Phytoremediation

Protecting the Environment with Plants

When dealing with a site contaminated by organic or inorganic substances, traditional methods of site remediation often involve:

- excavating and removing all contaminated soil and disposing of the soil in an environmentally sound manner;
- covering the site with a blanket of uncontaminated soil and installing a runoff control and drainage system to limit the potential contamination of surface water or groundwater;
- other in-situ treatment methods that involve complex physical and/or chemical neutralization or extraction processes.

Phytoremediation is an alternative to these disruptive, destructive, and expensive methods of site remediation.

What is phytoremediation?

Phytoremediation, more broadly referred to as phytotechnology, uses vegetation to contain, sequester, remove, or degrade inorganic and organic contaminants in soil, sediment, surface water, and groundwater.

How does it work?

Phytoremediation operates through several mechanisms or processes to remediate contaminants (Figure 1; Table 1). Some of these processes, such as phytoextraction and rhizofiltration, extract the contaminant from the soil or water, then assimilate it in the harvested biomass.

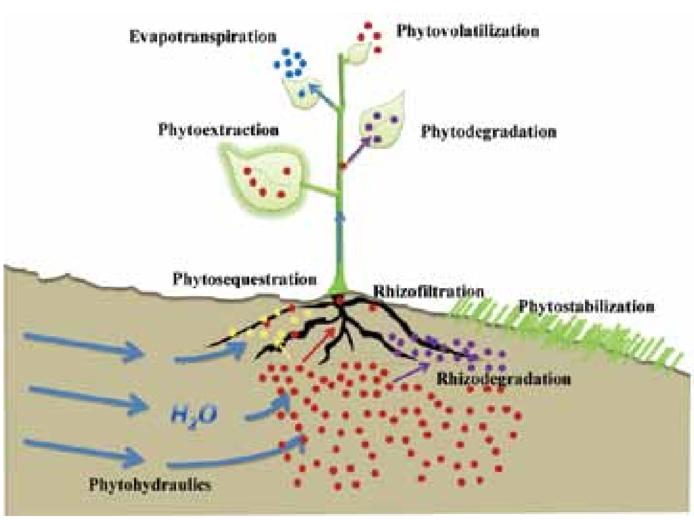

Figure 1. *Mechanisms by which plants can remediate contaminated soils, sediments, or water. The contaminant is represented by red circles, degradation products are purple, transformation products are yellow, and water is blue. Refer to Table 1 for a complete description of the mechanisms.*

In other mechanisms, such as phytovolatilization, the contaminant is taken up by plants and volatilized into the atmosphere, either unmodified or in modified form, as the plants transpire water. Some sites can be remediated by simply reducing the toxicity of the contaminant, which can be accomplished by either degrading it to less harmful by-products (phytodegradation, rhizodegradation) or transforming it into a stable, nonmobile, nonharmful compound (phytosequestration).

In some cases, the primary hazard is contaminant transport off site with groundwater movement or soil erosion. In these cases, phytoremediation could be used to reduce or control water movement through soils and subsoil (phytohydraulics) or reduce the risk of soil movement by wind and water erosion (phytostabilization). The mechanisms chosen for a phytoremediation project depend on the contaminant level, contaminant properties, and the contaminated matrix (Figure 2).

Plants are a logical choice for remediation of contaminated sites and other land rehabilitation projects because of their unique ability to establish, increase in mass, and renew growth in subsequent seasons, even in extreme soil, landscape, and climate environments. In general, vegetation creates aesthetics and revitalizes the landscape. They provide other conservation benefits by protecting and improving natural resources.

