OPERATIONALIZING PHYTOREMEDIATION: BEST MANAGEMENT PRACTICES

by Cheryl Hendrickson MSc[1]

INTRODUCTION

For at least three decades, plants and their associated microbes have been experimentally shown to extract, degrade and volatilize some contaminants of concern (CoC). But the greater promise of phytoremediation to be used widely and effectively has yet to be realized. One of the principal reasons is the gap between experimental and operational applications. Without effective operationalization, many projects fail and confidence is lost in the efficacy of the technology.

Several obstacles have materialized in the process of commercializing phytoremediation that have prevented this technology from being widely adopted: lack of field-based research on techniques; lack of qualified persons for design, installation and management; and few incentives to share BMPs among commercial providers. Each will be discussed below.

Operational guidelines and best management practices (BMPs) are presented based on 18 years of experience on 20 different phytoremediation projects in Canada and Northeast US, on projects ranging from square meters to tens of hectares. BMPs for the commercialization of phytoremediation are synthesized from other industries and adapted to overcome the challenges unique to "remeculture"—the practice of applied phytoremediation. Guidance for both client and consultant for selecting sites where phytoremediation will be successful are offered, and sequential steps outlined up to operationalizing and beyond, including suggestions for assessing progress on an ongoing basis.

KEYWORDS

Best Management Practices, applied phytoremediation, anthroposols, phyto-covers, remeculture, hybrid poplars, hybrid willows

PHYTOREMEDIATION FOUNDATIONS

The earliest intentional placements of plants to treat contaminated soil has been identified as the 1970s in a proposal by Cunningham and Lee (in McCutcheon and Schoor, 2003). In the 1980s, John Todd pioneered applied plant-based remediation, especially wastewater treatment, under many different proprietary titles, although the term "phytoremediation" was not coined

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until 1991 by Raskin *et al.* (in McCutcheon and Schoor, 2003). Once there was an intuitively sensible, shared and non-proprietary term for this technology, it brought the disparate disciplines into the same fold towards a common goal of bringing about remediation with plants.

With the new term "phyto-remediation," researchers could begin to describe plant based remediation in terms of function: *e.g.* phytoextraction, the physiological process in which a plant takes up and stores a contaminant—usually a metal or salt—from the soil into its tissues; rhizodegradation, in which the plant-associated microbes consume and breakdown certain contaminants such as petroleum hydrocarbons in soil; phytovolatilization, the physiological process in which plants with low water use efficiency such as hybrid poplars (*Populus* x) or hybrid willows (*Salix* x) take up groundwater with light molecular weight contaminants such as trichlorethylene, and volatilize it at the leaf surface through transpiration; and treatment wetlands which use many aquatic or wetland plants, such as cattail (*Typha* spp.) to transform various wastes, especially sewage and animal wastes.

The interest, research and practice of phytoremediation gained a higher profile in the 1990s, culminating in the McCutcheon and Schnoor (2003) volume *Phytoremediation: Transformation and Control of Contaminants*. It is an extensive reference volume for progress made in research—and to some extent, field trials—in the preceeding decade.

The International Phytoremediation Society (IPS) has held annual conferences since 2003 that serve as a venue for networking and current research and application of phytoremediation worldwide. The official peer-reviewed journal of the IPS is the *International Journal of Phytoremediation*. The website of the IPS is an efficient location for the phytoremediation newcomer to orient themselves into past and current research, and general operational guidance.

Clearly there is something about the promise of phytoremediation that has captured the imagination and attention of environmental professionals from chemical engineers, hydrologists, and soils scientists to plant pathologists and agroforesters, to name some of the usual figures. The door is usually opened to potential clients through the much touted cost-effectiveness, who may respond less enthusiastically when the remediation endpoint is vague, and after many years, the liability unextinguished, and cost-effectiveness unrealized when a poorly designed and managed project must be followed up by engineered solutions at a later date.

