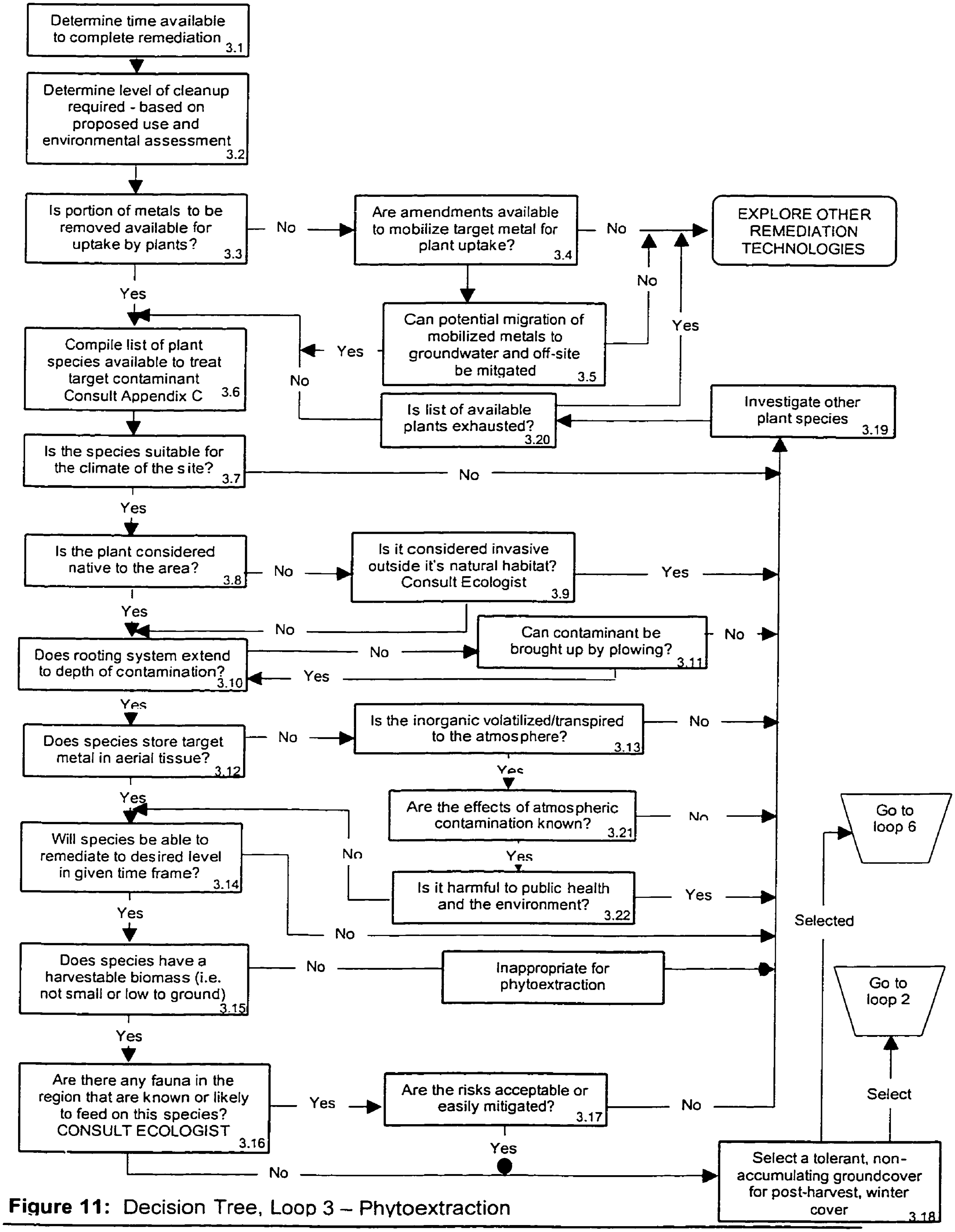

Figure 11: Decision Tree, Loop 3 – Phytoextraction

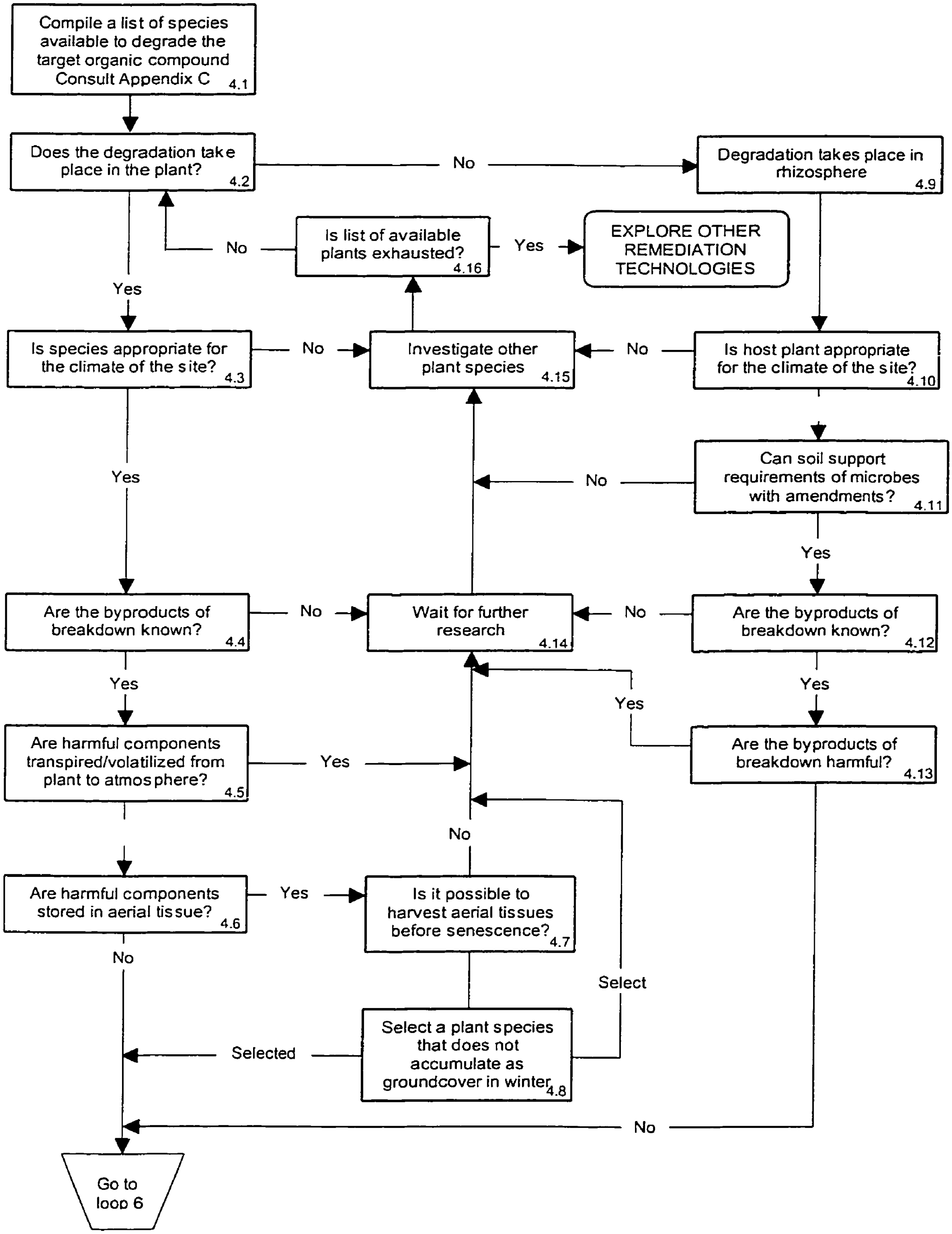

Figure 12: Decision Tree, Loop 4 – Phytodegradation and Rhizodegradation

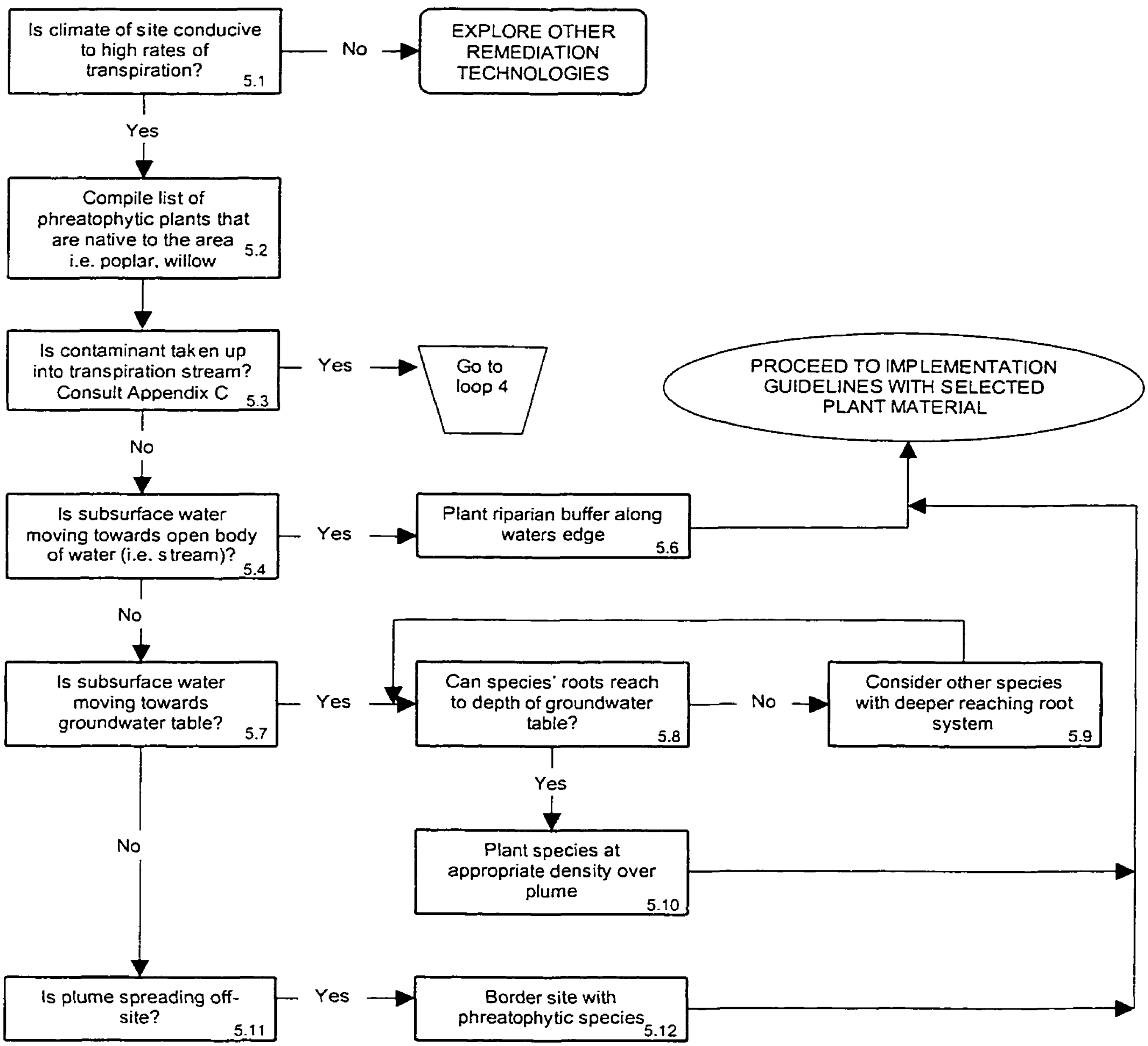

Figure 13: Decision Tree, Loop 5 – Hydraulic Control

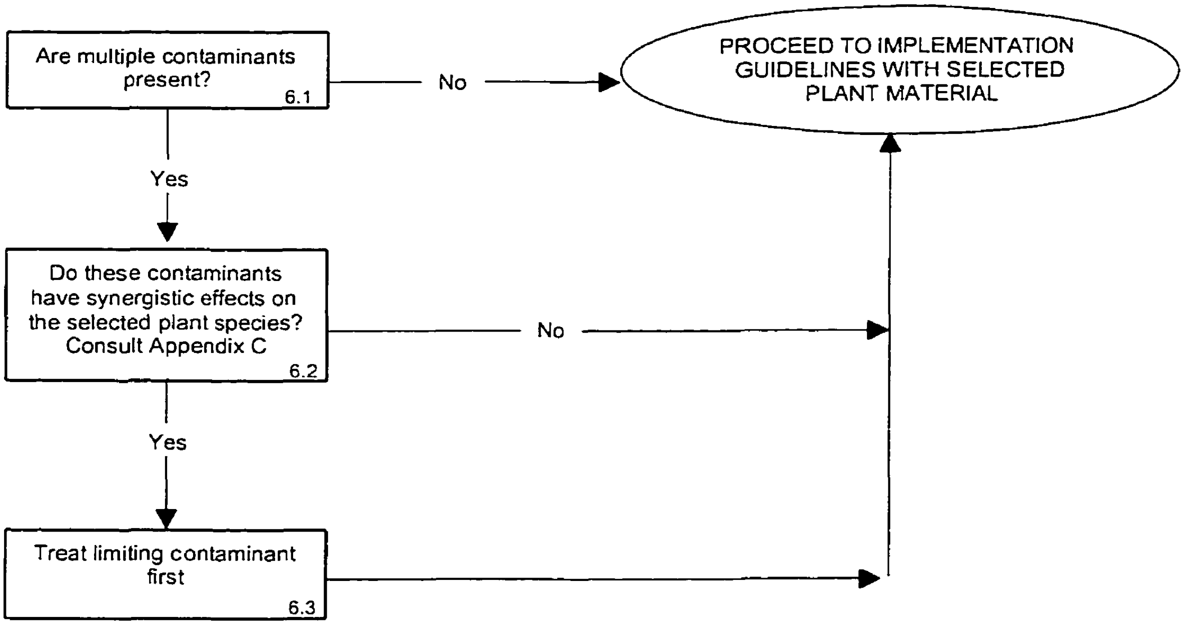

Figure 14: Decision Tree, Loop 6 – Multiple Contaminants

3.2 GUIDELINES

Once appropriate plant materials and associated soil treatment and amendments have been identified through use of the decision tree, the direction of the design process will become more site dependent. Below guidelines have been provided to help the designer implement and evaluate their design and aid in the development of a management program.