Commercially available sources of seed and vegetative rootstock, and accessibility to amendments and husbandry

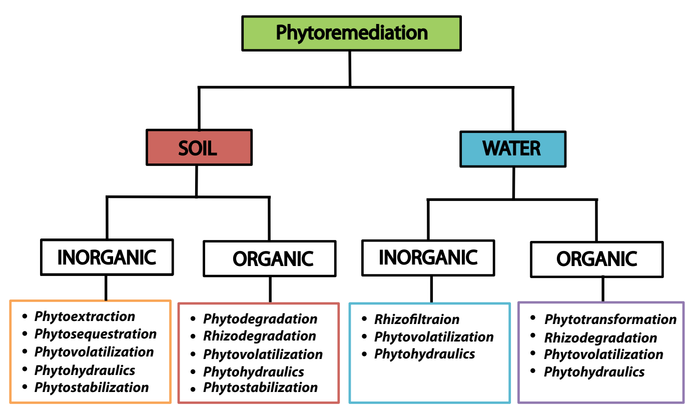

Figure 2. *Application of phytoremediation mechanisms as a function of both matrix (water or soil) and contaminant chemistry (inorganic or organic).*

Table 1. *Phytoremediation mechanisms and associated conservation practices.*

Phytoremediation mechanism	Definition	Facilitating USDA NRCS conservation practices
Phytoextraction/ Phytoaccumulation	The removal of inorganic contaminants from the soil through plant uptake and subsequent harvest and removal of biomass. Phytoextraction is typically used to remove metals from the soil.	327 – Conservation Cover 340 – Cover Crop 342 – Critical Area Planting 612 – Tree/shrub Planting
Phytodegradation (Phytotransformation)	The breakdown of contaminants by the metabolic processes in a plant. Also includes the breakdown of contaminants in the soil by enzymes or other products produced by the plant. Primarily used for organic contaminants.	311 – Alley Cropping 327 – Conservation Cover 390 – Riparian Herbaceous Cover 391 – Riparian Forest Buffer 393 – Filter Strip
Rhizofiltration/ Rhizodegradation	The breakdown or degradation of organic contaminants in the soil. The contaminants are either adsorbed onto the root surface or absorbed by the plant roots. The contaminants are broken down by enhanced microbial activity in the rhizosphere (the zone of soil influenced by the roots).	332 – Contour Buffer Strips 340 – Cover Crop 342 – Critical Area Planting 390 – Riparian Herbaceous Cover 391 – Riparian Forest Buffer 585 – Stripcropping 601 – Vegetative Barrier
Phytovolatilization	The uptake of contaminants by plants and release into the atmosphere as the plants transpire water. Contaminant is removed from the soil and may be degraded as it moves through the plant's vascular system before final removal from the system.	327 – Conservation Cover 340 – Cover Crop 342 – Critical Area Planting 512 – Forage and Biomass Planting 612 – Tree Planting
Phytosequestration/ Phytostabilization	This process sequesters or reduces contaminant bioavailability through precipitation or immobilization of contaminants in the soil, on the root surface, or within the root tissues.	327 – Conservation Cover 340 – Cover Crop 391 – Riparian Forest Buffer 612 – Tree Planting
Phytohydraulics	This process is used to limit the movement of contaminants with water. Plants are used to increase evapotranspiration, thereby controlling soil water and contaminant movement. This mechanism contains the contaminant by modifying site hydrology to reduce the vertical or horizontal movement of water in the soil.	340 – Cover Crop 391 – Riparian Forest Buffer 393 – Filter Strip 512 – Forage and Biomass Planting 612 – Tree Planting 635 – Vegetated Treatment Area
Phytostabilization	Plants are used to stabilize contaminated soils or sediments, thus protecting them from transport by wind or water erosion. The main function is to contain the contaminated material.	327 – Conservation Cover 329 – Residue and Tillage Management – No-till/Strip-till/Direct Seed 330 – Contour Farming 332 – Contour Buffer Strips 342 – Critical Area Planting 380 – Windbreak/Shelterbelt Establishment 585 – Stripcropping 589C – Cross Wind Trap Strips 601 – Vegetative Barrier 603 – Herbaceous Wind Barriers

equipment, make the establishment and management of vegetation easily achievable. Cultural specifications and technical guidance for establishment and management of vegetation are widely available from local NRCS offices and state extension services. Land users are familiar with many of these management techniques including seeding, mowing, watering, fertilizing, and harvesting.