OBSTACLES TO SUCCESSFUL COMMERCIALIZATION OF PHYTOREMEDIATION

The foundations of phytoremediation are by necessity research-oriented in order to provide proof of concept by identifying the physiological mechanisms by which a plant and or its associated microbes transform contaminants. Without sound research, experimental or opportunistic field phytoremediation is only supposition. But building a body of expertise and guidance on BMPs for field application and optimization of phytoremediation has slipped between the cracks compared to lab research.

Site remediation is the usual area of expertise of consulting engineers who may not always know of the vegetation expertise required to operationalize phytoremediation. It is not sufficient to have a plant pathologist or physiologist trained in experimental lab techniques for the field-scale application—although their knowledge is required as part of the team. Knowledge of the complex of physical and biotic components—such as soil, climate and biogeography—over space and time, along with installation and management techniques, are critical to success. Managing these components make up the BMPs and will discussed in more detail below.

Commercial phytoremediation may be considered confidential by the client, or proprietary by the service provider, so that lessons learned may not be shared in the professional community. Or, practices may be shared, but not all are relevant to every region where they might be replicated. For example, among widely-used hybrid poplars, many clones were bred for specific regions and are not transferable to others. Poor performance or failure provides a negative feedback loop where fewer and fewer sites employ poorly informed phytoremediation practices that result in this technology being used less and less.

The aim of this paper is to share lessons learned and BMPs to a wider audience to increase its efficacy, and help new practitioners and clients towards greater success. As with engineered remediation technologies, as phytoremediation becomes more effective and more predictable, it will enjoy wider acceptance among regulators, consultants, and potential clients, on the many sites where it can be effective.

OPERATIONAL GUIDELINES

Some of the guidelines discussed below—with the exception of Criteria for Selecting Phytoremediation, Site Visits and some aspects of the Site Specific Treatment Design—are typical practices already in place. All need to occur before BMPs come into play.

Candidate sites

Phytoremediation is ideal for very large and remote sites, and sometimes is the only cost-effective choice when there is no way to bring large equipment to a remote site, where distance to landfills for dig and dump is cost-prohibitive, or where the contamination occurs over many hectares. Aside from those extremes, gas stations, upstream and downstream oil and gas, landfill leachate, septage, and biosolids, are some potential and realized applications.

Criteria for selecting phytoremediation

In practice, the criteria for selecting phytoremediation are simple and clear. The following four criteria may be known in advance without an in-depth desktop review of the site history (Phase I) and subsurface investigation report (Phase II). If any one of the conditions below is not met, it suggests that phytoremediation may not be the best strategy.

1. Is the CoC known or can be shown to be treatable?

The body of literature of experimental results for the treatment of some elements or compounds is extensive, and the first place to start.[2] Among phytoremediation specialists the potential for successful phytoremediation for some compounds is already known, for example, petroleum hydrocarbons which have been and continue to be degraded in the rhizosphere of some plants experimentally and opportunistically over time. We can also say fairly certainly at this time that gross contamination of most elements and salts should be considered non-candidate CoCs, however, some trace elements and light salt contamination may be phytoextracted.

The literature must be searched keeping in mind that phytoremediation has evolved over decades to be more realistic and accurate about what we can and can't reasonably phytoremediate. For example, a literature search would show early interest in sunflower remediation of energetic materials, although we now know these studies were flawed.

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2. See for example, Kansas State University's searchable Phytoremediation Database http://www.agronomy.k-state.edu/extension/environmental-quality/phytoremediation.html

Similarly, even current studies may show favourable results of CoC transformation, but the study must be read carefully to see if the results are transferable to field application. For example, what are the experimental rates of transformation and is this time frame suitable for regulatory or practical application? Is the plant in the study suitable for the geoclimatic conditions of the subject area? If there is no literature on the phyto-treatment of the CoC, that does not mean it cannot be treated, as will be discussed below under Site Visit and Bench Trials.