3.2.1 Design Implementation Guidelines

- Include a soil erosion and sedimentation mitigation plan if soil is to be moved and/or exposed (Russ 2000).

- If contaminated soil to be treated is only on a portion of the site, ensure that this area can be accessed by machinery for plowing, harvesting and amendment application.

- If site, or portion thereof, is unsafe for human use ensure that there is appropriate fencing and signage.

- Mitigate water flow on-site, i.e. eliminate pools of standing water, re-route surface flow, buffer creeks and streams.

- If other areas of the site are to be planted with non-remedial plant species, consider their potential effects on the phytoremediation site, i.e. seed source for weeds, habitat for herbivores.

- Where systematic soil sampling has been done a site plan delineating contaminant extent, in manner of a topographical map, can help define a planting pattern. Contamination is not likely to be uniform and confined to the exact borders of the site. For example wind direction, chimney-stack height, and the particulate size and solubility of emissions can affect the spatial dispersion of metals from smelters and refineries (Alloway 1990).

3.2.2 Evaluation Guidelines

- When developing site plans care should be taken that assumptions about material substitutions not be made. The use of substandard materials may lead to recontamination or exacerbation of environmental and public health significance (Russ 2000).

- Consider whether the design is appropriate for the proposed post-remediation use.

- Consult the public on the acceptability of the design and potential associated risks.

3.2.3 Management Guidelines

- Develop a monitoring program to analyze the solubility and availability of the contaminants. The results will indicate the effectiveness of the program and the need for amendment application.

- Perform a biological evaluation to determine if contaminants are entering the foodchain. A variety of living organisms from different trophic levels should be used. Plants should also be monitored for signs of feeding by insects and wildlife, or harvesting by humans.

- Monitor increase of biodiversity in plants, mycorrhiza (Vangronsveld et al 1996; Jeffries and Barea 1994) and invertebrates. An increase in biodiversity can indicate that contamination has been well stabilized or that the soil has experienced a decrease in contaminant/toxicity level.

- Plant material should be monitored for presence of metals in plant tissue. This can determine whether the treatment is effective or not, depending on the goal of the program.

- Time harvest of hyperaccumulating plant material for peak biomass, but prior to dispersal of seed or senescence of leaves to avoid off-site migration.

- Time planting/sowing of material to allow for an optimal number of crop rotations and the establishment of a groundcover over the winter months.

3.3 SUMMARY OF DECISION TREES AND GUIDELINES

A process for the implementation of phytoremediation by a landscape architect with limited scientific understanding of the process is difficult to achieve. This attempt at integrating phytoremediation into the landscape design process highlights the necessity of the disciplines involved to work together in collaboration. Communication and sharing of information will be integral to the success and acceptance of phytoremediation as a soil remediation technique.

In the following chapter a case study will be done in order to demonstrate the use of the decision trees and guidelines, and to illustrate how phytoremediation and landscape architecture influence one another.

4.0 INTRODUCTION

The purpose of this case study is to demonstrate how the decision tree can help guide a landscape architect through the selection of the appropriate phytoremediation method, appropriate plant material, and highlight areas where design can help mitigate potential problems. It will important to keep in mind that the goal of this case study is not to provide a complete and implementable plan, but rather provide examples of where roadblocks may occur.

The site to be discussed in this case study is the International Malleable Iron Company Limited (IMICO) located in Guelph, Ontario, Canada. The site operated as a foundry for 77 years before it was turned over to the Bank of Montreal who retained Proctor & Redfern Limited (P&R) to conduct an environmental investigation of the site. P&R's report (1991) will be the source of soil sampling and contaminant identification information to demonstrate the use of the decision tree.

Demonstration of the decision tree will be done by referring to the box number of the tree, and answering that particular question using the information provided in P&R's (1991) report. Where the information provided is insufficient to answer the question assumptions will be made in order to move on to other questions in the tree.

4.1 DECISION TREE USE

Beginning with Loop 1 – Problem Definition (Figure 9):

Box 1.1. *Gather information on the industrial history of the site.*

The subject site was purchased by IMICO in 1912 and was developed as a foundry. The foundry operations continued until 1989 when the plant was abandoned. P&R found no evidence of any commercial and industrial use of this land prior to 1912 while performing a title search. Land north of the railroad tracks was also bought by IMICO in 1912, but was undeveloped and in 1989 was sold to 813383 Ontario. All built structures have since been demolished and only the concrete foundation of the buildings remain.

IMICO was registered with the Ministry of Environment (MOE) as a generator of spent capacitators containing PCB's and foundry sand with water. According to P&R's report the MOE was not aware of any spills, environmental concerns, or industrial landfilling on this property. A preliminary review of MOE water well records done by P&R did not identify any groundwater users within 300 m of the IMICO site.

The original drawings and site plans of the IMICO site were lost during site closure and new ones were generated by P&R using total station electronic survey equipment. This survey was limited to definition of the foundry structures and property boundaries (interpreted to be represented by the chain link fence surrounding the site). P&R conducted an interview with a former IMICO employee in order to identify areas of potential environmental concern and an understanding of what activities took place on site. The areas of concern were noted and further investigated through soil and groundwater sampling.

Box 1.2. *Perform site reconnaissance and consult environmental professional for soil sampling and characterization of soil and contaminant.*

Reconnaissance

The site is relatively flat with very little topographical variation. It is bordered to the north by railroad tracks, to the southeast by residential and commercial, and to the southwest by industrial and residential mix. Of interest among the industrial neighbours is Foseco Canada Inc. located to the southwest of the site. The MOE stated that at the time of P&R's study, in 1991, the Foseco site was involved in a subsurface toluene recovery program. A toluene contaminated groundwater plume had been identified on the Foseco property in the shallow groundwater aquifer and was migrating northward. The MOE reported that no toluene contamination had been detected by the observation well bordering the IMICO site.

Sampling

Proctor and Redfern Limited performed the sampling of this site in 1991. Twenty-four test pitting groups were located in areas of suspected soil contamination identified through site reconnaissance, interview with former employee and site investigation performed by Proctor and Redfern Limited in 1989. Each test pitting group consisted of a central test pit with one or more additional shallow test pits nearby to help delineate the extent of contaminants, if any, identified at the central test pit. At least one test pit at each sampling location was excavated until clean native soil or bedrock was encountered. Any visual and olfactory evidence of contamination was documented on-site and soil samples were taken at the discretion of the supervising engineer. The majority of the test pits were backfilled with original material the same day or by the end of the next working day. In addition to the test pits, 15 coreholes were drilled through the foundry floor to assess soil quality immediately beneath the foundry floor.

A total of 89 soil samples were submitted for analysis in three different phases (for sampling locations see Figure 15, Appendix B). Samples were analyzed for all or a portion of the metals identified in the Guidelines for the Decommissioning and Cleanup of sites in Ontario (Ontario MOE 1989), that are detectable through I.C.A.P. analysis (i.e. all metals excluding antimony, arsenic, selenium and mercury), some for total oil and grease, some further for hydride metals (antimony, arsenic, selenium) and mercury, and further still for soil pH and electrical conductivity. A few samples, where concern was indicated, were submitted for VOC analysis, base neutral extractables, phenols, PCBs, cyanide and total petroleum hydrocarbons (TPHs).

Soil Characterization

P&R reported that the stratigraphy of the subject property is typified by a thin layer, approximately 0.2m of either asphalt or gravel, underlain by industrial fill material. This fill layer is approximately 1.0m in thickness in the western and northern portions of the property, gradually disappearing toward the southwestern portion of the site. The fill material consists predominantly of black staining foundry sands, slag, cinders, silty sands and minor debris such as scrap metals or wood. The underlying native material consists of pale brown sands with frequent cobbles and boulders.

Groundwater

Groundwater elevations are higher in the northeast portion of the site, with a maximum elevation of 313.7 metres above sea level (masl). Levels decrease toward the south and west with a minimum elevation of 312.41masl. The groundwater table occurs in the bedrock approximately 1.5 – 3.5 meters below ground level. Little attenuation or biodegradation is likely to occur in bedrock and therefore leachable contaminants in the overburden/fill material are likely to migrate off-site. Flow occurs in a southwesterly direction toward the Eramosa and Speed Rivers.

Contaminant Characterization

Determining the character of the contaminants, especially bioavailability, requires specialized tests that were not done in Proctor and Redfern's 1991 study. For this case study it will be assumed that the contaminants are bioavailable to the extent required.

Box 1.3. *Is contamination present?*

At the time of P&R's study the redevelopment plans for the IMICO site were not certain. Therefore the analytical results were compared to both residential and commercial/industrial decommissioning guidelines published by the MOE in 1989 (Table 4).

Table 4. Guidelines for the Decommissioning and Clean-Up of Sites in Ontario (MOE 1989)

Parameter	Clean-Up Guidelines (1) Residential/ Parkland	Clean-Up Guidelines (1) Commercial/ Industrial
pH	6-8	6-8
EC (ms/cm)	2	4
SAR	5	12
Arsenic	20	40
Cadmium	3	6
Chromium IV	8	8
Chromium (total)	750	750
Cobalt	40	80
Copper	150	225
Lead	375	750
Mercury	0.8	1.5
Molybdenum	5	40
Nickel	150	150
Nitrogen (%)	0.5	0.6
Oil and Grease (%)	2	2
Selenium	2	10
Silver	20	40
Zinc	600	600
Antimony	20	40
Barium	750	1500
Beryllium	4	8
Vanadium	200	200

For the purposes of this case study it will be assumed that the future use will be commercial/industrial and contaminants in exceedance of those guideline levels will be targeted in the phytoremediation program and design.

Using the Commercial/Industrial Decommissioning Guidelines, 42 of the 89 soil samples had at least one elevated parameter (Tables 9, 10 and 11, Appendix B). Seven different metals exceeded the guidelines at least once with zinc elevated in 23 samples. Other metals exceeding guideline requirements for commercial/industrial decommissioning on this site are lead, chromium VI, cadmium, copper, nickel, and molybdenum. The areas where these metals were found are located on Fig 16 in Appendix B.

Box 1.4. *Is the area large enough to accommodate agricultural machinery?*

Agricultural machinery will be required to till the soil, apply amendments and harvest plant material. The area of the IMICO site is large enough to accommodate agricultural machinery and is also very flat, which will ease the use of the machinery.

Box 1.5. *Are plants available to treat the contaminants?*

Using the 'Research Guide' in Appendix C it was determined that plants for the treatment of lead, chromium, cadmium, copper and nickel have been researched. The use of this research guide did not indicate any research being done on the remediation of molybdenum-polluted soils using plants. Therefore it is recommended that another remediation technique be investigated for the remediation of molybdenum. The molybdenum in this case study will be removed and treated off-site.

Box 1.6. *Is contaminant present at levels that are likely to be phytotoxic?*

Phytotoxicity levels are specific to individual plant species and individual contaminants, and dependent on the bioavailability of the contaminant, which is determined by site-specific conditions. Specialized tests and consultation with an environmental specialist will be required to determine the phytotoxicity levels. For this study it will be assumed that phytotoxicity does not play a role, i.e. the levels present are not phytotoxic.