Advantages of phytoremediation

Phytoremediation includes a broad spectrum of treatment mechanisms and can be used to clean up a wide range of contaminants. A phytoremediation design can use multiple mechanisms to address multiple contaminants or concerns simultaneously. For example, plant species may be able to remove an organic contaminant through phytovolatilization and also remediate risks associated with inorganic contamination through phytosequestration and phytostabilization.

Phytoremediation is generally passive and performed without removal of the contaminated soil or water, which requires less maintenance and fewer external energy inputs than alternative treatments. Phytoremediation with vegetation also improves site aesthetics, creates habitat, and can restore ecological function to the site. The combined effect of these advantages makes phytoremediation a cost-competitive remediation technology.

Alternative treatments are more labor- and energy-intensive, often more costly, and unsustainable. These alternative treatments could require complete removal of the contaminant and the medium in which it is contained (the soil, water, and/or plants); containment, storage, and disposal of all runoff and erosion from the site; or additions of soil or water amendments.

Limitations of phytoremediation

Like any remediation technology, phytoremediation has limitations based on contaminant characteristics, site conditions, and remediation goals. Effectiveness may be reduced outside the growing season when plants are dormant. Phytoremediation usually works on sites with low levels of contamination, because these sites have reduced risks and immediate cleanup may not be required. Furthermore, high levels of contaminants could retard or limit plant growth. Rooting depth may limit the effectiveness of phytoremediation because plants take up pollutants as deep only as their roots grow. The area of influence of the plant can be defined as the bottom of its root zone, top of the vegetation canopy, and surface area protected by plant canopy or residue cover.

Toxic substances may enter the food chain via grazers, birds, or other animals that consume leaves or seeds of plants used for phytoremediation. The burning of leaves or limbs of plants containing harmful chemicals could contaminate the air. Phytoremediation generally requires more space and time than alternative remediation strategies. Success of phytoremediation will be site-specific. Because of these limitations, a thorough site assessment must be completed to assure that phytoremediation will meet the project goals and objectives. Then an overall conservation plan needs to be developed to meet those objectives.

Planning and designing a phytoremediation project

Once a contaminated site is discovered, a preliminary assessment should be performed to find the nature and extent of the contaminant. If there is strong evidence for the need of remediation, the preliminary assessment should be followed by a risk assessment. The risk assessment will determine the level of risk and whether remedial action should take place. In a case where remedial action is needed, a feasibility investigation should be performed. This is a more detailed investigation where remedial alternatives are suggested and may be tested at a smaller scale.

The preliminary assessment includes a site visit and looking for obvious physical signs of contamination (little or no vegetation, difference in soil color, odors, discolored runoff, or seepage water). Soil and water samples will be taken and analyzed for suspected contaminants. If the preliminary assessment indicates the presence of contaminants, a risk assessment is needed to determine the potential for the contaminants to cause environmental damage. This assessment involves more detailed site investigations, such as deeper soil sampling to determine depth of contamination and more extensive testing of surface water and groundwater to determine the extent of the contamination.

The risk assessment should focus on evaluating the nature, level, and extent of contamination, any evidence for contaminant level in soil, food, or water exceeding regulatory limits, and evaluating human and ecological harm of any type. A feasibility investigation, also known as remedial investigation, is conducted to collect and evaluate sufficient information to determine remediation options or alternatives suitable for a site, landscape, or a situation. The feasibility study becomes the basis for selecting a suitable remediation option that effectively eliminates or minimizes human and ecological harm.

The design of a phytoremediation system depends on the conditions at the site, such as soil type, contaminant characteristics and concentration, and size and depth of the contaminated area. Analysis of these variables helps with the selection of the plant species, phytoremediation mechanism, plant density and pattern design, and future maintenance. Selection of a specific phytoremediation mechanism mainly depends on contaminant characteristics (Figure 3).

Plant species used in phytoremediation must be adapted to the area of use and suitable for the project. The noxious or invasive potential of the plants must be determined during the planning process. Species with the potential to spread to adjoining land should be used only in dire circumstances. If noxious or invasive species are used, a plan must be established for their annual maintenance and control. Information on species distribution, noxious and invasive status, and other plant characteristics is maintained by the National Plants Data Center (*http://plants.usda.gov*).

