

Phytoremediation - and other techniques for using life to remediate contaminated sites

Cleaning up these sites is challenging and expensive.

What is Phytoremediation

Phytoremediation is the practice of using living plants to clean soil, air and water contaminated with hazardous substances. Plants can help clean up many types of contaminants including heavy metals, pesticides, explosives, and oil. However, they work best where contaminant levels are low because high concentrations may limit plant growth and take too long to clean up. Plants can also help prevent wind, rain, and groundwater flow from carrying contaminants away from the site to surrounding areas or deeper underground.

At its core principle, phytoremediation focuses on the ability of some plants to uniquely tolerate environmental pollutants.

Defining Contaminated Sites

Types of Contaminants and Where They Come From

Existing Site Remediation Procedures

When it comes to cleaning up contaminated sites, phytoremediation is one of several options, each with its own advantages and disadvantages. Many of these practices are more invasive and expensive, but they're likely not going away, even if phytoremediation continues to improve. For sites which are badly contaminated, or which have multiple co-contaminants in one place, or where the cleanup is urgent to prevent further spread or to protect human communities, the most straightforward solution is going to remain digging out it out and remediating it elsewhere, under controlled conditions.

Physical Methods:

- **Soil excavation and removal:** This involves testing to find the extent of the contamination and digging out all or some of the contaminated soil. This can be really harsh on the site, often involving both clearcut logging and deep excavation. The site crew then brings in fresh fill (possibly after laying down a barrier if they weren't able to remove contaminants under a certain depth for cost reasons), and plant new trees to help the site recover. The end result often isn't as pretty, but it's much safer and will heal with time. This is a common but logistically complex solution, - excavation, transportation, and storage can all pose some health risks and have to be done a certain way, and finding a suitable site for long-term storage of the contaminated soil can be expensive.
 - **Disposal in a regulated landfill** Once the soil has been removed, it may be transported to a per-arranged site. This long term storage will usually involve dumping it into a lined and capped pit. Essentially we seal the dangerous stuff in giant tupperware and leave it there.

- **Soil washing** Alternatively, after the soil is removed, it may instead be transported to a facility where it is mixed with a solvent or surfactant to remove contaminants, which are then separated from the soil. This can be more complex but reduces the amount of 'waste' the project needs to store.
- **Soil thermal treatment:** Similar to soil washing, heat is applied to the soil to volatilize or destroy contaminants.
- **Soil vapor extraction (SVE):** This method is used to remove volatile organic compounds (VOCs) from the soil by drawing them into the atmosphere.
 - This would be useful on newer sites, or ones that have been previously capped in some way blocking volatilisation.
- **Soil flushing:** Water or a chemical solution is injected into the soil to flush out contaminants. This is done when the area is well above the water table.

Chemical Methods:

- **Chemical oxidation:** Oxidizing agents are added to the soil to break down contaminants into less harmful substances.
- **Chemical reduction:** Reducing agents are used to convert contaminants into less harmful forms.
- **In-situ chemical stabilization:** Chemicals are added to the soil to immobilize contaminants and prevent their leaching.

Types of Phytoremediation

Phytoaccumulation/Phytoextraction

In some ways this is one of the more intuitive ways to clean up a site. Why dig out all the contaminated soil, transport it, and clean it, when you can grow plants that will extract the contaminant and then simply remove the plant.

Phytomining

[Phytomining](#), also known as Agromining, is another quite new field, looking to obtain various metals for industrial purposes using plants. It is currently the subject of several research studies and startups, including ones attempting to genetically modify more effective plants, and it seems like its overall viability is still undetermined at this time.

It is included in this list because the harvested hyperaccumulators need to be sent somewhere for containment, and it's possible that any industrial experience gleaned in commercial phytomining work will be useful in separating the contaminants from the plant matter. This would be ideal because reducing the mass of organic matter needing long-term storage will reduce both waste and cost. It may even be able to turn a waste product into a useful input in industry as many heavy metals have manufacturing uses.

Phytovolatilization

Some plants take up contaminants from the soil and release them into the atmosphere - this is known

as [Phytovolatilization](#). This can be a good thing, such as [when the contaminant is something like Dioxane which can be photodegraded and has a half-life measured in hours to days when exposed to sunlight](#) but it can also be a problem, like [when the contaminant is a heavy metal](#). Aerosolized mercury may be enough of a hazard to rule out some phytoremediation candidates. So far it seems like most of the time when I see phytovolatilization mentioned in a phytoremediation paper the authors are treating a low phytovolatilization rate as being a good thing but it definitely varies by contaminant.