Box 1.9. *Is contaminant present as an isolated hot spot?*

The sampling plan done by P&R is not ideal for determining the spread of contamination as it was biased towards investigating areas of known or suspected contamination and did not investigate marginal areas. P&R did take limited additional samples on the outskirts of suspected test pits to determine if the contaminant extended further, but these auxiliary test pits were selected randomly and therefore should not be considered conclusive as to the horizontal extent of contamination. For this case study where contaminants are found only at the test pit and not the related auxiliary test pits, these areas will be considered hotspots.

Using this criteria, chromium at test pit E will be removed, and cadmium at test pits H and I will be removed (see Fig. 17 in Appendix B).

Nickel is present as a hot spot in conjunction with six other contaminants where it is unlikely that phytoremediation can take place, and it is recommended that this area be completely excavated and treated off-site (see Fig. 17, Appendix B).

Box 1.10. *Is it acceptable to lower bioavailability and migration of the contaminant rather than remove it? Consult environmental professional.*

Determining if stabilization of the contaminants is acceptable for the remediation of a particular site will require a risk based assessment to be performed by an environmental specialist. It was not within the scope of this case study to consult an environmental professional, however, generally it is thought that if the contaminant is present at levels marginally above the limit for commercial/industrial use, immobilization of the contaminants may be sufficient. For this case study, where contaminants are in exceedance of the guidelines, removal rather than stabilization will be recommended.

Box 1.11. *Is contaminant inorganic?*

All contaminants present above the commercial/industrial decommissioning guidelines list in Table 4 are inorganic. Therefore it is recommended to move on to Loop 3, Decision Tree – Phytoextraction (Figure 11).

Box 3.1. *Determine the time available to complete remediation.*

For this case study it will be assumed that the time available is unlimited as the property is not currently owned by a developer.

Box 3.2. *Determine level of cleanup required – based on proposed use and environmental assessment.*

To determine the level of cleanup required a risk based assessment should be performed by an environmental specialist. In absence of such an assessment, for this case study it will be assumed that levels should be brought below those outlined in Table 4 for Commercial/Industrial use.

Zinc is identified in the Ontario Drinking Water Guidelines (MOE 1983) as an aesthetic related parameter, therefore, providing that appreciable migration within the groundwater is not occurring, remediation requirements may be reduced (Proctor & Redfern 1991).

Box 3.3. *Is portion of metals to be removed available for uptake by plants?*

For this case study assumptions will be made, due to the lack of bioavailability results, that the zinc and copper are at a level of bioavailability that will allow cleanup without amendments. Lead on the other hand, will be assumed to be unavailable, because it rarely is, and that amendments will be required.

Box 3.4. *Are amendments available to mobilize target metal for plant uptake?*

The 'Research Guide' in Appendix C indicates that chelating soil amendments are available to increase the bioavailability of lead for plant uptake.

Box 3.5. *Can potential migration of mobilized metals to groundwater and off-site be mitigated?*

As the groundwater table is considerably shallow, in the bedrock, and contaminated water will be prone to underground migration, it is recommended that chelating agents not be applied and other methods be explored for the treatment of the lead. In this case study the lead contaminated soil will be removed and treated off site.

Box 3.6. *Compile a list of plant species available to treat the target contaminant. Consult Appendix C.*

As chromium, cadmium, lead, molybdenum and nickel have now been cancelled out, we are left with zinc and copper to treat by phytoextraction. (See Figure 17, Appendix B, for a site plan showing the areas to be excavated and areas to remain for remediation).

Using Appendix C and additional research, the following species were found to be capable of hyperaccumulating zinc and copper.

Zinc – *Thlaspi* spp. and *Brassica* spp.

Copper – *Thlaspi* spp. and *Brassica* spp.

Fortunately zinc and copper are often taken up by the same plants, and therefore it may be possible to treat this site with one plant species.

For the purposes of this case study plants will be considered at the genus level, although in an actual implementation plan it would be necessary to select the appropriate species. Although plant families and genus' that are known to have hyperaccumulating species often have many, not all species within those families and genus' will have the hyperaccumulating characteristic. Consultation with a phytoremediation specialist is suggested in the selection of actual species that have perhaps been selectively bred or modified for the accumulation of the target metal.

Box 3.7. *Is the species suitable for the climate of the site?*

Both *Thlaspi* spp. and *Brassica* spp. are known to grow in Northeastern America (Gleason and Cronquist 1991).

Box 3.8. *Is the plant considered to be native to the area?*

Thlaspi arvense L., *T. perfoliatum* L., *Brassica juncea* (L.) Czernj., *B. nigra* L., *B. rapa*, *B. campestris* L., *B. oleracea* L., *B sylvestris* (L.) Miller, and *B. napus* are all found growing in North America (Gleason and Cronquist 1991). *Thlaspi arvense* L. and *T. perfoliatum* L. are both found in fields, at roadsides or in waste places (Gleason and Cronquist 1991).

Brassica juncea (L.) Czernj and *B. nigra* L. are weeds that are naturalized in fields and waste places (Gleason and Cronquist 1991). *Brassica rapa*, *B. campestris* L., *B. oleracea* L., *B sylvestris* (L.) Miller, and *B. napus* are more similar, or contain cultivars, that include turnip, bird's rape, cabbage, cauliflower, and broccoli.

This case study will consider the plants listed in Gleason and Cronquist's (1991) Manual of Vascular Plants of Northeastern United States and Adjacent Canada, 2nd Edition, as native and non-invasive.

Box 3.10. *Does the rooting system extend to the depth of contamination?*

The depth of contamination varies over the site. It is not likely that the root systems will be able to reach to the full extent of all contamination as it can reach depths greater than 2.0 m.

Box 3.11. *Can the contaminants be brought up by plowing?*

Zinc contamination in areas A and B will likely have to be dug up entirely as plowing machinery is unlikely to bring the contaminant up to the surface from a depth of 2.0 m. Once the material is dug up it may be possible to spread it out where lower levels of zinc contamination have occurred in order to include it in the phytoremediation program and prevent it from going to a hazardous waste landfill.

Box 3.12. *Does species store target metal in aerial tissue?*

Yes for members of both the *Thlaspi* and the *Brassica* genus'.

Box 3.14. *Will species be able to remediate to desired level in given time frame?*

As it has been assumed that the amount of time available for remediation of the site is indefinite, the answer will be yes for both *Thlaspi* spp. and *Brassica* spp.

In situations where time is more limited it will be necessary to calculate the biomass that can be produced by a crop in a growing season, the dry weight of that crop, and the percentage of that dry weight that is predicted to be metal. Dushenkov et al. (1997) suggest an equation which can be found on page 25 of this thesis, but it is not likely to be accurate as it assumes that the depth and concentration of the contamination will be constant over the entire site. The assistance of a specialist or researcher is recommended to determine the ability of a plant species to remediate within a given timeframe.

Box 3.15. *Does species have a harvestable biomass?*

It is important that the plants selected for phytoextraction have a biomass that allows harvesting machinery to cut the material off above the root and transport it off site.

Plants in the *Thlaspi* genus do not have an easily harvestable biomass, they are very small and grow low to the ground. Plants in the *Brassica* genus on the other hand do have a harvestable biomass as they are from the same family as many crop plants such as turnips and broccoli and harvesting methods have already been established. Therefore we will continue the decision trees considering only plants in the *Brassica* genus.

Box 3.16. *Are there any fauna in the region that are know or likely to feed on this species? Consult Ecologist.*

In absence of ecologist, more assumptions will be made. As *Brassica* species are in the mustard family and have agricultural crops among their genus, such as turnip, they are likely to be a food source for small animals such as rabbits. They are also likely to have insect pests.

Box 3.17. *Are the risks acceptable or easily mitigated?*

Assuming that the risks are acceptable (for reasons stated above in Box 3.16), fencing dug into the ground may mitigate the access to small animals, and pesticides may mitigate consumption by insects.

Box 3.18. *Select a tolerant, non-accumulating groundcover for post-harvest, winter cover.*

Because phytoextracting plants need to be harvested and treated for disposal off site, the ground will be left bare over the winter. It will be necessary to provide a groundcover in order to reduce the mobility and/or migration of contaminants that have not yet been extracted, until the next growing season. Selecting a plant that can tolerate these conditions can be aided by the use of Loop 2, Phytostabilization.

Box 6.1. *Are multiple contaminants present?*

Yes, multiple contaminants are present. Zinc and copper are to be treated simultaneously in areas I and 12.

Box 6.2. *Do these contaminants have synergistic effects on the selected plant species?*

Yes, Ebbs & Kochian (1998) studied the synergistic effects of copper and zinc on *Brassica* species that might potentially be used in a remediation program. Their study found that the copper was more toxic to the plants than zinc, and that exposure to both of these metals together induced iron deficiency in the plants, thus causing a significant inhibition of root growth and a decrease in the accumulation of each metal in the shoots. They suggested that it may be necessary to use leaf applications of iron to promote better plant health and shoot biomass production, as well as apply organic materials to the soil to tie up the copper and minimize its toxic effects.

Final Plant Selections

Due to the limitation of consulting resources, lead (Pb) and molybdenum (Mo) have been excluded from the phytoremediation program for this case study. Cadmium (Cd), chromium IV (Cr), and nickel (Ni) have been excluded due to their limited extent (hot spot nature) or presence in a highly and deeply contaminated area. With these metals cancelled out only zinc and copper contamination are left for remediation.

Reasons that the zinc contamination is considered more treatable than the others are that it occurs (at varying concentrations) over the entire site, this full coverage of the site warrants the use of agricultural machinery; the contaminant is limited to a depth that is treatable by the root system with the additional help of plowing equipment; and extensive studies have been done on plants that are capable of extracting this metal.

The copper contamination occurs in only two small areas of the site, which is not ideal for implementing a phytoremediation program as small areas don't warrant the cost of bringing in agricultural machinery, but as most of the species that are able to treat zinc are able to treat copper, it can remain and be treated simultaneously, therefore negating the need for digging up and disturbing the soil in those areas.

This case study is continuing on the assumptions that: the zinc and copper levels are not phytotoxic to the *Brassica* species chosen; and the samples taken provide a representative example of site conditions. Ideally a test should be done on the bioavailability of the metals for plant uptake and consultation with a researcher on the phytotoxicty to the chosen plant material. It may also be beneficial to do a treatability study, as suggested by Berti et al (1998), as there are a number of other contaminants present at levels below the guideline, and their synergistic effects may not be known. Also, in an ideal situation, after the primary hot spots had been identified through a judgmental sampling program, a systematic sampling should be done in order to enable delineation of the marginal extent of a contaminated area and map it in a manner similar to a topographical map.

4.2 IMPLEMENTATION

The area to be planted with the *Brassica* sp. chosen is identified on Figure 18 in Appendix B. The area to be planted for zinc and copper remediation does not include the areas to be excavated at the east end of the site, nor does it include the area to the north where limited excavation of lead and cadmium is to take place. Zinc levels in this northern area were low (well below the residential and commercial/industrial guidelines) in comparison to the rest of the site, and as there is already a considerable amount of vegetation established in this area it may remain to provide cover and prevent soil erosion. The area to the east should be planted with material that will provide cover during remediation of the rest of the site, but material that will attract animals that are likely to feed on the *Brassica* plants should be avoided.

As the *Brassica* species chosen may be an annual plant it will be necessary to plant a cover material to prevent erosion and leaching of contaminants over the winter and spring, assuming that it will take more than one growing season to bring zinc and copper levels below the commercial/industrial guidelines. The cover material would preferably be a grass that could be turned under before planting the next crop of *Brassica* spp. in the following season.

With the information provided for this case study it is difficult to assess the amount of time that would be required to bring the zinc levels down below the commercial/industrial guidelines as the bioavailability of the contaminant isn't known. It will be assumed for this study that time is not a factor as the site is sitting idle and has not yet been purchased by a potential developer.

4.3 EVALUATION

Evaluation was an integral part of the plant selection process that lead to the exclusion of treating lead, cadmium, chromium, nickel, and molybdenum by phytoremediation. Ideally this design process would take place in direct cooperation with an environmental professional or researcher that could provide more input and affirm that the assumptions made are correct. The purpose of this case study is not to provide a complete and implementable plan but to provide a basic overview of the issues involved, based on the information available.

4.4 MANAGEMENT

The *Brassica* species chosen will have to be harvested annually at peak biomass, before senescence occurs and then taken to a facility where they may be reduced by ashing or drying and either recycled for zinc or treated as hazardous waste. Immediately after the removal of the *Brassica* crop a cover will need to be planted in time for it to establish itself before the winter.