Phytoremediation mechanisms

Table 1 describes and defines phytoremediation mechanisms and the conservation practices recommended by the Natural Resources Conservation Service that can be used to implement these processes. For example, conservation buffers are designed to trap sediment and slow runoff; these techniques are phytostabilization and phytohydrology. In these processes, contaminants can be absorbed by plant roots, adsorbed to clay or organic matter, and sequestered in the conservation buffer soil profile (phytoextraction, phytodegradation, phytofixation). Other mechanisms like phytovolatilization, phytosequestration, and phytofiltration also are achieved.

Soil erosion control practices (residue and tillage management, contour farming, terraces, etc.) slow or reduce sediment and water runoff and perform phytostabilization-like mechanism; however, these practices do not directly use vegetation in the establishment of the conservation practice. One conservation practice, critical area planting (NRCS code 342), does use vegetation, and the standard gives guidance on establishment and management of vegetation on affected sites. Use appropriate conservation practices from the NRCS Field Office Technical Guide (FOTG) in your state (*http://efotg.sc.egov.usda.gov//efotg_locator.aspx*) and plant information from the PLANTS database (*www.plants.usda.gov*) and Plant Materials Center (*www.nrcs.usda.gov/wps/portal/nrcs/main/national/plantsanimals/plants/centers*) for assistance in developing a conservation plan for phytoremediation. Other conservation practices are suggested in Table 1 for implementing various phytoremediation mechanisms.