Rhizofiltration

Phytostabilization

This title seems to encompass two different processes with similar results. The first is when plants change the soil's physical and chemical properties, making it less suitable for contaminant leaching. The second is when the plants take up contaminants but trap them in their roots to protect themselves. Obviously this would make it challenging to remove the contaminated plant matter from the site as you would with hyperaccumulators, but it does have the effect of stopping the contaminant from spreading or migrating underground.

Phytodegradation/bioremediation

Out of all these options, this is probably the closest fit to “remediation” in “phytoremediation.” [Phytodegradation](#) is a process where plants absorb organic pollutants and break them down into less harmful substances through metabolic processes or by releasing enzymes. It's not possible for every contaminant (for example, most? all? heavy metals) but for organic ones like Dioxins or VOCs, it can be a pretty miraculous. We'll talk more about bioremediation through fungus and bacteria in the next sections, it seems like they may be even better for this work. For example, ligninolytic fungi evolved to digest tree lignin, one of the complex, tough organic polymers used by trees to make strong wood. Lignin is unusually hard to break down, and the chain of tools some of the fungus developed is so powerful it is general purpose, enabling them to break down many organic chemicals (like dioxins).

Hydraulic Control

There are other ways to utilize plants in environmental remediation. One of the big challenges of restoring contaminated land is managing the flow of groundwater below the site - many contaminants are quite stable underground, meaning they'll persist and remain dangerous for a very long time, and they can often spread and migrate with the groundwater flow. This plume can eventually contaminate wells and underground aquifers people rely on for drinking water and emerge from springs into surface water bodies.

Certain plants, such as poplar trees, can be used as natural water pumps, operating so well during their growing season that they can actually [reverse the flow of groundwater](#).

This was used to interesting effect in [this project](#), which used biochar to trap PFAS in groundwater, and used poplar trees to draw groundwater into that 'trap'.

It's important to note that the efficacy of these projects varies by site and it can be hard to tell why

the trees seem serve as an excellent barrier in one case, and have minimal impact in others.

Other Types of Bioremediation

Fungal

Bacterial

The term Bioremediation seems to apply both to the general practice of using living things to clean up contaminated sites, and specifically to using microorganisms to break down contaminants into less harmful substances. In fact, from what I've seen so far, it seems the second use-case is more common. At the very least “bioremediation <contaminant name>” has been a very useful search when I need to find research on cleaning a particular poison using bacteria.

This is an entire massive field of study with some remarkable successes to its credit. It probably deserves its own page at some point, but for now we're going to consolidate it here.

Bioremediation can be done in situ or ex situ. It seems like bioremediation is often used in situations where liquid medium has been contaminated, such as with industrial oil spills or other organic pollutants, or where a contaminant plume is spreading through groundwater.

As with plants, these microorganisms exist in and thrive in complex network of symbiosis we don't fully understand, and their performance in a given cleanup will depend strongly on whether they have the right tools to do their job. Some are provided by other bacteria, others can be provided as chemical inputs, added via the same liquid medium the bacteria is introduced through.

Bacterial bioremediation can also be used in combination with phytoextraction, such as in [this example](#) where poplar trees were used almost like biological pumps to draw in groundwater and transpire it into the atmosphere. The trees had been inoculated with specific strains of symbiotic bacteria, known as endophytes, that would eliminate the TCE the trees absorbed from the soil and would help protect them from the toxin while doing so. The bacteria thrive on eating TCE and similar compounds, consuming the molecule's carbon backbone and exuding chloride ions that end up as a harmless by-product in adjacent soil. The trees were soaked in a solution containing the endophyte bacterial inoculum as bare root cuttings, before being brought onsite and planted.

Finding Phytoremediation Options That Fit Your Story and Setting

Bioremediation/Phytoremediation are very new fields, with tons of ongoing research. Unless you go in with very specific requirements already in mind, you'll likely notice that there's an almost overwhelming number of options and variables to consider - there are hundreds of contaminants of concern, far more species that may work on them, and complex relationships where some species work on some contaminants but will be poisoned by others, or work best when supported by other species. Add to that concerns about accidentally importing invasive species and it can become quite a tangle. This isn't helped by the density of academic research language and the fact that these reports are often short on the sort of details which help when planning/writing depictions of remediation work in the field.

My workflow for finding suitable plants while not going insane

Start with the contaminant of concern. Pick your poison, then look up which plants can be used to remediate, accumulate, or stabilize it.

[Wikipedia's list of known hyperaccumulators](#) can be a start but it may also be incomplete or out of date and it focuses mostly on heavy metals. For each contaminant you can often find [a review paper such as this one](#) which will provide lists of phytoremediation species which have been tested for suitability in other studies.