The *Brassica* plants will need to be monitored for signs of herbivory and nutrient deficiencies. The site should be well fenced off, with fencing reaching below the ground to avoid animals that may dig under. An ecologist should be consulted to determine what the likely herbivores are in the area. The site to the north is wooded and is likely home to a number of small animals such as voles and rabbits that would find *Brassica* species an attractive food source.

Likely nutrient deficiencies include iron (Fe) as was indicated by the Ebbs and Kochian (1997) study that suggested a foliar application of Fe to the plants, and application of organic matter to the soil, may help remedy the stunted root and shoot growth.

4.5 SUMMARY OF CASE STUDY

This case study demonstrates the necessity of cooperation among disciplines in the design and implementation of a phytoremediation program. In order to carry out this case study it was necessary to make a number of assumptions and inferences that would not be possible in a real-life situation. The design of a phytoremediation program by a landscape architect can clearly not proceed to site implementation without the consultation of an environmental and phytoremediation specialist.

It is obvious from Figure 18 in Appendix B that the science of phytoremediation is very demanding and does not allow for great flexibility and artistic expression that can often be a landscape architect's signature. This partially due to the limited range of plant material available to choose from, at this time, as well as the patterns dictated by the distribution of contamination in the soil.

What this case study does offer is an excellent opportunity for a field study to test the research that has been done to date. The unique circumstances presented by the mixed contaminants could help to further the development of phytoremediation where it is currently lacking. Currently phytoremediation researchers are looking at single contaminants and their relation to plants. In actual fact, contaminants rarely occur singularly.

The following chapter will discuss concerns similar to those mentioned in the paragraphs above and discuss what the implications are for landscape architecture in the development and use of phytoremediation.

5.0 SUMMARY

The goal of this thesis was to develop a framework for the translation and synthesis of the scientific information into a format that can be used by landscape architects to integrate phytoremediation into the landscape architectural design process. The resulting decision tree and guidelines demonstrated that the implementation of phytoremediation requires a large amount of scientific knowledge that is outside the scope of work for a landscape architect. The case study also demonstrated that the science of phytoremediation will ultimately define what the design will look like. This being said, the decision tree and guidelines produced in Chapter 3 are reflective of the current state of knowledge concerning phytoremediation and implementation thereof, and should be reviewed and altered accordingly as new research dictates.

To conclude this thesis, the present limitations of phytoremediation and the implications of these limitations to the use of phytoremediation in landscape architecture will be discussed, and recommendations will be made for the future use of phytoremediation by landscape architects.

5.1 DISCUSSION

Through the research undertaken in this study it becomes apparent that there is still much research to be undertaken in both science and application before phytoremediation will be considered a viable and widely applicable form of soil remediation. The wide spread application of phytoremediation is currently limited by the unknown effects of multiple contaminants, small selection of plants, and unknown byproducts of organic contaminant breakdown.

In part, the future success of phytoremediation currently lies in the further development of plant species that are capable of extracting larger concentrations of contaminants, faster, i.e. more effective plants. The method of developing these plants will either be by genetic engineering (i.e. creating genetically modified organisms) or selective breeding. Currently research is being done to determine the mechanisms involved in the hyperaccumulation or breakdown of contaminants in plants, and subsequently locate the genes responsible for these mechanisms. This presents both an opportunity and a potential barrier to the furthering of phytoremediation. Flavell (2000, pg 146) posed the question:

> "Will governments and societies consider that any risks associated with populating polluted sites with transgenic plants is much less than the hazards caused by the pollutants? Will these ethical issues be considered very different from introducing transgenics into human food chains?"

Public perception and acceptance have the ability to make or break this technology as can be witnessed by the recent public opposition to unlabelled, genetically modified organisms (G.M.O's) in grocery stores. In support of opposition, many of the species, genetically altered and non-native, being considered for use in phytoremediation have established records as invasive species beyond their natural ranges and may therefore threaten regional ecological systems and others may pose future issues of introgression (repeated hybridization between native and non-native species) in some ecosystems (Randazzo 1999).

If public and governmental opposition to the use of G.M.O.'s prevents the development of more effective plants, phytoremediation may remain limited to sites that are to remain idle indefinitely, where time is not a factor in clean up. Whether G.M.O.'s will be allowed or not, it is vital that rare and endemic metal-accumulating plant species are identified and preserved before they become extinct. These plants serve as a valuable source of both genetic information and selective breeding material.

Of the approximately 1000 sites identified in the EPA's 1986 National Priority List, approximately 40% reported metal problems, the majority of which were combined with organics. Most of the metal problems (70%) were connected with two or more metals. The metals most often cited are lead (Pb), chromium (Cr), arsenic (As), cadmium (Cd) (at more than 50 sites each) and copper (Cu), zinc (Zn), mercury (Hg) and nickel (Ni) at over 20 sites each. Currently research is looking at contaminants in isolation from one another and which plants can treat that contaminant alone. This approach, while useful, does not help to determine the synergistic effects that are likely to happen due to the mixed nature of contaminants at brownfield sites. Some research has been done on the synergistic effects of mixed heavy metal contamination, but from the statistics given above, it is more likely that metal contamination will occur with organics. Research has shown that the microbial communities and fungi that aid in the degradation of organic contamination can inhibit the uptake of metals. This may be a beneficial relationship as the metals are bound while organics are breaking down and perhaps metals can be taken care of in a second round of phytoremediation. More research is required if phytoremediation is to become a widely implementable remediation option and gain acceptance and approval from governing agencies.

5.2 IMPLICATIONS FOR LANDSCAPE ARCHITECTURE

In terms of implementing phytoremediation there was very little evidence of recognition by landscape architecture, much less evidence of application, in the literature. This is a surprising result as a variety of researchers working in the natural sciences have noted the importance of taking an interdisciplinary approach to implementing phytoremediation. Including designers in this process would not only improve the knowledge of contaminated land issues within the design profession, it would also result in more environmentally and ecologically responsible design. Educating design professionals about the interactions that take place between plants and contaminated soils will aid in their understanding of the potential negative impacts that their choices can have on the public and the environment.

Avoiding the potential negative impacts on the public and environment is important to the profession of landscape architecture for two reasons. Firstly, according to the Canadian Society of Landscape Architects (CSLA):

> Landscape Architecture is the profession which applies artistic and scientific principles to the planning, design and management of both natural and built environments. ...Landscape Architects create design solutions and implement projects that respect and balance the needs of the people and the requirements of the environment. (1999)

Respecting the needs of people and environment involves understanding the potential risks involved in the implementation of phytoremediation. Secondly, the improper use of phytoremediation, resulting in negative impacts on public health and the environment, has the potential to damage its reputation and thereby hinder it's further development. Nyer and Gatliff (1998) voiced their concern that often when new technologies come along that have certain advantages over other technologies that have been used in the past they all of a sudden become the remediation technology that everyone in the remediation field must use in order to be “state of the art”. Their fear is that this leads to overuse and application of the technique in improper locations and it finally obtains a marred reputation. Therefore it is imperative that landscape architects considering the use of this technology take the initiative to properly educate themselves and consult with an environmental professional to ensure, as much as is possible, that the design will have no negative impacts on the public or environment.

Developing confidence in this technology and its use in design will require field trials before large-scale implementation occurs. Laboratory studies have shown promising results for phytoremediation, and although laboratory studies can be designed to mimic field conditions, they cannot always predict the practical or logistical constraints of the technique at an actual site. Field studies address these matters more directly (Berti et al 1998). Field trials provide the opportunity to: validate the technology applications and assumptions; educate the public about phytoremediation; accrue on-site experience; and evaluate methods and approaches.

Although there are still many questions waiting to be answered in the scientific research before full-scale implementation of phytoremediation will occur, landscape architects can begin to actively participate in the development of phytoremediation by becoming involved in the field trials. Landscape architecture's involvement in field studies can help develop the protocols and application techniques that will help phytoremediation gain regulatory acceptance.

In much the same way that it will be necessary for landscape architects to learn the science involved in phytoremediation, it would also be beneficial for the science professions to learn about the role of design and design professionals. This mutual understanding of the disciplines involved can enhance the exchange of information and avoid miscommunications.

Although it may have been ideal to create a framework for the use of phytoremediation by a landscape architect with limited scientific knowledge it is presently not appropriate to do so. Not understanding the science involved will result in negative impacts on human health, ecosystem health, the furthering of phytoremediation as a viable remediation technique, as well as damaging the profession of landscape architecture. This suggests that it would be beneficial for landscape architecture schools to teach more applied sciences to provide future design professionals with the ability to assimilate scientifically based technology and adopt it effectively.

Phytoremediation research is continuing at an ever increasing scale and positive developments will surely present themselves within the next five to ten years that will increase the applicability of this technique to a wider range of sites, with more straightforward and defined implementation strategies. Therefore, landscape architects interested in employing this technology should make an effort to keep up with the scientific developments and work in collaboration with researchers in the development of new plant materials and implementation techniques at the field trial scale. Not only will this ensure landscape architects a role in the future application of phytoremediation, but it may also serve to strengthen the reputation of landscape architecture as a respected research discipline.

Phytoremediation is still a relatively young technique that has only seen significant developments in the last ten years. Therefore the results of this thesis should not deter landscape architects from ever employing this technology, but rather caution them to use it appropriately, with the hope that in the years to come it will be become a safer remediation alternative, and a viable tool for cleaning soil in an integrated and aesthetically pleasing manner.

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Note: All tables after Brooks (1998)

Table 5. Hyperaccumulators of nickel (maximum concentration in µg/g [ppm] dry mass).

FAMILY/Genus	Location	Ni Conc.
ACANTHACEAE		
Blepharis acuminata	Zimbabwe	2000
Justicia lanstyakii	Brazil	2690
Lophostachys villosa	Brazil	1890
Ruellia geminiflora	Brazil	3330
ADIANTACEAE		
Adiantum sp.	Brazil	3540
ANACARDIACEAE		
Rhus wildii	Zimbabwe	1600
ASTERACEAE		
Berkheya coddii	South Africa	11,600
B. zeyheri	South Africa	17,000
Chromolaena meyeri	Brazil	1100
Dicoma niccolifera	Zimbabwe	1500
Leucanthemopsis alpina	Italy	3200
Senecio caronatus	South Africa	24,000
S. pauperculus	Newfoundland	1900
Solidago hispida	Newfoundland	1020
BORAGINACEAE		
Heliotropium sp.	Brazil	2020
BRASSICACEAE		
Alyssum 48 taxa	S. Europe/Turkey	1280-29,400
Bornmuellera 6 taxa	Balkans/Turkey	11,400-31,200
Cardamine resedifolia	Italy	3270
Cochlearia aucheri	Turkey	17,600
C. sempervivum	Turkey	3140
Peltaria emarginata	Greece	34,400
Streptanthus polygaloides	California	14,800
Thlaspi 23 taxa	Worldwide	2000-31,000
BUXACEAE		
Buxus aneura	Cuba	1450
B. baracoensis	Cuba	1590
B. crassifolia	Cuba	830-12,250
B. excisa	Cuba	2150
B. flaviramea	Cuba	4500-8360
B. foliosa	Cuba	1320
B. gonoclada	Cuba	2610

Table 5. Hyperaccumulators of nickel (maximum concentration in µg/g [ppm] dry mass).

FAMILY/Genus	Location	Ni Conc.
B. heterophylla	Cuba	3480-8740
B. historica	Cuba	4810
B. imbricata	Cuba	1940
B. moana	Cuba	1100-1760
B. pilosula	Cuba	4870-9200
B. pseudoneura	Cuba	1240
B. retusa	Cuba	310-10,310
B. revoluta	Cuba	7870-15,630
B. serpentinicola	Cuba	10,410
B. vaccinioides	Cuba	25,420
CAMPANULACEAE		
Campanula scheucheri	Italy	1090
CARYOPHYLLACEAE		
Arenaria 3 species	USA/Canada	2300-2370
Minuartia laricifolia	Italy	2710
M. verna	Italy	1390
CONVOLVULACEAE		
Merremia xanthophylla	Zimbabwe	1400
CUNONIACEAE		
Geissois 7 species	New Caledonia	1000-34,000
Pancheria engleriana	New Caledonia	6300
DICHAPETALACEAE		
Dichapetalum gelonioides		
Subsp. *tuberculatum*	Philippines	26,600
Subsp. *andamanicum*	Andaman Is.	3160
DIPTEROCARPACEAE		
Shorea tenuiramulosa	Sabah	1000
ESCALLONIACEAE		
Agrophyllum grunowii	New Caledonia	1380
A. laxum	New Caledonia	1900
EUPHORBIACEAE		
Baloghia sp.	New Caledonia	5380
Cleidion viellardii	New Caledonia	9900
Cnidoscolus bahianus	Brazil	1020
Leucocroton acunae	Cuba	10,140
L. angustifolius	Cuba	6790-19,160
L. anomalus	Cuba	13,330
L. baracoensis	Cuba	2260

Table 5. Hyperaccumulators of nickel (maximum concentration in µg/g [ppm] dry mass).

