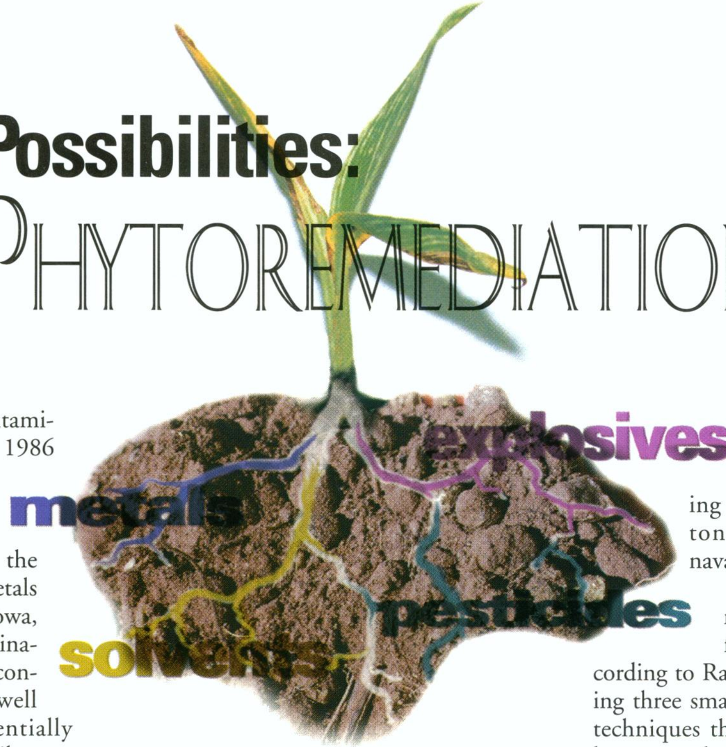
Absorbing Possibilities: PHYTOREMEDIATION



Joseph Tart

Confronted with the task of decontaminating soil made radioactive by the 1986 Chernobyl nuclear accident, American and Ukrainian scientists are field testing the ability of Indian mustard plants to clean the soil in the region by absorbing radioactive metals such as cesium and strontium. In Iowa, where soil and groundwater contamination by the pesticide atrazine is a concern, researchers are testing how well poplar trees can remove the potentially cancer-causing chemical from the soil.

These are examples of phytoremediation—an approach to cleaning up contamination that is attracting increasing attention from scientists and regulators because it appears to be cheaper than chemical and engineering-oriented methods and may also offer immediate and long-term environmental benefits.

New Name, Old Idea

Ilya Raskin, a professor of plant biology at Rutgers University in New Jersey, defines phytoremediation, as "the use of plants for environmental remediation. That involves removing organics and metals from soils and water." Raskin, a biochemist and plant physiologist who coined the term, notes that using plants to alter the environment "has been around forever, since the time plants were used to drain swamps."

What is new, he asserts, is the systematic, scientific investigation of how plants can be used to decontaminate soil and water. Interest in phytoremediation has been growing as the United States continues to face the daunting task of cleaning up a wide range of sites contaminated with toxic heavy metals such as selenium and cadmium, as well as organic compounds including pesticides, explosives, and solvents.

Scientists have found that many plants naturally absorb metals from the ground and store them in their tissues. Plants, like animals, need metals such as zinc and copper for growth. In many instances, according to Raskin, plants can't distinguish between heavy metals such as cadmium and those that are needed nutrients. Among the metal-absorbing plants is *Streptanthus polygaloides*, which grows in California on nickel-contaminated soil and accumulates large amounts of the metal. Members of the genus *Thlaspi* also take up large amounts of heavy metals. These plants are called hyperaccumulators—their tissues an contain from 1,000 to 10,000 parts per million (ppm) of certain heavy metals.

Organic compounds can be degraded by enzymes expressed in the plant membranes of poplar trees. These plants may also stimulate the growth of chemical-degrading bacteria around their roots.

Pluses

The potential benefits of phytoremediation seem to be as numerous as the problems it might address. One reason phytoremediation is gaining attention is because it is potentially cheaper than conventional treatment approaches such as incineration and soil washing, a chemically based, energy intensive approach.

