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Trends in phytoremediation of radionuclides

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Abstract

Phytoremediation, a novel plant-based remediation technology, is applied to a variety of radionuclide-contaminated sites all over the world. Phytoremediation is defined as the use of green plants to remove pollutants from the environment or to render them harmless. Current status of several subsets of phytoremediation of radionuclides is discussed: (a) phytoextraction, in which high biomass radionuclide-accumulating plants and appropriate soil amendments are used to transport and concentrate radionuclides from the soil into the above-ground shoots, which are harvested with conventional agricultural methods, (b) rhizofiltration, in which plant roots are used to precipitate and concentrate radionuclides from polluted effluents, (c) phytovolatilization, in which plants extract volatile radionuclides from soil and volatilize them from the foliage and (d) phytostabilization, in which plants stabilize radionuclides in soils, thus rendering them harmless. It is shown that phytoremediation is a fast developing field and the phytoremediation of radionuclides might soon become an integral part of the environment management and risk reduction process.

Introduction

The presence of radionuclides in soil and water often jeopardizes ecosystem stability and poses a serious risk to human health. As the result of Chernobyl accident, in Ukraine alone, over 260 000 km^2 have received more than 1 Ci km^{-2} of contamination with ^{137}Cs, the level of radiation that corresponds to an additional lifetime dose of 4.3 mSv and relates to a 0.1% increase in the risk of fatal cancer. Radioactive contamination is also caused by nuclear explosion and accidental spills and emissions from all nuclear fuel cycle operations, and most notably mining and milling. Selection of appropriate technology for the remediation of soil and aqueous streams contaminated with radionuclides is based on the environmental chemistry of each element, character of deposition and the rate of radioactive decay. Removal of the top soil layer, or soil excavation and transfer to designated repositories remains the most common and often the most effective method of treating contaminated soil. A variety of physico-chemical methods for treatment of radionuclide contamination includes soil washing, ion exchange, leaching with chelating agents, flocculation, and reverse osmosis-ultrafiltration. Recently, there has been a spark of interest in biological methods for radionuclide removal. Microorganisms and cell cultures were used to remove radionuclides from aqueous streams. There is also growing interest in using plants to remove radionuclides from the environment (Entry et al., 1997; Zhu and Shaw, 2000). Phytoremediation, a novel plant-based remediation technology, is being applied to a variety of radionuclide-contaminated sites. Phytoremediation is defined as the use of green plants to remove pollutants from the environment or to render them harmless. Negri and Hinchman (2000) have recently summarized data on the use of the plants for treatment of ^{3}H, U, Pu, ^{137}Cs and ^{90}Sr. Several subsets of phytoremediation of radionuclides are being developed: (a) phytoextraction, in which high biomass radionuclide-accumulating plants and appropriate soil amendments are used to transport and concentrate radionuclides from the soil into the above-ground shoots, which are

harvested with conventional agricultural methods, (b) rhizofiltration, in which plant roots are used to precipitate and concentrate radionuclides from polluted effluents, (c) phytovolatilization, in which plants extract volatile radionuclides (e.g., ^{3}H) from soil and volatilize them from the foliage and (d) phytostabilization, in which plants stabilize radionuclides in soils, thus rendering them harmless.

Phytoextraction

Conventional methods of radionuclide-contaminated soil remediation are often environmentally destructive and may be prohibitively expensive when a large area of land or water volume is involved. There is a great need for environmentally sound affordable technologies to remediate radionuclide-contaminated soils. Phytoextraction removes radionuclides from soil without destroying the soil structure and with a limited impact on soil fertility. The phytoextraction technology is also particularly appealing for treatment of large areas of low-level contamination.

Phytoextraction exploits vascular plants' natural ability to take up a variety of chemical elements through the root system, deliver these elements to the vascular tissue, and transport and compartmentalize radioactive elements in the aboveground biomass. Above-ground biomass loaded with radionuclides is harvested, processed for volume reduction and further radionuclide concentration, and disposed of as radioactive waste. Successful phytoextraction of radionuclides depends on the bioavailability of radionuclides in soil, on the rate of uptake by plant roots and efficiency of radionuclide transport through the vascular system. The efficiency of phytoextraction is often evaluated by the bioaccumulation coefficient (BC) (ratio of particular radionuclide concentration in plant shoots to the radionuclide concentration in soil, also known as a transfer coefficient, soil–plant transfer factor, concentration ration) and/or total radionuclide removal per m^2 (calculated as plant biomass multiplied by radionuclide concentration). For practical purposes, total radionuclide removal per given area is the key figure, hence, the most suited phytoremediation crop must have high biomass production along with a high BC.