FAMILY/Genus	Location	Ni Conc.
L. bracteosus	Cuba	11,660
L. brittonii	Cuba	5800
L. comosus	Cuba	6470-11,740
L. cordifolius	Cuba	2040-19,620
L. cristalensis	Cuba	4970-8070
L. discolor	Cuba	7670
L. ekmanii	Cuba	4610-8550
L. flavicans	Cuba	6710-15,500
L. incrustatus	Cuba	4260
L. linearifolius	Cuba	13,310-27,240
L. longibracteatus	Cuba	3850
L. moaensis	Cuba	9770-15,510
L. moncadae	Cuba	15,330
L. obobatus	Cuba	5070-9980
L. pachyphylloides	Cuba	5800-18,050
L. pachyphyllus	Cuba	693-9220
L. pallidus	Cuba	10,760
L. revolutus	Cuba	8910-17,240
L. sameki	Cuba	13,080
L. saxicola	Cuba	10,820-18,480
L. stenophylla	Cuba	12,090-24,500
L. subpeltatus	Cuba	13,890
L. virens	Cuba	5630-24,360
L. wrightii	Cuba	7410-12,600
Phyllanthus 16 taxa	New Caledonia	1090-38,100
P. chamaecristoides		
Subsp. *chamaecristoides*	Cuba	18,530
Subsp. *baracoensis*	Cuba	3400-31,740
P. chryseus	Cuba	10,790-13,740
P. cinctus	Cuba	11,510-21,870
P. comosus	Cuba	9340-19,380
P. comptus	Cuba	7260
P. cristalensis	Cuba	4200-8750
P. discolor	Cuba	13,670-31,499
P. ekmanii	Cuba	12,060-19,060
P. formosus	Cuba	7400
P. incrustans	Cuba	10-1582
P. microdictyus	Cuba	4950-19,750
P. mirificus	Cuba	4480-7690
P. myrtilloides		
subsp. *alainii*	Cuba	14,330
subsp. *erythrinus*	Cuba	16,940-33,240
subsp. *myrtilloides*	Cuba	8490-9970
subsp. *shaferi*	Cuba	7910-21,710
subsp. *spthulifolius*	Cuba	5780-8900

Table 5. Hyperaccumulators of nickel (maximum concentration in µg/g [ppm] dry mass).

FAMILY/Genus	Location	Ni Conc.
P. nummularioides	Cuba	12,240-22,930
P. orbicularis	Cuba	4140-10,950
P. x *pallidus* (=*disolor* x *orbicularis*)	Cuba	15,390-60,170
P. phebocarpus	Cuba	4890-19,400
P. pseudocicca	Cuba	9460-22,670
P. scopulorum	Cuba	13,650-21,930
P. williamioides	Cuba	232-18,100
FABACEAE		
Anthyllis sp.	Italy	4600
Pearsonia metallifera	Zimbabwe	10,000
Trifolium pallescens	Italy	1990
FLACOURTIACEAE		
Casearia silvana	New Caledonia	1490
Homalium 7 species	New Caledonia	1160-14,500
Xylosma 11 species	New Caledonia	1000-3750
JUNCACEAE		
Juncus lutea	Italy	2050
MELIACEAE		
Walsura monophylla	Philippines	7090
MYRISTICACEAE		
Myristica laurifolia	Indonesia	1100
OCHNACEAE		
Brackenridgea palustris		
subsp. *foxworthyi*	Philippines	7600
subsp. *kjellbergii*	Sulawesi	1050
ONCOTHECACEAE		
Oncotheca balansae	New Caledonia	2500
POACEAE		
Trisetum distichophyllum	Italy	1710
RANUNCULACEAE		
Ranunculus glacialis	Italy	1260
RUBIACEAE		
Mitracarpus sp.	Brazil	1000
Psychotria douarrei	New Caledonia	19,900
SAPOTACEAE		

Table 5. Hyperaccumulators of nickel (maximum concentration in μg/g [ppm] dry mass).

FAMILY/Genus	Location	Ni Conc.
Sehetia acuminata	New Caledonia	11,700
SAXIFAGACEAE		
Saxifraga 3 species	Italy	2970-3840
SCROPHULARIACEAE		
Esterhazya sp.	Brazil	1060
Linaria alpina	Italy	1990
STACKHOUSIACEAE		
Stackhousia tryonii	Queensland	21,500
TILIACEAE		
Trichospermum kjellbergii	Sulawesi	1600
TURNERACEAE		
Turnera subnuda	Brazil	6130
VELLOZIACEAE		
Vellozia sp.	Brazil	3080
VIOLACEAE		
Agatea deplanchei	New Caledonia	2500
Hybanthus 5 taxa	New Caledonia	3000-17,600
H. floribundus	W. Australia	10,000
Rinorea bengalensis	SE. Asia	17,500
R. javanica	Kalimantan	2170

After: Brooks et al (1995); Reeves et al (1996)
NB – This list does not include the last 48 Cuban species discovered by Reeves (pers. comm. 1997)

Table 6. Hyperaccumulators of zinc (maximum concentration in % dry weight).

Species	Location	% Zinc
Arenaria patula - CARYOPHYLLACEAE	USA	1.31
Cardaminopsis halleri – BRASSICACEAE	Germany	1.36
Haumaniastrum katangense – LAMIACEAE	Zaire	1.98
Noccaea eburneosa – BRASSICACEAE	Switzerland	1.05
Silene cucubalus – CARYOPHYLLACEAE	USA	0.47
Thlaspi alpestre – BRASSICACEAE	UK	2.50
T. brachypetalum	France	1.00
T. bulbosum	Greece	1.05
T. caerulescens	Germany	2.73
T. calaminare	Germany	3.96

Table 6. Hyperaccumulators of zinc (maximum concentration in % dry weight).

Species	Location	% Zinc
T. limosellifolium	France	1.10
T. praecox	Bulgaria	2.10
T. rotundifolium subsp. *cepaeifolium*	Italy	2.10
T. stenopterum	Spain	1.60
T. tatraense	Slovakia	2.70
Viola calaminaria – VIOLACEAE	Germany	1.00

Source: Brooks et al (1995)

Table 7. Hyperaccumulators of selenium and their elemental content (µg/g dry weight).

Species (No.)	Location	Mean	Range
Acacia cana (1)	Queensland	1121	
Aster venusta (1)	United States	2070	
Astragalus beathii (3)	United States	1906	1034-3135
A. bipinnata (1)	United States	1456	
A. bisulcatus (16)	United States	2276	1144-5330
A. haydenianus (3)	United States	2147	1916-2377
A. limatus (1)	United States	2175	
A. osterhoutii (2)	United States	2017	1356-2678
A. pattersoni (23)	United States	2696	1006-5993
A. pectinatus (16)	United States	2397	1330-6801
A. praelongus (11)	United States	2531	1030-4500
A. preussi (3)	United States	1189	1000-1438
A. racemosa (8)	United States	2145	1330-3920
A. sabulosus (3)	United States	1989	1734-2210
A. scobinatulus (1)	United States	1282	
Atriplex confertifolia (1)	United States	1260	
Neptunia amplexicaulis (14)	Queensland	2661	1143-4164
Oonopsis wardi (1)	United States	1422	
Stanleya pinnata (4)	United States	1510	1110-2490

NB – Values reported are only for individuals with > 1000µg/g Se (dry weight). Individuals can usually be found with only a few µg/g Se.
Source: Brooks 1989

Table 8. Zäirean hyperaccumulators of copper and cobalt (maximum concentrations in µg/g dry weight).

Species	Copper	Cobalt
Aeollanthus biformisfolius – LAMIACEAE	3290	2820
A. saxatilis	-	1000
Alectra sessiliflora - SCROPHULARIACEAE		

Table 8. Zäirean hyperaccumulators of copper and cobalt (maximum concentrations in µg/g dry weight).

Species	Copper	Cobalt
var. *sessiliflora*	-	2782
var. *senegalensis*	1590	-
A. welwitschii	-	1561
Anisopappus davyi – ASTERACEAE	2889	2650
A. hoffmanianus	1065	-
Ascolepis metallorum – CYPERACEAE	1200	-
Becium aureviride – LAMIACEAE		
subsp. *lupotonese*	1135	-
Buchnera henriquesii – SCROPHULARIACEAE	3520	2435
Bulbostylis mucronata – CYPERACEAE	7783	2130
Celosia trigyna – AMARANTHACEAE	2051	-
Commelina zigzag – COMMELINACEAE	1210	-
Crassula alba – CRASSULACEAE	-	1712
C. vaginata	-	1405
Crotalaria cobalticola – FABACEAE	-	3010
Cyanotis longifolia – COMMELINACEAE	-	4200
Eragrostis boehmii – POACEAE	2800	-
Gutenbergia cupricola – ASTERACEAE	5095	2309
Haumaniastrum homblei – LAMIACEAE	-	2633
H. katangense	8356	2240
H. robertii	2070	10,200
H. rosulatum	1089	-
Hibiscus rhodanthus – MALVACEAE	-	1527
Icomum tuberculatum – LAMIACEAE	-	1429
Ipomoea alpina – CONVOLVULACEAE	12,300	-
Lindernia damblonii – SCROPHULARIACEAE	-	1113
L. perennis	9322	2300
Monadenium cupricola – EUPHORBIACEAE	-	1234
Pandiaka metallorum – AMARANTHACEAE	6260	2139
Rendlia cupricola – POACEAE	1560	-
Silene cobalticola – CARYOPHLLACEAE	1660	-
Sopubia dregeana – SCROPHULARIACEAE	-	1767
S. metallorum	-	1742
S. neptunii	-	2476
Striga hermontheca – SCROPHULARIACEAE	1105	-
Triumfetta digitata – TILIACEAE	1060	-
T. welwitschii var *descampii*	-	2201
Vernonia petersii – ASTERACEAE	1555	-
Vigna dolomitica – FABACEAE	3000	-
Xerophyta retinervis var. *retinervis* – VELLOZIACEAE	-	1520

Source: Brooks et al (1995)

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
TEST PITTING LOCATIONS
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Parameter	Clean-Up Guidelines (1) Residential/ Parkland	Clean-Up Guidelines (1) Commercial/ Industrial	A1*	A-1	A-2	AN21-1	AN21-2	AN21-3	ASW14-1	B1*	B-2	B-3	BW11-1
pH	6-8	6-8	-	-	8.2	-	-	-	-	-	7.3	-	-
EC (ms/cm)	2	4	-	-	0.071	-	-	-	-	-	0.024	-	-
SAR	5	12	-	-	-	-	-	-	-	-	-	-	-
Arsenic	20	40	5.68	-	-	-	-	-	-	6.16	-	-	-
Cadmium	3	6	2.17	1.1	<0.3	<0.3	0.4	<0.3	0.56	<0.5	0.93	-	<0.5
Chromium IV	8	8	<2	-	-	-	-	-	<10	2.4	<10	-	<10
Chromium (total)	750	750	31.3	22.7	20.9	28.6	25.3	<0.3	7.4	38.8	10.5	-	9.1
Cobalt	40	80	10	7	4	3	2	<2	7.6	10	6	-	4
Copper	150	225	29	15	34	68	11	54.5	34	176	19	-	31
Lead	375	750	205	100	167	253	18	145	417	77	162	70	83
Mercury	0.8	1.5	0.06	-	-	-	-	-	-	0.012	-	-	-
Molybdenum	5	40	3.03	8	<3	4	6	<3	-	60.1	1.23	<3	1.11
Nickel	150	150	18.7	13	10	12	4	<2	15	16.7	10.5	-	13
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	0.24	-	-	-	<0.01	-	-	1.39	-	-	-
Selenium	2	10	<0.10	-	-	-	-	-	-	0.1	-	-	-
Silver	20	40	<2	<0.2	<0.2	<0.2	<0.2	<0.2	<1	<2	<1	-	<1
Zinc	600	600	2599	2660	1920	948	27	2260	2375	266	376	882	235
Antimony	20	40	1.7	-	-	-	-	-	-	2.24	-	-	-
Barium	750	1500	62.2	56	31	74	21	43.9	-	38.4	-	-	-
Beryllium	4	8	0.61	0.6	0.5	0.5	0.3	0.4	-	3.93	-	-	0.89
Vanadium	200	200	30.8	26.2	10.9	15.6	13	7.5	-	60.1	-	-	-

Notes:

1) Taken from the "Ontario Ministry of the Environment, Guidelines for the Decommissioning and Clean-Up of Sites in Ontario, January 1989".

2) All values are as milligrams per kilogram (mg/kg) unless otherwise stated.