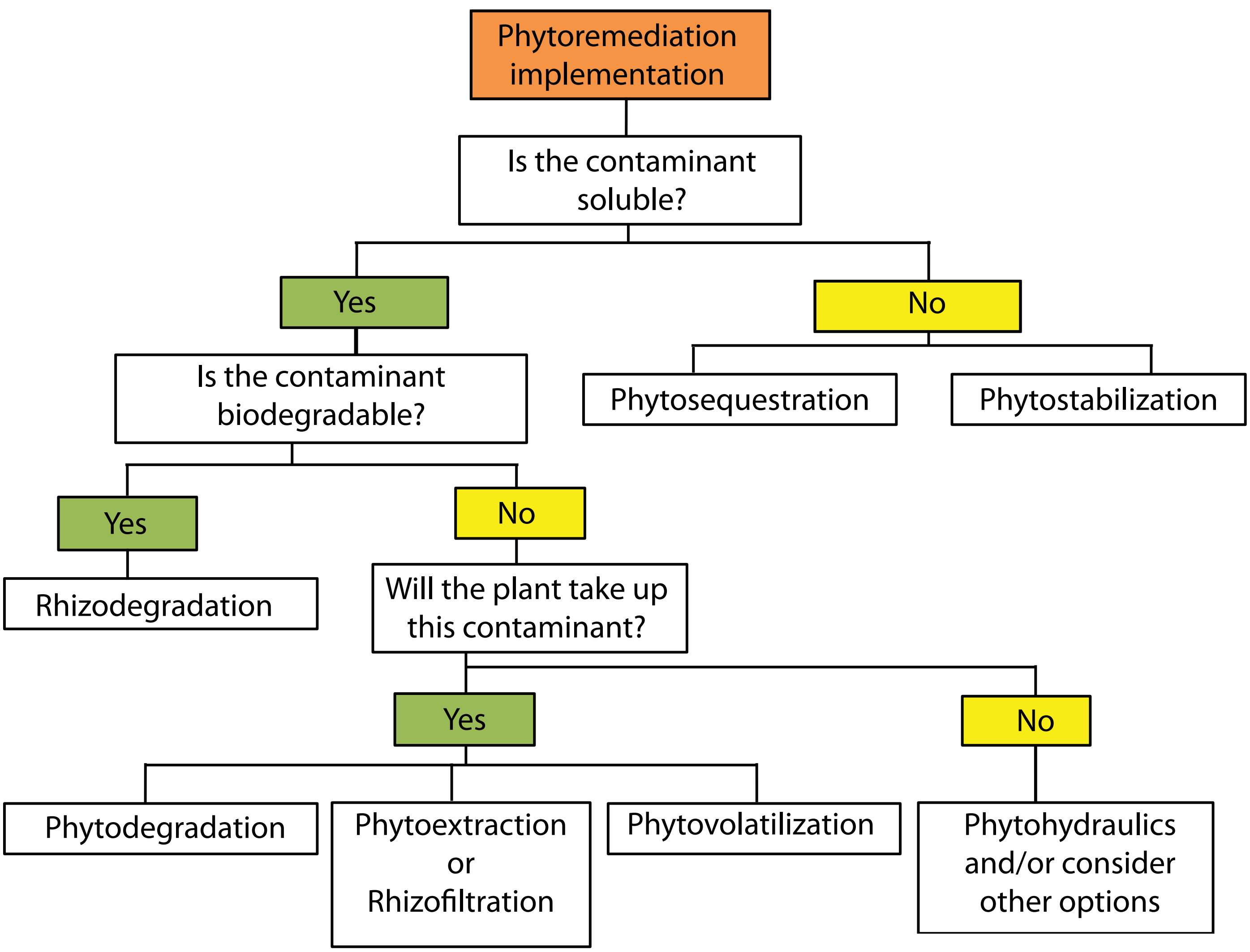

Figure 3. *Decision tree for phytoremediation technology selection.*

Resource management plan

To ensure all resources in the contaminated area of concern are protected, a resource management plan should be implemented. Conservation practices that directly treat the phytoremediation mechanisms for the contaminant of concern should be emphasized. As with all planning for the management of any resource of concern, the presence of contaminants in the soil, water, plants, or air will require a comprehensive conservation plan.

Phytoremediation is a rapid response to a critical, sometimes long-term, resource problem. The use of vegetation requires appropriate establishment and immediate attention to operation and maintenance of that vegetation; therefore, a detailed plan of cultural practices and management techniques is essential in the resource management plan. Treating the wind and water erosion process, water runoff, and/or leaching will lessen the physical potential of contaminant transport. Establishing conservation buffers can contain the contaminant to the field landscape. Nutrient management planning allows for modification of the soil reaction and provides nutrients for plant growth. Husbandry of the vegetation by pest control and harvesting provides for healthy plant growth and managed biomass removal. Putting all the management practices together in a comprehensive plan will result in successful phytoremediation.

How long does phytoremediation take?

The remediation of a site using phytoremediation depends on many factors. Some major factors are:

- type of contaminant
- type of plant
- contamination levels
- size and depth of the contaminated area
- site conditions such as nutrient availability, soil organic matter content, soil water, soil aeration, and other desirable soil quality parameters conducive to initiation and survival of plant species
- type and number of plants needed to remediate the site.

Viability and length of phytoremediation greatly depend on the type of contaminant. For example, use of phytoextraction to remediate trace-element contaminated soils would be extremely challenging and require more time as most potentially toxic trace elements do not easily move from soil to plant, because they are relatively insoluble in soils.

Even if plants take up some, trace elements will be retained in plant roots, thereby minimizing the concentration in the harvestable, aboveground biomass. Similarly, key properties of organic contaminants, such as solubility in water, octanol-water portioning coefficient, sorption/desorption, and half-life determine the length of time needed for remediation.

Ability of plants to produce biomass and uptake, degrade, transform, and/or sequester a particular contaminant are important in determining length of phytoremediation. The type and number of plants needed to remediate a site are dependent on contaminant type and other site characteristics. Although thinning will occur both naturally and during site maintenance, follow recommended spacing for selected plant type.

Phytoremediation database

Kansas State University developed a phytoremediation database. The database contains more than 120 contaminants and 1,130 plant species. There are more than 1,000 publications on the use of vegetation for phytoremediation and more than 25 case studies describing full-scale phytoremediation in practice.

The database serves the following three purposes:

1) It provides a three-way linkage between species used for phytoremediation, remediated contaminants, and research studies investigating phytoremediation;

2) It classifies studies based on phytoremediation mechanisms, study characteristics, and success of the plant species used to remediate the contaminant;

3) It identifies case studies where phytoremediation has been employed successfully in full scale remediation projects.