Elements of the phytoextraction process, notably radionuclide plant uptake, were applied to ^{90}Sr, ^{95}Nb, ^{99}Tc,^{106}Ru, ^{144}Ce, $^{226,228}Ra$, $^{239,240}Pu$, ^{241}Am, $^{228,230,232}Th$, ^{244}Cm, ^{237}Np (Adriano et al., 1980; Cline and Rickard, 1972; Ebbs et al., 1998; Echevarria et al., 1997; Garten and Lomax, 1989; Garten and Tucker, 1986; Garten et al., 1986; Grodzinsky et al., 1991; Hoffman et al., 1982; Kabata-Pendias and Pendias, 1996; Mortvedt, 1994; Nisbet and Shaw, 1994; Schreckhise and Cline, 1980; Sheppard et al., 1989; Vandecastelle et al., 1986). However, only phytoextraction of ^{137}Cs, ^{90}Sr, and $^{235,238}U$ is approaching field deployment (Dushenkov et al., 1999; Huang et al., 1998), being an element specific and site-specific technology. Nevertheless it is possible to formulate a general approach to developing a phytoextraction process for radionuclides, even though numerous challenges must be overcome to insure a substantial flux of radionuclide from soil to aboveground biomass.

Radiostrontium is one of a few mobile radionuclides in soil and readily available for uptake by plant roots. Usually only a tiny portion of a radionuclide is mobile in soil. Coprecipitation with oxides and adsorbtion to clay minerals are believed to be the major factors reducing radionuclides bioavailability. Radionuclide speciation along with formation of complexes like in the case of U (Ebbs et al., 1998; Echevarria et al., 2001) and reduction to species with high affinity to organic matter in the case of Tc may play a crucial role in determining radionuclide mobility in soil (Echevarria et al., 1997). Bioavailability of radionuclides differs dramatically depending on soil characteristics (Fesenko et al., 1997; Krouglov et al., 1997; Rigol et al., 1999; Roca et al., 1997) and properties of a specific element. It was found that ^{137}Cs transfer might correlate with soil contamination by heavy metal deposition from smelter (Bunzl et al., 1999). Type of radionuclide deposition (Fesenko et al., 1997) and aging (Krouglov et al., 1997; Sanzharova et al., 1997) has a significant impact on radionuclide bioavailability. It was demonstrated that ^{137}Cs accumulation by plants is determined by the content of exchangeable and mobile forms of radionuclide in the soil (Fesenko et al., 1997). In Chernobyl fallouts, for example, ^{137}Cs associated with coarse and fine dispersed fragments of irradiated fuel having a mixed uranium oxide core (fuel type of deposition) was initially less mobile in soil compared to a aerosol consisting of a core, covered by recondensed cesium (condensed type of fallout) (Dushenkov et al., 1999). It was found that the ^{137}Cs rhizospheric mobilization was strongly correlated with the sodium tetraphenylboron-extractable ^{137}Cs, supporting that K depletion in the rhizosphere might be a principal driving force in ^{137}Cs uptake. The ^{137}Cs BC was strongly negatively correlated to the radiocesium interception potential (RIP) a common Cs

binding characteristic in soil directly related to the soil vermiculite content (Delvaux et al., 2000).

A variety of factors that may help to bring radionuclides into the soil solution and make it more available for plant uptake include manipulating soil pH (Ebbs et al., 1998; Echevarria et al., 2001; Elless et al., 1997; Guibal et al., 1992; Langmuir, 1978), adding chelators (Huang et al., 1998), amending soil with chemicals stimulating radionuclide desorption (Dushenkov et al., 1999; Grodzinsky et al., 1997; Lasat et al., 1998), interaction with microorganisms (Entry et al., 1999) and plant exudates. For example, in hydroponic experiments it was shown that shoots to roots ratio of ^{137}Cs was significantly higher in mycorrhizal plants of *Calluna vulgaris* L. (heather) compared to non-mycorrhizal plants (Clint and Dighton, 1992). In greenhouse experiments, shoots U concentration in plants grown in a U-contaminated soil increased to more than 5000 mg kg^{-1} in citric acid-treated soil compared to 5 mg kg^{-1} in control pots (Huang et al., 1998).