Burt Ensley, president of Phytotech, a firm in Monmouth Junction, New Jersey, seeking to turn phytoremediation into a money maker, says washing metal-contaminated soil can cost about $250 per cubic yard. One EPA project that cleaned up 19,000 tons of contaminated soil cost over $7 million, approximately $400 per ton (one ton is roughly equivalent to one cubic meter). Incineration costs range from $400 to $1200 per ton (for explosives). And an incineration project to clean up explosives-contaminated soil at the Department of Energy's Idaho National Engineering Laboratory cost $4,000 per ton to clean hot spots at the naval proving ground.

That compares with estimates of $80 per cubic yard for phytoremediation, according to Rashalee Levine, who is managing three small field studies exploring new techniques that may be used to clean up heavy metal and radioactive contamination at the DOE weapons facilities and labs.

Phytoremediation is also being explored because it may increase the slow pace of hazardous waste cleanup. "In 1995, few hazardous was sites have been cleaned-up . . . because of the impracticality or cost of engineering solutions," Rufus Chaney, a scientist at the USDA's Environmental Chemistry Laboratory told phytoremediation researchers at a conference at the University of Missouri this spring. Although some types of phytoremediation may take longer than conventional methods at a site, more sites may be cleaned up simultaneously because the cost for each one is less.

Still another attraction of this technology is that it may leave topsoil in usable condition and reduce the amount of contaminated material to be landfilled or incinerated, distinct advantages over the chemical and engineering technologies used now to treat contaminated soil, according to Leon Kochian, a USDA scientist and professor of plant biology at Cornell University. For example, phytoremediation of toxic heavy metals actually reduces the volume of contaminated material. According to Ensley, removing heavy metal-contaminated soil from two and a half acres to a depth of about 18 inches creates about 5,000 tons of soil that must be disposed of in a hazardous landfill. In contrast, plants that take up the metal and are burned leave a residue of between 25 and 30 tons of ash to be disposed of. "It's an immense reduction of mass and volume," Ensley says.

Phytoremediation may also have direct health benefits. "This technique seems particularly attractive for the cleanup of lead in soils," says Robert Tucker, director of the Eco Policy Center at Rutgers University. "Actually having [ground] cover on property is a way to decrease exposure risk. Kids may not play in an area where there is plant growth. And the presence of plants also limits the direct hand-to-mouth exchange of dirt in children." Tucker, who is the former head of the division of research in the New Jersey Department of Environmental Protection, cites a number of small phytoremediation demonstration projects in the state, including one where plants are being used to remove lead from lagoon sediments near a facility where lead tetraethyl was made for leaded gasoline.

Minuses

Phytoremediation also has its drawbacks, which even its ardent champions are quick to acknowledge. For one thing, it is a time-consuming process that can take several growing seasons to clean a site. "Suppose there's a site that's contaminated with heavy metals that's just been bought by a real estate developer and he wants to build a K-Mart on it," says Ensley. "This technology is probably going to be a problem for him, because he doesn't want to sit on that property for two or three years while it gets cleaned up. He's going to want it cleaned up now."

Vegetation that absorbs toxic heavy metals may also pose a risk to wildlife that eat the plants, Ensley acknowledges. The possible scenario is that these harmful metals can work their way up the food chain. For instance, moles or voles that eat metal-contaminated plants are eaten by predators, which then become victims of metal intoxication. To address this problem, Ensley says, "All we can do is when we're doing the field trials of phytoremediation, make sure that's one of the things we measure . . . One of the things we'll have to do is trap insects off the plants and analyze them, and trap moles and voles and analyze them."

While Ensley suggests that insecticides might be used to prevent insects from eating heavy metal-containing plants, he says that such plants aren't appetizing to insects in the first place. "We've discovered that some insects that you would normally expect to eat these plants, when they have metals in them, won't eat them. That hasn't been published, but we have seen that," he says.

But Robert Boyd, associate professor of botany and microbiology at Auburn University, worries that insects might adapt to eating such plants. "I would predict these phytoremediation crops would be subject to pests as they become adapted to these plants," he says. That might lead to heavy metals working their way through the food chain. Boyd says that this whole issue remains to be explored. "There is a knowledge void."

Ensley emphasizes that there's more to phytoremediation than merely putting plants in the ground and letting them do the work. He says that cleanup areas have to be engineered to prevent flooding and erosion. And phytoremediation isn't necessarily chemical free. Researchers talk of needing chelating agents that will free metals and other contaminants from soil particles to allow them to be taken up by the plants. Researchers also need to find the depth to which plants can sink their roots to clean up contamination.