* Results taken from P&R's "Environmental Investigation, August 1989".

_ Underlined values exceed the guidelines for residential/parkland redevelopment.

▨ Shaded values exceed the guidelines for commercial/industrial parkland.

\- Analysis not performed

SOURCE: Proctor & Redfern Limited (1991)

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
TEST PITTING LOCATIONS
Former IMICO Foundry, Guelph, Ontario

Parameter	Clean-Up Guidelines (1)												
	Residential/ Parkland	Commercial/ Industrial	C-1*	C-2	C-4	CW10-2	CE10-2	D-1*	D-1	D-2	DSW7-1	E1*	E2*
pH	6-8	6-8	-	8.2	-	-	-	-	7.4	-	-	-	-
EC (ms/cm)	2	4	-	0.056	-	-	-	-	0.048	-	-	-	-
SAR	5	12	-	-	-	-	-	-	-	-	-	-	-
Arsenic	20	40	3.02	-	-	-	-	4.05	-	-	-	2.91	7.63
Cadmium	3	6	1.4	<0.5	-	<0.3	<0.3	1.11	-	0.82	<0.3	1.16	3.13
Chromium IV	8	8	4	<10	-	-	-	<2	-	<10	-	12.4	16.2
Chromium (total)	750	750	8.14	5.1	-	6.9	18.6	90.8	-	10	14.4	88.8	134.9
Cobalt	40	80	<5	1.9	-	<2	6	<5	-	11	4	8	6
Copper	150	225	18	11	-	4	10	38	-	50	20	125	102
Lead	375	750	91	1727	32	10	92	49	-	60	26	101	281
Mercury	0.8	1.5	0.23	-	-	-	-	0.118	-	-	-	0.035	0.049
Molybdenum	5	40	5.86	<1	<3	<3	10	13.28	-	1.39	5	7.72	8.71
Nickel	150	150	5.2	5.6	-	5	12	22.3	-	23	10	42.5	19.4
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	0.22	-	-	-	-	0.38	-	-	-	8.91	8.23
Selenium	2	10	<0.1	-	-	-	-	<0.1	-	-	-	<0.1	<0.1
Silver	20	40	<2	<1.0	-	<0.2	<0.2	<2	-	1.2	<0.2	<2	<2
Zinc	600	600	889	74	412	39	57	244	-	1434	60	249	428
Antimony	20	40	0.92	-	-	-	-	0.35	-	-	-	0.34	0.82
Barium	750	1500	17.6	-	-	18	44	37.7	-	-	30	34.7	82.4
Beryllium	4	8	0.33	-	-	0.2	0.5	0.64	-	-	0.4	1.03	0.71
Vanadium	200	200	5.86	-	-	8.8	19.2	13.3	-	-	16.1	18.9	17.0

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
TEST PITTING LOCATIONS
Former IMICO Foundry, Guelph, Ontario

Parameter	Clean-Up Guidelines (1) Residential/ Parkland	Commercial/ Industrial	EW8-1	EW8-3	ESW8-1	ESW8-2	F1*	G*	H*	H-2	HW16-1	HW16-2	HNE19-1
pH	6-8	6-8	-	-	7.5	-	-	-	-	-	-	-	-
EC (ms/cm)	2	4	-	-	0.054	-	-	-	-	-	-	-	-
SAR	5	12	-	-	-	-	-	-	-	-	-	-	-
Arsenic	20	40	-	-	-	-	2.97	1.55	4.98	-	-	-	-
Cadmium	3	6	-	<0.3	-	<0.3	0.81	0.75	51.8	<0.5	0.6	<0.3	<0.5
Chromium IV	8	8	<1	-	-	<10	2.3	<2	<2	<10	-	-	<10
Chromium (total)	750	750	-	14.9	-	18.6	100.2	24.1	28.3	8.1	22.1	-	6.4
Cobalt	40	80	-	<2	-	<2	44	<5	<5	2.8	5	-	3.2
Copper	150	225	-	5	-	6	52	21	43	12	26	-	29
Lead	375	750	-	24	-	46	64	34	110	79	830	48	27
Mercury	0.8	1.5	-	-	-	-	0.008	0.009	0.041	-	-	-	-
Molybdenum	5	40	<3	<3	-	<3	4.33	7.48	3.6	-	6	<3	-
Nickel	150	150	-	<2	-	<2	27.1	14.5	21.6	8.5	11	-	7.3
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	<0.01	<0.01	-	-	0.23	0.21	1.76	<0.01	-	-	-
Selenium	2	10	-	-	-	-	<0.1	<0.1	<0.1	-	-	-	-
Silver	20	40	-	<0.2	-	<0.2	4.3	3.3	<2	1.7	<0.2	-	<1
Zinc	600	600	-	331	-	394	255	19	255	576	303	-	41
Antimony	20	40	-	-	-	-	0.07	0.12	1.47	-	-	-	-
Barium	750	1500	-	14	-	25	25.7	12.5	35.1	-	44	-	-
Beryllium	4	8	-	0.4	-	0.5	0.16	0.33	0.45	-	0.5	-	-
Vanadium	200	200	-	<0.3	-	<0.3	14.4	4.98	18.4	16.1	17.5	-	-

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
TEST PITTING LOCATIONS
Former IMICO Foundry, Guelph, Ontario

Parameter	Clean-Up Guidelines (1) Residential/ Parkland	Clean-Up Guidelines (1) Commercial/ Industrial	I*	I-1	I-4	INE15-1	IE15-1	J*	JE15-2	JS15-3	K1*	K2*	K-1
pH	6-8	6-8	-	7.9	-	-	-	-	-	-	-	-	7.8
EC (ms/cm)	2	4	-	0.047	-	-	-	-	-	-	-	-	0.038
SAR	5	12	-	-	-	-	-	-	-	-	-	-	-
Arsenic	20	40	5.79	-	-	-	-	4.01	3.49	1.36	6.93	3.71	-
Cadmium	3	6	125	<0.3	<0.3	<0.3	<0.3	1.26	<0.5	<0.5	<0.5	1	<0.3
Chromium IV	8	8	<2	-	-	-	-	14.7	<10	<10	4.1	5.6	-
Chromium (total)	750	750	31.8	71.6	18	8.6	17.6	43.8	5.1	3.4	66.1	77.5	84.7
Cobalt	40	80	6	8	<2	2	4	9	2.3	2	7	<5	10
Copper	150	225	57	2460	14	17	19	31	19	6.2	211	64	92
Lead	375	750	33	2450	35	42	51	138	31	12	140	26	103
Mercury	0.8	1.5	0.016	-	-	-	-	0.01	0.06	<0.01	0.012	0.021	-
Molybdenum	5	40	8.17	25	<3	4	9	3.16	<1	<1	23.9	6.35	35
Nickel	150	150	22.9	17	<2	6	10	12.2	4.7	4.2	62.1	33.1	55
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	2.65	<0.01	-	<0.01	<0.01	8.9	<0.01	0.01	0.26	0.36	-
Selenium	2	10	<0.1	-	-	-	-	<0.1	0.24	<0.22	0.1	<0.1	-
Silver	20	40	2.4	<0.2	<0.2	<0.2	<0.2	24.5	<1	<1	3.5	10.4	<0.2
Zinc	600	600	253	1810	586	141	94	323	65	16	433	335	431
Antimony	20	40	0.27	-	-	-	-	2.07	0.24	0.91	1.45	0.11	-
Barium	750	1500	18.4	43	14	25	36	74.6	35	29	42.7	54.5	41
Beryllium	4	8	0.49	0.4	0.4	0.3	0.4	0.71	3	<1	2.53	0.91	0.04
Vanadium	200	200	15.5	30.4	<0.3	10.3	16.9	61.5	32	6	31.8	13.6	15.1

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
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	Clean-Up Guidelines (1)												
Parameter	Residential/ Parkland	Commercial/ Industrial	KE13-5 (Org)	KW32-1	KNW10-1	L1*	L2*	L-3	LW23-2	LW23 (Org)	LW23-4	LW23-5	LW14-2
pH	6-8	6-8	-	-	-	-	-	-	6.7	-	-	-	-
EC (ms/cm)	2	4	-	-	-	-	-	-	0.051	-	-	-	-
SAR	5	12	-	-	-	-	-	-	-	-	-	-	-
Arsenic	20	40	-	-	-	10.23	7.38	15.2	3.23	-	-	-	-
Cadmium	3	6	-	0.4	<0.3	2.73	<0.5	<0.5	<0.5	-	0.3	-	<0.3
Chromium IV	8	8	-	-	-	**28.7**	**11.3**	<10	<10	-	-	-	-
Chromium (total)	750	750	-	16.7	11.1	67.4	7.5	15	8.7	-	23.1	-	9.4
Cobalt	40	80	-	7	8	12	8	6.2	3.1	-	22	-	6
Copper	150	225	-	45	9.8	**600**	60	22	11	-	68.2	-	20.7
Lead	375	750	-	94	138	**645**	52	215	99	-	10	-	72
Mercury	0.8	1.5	-	-	-	0.039	0.186	0.15	0.05	-	-	-	-
Molybdenum	5	40	-	6	<3	3.97	**6.67**	1	<1	-	<3	-	<3
Nickel	150	150	-	18	10	43.7	17.6	19	5.1	-	27	-	13
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	<0.01	<0.01	-	**4.95**	1.87	<0.01	<0.01	<0.01	**3.22**	1.743	1.51
Selenium	2	10	-	-	-	<0.1	<0.1	0.27	<0.31	-	-	-	-
Silver	20	40	-	<0.2	<0.2	17.9	<0.2	<1	<1	-	<0.2	-	<0.2
Zinc	600	600	-	209	**753**	**9774**	**1348**	**740**	281	-	**4340**	-	**9710**
Antimony	20	40	-	-	-	5.7	0.16	0.24	0.31	-	-	-	-
Barium	750	1500	-	43	65.5	27.8	38	89	134	-	42.6	-	69.7
Beryllium	4	8	-	0.7	0.7	1.29	1.07	3	3	-	0.6	-	0.8
Vanadium	200	200	-	13.3	23.2	11.4	44.3	60	37	-	23.7	-	16.6

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
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Parameter	Clean-Up Guidelines (1)												
	Residential/ Parkland	Commercial/ Industrial	LN2-2	1-1	2-1	3-1	4-1	5-1	6-1	7-2	7-4	8-2	9-1
pH	6-8	6-8	6.7	6.6	7.7	8.2	7	8.3	8.2	9	-	7.7	8.8
EC (ms/cm)	2	4	0.027	0.015	0.042	0.047	0.026	0.092	0.055	0.056	-	0.137	0.06
SAR	5	12	-	-	-	-	-	-	-	-	-	-	-
Arsenic	20	40	-	3.08	7.16	13.2	3.18	1.74	2.28	2.02	-	8.72	2.75
Cadmium	3	6	<0.3	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.3	<0.5	<0.5
Chromium IV	8	8	-	<10	<10	<10	<10	<10	<10	<10	-	<10	<10
Chromium (total)	750	750	29.1	7	3.4	3.9	4.1	5.5	5.9	3.3	16.5	9	6.6
Cobalt	40	80	15	1.4	2.5	1	1.6	1	2.1	1	<2	2.9	<1
Copper	150	225	37	13	17	19	10	12	9.2	8.2	11	16	12
Lead	375	750	50	18	26	46	9.8	10	12	30	51	15	6.5
Mercury	0.8	1.5	-	0.02	0.02	0.06	0.01	<0.01	0.01	0.03	-	0.02	0.02
Molybdenum	5	40	21	<1	<1	<1	<1	<1	<1	<1	<3	<1	<1
Nickel	150	150	28	2.7	8.8	4.9	4.1	3.6	4.5	1.8	<2	9.4	3.5
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Selenium	2	10	-	0.22	0.23	0.23	0.23	<0.22	<0.22	0.24	-	0.23	0.22
Silver	20	40	<0.2	<1	<1	<1	<1	<1	<1	<1	<0.2	<1	<1
Zinc	600	600	2220	31	45	231	31	30	42	20	496	92	19
Antimony	20	40	-	1.76	1.14	2.21	0.45	0.22	0.22	0.48	-	1.51	0.44
Barium	750	1500	63	25	42	116	34	21	31	23	13	135	42
Beryllium	4	8	1.1	1	3	3	1	2	3	2	0.4	3	2
Vanadium	200	200	23.7	38	45	21	15	18	27	19	<0.3	33	18

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
TEST PITTING LOCATIONS
Former IMICO Foundry, Guelph, Ontario