It is generally agreed that K^+, NH^{4+}, Rb^+, and Cs^+ form a homologous series of ions with considerable physico-chemical similarity. It was found that the addition of monovalent cations similar to Cs^+ physico-chemical properties resulted in the most significant levels of ^{137}Cs desorption from soil (Dushenkov et al., 1999; Grodzinsky et al., 1997; Lasat et al., 1997). However, excessive addition of monovalent cations resulted in strong ion competition for plant uptake and did not necessarily lead to high levels of ^{137}Cs accumulation in plants (Lasat et al., 1998). It was shown that the addition of potassium fertilizers decreased Cs uptake by vegetable crop (Seel et al., 1995). Strontium is known to be an analogue of Ca in living organisms (Kabata-Pendias and Pendias, 1996). Concentration of these elements in plants grown in the same soil was found to be positively linearly correlated to extractable Ca in soil (Veresoglou et al., 1996).

The radionuclide uptake by plant roots did not necessary result in translocation to shoots. The majority of ^{137}Cs taken by plants tends to be tied into roots (Clint and Dighton, 1992). Only about 25% of ^{137}Cs taken up by a plant is usually translocated to shoots. Ebbs et al. (1998) demonstrated in hydroponic U uptake studies that at pH 5, the uranyl (UO_2^{2+}) cation was more readily taken up and translocated by plants, than hydroxyl (pH 6) and carbonate (pH 8) U complexes. Respectively, at pH $>$ 5 only a small fraction of U presented in plants was found in shoots. Formation of stable U-phosphate complexes in roots may prevent U translocation to aboveground plant parts. In contrast to Cs and U, almost 80% of ^{90}Sr is usually located in the shoots.

Plants differ dramatically in their ability to accumulate radionuclides. For example, the ability of plant species to accumulate ^{137}Cs in the aboveground parts may differ by an order of magnitude (Grodzinsky et al., 1991). The difference in ^{137}Cs accumulation varied from 2- to 4-fold within cereals and reached 27-fold for all field crops (Sanzharova et al., 1997). Significant variation in radiocesium accumulation was observed in the cultivars of the same species. We found *Amaranthus* species *A. cruentus* L., *A. retroflexus* L., and *A. caudatus* L. were able to concentrate ^{137}Cs in the above-ground parts (Dushenkov et al., 1999). Lasat et al. (1998) reported a BC of $>$ 2 for *A. retroflexus* grown on a ^{137}Cs-contaminated soil at Brookhaven National Laboratory, USA. This data compared favorably to the BC of $<$1 for Indian mustard (*Brassica juncea* (L.) Czern.) and tepary bean (*Phaseolus acutifolius* A. Gray) at the same plot (Lasat et al., 1998). Uranium accumulation in shoots also depends on the species (Ebbs et al., 1998). Difference in U concentrations in tested plant species was even more pronounced when soil was amended with citric acid (20 mmol kg^{-1}) (Huang et al., 1998). Uranium concentration in *Brassica chinensis* L. and *Brassica juncea* was at least 100-fold higher compared with corn. Accumulation of radionuclides by plant not only heavily depends on soil and growing conditions, it is also positively correlated with radionuclide concentration in the underlining soil (Dushenkov et al., 1999; Lasat et al., 1998). This makes it difficult to normalize and compare plant species screening results obtained by many scientists in different environmental conditions.

Among other factors that may significantly influence the efficacy of phytoextraction, it is important to notice previous year's crop, type of mechanical soil amendment, irrigation, all of which may significantly influence biomass production and radionuclide uptake and translocation to aboveground biomass. Kutlakhmedov et al. (1998) demonstrated that in the Chernobyl Exclusion zone corn grown in the previous year was associated with a 10-fold increase in radiocesium removal by corn. Other crops preceding the phytoremediation crop in crop rotation cycle had similar but less pronounced effect. Hence, by designing a crop rotation it is possible to maximize ^{137}Cs removal from soil.