Finding the Right Plants

In spite of these concerns, phytoremediation research is widespread. Scientists at numerous laboratories are exploring the power of plants to cope with contamination, both of metals and of toxic organics.

Thlaspi, like other hyperacculumulators, isn't very good at phytoremediation, says Ensley. These plants are too small and grow too slowly. As a result of screening various plants, Ensley has found that *Brassica*, the genus to which broccoli and Indian mustard belong, do a much better job. Because they grow faster and have more tissue, they can take more metal out of the soil. In the Ukraine, Ensley, Raskin, and their Ukrainian colleagues are studying dozens of varieties of Indian mustard and related plants to see how good they are at removing radioactivity.

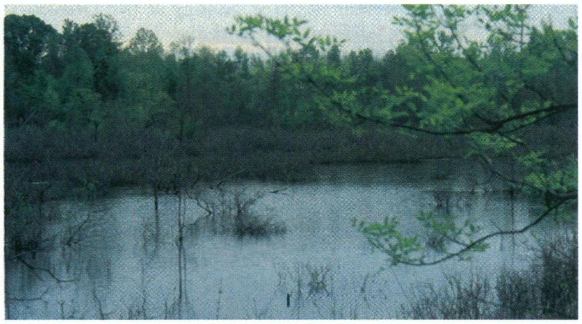
In the United States, Norman Terry, professor of plant biology at the University of California at Berkeley is exploring the possibility of using Indian mustard to remove naturally occurring selenium from soil. A necessary nutrient, selenium can leach into water. In high amounts, this metal can poison wildlife and livestock. In laboratory research, Terry has found that Indian mustard not only takes up selenium but converts it into dimethyl selenide, a gas which he describes as relatively nontoxic. "We're trying to genetically alter plants so that we step up the volatilization, so that much of the selenium removed by the plant from the soil goes straight into the atmosphere," he says. According to Terry, there are huge amounts of this gas in the atmosphere from volcanoes, soil, and plants, and it is continually recycled. The amount that would be added via phytoremediation would be negligible, he insists. Terry has not yet tested the genetically engineered plants in the field.

Raskin is also creating transgenic plants to improve their ability to take up metals from soil. He has added the gene for the protein metallothionein, which binds metals, to several plants that have yet to be field tested. Raskin has found that even though Indian mustard is a terrestrial plant, it can remove heavy metals from water.

The DOE began field tests this year on plots that are several hundred square feet to see how well plants take up cadmium, zinc, and radioactive cesium and strontium. Plants including Indian mustard, rape, and turnip—all varieties of *Brassica*—and grasses are being tested at a contaminated site in Butte, Montana, said Kochian, who helped screen plants in the lab for their ability to take up metals prior to field testing. Alfalfa and beans are being

Steven C. McCutcheon/EPA

Nature's kidneys. Researchers are showing that some plants, such as parrot feather, can absorb metals, solvents, and pesticides from soil and water.



Steven C. McCutcheon

Beaver pond. Eurasian water milfoil growing in a beaver pond absorbs TNT from runoff of contaminated soil.

tested at the Idaho National Engineering Laboratory for their ability to accumulate radioactive cesium and strontium. The uranium-absorbing ability of sunflower plants is being tested at a DOE facility in Ashtabula, Ohio.

While some plants may be able to decontaminate soil by simply absorbing metals, others break down organic compounds, and can also enlist soil bacteria to detoxify these compounds.

In his field research, Jerald Schnoor, professor of civil and environmental engineering at the University of Iowa, has found that poplar trees can break down between 10% and 20% of atrazine in soil. Schnoor found that poplars detoxify atrazine in two ways. They absorb atrazine through their roots and break it down, possibly by the enzymes dehalogenase and laccase, to several harmless compounds, including short-chain metabolites. "That was a surprise to us," says Schnoor. He expected only that the trees would stimulate bacteria living around the trees' roots to attack and degrade atrazine, which they do. Exudates—sugars, alcohols, and volatile acids—are secreted by the trees and "seem to enhance the rate of microbial transformation of atrazine," says Schnoor. In sandy soil, virtually 100% of the atrazine was metabolized.