The information in the database for each publication includes titles of reported studies, authors of the study, journals citation, website link to the full document (when available), contaminant of interest in the study, the type of species used to remediate contaminants, the targeted media to be remediated, the mechanism of phytoremediation, and the success of remediation process. In addition, definitions of terms used in the database also can be accessed. The database is organized so users can systematically sort and search the information from multiple publications based on contaminants, phytoremediation mechanisms, species, media, study type, or a combination of two or more of these items.

Retrieval of database information is facilitated with a graphical user interface. When the database is opened, a dialog box displays six options: search by contaminant, search by species, search references, database summary reports, database information, and exit database (Figure 4). A full listing of the hierarchical database menu choices is presented in Figure 5. The primary database functions are described in the following sections.

Search by Contaminant

The primary design of the database interface is to facilitate searching for species that can be used to remediate a given contaminant, which is accomplished with the "Search by Contaminant" form (Figure 6). The user selects the desired contaminant from the drop-down box (A). Only contaminants included in the database are listed. The user can then open any of the four possible reports with the command buttons at the bottom of the form (B) depending on the level of detail desired.

1) Abbreviated Report — Lists all species that have been used to remediate the selected contaminant, followed by references (grouped by species)

2) Standard Report — Lists all species used to remediate the selected contaminant, including the mechanisms, study type, media, and success rating. The report is grouped by reference, with a hyperlink to the reference.

3) Full Report — Lists all data, including notes, in the database for species that have been used to remediate the selected contaminant. A hyperlink to the NRCS Plants Database is included for each species found in the United States.

4) Case Study Detail — Lists additional details about case studies that have been used to remediate the selected contaminant.

Users can narrow their searches by filtering results. The results are filtered by selecting items from the four lists (Figure 7). For example, if a user wanted to show only results for field studies, case studies, and greenhouse studies that were successful, then the user would select those values from the respective list as shown in Figure 7. Holding the control key selects multiple items; unselect items by clicking them. Leave all items unselected to search for all results (no-filter). The filter applies to the Abbreviated, Standard, and Full Reports but does not affect the Case Study Details Report. If no records

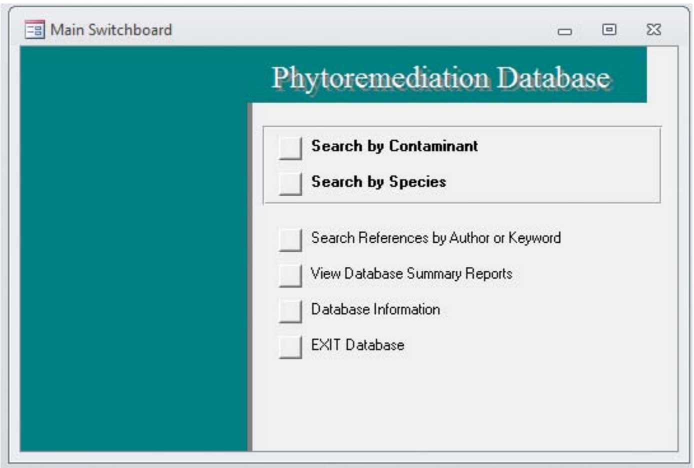

Figure 4. *Main menu and options available upon opening the Phytoremediation Database.*