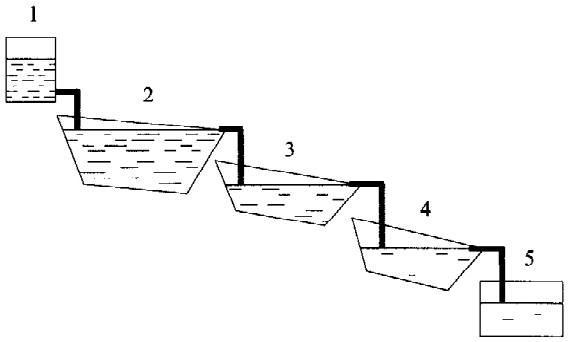

Figure 1. Diagram of the connected pond system with slow water flow. (1) Reservoir; (2) first pond, 23 m^3; (3) second pond, 14 m^3; (4) third pond, 14 m^3; (5) collecting pond. Reconstruction of 1963 drawing (Timofeeva-Ressovskaia, 1963).

A pilot scale phytoextraction project was conducted in the Chernobyl Exclusion Zone (Dushenkov et al., 1999). Three sequential Indian mustard crops were used to achieve noticeable decrease in ^{137}Cs activity that was reduced from an average of 2558 Bq kg^{-1} to an average of 2239 Bq kg^{-1}. In one growing season, areas having ^{137}Cs levels >3000 Bq kg^{-1} decreased from 29.4% of the total plot area before treatment to 7.7% after treatment. After the final harvest of the phytoremediation crop, areas having ^{137}Cs levels <2000 Bq kg^{-1} increased to 33.3% compared to 27.4% before treatment.

The demonstrated efficacy of ^{137}Cs phytoremediation is quite limited; nevertheless, it is sufficient for phytoremediation to play an important role in the Risk-Based Corrective Action Program at ANL-West site in Idaho (Negri and Hinchman, 2000). It was estimated that phytoremediation of a ^{137}Cs-contaminated plot will return land to general use 30 years earlier than without any action (Scott Lee, oral communication).

The Idaho National Engineering and Environmental Laboratory web site (INEEL Facilities ANL-West — Current status, Remediation Designation: WAG 9 reports: http://www.inel.gov/facilities/anl-w-status.shtml) reported that *Kochia scoparia* plants were again grown in a half-acre area of soil contaminated with ^{137}Cs. The cesium-extracting plants were harvested and analyzed late in 2000. As with the first year's results, the analysis of the plant matter showed that the 6-year remediation plan for the contaminated soil sites is still on track. The harvested plant matter was packaged and treated and disposed of at an off-site disposal facility. DOE, the State of Idaho, and the EPA are reviewing the data from the field studies.

Rhizofiltration

Rhizofiltration, use of plant roots to precipitate and concentrate toxic metals from polluted effluents, originated from an approach of employing hydrophytes to contain environmental contamination. In this respect it initially bordered with phytostabilization and constructed wetland technologies. First attempt to use water plants to stop radionuclide dissemination can be traced to the work initiated in early 1950s by Timofeeva-Ressovskaia et al. (1962) in Russia. A study of radionuclide distribution in a freshwater pond ecosystem showed that the majority of radionuclides were adsorbed by the sludge and water plants. It was found that water plants accumulate significant amounts of radionuclides with BC reaching ^{90}Sr (1910) and ^{137}Cs (1230) for *Cladophora glomerata* (L.) Kütz., and ^{90}Sr (805) and ^{137}Cs (285) for *Elodea canadensis* Michx. These results led to an idea of using a sequence of ponds with a slow water flow to clean water contaminated with radionuclides. A diagram of the pond system for radionuclide remediation is shown in Fig. 1. To the best of our knowledge, this was the first pilot scale system for cleaning radionuclide-contaminated water. This system was tested for removal of depleted uranium. Water supplemented with depleted U at a concentration approximately 10^{-5} Ci l^{-1} was poured into the first pond at the rate of 1000 l day^{-1}. A total of 1.04 Ci of radioactivity was released into the system. Samples of water, sludge and plants were taken regularly from all parts of the system to calculate complete mass balance of radioactivity. Out of all radiation administered to the system, 97.2% were retained by the first pond. Out of that 94.9% were absorbed by sludge and water plants and 2.3% remained in water. The percent of total radioactivity that escaped the second and third pond were 1.8 and 0.7%, respectively. Thus, the three-pond system with a flow rate of 1000 l day^{-1}, removed 99.3% of the radioactivity. A similar approach was used to study removal of ^{90}Sr and ^{137}Cs from water. Radioactive water was streamed through the sequence of 10 reservoirs with the imitation of pond sludge and vegetation. Radiocesium was not found in exiting water and only 1.5–2.0% of ^{90}Sr exited the system.