Parameter	Clean-Up Guidelines (1) Residential/ Parkland	Clean-Up Guidelines (1) Commercial/ Industrial	9-3	10-2	11-1	12-1	12-2	12SE10-1	12SE10-2
pH	6-8	6-8	-	8.7	7.7	-	-	-	-
EC (ms/cm)	2	4	-	0.043	0.034	-	-	-	-
SAR	5	12	-	-	-	-	-	-	-
Arsenic	20	40	-	3.49	3.23	-	23	10.4	4.7
Cadmium	3	6	<0.3	-	<0.5	-	<0.5	<0.5	<0.3
Chromium IV	8	8	-	<10	<10	-	<10	<10	-
Chromium (total)	750	750	<0.3	4.6	5.8	-	4.2	18	17.9
Cobalt	40	80	<2	1.9	1.6	-	3.8	3.8	13
Copper	150	225	8.9	22	14	-	25	37	322
Lead	375	750	51	31	17	-	13	49	48
Mercury	0.8	1.5	-	<0.01	0.02	-	0.01	0.04	-
Molybdenum	5	40	<3	<1	<1	-	3	<1	7
Nickel	150	150	<2	3.8	4.5	-	8.3	10	27
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	-
Oil and Grease (%)	2	2	-	<0.01	<0.01	<0.01	<0.01	<0.01	-
Selenium	2	10	-	0.23	0.22	-	0.92	0.22	-
Silver	20	40	<0.2	<1	<1	-	<1	<1	<0.2
Zinc	600	600	652	37	47	-	21	356	516
Antimony	20	40	-	0.7	0.32	-	0.92	3.56	-
Barium	750	1500	67.6	28	24	-	50	62	59.7
Beryllium	4	8	0.5	2	2	-	4	1	1.3
Vanadium	200	200	6.8	20	23	-	16	10	38.4

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
COREHOLE AND DRYWELL SAMPLES
Former IMICO Foundry, Guelph, Ontario

Parameter	Clean-Up Guidelines (1)								
	Residential/ Parkland	Commercial/ Industrial	C2-2	C6-2	C7-2	C8-1	C10-1	C11-1	C12-1
pH	6-8	6-8	-	-	-	-	-	-	7.7
EC (ms/cm)	2	4	-	-	-	-	-	-	-
SAR	5	12	-	-	-	-	-	-	-
Arsenic	20	40	-	-	-	-	-	-	-
Cadmium	3	6	0.6	<0.3	1.2	0.5	<0.3	<0.3	<0.3
Chromium IV	8	8	-	-	-	-	-	-	-
Chromium (total)	750	750	11.7	11.2	15.5	10.4	8.9	<0.3	4.8
Cobalt	40	80	22	16	6	24	116	393	52
Copper	150	225	29.6	23.7	30.1	12.5	48.9	24.5	32.2
Lead	375	750	120	38	24	23	140	17	55
Mercury	0.8	1.5	-	-	-	-	-	-	-
Molybdenum	5	40	<3	<3	<3	<3	<3	<3	<3
Nickel	150	150	11	11	12	9	33	<2	4
Nitrogen (%)	0.5	0.6	-	-	-	-	-	-	0.184
Oil and Grease (%)	2	2	2.87	0.32	<0.04	3.14	2.79	-	0.56
Selenium	2	10	-	-	-	-	-	-	-
Silver	20	40	<0.2	<0.2	<0.2	<0.2	<0.2	7.8	<0.2
Zinc	600	600	507	2430	79	83.0	840	133	9950
Antimony	20	40	-	-	-	-	-	-	-
Barium	750	1500	53.9	22	32.6	32.0	43.0	25.0	19.0
Beryllium	4	8	0.5	0.4	0.9	0.4	0.5	0.4	0.2
Vanadium	200	200	20.7	3.7	22.9	15.7	1.6	<0.3	3.8

TABLE 9
RESULTS OF SOIL ANALYSIS FOR DECOMMISSIONING PARAMETERS
COREHOLE AND DRYWELL SAMPLES
Former IMICO Foundry, Guelph, Ontario

	Clean-Up Guidelines (1)				
Parameter	Residential/ Parkland	Commercial/ Industrial	C14-1	D2	D3
pH	6-8	6-8	-	-	6.8
EC (ms/cm)	2	4	-	-	0.163
SAR	5	12	-	-	-
Arsenic	20	40	-	-	**36**
Cadmium	3	6	<0.3	1.9	2.9
Chromium IV	8	8	-	-	<10
Chromium (total)	750	750	14.5	109	98
Cobalt	40	80	21	13	4.4
Copper	150	225	45.4	**276**	**2110**
Lead	375	750	50	190	**4526**
Mercury	0.8	1.5	-	-	0.38
Molybdenum	5	40	<3	7	**9.06**
Nickel	150	150	14	**300**	35
Nitrogen (%)	0.5	0.6	-	-	-
Oil and Grease (%)	2	2	**2.35**	-	**8.1**
Selenium	2	10	-	-	<0.22
Silver	20	40	<0.2	<0.2	3
Zinc	600	600	278	**1090**	**22573**
Antimony	20	40	-	-	14
Barium	750	1500	32	55.2	157
Beryllium	4	8	0.4	0.5	1.71
Vanadium	200	200	11.7	10.4	31.2

TABLE 10
RESULTS OF SOIL AND PROCESS WASTE ANALYSIS
VOLATILE ORGANIC COMPOUNDS
Former IMICO Foundry, Guelph, Ontario

Parameter	Guidelines (1) Industrial/ Commercial	Method Detection Limit	Results (2) Soil Samples 12-1	Results (2) Soil Samples C12-1
Chloromethane	50	1	--	--
Vinyl Chloride	50	1	--	--
Chloroethane	50	1	--	--
Trichlorofluoromethane	50	2	--	--
1,1-Dichloroethene	50	0.5	--	--
Dichloromethane	50	0.2	--	--
Trans-1,2-Dochloroethene	50	0.5	--	--
1,1-Dichloroethane	50	0.1	--	--
Cis-1,2-Bichloroethene	50	0.1	--	--
Chloroform	50	0.1	--	--
1,1,1-Trichloroethane	50	0.1	--	--
Carbon Tetrachloride	50	0.1	--	--
Benzene	5	0.1	--	--
1,2-Dichloroethane	50	0.1	--	--
Trichloroethene	50	0.1	--	--
1,2-Dichloropropane	50	0.1	--	--
Bromodichloromethane	50	0.1	--	--
Cis-1,3-Dichloropropene	50	0.2	--	--
Toluene	30	0.1	0.2	--
Trans-1,3-Dichloropropene	50	0.2	--	--
1,1,2-Trichloroethane	50	0.5	--	--
Tetrachloroethene	50	0.2	--	--
Dibromochloromethane	50	0.5	--	--
1,2-Dibromoethane	50	0.5	--	--
Chlorobenzene	10	0.1	--	--
Ethylbenzene	50	0.1	0.3	--
Xylenes (m,p and o)	50	0.1	<u>8.8</u>	--
Styrene	50	0.1	--	--
Bromoform	50	1	--	--
1,1,2,2-Tetrachloroethane	50	0.5	--	--
1,3-Dichlorobenzene	10	0.1	--	--
1,4-Dichlorobenzene	10	0.1	--	--
1,2-Dichlorobenzene	10	0.1	--	--

Notes:
1) Taken from "Contaminated Site Rehabilitation Policy, MENVIQ, Feb., 1988" (where level B concentrations correspond to Res. criteria and level C concentrations correspond to Com/Ind criteria) and "Canadian Interim Enviromental Quality Criteria for Contaminated Sites, CCME".
2) All values are as milligrams per kilogram (mg/kg).
_ Underlined values exceed the guidelines for residential/parkland redevelopment.
▨ Shaded values exceed the guidelines for commercial/industrial parkland.
-- Parameter NOT DETECTED in analysis.

SOURCE: Proctor & Redfern Limited (1991)

TABLE 11
RESULTS OF SOIL ANALYSIS
BASE NEUTRAL EXTRACTABLES
Former IMICO Foundry, Guelph, Ontario

Parameter	Guidelines (1) Commercial/ Industrial	Method Detection Limit	Sample Location						
			LW14-2	LN2-2	7-2	CW10-2	D-1	I-1	JS15-3
Bis (2-Chloroethyl) ether		0.2	–	–	–	–	–	–	–
1,3-Dichlorobenzene	10	0.2	–	–	–	–	–	–	–
1,4-Dichlorobenzene	10	0.2	–	–	–	–	–	–	–
1,2-Dichlorobenzene	10	0.2	–	–	–	–	–	–	–
Bis (2-Chloroisopropyl) ether		0.5	–	–	–	–	–	–	–
Hexachloroethane	50	0.5	–	–	–	–	–	–	–
N-Nitorsodi-N-Propylamine		1	–	–	–	–	–	–	–
Nitrobenzene		0.2	–	–	–	–	–	–	–
Isophorone		0.2	–	–	–	–	–	–	–
Bis (2-Chloroethoxy) methane		0.2	–	–	–	–	–	–	–
1,2,4-Trichlorobenzene		0.2	–	–	–	–	–	–	–
Naphthalene	50	0.2	5.9	0.1	–	–	0.1	0.1	–
Hexachlorobutadiene		0.5	–	–	–	–	–	–	–
Hexachororcyclopentadiene		2	–	–	–	–	–	–	–
2-Chloronaphthalene		0.2	–	–	–	–	–	–	–
Acenaphthylene	100	0.2	0.6	–	–	–	–	–	–
Dimethyl Phthalate		1	–	–	–	–	–	–	–
2,6-0Dinitrotoluene		0.5	–	–	–	–	–	–	–
Acenaphthene	100	0.2	1.4	–	–	–	–	–	–
2,4-Dinitrotoluene		0.5	–	–	–	–	–	–	–
Fluorene	100	0.2	2.3	–	–	–	–	–	–
4-Chlorophenyl Ether		0.2	–	–	–	–	–	–	–
Dethyl Phthalate		0.2	–	–	–	–	–	–	–
N-Nitrosodiphyenylamine		0.5	–	–	–	–	–	–	–
4-Bromophenyl Phenyl Ether		0.5	–	–	–	–	–	–	–
Hexachlorobenzene		0.5	–	–	–	–	–	–	–
Phenathrene	50	0.2	7.2	0.2	–	–	0.3	0.2	0.1
Anthracene	100	0.2	0.7	–	–	–	–	–	–
Di-N-Butlyl Phthalate		0.2	–	–	–	–	–	–	–
Fluoranthene	100	0.2	0.2	0.1	–	–	0.2	0.2	0.1
Pyrene	100	0.2	0.4	0.1	–	–	0.1	0.1	0.1
Bnzyl Butyl Phthalate		0.5	–	–	–	–	–	–	–
Benzo (a) anthracene	10	0.5	–	–	–	–	–	–	–
Chrysene	10	0.5	–	–	–	–	–	–	–
3.3-Dichlorobenzidine		10	–	–	–	–	–	–	–
Bis (2-Ethylhexyl) phthalate		0.5	–	–	–	–	–	–	–
Di-N-Octyl Phtalate		0.5	–	–	–	–	–	–	–
Benzo (b) fluoranthene	10	0.5	–	–	–	–	–	–	–
Benzo (k) fluoranthene	10	0.5	–	–	–	–	–	–	–
Benzo (a) pyrene	10	0.5	–	–	–	–	–	–	–
Indeno (1,2,3-cd) pyrene	10	0.5	–	–	–	–	–	–	–
Dibenzo (a,h) anthracene	10	0.5	–	–	–	–	–	–	–
Benzo (ghi) perylene	10	0.5	–	–	–	–	–	–	–
TOTAL PAH'S	200		18.7	0.5	–		0.7	0.6	0.3

Notes:

1) Taken from "Contaminated Site Rehabilitation Policy, MENVIQ, Feb., 1988" (where level B concentrations correspond to Res. criteria and level C concentrations correspond to Com/Ind criteria) and "Canadian Interim Enviromental Quality Criteria for Contaminated Sites, CCME".