2. Is the CoC in the rootzone or can be made to be in the rootzone of the plant?
The depth of the rootzone depends on the plants deployed, for example, for hybrid poplars and willows 1 meter is a good rule of thumb. For some prairie grasses 1–4 meters may be assumed, depending on the species. Some phytoremediation practitioners have found several novel ways of artificially putting roots into the contaminated zone beyond 1 meter that would have to be individually verified for efficacy.

3. Is there regulatory approval for phytoremediation, or is the contamination contained on site?
Acceptance of phytoremediation by regulators as a legitimate remediation choice varies by jurisdiction, and is still not widely accepted. If the contaminant is contained on site, then it is usually not yet under regulatory oversight and phytoremediation may be chosen.

4. Is there time pressure to remediate?
Phytoremediation is not an option if site clean-up is necessary in a short timeframe of one to five years. Practitioners have always been challenged to achieve regulatory standards on timescales comparable to engineered technologies. While phytoremediation processes can be optimized based on the guidelines and practices presented here, other applications where there are no CoC receptors may take place over decades with the proper design and statutory support. In some jurisdictions, it may be possible to combine phytoremediation with reclamation, where that is required.

If all of the above criteria can be met, a feasibility study is warranted which involves a desktop review and assessment of Phase I site history and Phase II subsurface investigation to further assess opportunities and constraints.

Site Visit: Identifying opportunities and constraints
Even imagery of a site, both aerial and at grade, can't capture the many important nuances visible to the trained eye on a site visit. Geographic or biogeographic professionals can assess conditions related to site physiography at the regional and site scale, for instance, drainage, topography, soils, existing vegetation species, their health and age, all inform the eventual treatment design. Are there seeps or low, wet areas that require different phytoremediators from the surrounding upland? Are there species that have colonized the site, such as early successional species of willow and poplar, that may be providing remediation already?

In the event that there is no known phytoremediating species for the contaminant, the site may host opportunistic contaminant-tolerant species that show potential as new phyto-stabilization or remediation candidates. The treatment pathway and effectiveness (in terms of completeness of the process and relevant time for commercial application) would have to be shown in a bench trial if not proven before for a new candidate to be considered.

The other advantages of choosing site-specific vegetation as remediation candidates is that, whether native or introduced, it has a demonstrated tolerance to site conditions, and has a known presence in a geographic region with little to no risk of escaping and becoming invasive or a nuisance offsite. The same cannot be said for new plants imported for their ability to remediate from outside the region (or beyond the continent) where there are no acceptable tests for invasive potential, and none that can be done safely or in a timeframe that is relevant to deployment.

A site visit in the growing season also exhibits signs of phytotoxicity if plants were impacted, further informing the treatment design. Examples include: chlorosis (due to a variety of causes such as salt stress), purpurescence, stenophylly, necrosis and dieback. Only a plant pathologist can correctly connect contaminant-related pathology to the symptom, and therefore to the site. But in doing so it can inform the selection of phytoremediating species. For example, mature balsam poplars growing opportunistically on a closed landfill show dieback that may be related to root access to buried municipal solid waste (Fig. 1).

Bench trial: proof of concept

Where there is no literature proving treatment of the contaminant by a plant species, a bench trial is required to show treatment pathway in the plant, phytotoxicity levels, and to provide data to support estimates of remediation endpoints. Bench trials are the purview of plant physiology research where established experimental methods are known and general concepts only are presented here.

Dose-response experiments incrementally increase the CoC in the media (water or soil) to demonstrate at what level plant growth is compromised, and therefore its ability to remediate at specific toxicity levels, and what level causes complete mortality. These can be used to compare the site contaminant levels to assess which species, if any, can tolerate and remediate the contaminants on site. Phyto-toxicity levels will vary across plant species for the same CoC.

FIGURE 1. These balsam poplars (*Populus balsamifera*) on a closed landfill may be indicating root penetration into the municipal solid waste stratum as indicated by the top dieback.

FIGURE 2. Set up of blind bench/field trial comparing treatment of and tolerance to petroleum hydrocarbon contamination between different hybrid and native willow clones. The bench/field approach was used to combine the controls of a bench study with containers, in a long term (two year) field setting.