Since those pioneering experiments, excessive data has been collected on the distribution of radionuclides in ponds, lakes and wetlands (Akber et al., 1992; Cowart and Burnett, 1994; Gambrell, 1994). This data may be used for modeling radionuclide distribution and constructing wetlands for retaining radionuclides.

Recently, a more aggressive engineering approach was developed for removing contaminants from aqueous streams by terrestrial plant roots (Dushenkov et al., 1995) or seedlings (Salt et al., 1997). In controlled greenhouse experiments, Cs, Sr, and U were successfully removed from contaminated water. A different removal kinetic was observed for these elements (Dushenkov et al., 1997b). The plants were most effective in removing U from water. In greenhouse experiments sunflower (*Helianthus annuus* L.) proved to be more effective than beans or Indian mustard by removing greater than 95% of U from contaminated water in 24 h. In pilot rhizofiltration system sunflower plants accumulated more than 1% of U in roots (Dushenkov et al., 1997b).

In the set of experiments in conducted in the Chernobyl Exclusion Zone, Ukraine, the ability of terrestrial plants to treat surface water contaminated with ^{137}Cs and ^{90}Sr was evaluated. Radionuclide concentrations in a natural pond located 1 km west of the Chernobyl Nuclear power plant were close to 80 Bq l^{-1} for ^{137}Cs and 1200 Bq l^{-1} for ^{90}Sr at the beginning of the experiment. Plants were transplanted or grown directly on 1×1-m rafts constructed with Styrofoam^{TM}. Plant nutrients were supplied as Hydrosol^{TM} solution applied to a layer of Perlite on the surface of the raft. A 0.5-m^2 cavity in the center of the raft permitted plant roots to extend into the pond water. The highest BC calculated as a ratio of radionuclide content in plant tissue to the concentration in water for ^{137}Cs and ^{90}Sr were measured in sunflower roots (Dushenkov et al., 1997a; Sorochinsky et al., 1998). Sunflower roots accumulated up to eight times more ^{137}Cs than the roots of timothy (*Phleum pratense* L.) or foxtail (*Alopecurus pratensis* L.). In addition, the sunflower shoots contained 2.5×10^6 Bq of ^{90}Sr per kg^{-1} dry weight. The BC measured for sunflower plants in these experiments demonstrated that all of the radioactivity in this 75-m^2 surface area pond, estimated at 9.2×10^6 Bq of ^{137}Cs and 1.4×10^8 Bq of ^{90}Sr, could be concentrated into 55 kg dry weight of sunflower plants. The plants could then be stabilized, ashed, or vitrified and the resulting radioactive waste stored in a disposal facility.

Rhizofiltration was successfully used to remove excessive U from water at a former U-processing facility in Ashtabula, OH (Dushenkov et al., 1997b). For several months a pilot rhizofiltration system effectively removed U from contaminated water (Fig. 2). The sunflower roots used in the system proved to be effective in removing up to 95% U from water in 24 h. The U concentration exceeded 1% in dried sunflower roots. In greenhouse experiments, BC based on the ratios of U concentrations in the roots versus U concentrations in the aqueous phase reached 30 000.

Rhizofiltration proved to be a feasible approach in removing radionuclides from aqueous streams. Nevertheless, it requires optimization and economic evaluation against conventional technologies.

Phytostabilization

Phytostabilization is particularly appropriate for radionuclide-contaminated sites, where one of the alternatives is to hold contaminants in place to prevent secondary contamination and exposure. Capturing radionuclides *in situ* is often the best alternative at sites with low contamination levels or vast contaminated areas where a large-scale removal action or other *in situ* remediation is not feasible. This can result in a considerable risk reduction, especially if radionuclides with relatively short half-lives are involved. Establishment of rooted vegetation prevents windblown dust, a major pathway for human exposure at radionuclide-contaminated sites. A dense root system stabilizes the soil and prevents erosion (Berti and Cunningham, 2000). Plant roots also help to minimize water percolation through soil, hence reducing radionuclides leaching. Deployment of plant species capable of further rendering radionuclides immobile doubles the benefits of the sites revegetation. Phytostabilization may be especially useful in controlling tailings from strip and open pit uranium mines. Overcoming U toxicity to plants and increasing fertility of tailing material are often the major challenge.