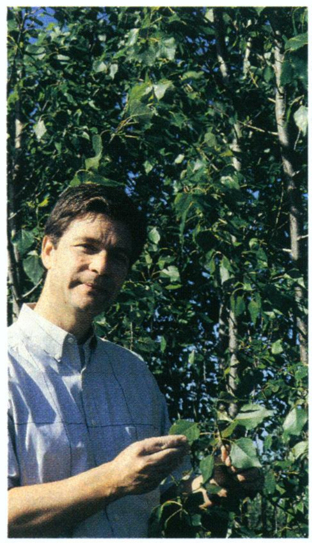
At the University of Washington, Stuart Strand, a professor in the College of Forest Resources, and Milton Gordon, a professor of biochemistry, have found in lab experiments using small poplar trees that monooxygenase enzymes break down trichloroethylene, a suspected carcinogen and groundwater contaminant, to carbon dioxide. Although the majority of TCE is transpired to the atmosphere, the breakdown is still significant as a potential cleanup technique.

Strand says that the plant enzymes appear to be solely responsible for the breakdown, and he finds the same results in tissue culture experiments in the laboratory. The researchers are currently testing poplar trees in the field to see if the lab results are borne out.

EPA researchers are studying plants such as parrot feather weed and Eurasian water milfoil for their ability to break down the explosive TNT, a toxic compound which contaminates both groundwater and soil at U.S. Army ammunition facilities.

These plants, and the variety of poplars studied by Schnoor, contain the enzyme nitroreductase, which can rapidly break down TNT, explains Steven McCutcheon, an environmental engineer with the EPA's Athens, Georgia, laboratory. McCutcheon and his colleague David Young at Auburn University have tested Eurasian milfoil on 2–4 inches of soil from the Alabama Army ammunition plant contaminated with 5,000 ppm of TNT. The soil, which is essentially sterile, was put in small plastic pools, covered with water, and the plants were added. "Within a week the dissolved TNT is near detection; a few days later it's below detection," McCutcheon said. The TNT is broken down and becomes part of the lignin or plant structure. Toxicity analysis is needed, McCutcheon says, to determine if the TNT breakdown products represent a residual risk. However, he said, in experiments, tadpoles and snails have thrived in the pools with the plants, but are unable to live in the control pools that do not contain the plants. In the spring, the EPA and the Army Environmental Center will be field testing these plants on a one-eighth of an acre wetland at an Army ammunition plant in Milan, Tennessee.

McCutcheon's team has compiled some information on the breakdown pathways of chlorinated solvents, as well as identified four plant proteins that degrade organics. The team has also developed an antibody assay that allows them to screen plants for the presence of nitroreductase, thus allowing them to find native plants that can be used in phytoremediation. About 20% of the aquatic plants tested contain the nitroreductase, McCutcheon said.



Jerald Schnoor/U. of Iowa

Poplar conception. Jerald Schnoor has found that poplar trees can break down atrazine in soil.

Future of Phytoremediation

Phytoremediation is still in its early stages. While many scientists, engineers, and regulators are optimistic that it will eventually be used to clean up organic and metallic contaminants, at least two or three years more of field tests and analyses are necessary to validate the initial, small-scale field tests. Issues like soil characteristics and length of the growing season will also have to be taken into account. Scientists must also determine what sites are most amenable to phytoremediation. Other issues such as the potential impact on wildlife remain to be fully explored. Simultaneously, researchers working in the lab are trying to better detail the processes behind phytoremediation to possibly improve it.

While it may offer a number of advantages, it is not, Schnoor cautions, a panacea. Still, the information gathered thus far, says McCutcheon, "establishes that phytoremediation and ecological engineering are powerful approaches that should be fully explored."

Harvey Black

Suggested Reading

Raskin I, Kumar PBAN, Dushenkov S, Salt D. Bioconcentration of heavy metals by plants. Curr Opin Biotechnol 5:285-290 (1994).

Rauser WE. The heavy metal-binding peptides of plants. Annu Rev Plant Physiol Plant Mol Biol 41:553-575 (1990).

Schnoor JL, Licht LA, McCutcheon SC, Wolfe NL, Carreira LH. Phytoremediation of organic and nutrient contaminants. Environ Sci Technol 28:318A-323A (1995).

Terry N, Carlson C, Raab TK, Zayed A. Rates of Se volatilization among crop species. J Environ Qual 21:341-344 (1992).