FIGURE 3. Results show no phytotoxicity at 20,000 ppm TPH (total petroleum hydrocarbon) after five months.

For species planted at doses that do not compromise plant health, contaminated media should be sampled over time to show remediation, and at the same time measuring and identifying the treatment pathway through additional verification. For example a reduction in a trace metal in the soil should be verified by uptake in certain plant tissues, showing phytoextraction and sequestration as the remediation pathways, and suggesting remediation endpoint based on the rate of removal.

Bench trials are essential to show proof of concept where none exists previously, or to verify contaminant transformation on site-specific media. However, all bench trials are limited by the artificial greenhouse conditions that are required to show cause and effect. Limitations occur when the demonstrated performance may not be reproduced in the complex field environment where these physiological remediating functions take place. The precariousness of this technology transfer from greenhouse or lab to field cannot be underestimated and is another reason why plants selected from the site may be a preferential treatment proof of concept approach because they have a demonstrated ability to live or thrive on the site and in the geoclimatic region.

Field scale trial

A field scale trial as the next step is not always necessary and is assessed on a cost-basis. A field-scale trial is warranted if there are many unknowns whose adjustments multiplied out over a large area or timescale would be costly. If the subject area is small, the installation practice well known and understood (such as with site-appropriate hybrid poplar or hybrid willow clones planted according to known agroforestry principles) then a field scale trial may be considered optional.

Site Specific Treatment Design

With the Feasibility Review, Site Visit and Bench trial/Field scale trial in place, a Site Specific Treatment Design can be created. The temporal scope should be from site prep through to regulatory remediation endpoints.

The Site Specific Treatment Design will summarize relevant data from the Phase I and II reports, such as kind and levels of CoC, their distribution and depth.

The chosen phytoremediating plant(s) will be identified, along with the evidence supporting its efficacy, its treatment pathway and expected remediation endpoint based on literature review, bench trials, or both. But more importantly, there must be solid evidence that the chosen remediating species is/are hardy in the geoclimatic area over the expected length of the remediation period. Without plant hardiness to the local area, a plant's proven ability to remediate is irrelevant.

For example, is the candidate species known to be winter-hardy in the north? Winter hardiness means that not only will it survive extreme cold and other factors of winter, such as frost cracking and dessication in the case of trees, but that it will do so reliably and continue to increase in biomass every year. In some applications the remediating vegetation must also be tolerant of de-icing compounds used adjacent to the installation; for example, cedar (*Thuja occidentalis*) are not. These are examples of where the landscaping trades (not landscape architects) can provide input and should be knowledgeable of what is hardy in the local area.

A Site Specific Treatment Design will detail how the BMPs of site prep, installation, management and monitoring outlined below will be met, which may also draw from the constraints and opportunities observed on the site visit, for example identifying locations where existing vegetation may be providing treatment.

A multidisciplinary team should be in place at this time that includes a chemist/chemical engineer, plant pathologist, hydrologist, soil scientist, and regional vegetation specialist with knowledge of the installation and maintenance of the specific phyto-cover. Because phytoremediation is a dynamic complex ecological system the team must work together to anticipate and manage all of the reactions—chemical, physical, and biotic—over the lifetime of the remediation.

Like all other conventional remediation technologies, the consultant should account for all regulations and requirements of their jurisdiction and for their client in the Site Specific Treatment Design.

It is necessary in costing out the system to ask whether phytoremediation is economically viable compared to conventional remediation solutions; whether costs are offset by other ecological/social benefits that might be provided, for example, improvement in civic or neighbourhood aesthetics that improve property values and business investment; or whether or not the system has significant advantages over monitored natural attenuation.

The Site Specific Treatment Design will be the document against which yearly monitoring and progress will be measured. Milestones of progress and success should include goals for vegetation establishment and growth and for remediation performance. Plant densities achieved and maintained and increases in growth from year to year are examples of the former; for the latter, reduction in groundwater elevations down gradient for stands that are intended for hydraulic control (as one possible remediation function) should be projected by certain volumes based on tree size and evapotranspiration potential in the geographic region.