Ability of plant to transpire high water volumes is widely used for hydraulic control, which prevents migration of leachate towards groundwater or receiving waters. Fast growing deep-rooted green plants have gained popularity in their use for hydraulic control and radionuclides stabilization in soil. This approach may be effective in confining areas leaking radioactive materials.

It is important to keep in mind that while phytostabilization of radionuclides may considerably reduce the environmental and human health risk it does not remove the source of radioactivity from the site. Thus, the potential risk of radiation exposure to wildlife and humans remains. It must be taken into account when decision on the best remediation approach is made.

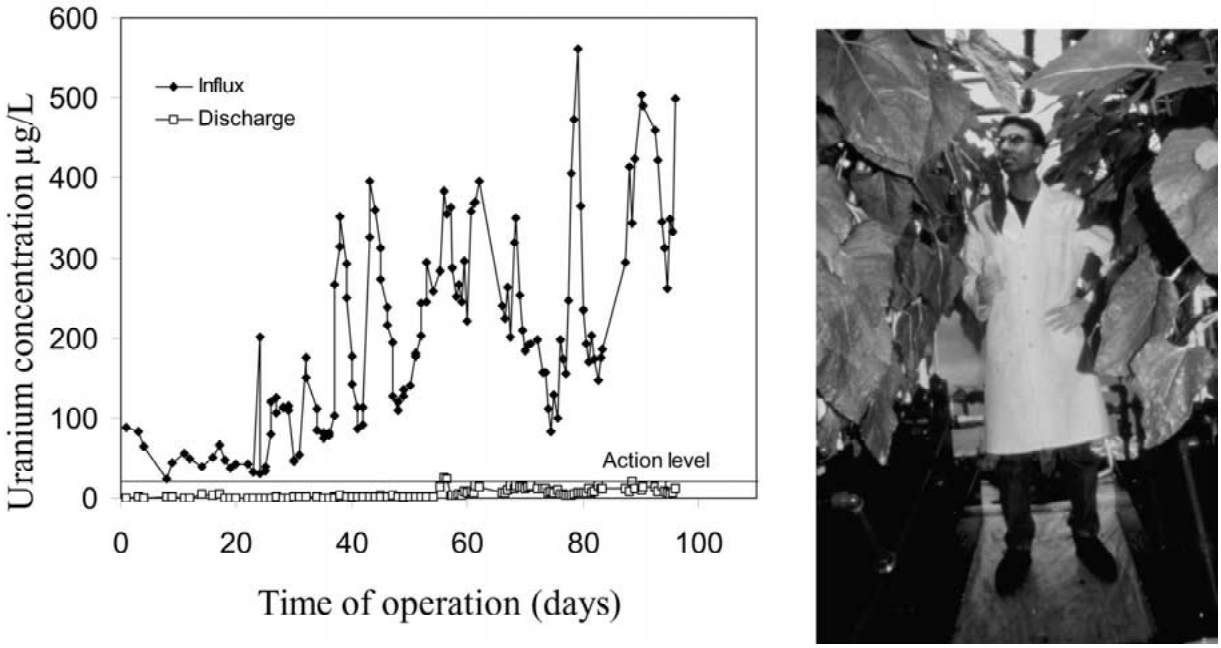

Figure 2. Pilot rhizofiltration system performance at the Ashtabula, OH, site. The pilot rhizofiltration system was assembled in the greenhouse using hydroponically grown sunflower plants. Plants were periodically harvested and replaced with fresh plants from the nursery. A surge tank was used for the pretreatment of the source water. The water temperature was maintained at 24 °C, and the pH was automatically adjusted to 5.

Phytovolatilization

Phytovolatilization of radionuclides exploits a plant's ability to transpire enormous amounts of water and is currently used for ^{3}H remediation. Tritium (^{3}H), a radioactive isotope of hydrogen, decays to a stable helium with a half-life of about 12 years. It shares physical and chemical properties of hydrogen. Tritium is found in the environment typically as tritiated water that integrated into the biogeochemical water cycle. As a weak β emitter, ^{3}H is easily shielded by air and skin and produces almost no external radiation exposure; however, its incorporation in water and organic compounds presents a health hazard when absorbed into the body.