You don't need to read up on how these plants work yet - some contaminants have dozens or hundreds of suitable plants so you need to narrow it down. First check each one to see if they're native or naturalized in the region where your story is set (or decide if they're an invasive that's already present that might also be tolerated as part of the cleanup). Introducing an invasive or potentially-invasive species is generally a really bad idea, which makes it a hard sell in an environmental justice related story. (If your list is especially short or you really need a particular plant, consider whether its range may have moved with climate change.)

The academic papers will generally use the plants scientific name so just search for that in your search engine of choice with the word 'range' tacked on the end. Wikipedia or a plant database like [Plants of the World Online](#) will generally have a listing complete with a map. If it's listed as 'introduced' in my story's setting, I like to then search "<plant name> invasive" and see if it has a listing in my relevant invasive species databases (in my case <https://www.naisn.org/> and <https://www.invasiveplantatlas.org/>).

Make a shortlist of any relevant plants that seem to be effective in some way, and are native/naturalized in your region, then look more into how they work, and use that to shape the scene/setting in your story. This is a good time to look into specific scientific studies on phytoremediation with that one plant and to try to parse them as best you can.

Some plants are hyperaccumulators, meaning they take up an outsized portion of the poison into their tissues and trap it there. This is great in the short term, but they're not destroying it, just extracting/containing it, so humans will need to remove the plants at some point. For small plants this might mean pulling them up stem and root and bagging them, while for bigger trees it could mean collecting the leaves that fall annually or even cutting them down or pollarding/coppicing them routinely to capture and remove some of the contaminant they've contained. It will depend on the type of plant and how they store the contaminant.

Other plants actually remediate the poison by breaking it down, or by expiating it into the air where it is exposed to sunlight and broken down, or through other biochemical processes. These are more of a set-it-and-forget-it solution.

Still others only stabilize it, holding it in place inside their roots or causing it to bind chemically to other elements and become less bioavailable. This doesn't remove it exactly, but it might keep it contained or stop a plume of contaminant spreading underground. There are also plants like poplars which both accumulate a range of contaminants, but also drink up so much water that they can actually redirect groundwater movement.

There are so many plants, contaminants of concerns, and varying ways the two interact that it really does need some review

General details which might be useful

Bioremediation - [This paper](#) provides a detailed description and diagrams of the process of introducing bioremediation bacteria to contaminated aquifers. It includes details on the arrangement of wells for testing and remediation. The paper is about dechlorinators but it seems likely that other groundwater bioremediation projects might follow similar steps.

1. Test the groundwater to determine the level of contamination and extent of the plume
2. Test for the presence of suitable bioremediation bacteria (and the symbiotic bacteria which enable them). Using native bacteria already present in the groundwater is preferred. Bacteria can also be invasive.
 - If they are present, test to determine what, if any, chemical nutrients/additives/remediation would help them to thrive and work quickly
 - Biostimulation - pump the necessary solution into the aquifer
3. If the concentration of contaminants is too high, or the right mix of dechlorinators aren't present, they would try bioaugmentation - injecting pre-grown dechlorinator cultures along with the necessary substrate.

Resources

- [Wikipedia's list of known hyperaccumulators](#)
- [This document](#) is an open source attempt to collect options for the bioremediation of dioxin, vinyl chloride and related toxins.
- The following documents provide decent lists of likely contaminants produced by internal combustion engine automobiles (such as you might find in a scrapyard, salvage operation, or car graveyard).
 - https://www.epa.gov/sites/default/files/2015-10/documents/sector_m_autosalvage.pdf
 - <https://web.archive.org/web/20230309211038/https://eeuroparts.com/blog/how-toxic-are-the-chemicals-in-your-car/>
- [This paper](#) has some details on deep rooting poplar trees.

Other concerns

Many invasive species are strong phytoremediators since they can tolerate and take in nonessential metals, as well as handle poor growing medium and climate conditions. Therefore extensive knowledge of the plant selected within the site-climate must be known

Related concepts

[This paper](#) suggests using biofuel crops to slowly extract some amount of heavy metals from a site, until bioavailable metals in the soil are low enough for a second phase. The idea is that even if these crops don't qualify as hyperaccumulators, as long as they take up some amount of the contaminant of concern, their commercial use would make the effort profitable enough to be worth continuing. One of the main challenges with remediation efforts in the real world is cost - there's usually no profit in remediating contaminated sites for anyone other than contractor companies doing the digging and transportation. Phytoremediation is often cheaper than the alternative, but it may still require ongoing labor such as soil and water testing, site assessments, or the harvesting of contaminated plant

material. This may be of less concern in a solarpunk society where this work is better prioritized, or even where basic needs are met through systems like universal basic income, and people are more free to pursue their callings, including cleaning up damaged sites.

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