Because each site has individual characteristics, and each Site Specific Treatment Design is unique, once the Site Specific Treatment Design has been drafted, it may be desirable to involve a third party or parties for review coming from one or more of the disciplines involved. They can have a second opinion, especially on aspects for which there is uncertainty, or for overlooked issues, the identification of which will possibly save time and money.

Since phytoremediation of the many possible candidate contaminants in a field environment has few replications, measuring remediation against projected site-specific remediation milestones will guide adaptive management, and may eventually point to the inability of the system to meet desired regulatory endpoint in an acceptable time. Although this is a suboptimal conclusion, it is a safeguard to the client, regulator and the public that the project will not run indefinitely waiting for the anticipated remediation response. It is also a measure of accountability for commercial phytoremediation that will help to build confidence initially for the client and industry-wide over the long-term.

OPERATIONALIZING: BEST MANAGEMENT PRACTICES

Remeculture

The term “remeculture” is coined here for the first time to describe the unique parameters involved in the installation and maintenance of phyto-covers; the word combines “remediation” with the suffix culture common to many plant growing systems *e.g.* horticulture, agriculture. It is defined as the design, installation and management of plant cover in contaminated agronomically compromised anthroposols (see below) or waste water to optimize their ability to remove or transform contaminants. The product of remeculture is the removal of legal liability through the remediation of soil or water.

In 2012 the term anthroposol was proposed in Canada by Naeth *et al.* (2012) to describe the kind of human modified soils only a soil scientist or a remeculturalist would notice. Anthroposols found on contaminated industrial sites (brownfields) in particular consist of soils with no recognizable topsoil, instead consisting of subsoil or fill containing cement, rebar, asphalt, brick, plastics and metal that usually have their origin in the demolition of onsite infrastructure. Besides contamination, these anthroposols have low fertility, often poor drainage, and present structural impediments to cultivation and root growth.

BMPs draw from a variety of existing agricultural, horticultural, forestry, landscape and restoration practices, since many different plants are deployed and many different knowledge bases are required. For example, phytoremediation that deploys hybrid poplars or hybrid willows can rely on the body of research and practice already in place from the agro-forestry sector. The difference is, however, that all plants are often installed into structurally and nutritionally challenging anthroposols that are also contaminated. These features set remeculture apart from its parent practices. A phyto-cover may also be novel in that it has never been planted as a monoculture, for example heavy metal or salt accumulating plants selected from natural environments deployed into impacted sites.

By creating the new term "remeculture" to describe all of the unique traits brought together to operationalize phytoremediation—that the *function* of these plants to bring about remediation is the product, not food, not wood fibre, not aesthetics; that its culture draws from many established systems, but that may also need to invent novel or hybrid ones; where productive, plant-friendly soils that are the norm for other cultures are replaced by plant-hostile anthroposols—then we recognize and value all that is unique and necessary to operationalize phytoremediation and look for the best human and other resources for it to be successful.

Site prep: soil amendments

Phytoremediation depends on healthy plants. Healthy plants are unlikely to be the product in the anthroposols of industrial brownfields. These challenging edaphic conditions must be accounted for and remedied in any treatment design. Approaches to site preparation that promote better plant growth include organic amendments to improve structure and drainage, biochar application to promote increased microbial activity, chemical or natural fertilizers, and agricultural practices such as plowing, discing and or tilling.

FIGURE 4. Using dozer-drawn harrows on former industrial dump site to prepare for hybrid willow planting.

Planting in anthroposols

Because of the difficult soil structure presented by anthroposols, usual planting methods—whether it be seed drill, shovel or cutting planter—will not likely be effective. An extra layer of soil disturbance, such as a small backhoe, mechanical auger, plow, or ripper may need to be deployed in advance of planting. Another strategy that has been used successfully is to irrigate to make heavy clay subsoils at the surface easier to penetrate. The level of difficulty of each soil for planting should be explored and determined in advance of deploying machinery and planting crews.