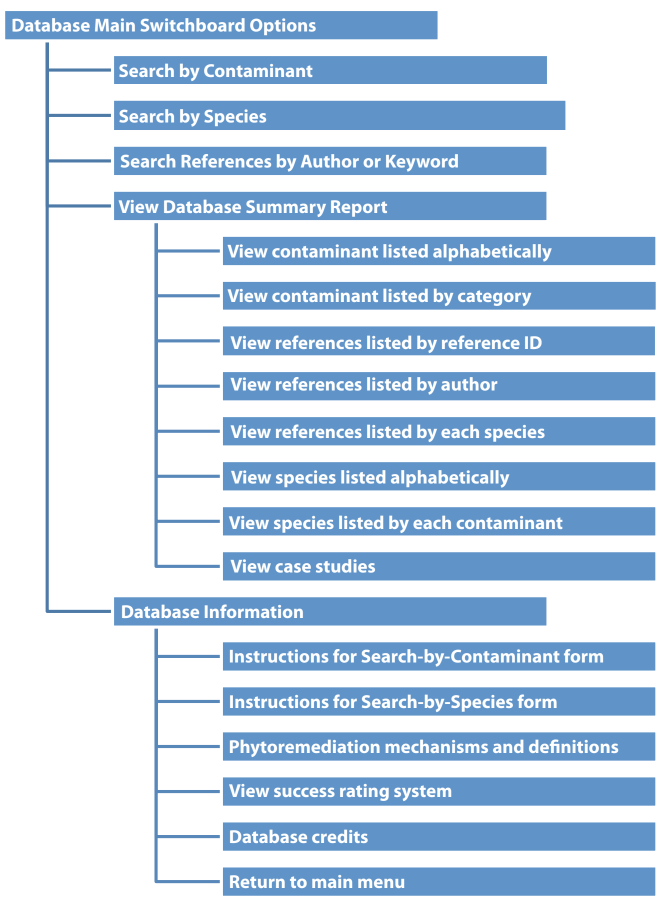

Figure 5. *Hierarchal listing of menu choices in the Phytoremediation Database.*

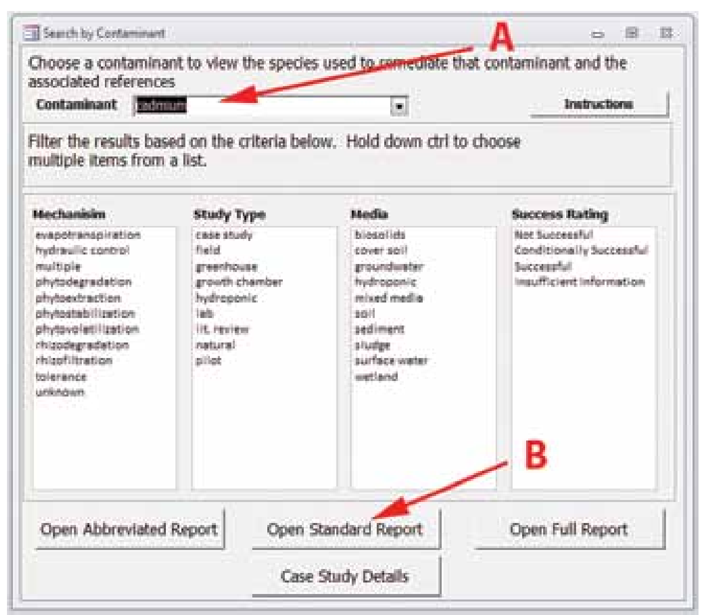

Figure 6. *Primary search form for displaying plant species capable of remediating a given contaminant listed in the Phytoremediation Database. A contaminant of interest is selected from the drop-down box (A) and the reports are opened with the buttons (B).*

Figure 7. *Example of how to filter search results based on study type and success rating. Results can also be filtered based on phytoremediation mechanisms or contaminated media.*

correspond to the filter results, then a message box will be displayed when the report is run.

Search by Species

A search-by-species option was included for users who would like to list all contaminants that have been evaluated for a specific species and the associated references. The search-by-species form is similar to the search-by-contaminant form, except the drop-down box lists all the species contained in the database. The form has the same filtering and report options described for the search-by-contaminant form.

Other Options

The other menu items allow users to perform keyword searches on the titles and authors of references contained in the database and view summary reports for the database and general information about database creation, definitions, and instructions (Figure 5).

Database distribution

The database is distributed as a Microsoft Access 2002 database file, which can be downloaded from the Kansas State University Department of Agronomy website (*www.agronomy.ksu.edu/extension/phytoremediation*).

Summary

Phytoremediation is a low-cost technology that can remove or reduce the amount of organic and inorganic contaminants from the soil. This technology is well suited for areas with low to moderate levels of contaminants. Ability of plants to produce biomass and uptake, degrade, transform, and/or sequester particular contaminant will determine the length of phytoremediation.

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