Tritium releases by the Brookhaven National Laboratory (BNL), Savannah River Site (SRS) and other nuclear facilities has led to a raise in interest in remediation techniques for removal of tritiated water from surface and ground aqueous streams. The analysis of conventional technologies for tritiated water decontamination or isolation suggests that the cost is generally greater than considered practical for treatment (Fulbright et al., 1996). It was suggested that the most cost-effective approach for the minimization of ^{3}H risk is neither removal of ^{3}H from the effluent nor a typical isolation of the water, but rather a change in the path of ^{3}H exposure to the public. Calculations based on many years of experience at the Savannah River Site indicated that a 40% reduction in dose can be achieved by releasing tritiated water to the atmosphere, as water vapor, as opposed to allowing it to flow off site in surface water streams (Fulbright et al., 1996).

Tritiated water applied as irrigation to the floor of forests enters the hydrological cycle as it reaches the soil beneath the forest. This water either evaporates from the soil surface, is absorbed into the transpiration stream by plant roots or drains through the soil to the water table. A small portion of ^{3}H that was absorbed by plant roots remains in the plant tissues in the form of largely easily exchangeable hydroxyl ions or is incorporated into organic molecules through photosynthesis. A simple model of ^{3}H uptake in forests irrigated by tritiated water was developed and analyzed (Murphy, 2001). The conditions of the simulation were set to those expected for an actual irrigation scenario at the SRS with the initial ^{3}H concentration of the irrigation water at 11 000 pCi ml^{-1}. In simulations, the ^{3}H concentration of the water source had been observed to decrease at a rate that approximated the decay rate of ^{3}H. The irrigation rate was set at

23 cm year^{-1}. This compares to the annual rainfall of about 120 cm year^{-1}. For this scenario the maximum ^{3}H concentration in the green wood was 1228 pCi g^{-1} occurring during the fifth year after the beginning of the irrigation. Five years after the termination of irrigation, the ^{3}H concentration had dropped to 34 pCi g^{-1}. The maximum and 5-year, post-irrigation ^{3}H inventories for the forest were 696 and 22 mCi km^{2}, respectively (Murphy, 2001). The inventory of ^{3}H in the forest never exceeded 1% of the total ^{3}H supplied through irrigation. At the end of the exposure period, the inventory was less than 0.1% of the ^{3}H applied. The levels of ^{3}H calculated suggest that there is minimum risk to workers harvesting trees 5 years after the irrigation has stopped. Dose estimates for on site workers and the public from handling the harvested trees should be considerably less than 1 mrem.

Phytoremediation of ^{3}H trough irrigation of forest area has been investigated at SRS for consideration as part of a system to reduce the discharge of ^{3}H from the Burial Ground Complex southwest plume, otherwise known as the Mixed Waste Management Facility (MWMF), into Four Mile Branch. The system is a combination of hydraulic control and enhanced evapotranspiration. Tritium contaminated water is collected, moved to a location upgradient of the discharge point, and used to irrigate plants.

A phytoremediation system of high-transpiring, deep-rooted phretophytes was deployed at the 317/319 area at Argonne with the objectives to minimize water infiltration into the source soil, stabilize the tread soil surface to prevent erosion, runoff, and downstream sedimentation; hydraulically contain ^{3}H and VOCs migration to the groundwater, and continued remediation of the residual VOCs in the plume (Negri et al., 2000). The phytoremediation system was installed with savings of 33% compared to expected cost of the conventional pump-and-treat approach combined with asphalt capping. The plant-based system has a low operating and maintenance cost, providing an additional 40% savings over the lifetime of the deployment. In addition, the phytoremediation approach is attractive because of the reduction in risk of spills and workers' exposure, avoidance of secondary waste and related treatment. At the same time plant roots penetrate both pore spaces and the less permeable soil zones, providing more effective remediation. The presence of vegetation was also considered an optimal fit with the planned future land use. The phytoremediation system will provide full hydraulic control by the year 2003 and be self sustaining for the full-expected life of the engineered plantation. Parameters of the phytoremediation installation performance, including ^{3}H concentration in air, are being closely monitored (Negri and Hinchman, 2000).

Conclusion

Phytoremediation is a fast developing field. For the last 5 years over 20 projects that include at least some of the field applications of phytoremediation of radionuclides were initiated in USA, Belarus, Ukraine, United Kingdom, Yugoslavia, China and the Czech Republic. Even though there is still a lot of development of the phytoremediation technology to be done, it is clear that in the near future phytoremediation of radionuclides will become an integral part of the environment management and risk reduction process.

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