Overplant

Overplanting of all vegetation offsets the risks of brownfield-type anthroposols, and in the event that the BMPs below have not adequately addressed risks. For example, poor or patchy fertility will produce irregular and suboptimal growth than can be offset by more individuals. Mortality caused by rodent girdling will be of less consequence if densities are higher. Inadequate vegetation control may be offset by more, smaller individuals. Planting more than one species that provides remediation, for example, hybrid poplars together with hybrid willows, or even more than one poplar or willow clone, will offset ecological risks avoiding the well-known hazards to which monocultures—especially genetically identical clonal monocultures—are prone.

FIGURE 5. Planting rooted hybrid poplars with hand shovels into an anthroposol in holes prepared by a backhoe. Site was seeded with clover in advance, although the initial take is low due to poor soil structure and low inherent fertility.

Planting controls offsite

A method to compare the rate of growth for phytocovers is to plant a few specimens or small area offsite with average growing conditions with regards to soils, nutrients, and little to no competition. This also helps to assess whether symptoms of pathology on the subject area are related to contamination, or to some other regional-scale phenomenon, such as insect outbreaks and climate extremes.

Correct timing for planting

It is very common in all plant-related industries for colleagues or clients not trained in vegetation sciences or trades to be unaware of the progress of the growing season and the urgency to plant as soon as it is safe as it is to do so. All of the desktop reviews, treatment design, discussion and negotiation with regulators, client, suppliers and supply mechanisms (such as tendering) should take place in the non-growing season—in southern Canada and the adjacent US approximately October through March—so that site prep and planting can begin as soon as the soil can be worked and frost hazards are passed (in regions where these conditions exist). The concept is to give any phytoremediating vegetation the maximum time in the region's growing season to become established. The later vegetation is planted in the growing season, the less time it has to become established, and the less likely to make it through to the next growing season. This is especially true of hybrid poplar and hybrid willow cuttings, which should not be installed after the first week of June, after which rooted cuttings may be planted up to the end of the growing season. Of course, these principles are regionally specific and will have to be accounted for through local expertise. The concept of the non-growing season around the globe could translate to the dry season, the monsoon season etc. relative to the locality.

All phytoremediating species must be properly planted according to the specifications of the industry under which that the plant falls. For example, for phyto-covers using grass species, look to farming practices for equipment and timing for sowing seed. For hybrid poplars and willows, whose conventional use is for the production of fibre in the former, and the production of renewable energy (wood chips or pellets) in the later, there is a well established body of agroforestry BMPs from many jurisdictions worldwide for handling, planting and managing them. Horticultural practices may be consulted for other plants, such as ferns. Some of these practices may be combined—for example—sewing a cover crop according to farming BMPs, combined with planting trees according to forestry BMPs.

Maintenance

Irrigation

The value of the phytoremediating vegetation is the long-term removal of the site liability. As such, no expense should be spared in preparation for a chronic or prolonged precipitation deficit that threatens the short-term survival or long-term growth of the phyto-cover. The method of irrigation should be identified in advance in the treatment design and will vary depending on the size of the site and on the phytoremediating vegetation. The provider and their availability should be identified and confirmed. The source of water, for example municipal hydrant, water truck, withdrawal from local creeks, rivers or lakes, should be identified and in case of surface waters, restrictions and permits identified and arranged. Quantities of water and frequencies of watering should be calculated, remembering that shallow irrigation has the effect of encouraging shallow rooting, and further susceptibility to drought. If possible, irrigation infrastructure should be part of the installation to minimize delivery and setup time. Traditionally, precipitation deficits have been assessed in the vernacular method of anecdotal assessment, leading to the "wait and see" approach that causes drought stress before rain falls or irrigation occurs. Alternatively, a statistical approach could be taken of average weekly or monthly rainfall beneath which irrigation would be triggered.