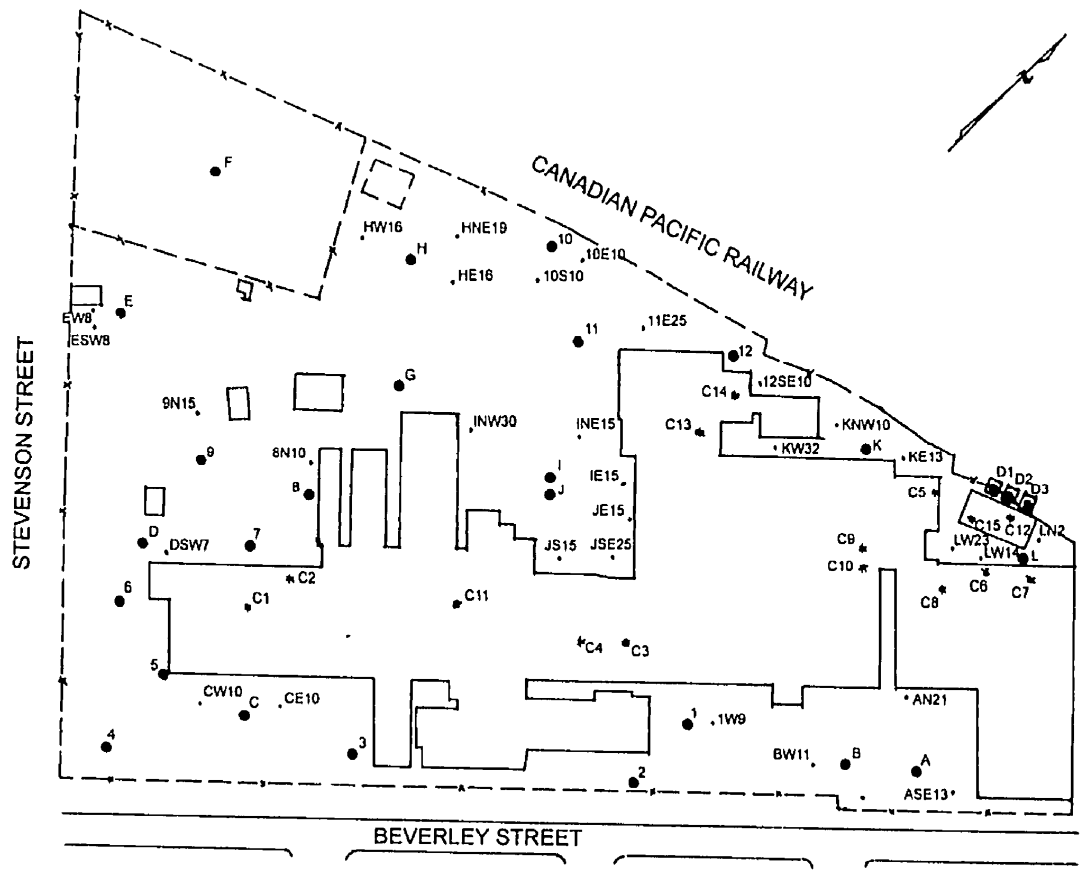
2) All values are as milligrams per kilogram (mg/kg).

_ Underlined values exceed the guidelines for residential/parkland redevelopment.

Shaded values exceed the guidelines for commercial/industrial parkland.

– Parameter NOT DETECTED in analysis.

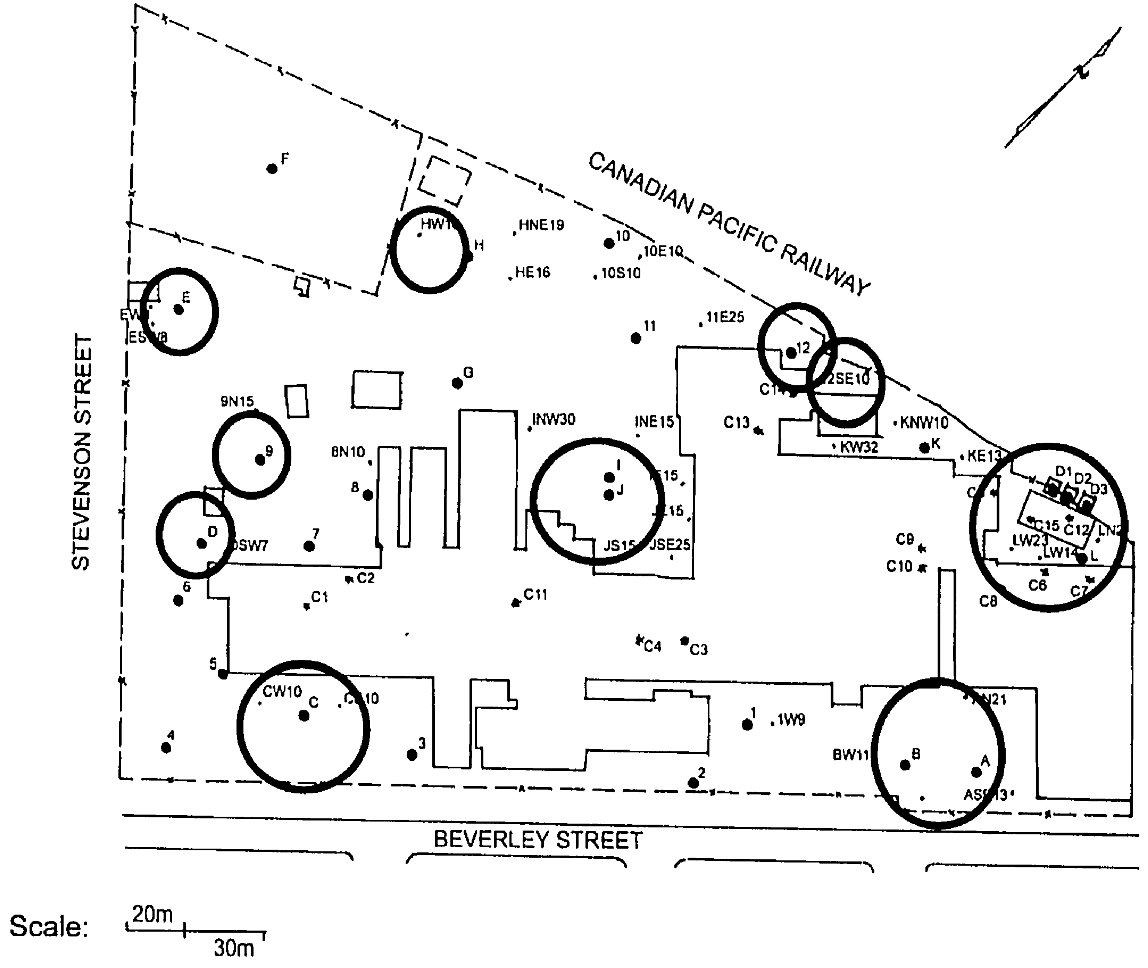
SOURCE: Proctor & Redfern Limited (1991)



Scale: 20m 30m

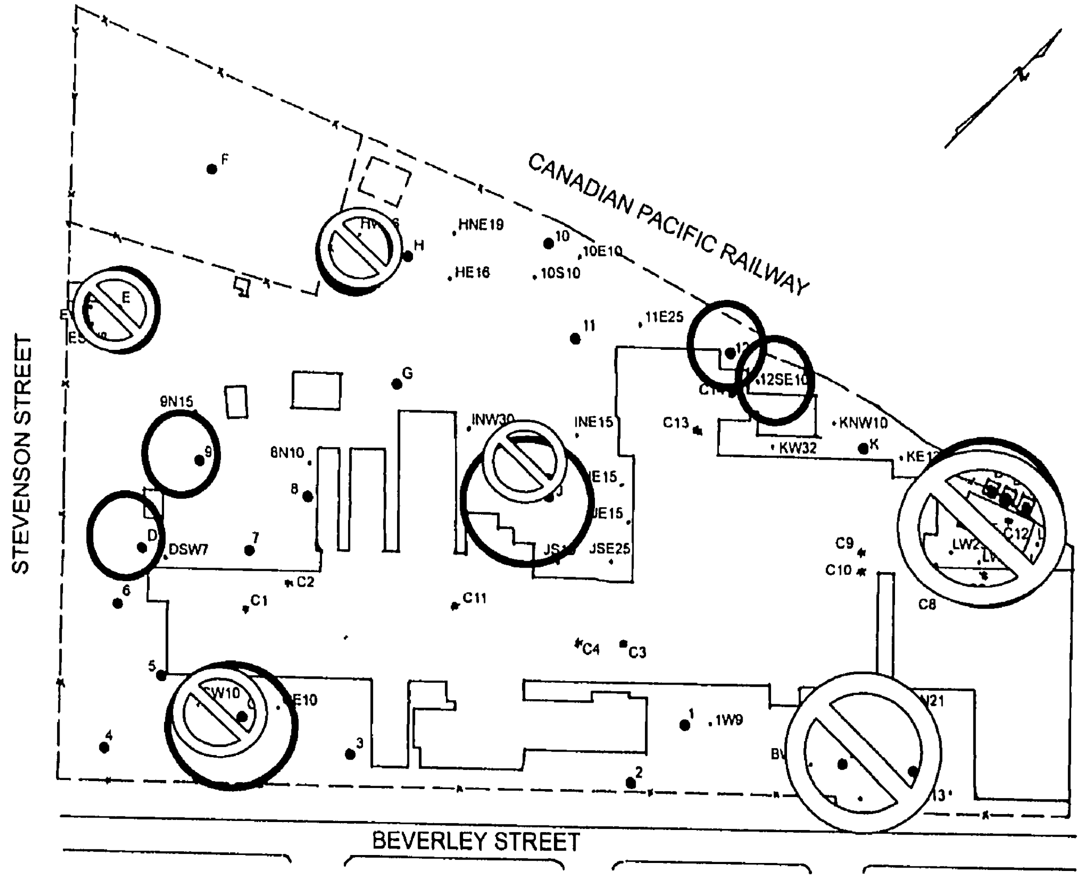
After: Proctor and Redfern (1991)

Figure 15
Location of Soil Samples corresponding to Tables 9, 10, and 11



After: Proctor and Redfern (1991)

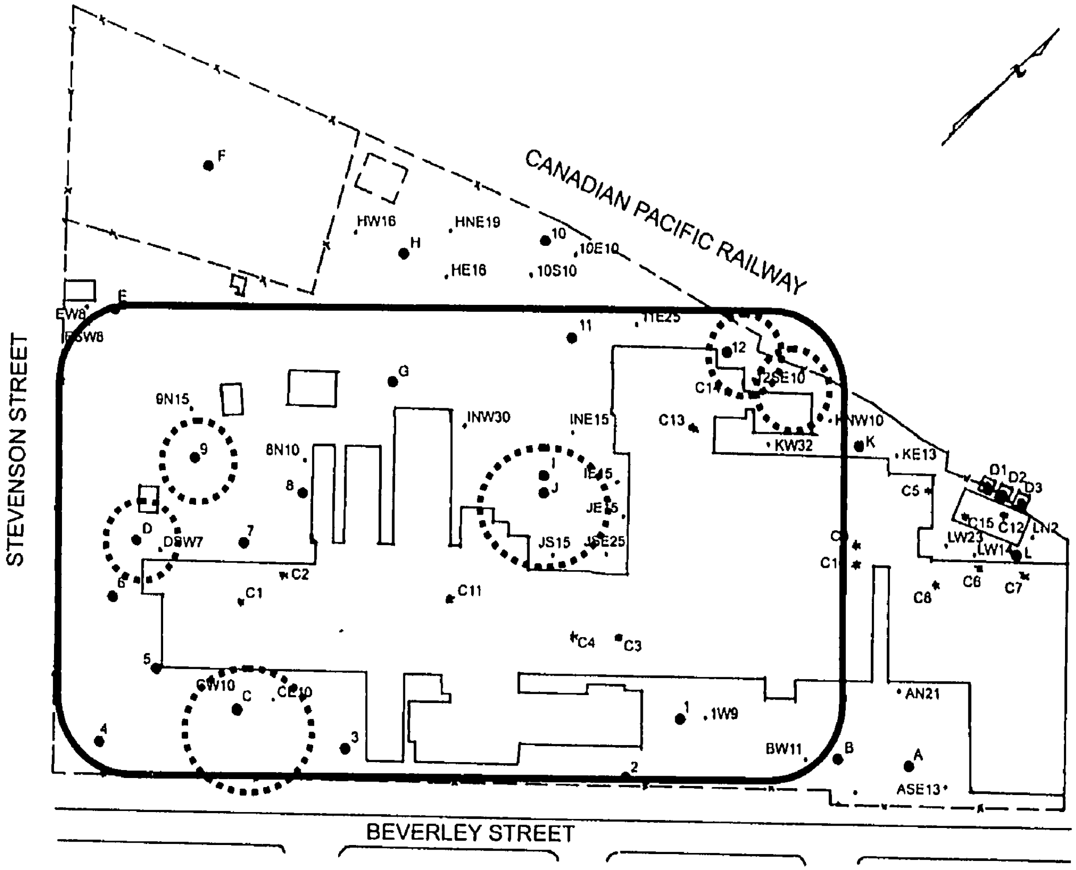
Figure 16
Areas exceeding commercial/industrial decommissioning guidelines



Scale: 20m 30m

Figure 17
Soil to be excluded from phytoremediation by excavation

After: Proctor and Redfern (1991)



Scale: 20m 30m

After: Proctor and Redfern (1991)

Figure 18
Area to be phytoremediated for elevated zinc and copper levels

INORGANICS

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