Protection

A phytoremediation system is a novel ecosystem that is subject to all of the risks and benefits shared by every organism in every ecosystem. Plants benefit from free, spontaneous photosynthetically active radiation (sunlight) and precipitation. But they are also now part of the local ecosystem, providing habitat for both neutral organisms, such as amphibians and nesting birds, and to animals that regard them as food, such as deer, leaf miners or stem borers, particularly in the case of trees.

Ecological risks in general

Common pests of the phytoremediating vegetation should be identified by a plant pathologist, through trade organizations and their publications, and pathology databases, to name just a few possible sources. All ecological risks should be addressed in the Site Specific Treatment Design.

Competing vegetation

Protection from competing vegetation is perhaps the most critical BMP because, beyond extreme and unpredicted weather events that would cause instant widespread mortality, competing vegetation occurs at a growth rate faster than the phyto-cover and must be controlled not once, but regularly, particularly in the first two growing seasons, until the phyto-cover is well established. Not doing so threatens the installation so that widespread underdevelopment or mortality of the phyto-cover occurs. Even if the site is clear of vegetation at the time of installation, volunteer plants will arrive from the seedbank, on equipment, and dispersed on the wind from offsite. It is the intention of a phyto-cover to preferentially install vegetation that will bring about remediation, and competing vegetation that does not do so and crowds out the intended phyto-cover is detrimental. The exceptions are opportunistic colonization of nitrogen fixers such as sweetclover (*Melilotus* spp.), which also add biomass to the soil during their short tenure, and native or introduced poplars or willows. There are many different ways to manage this critical issue, as outlined below.

Ground cover

Planting a low growing non-competitive ground cover such as white clover (*Trifolium repens*) will exclude larger more aggressive weeds and also fix nitrogen. This cover needs to be established after site prep and before phytoremediation installation. It is good to proceed with this choice if all other administrative tasks are accomplished by mid-growing season, so that forward motion continues and there is sufficient time for the groundcover to be established in advance of planting. Because it is low-growing, it will significantly reduce the need for weed management in subsequent years.

Brush blankets

Brush blankets (specially designed squares of plastic that block sunlight around the tree, smother/exclude weeds but allow in precipitation) for hybrid poplar plantations are successful in the first one or two years in protecting the developing trees from weedy competition. They are labour intensive to install and have a high unit cost for materials. The other drawback is the kilograms of metal they leave in the ground as each blanket is pinned in place by five staples, and plans to remove blankets and staples around year three could be considered. However, they are excellent insurance if there is reluctance or inability to perform the required vegetation control in a timely fashion.

Mulch

If there is a nearby source of biomass that can be efficiently spread to smother competing vegetation in early stages of growth, this has the added benefit of adding organics to the soil, protecting bare soil from erosion, and conserving moisture where precipitation is adequate. Some examples include straw bales, old silage and waste pulp. Hay bales may or may not contribute seeds, depending on the maturity of the forage species at harvest.

Mow/blade

Controlling vegetation by mowing—whether walk-behind or tractor-drawn—is also viable, or with professional grade blade-trimmers. However, in most cases mowing may not control the vegetation closest to the plants. This strategy is variable depending on the size and structure of the phyto-cover. It may be used in tandem with brush blankets, although there must be sufficient clearance between the mower blade and blanket so they do not get caught up in the machinery. It is also effective in tandem with planting larger caliper, rooted plugs in the case of hybrid poplars and willows. Blade trimmers may be used only if accidental girdling to plants, trees and shrubs can be avoided.

Hand pulling

In the case of smaller installations, removal of weeds by hand or with hand tools is desirable. However, the individual weeding must be able to identify the difference between the weeds and the phytoremediating species.

FIGURE 6. Brush blankets smother existing competing vegetation around young trees and exclude new weeds, while letting in precipitation. However, metal staples and plastic adds to onsite waste and removal after year three may be considered.

FIGURE 7. Containerized hybrid poplars for installation in early summer to late fall. Larger, mature specimens also have a competitive advantage over weeds.

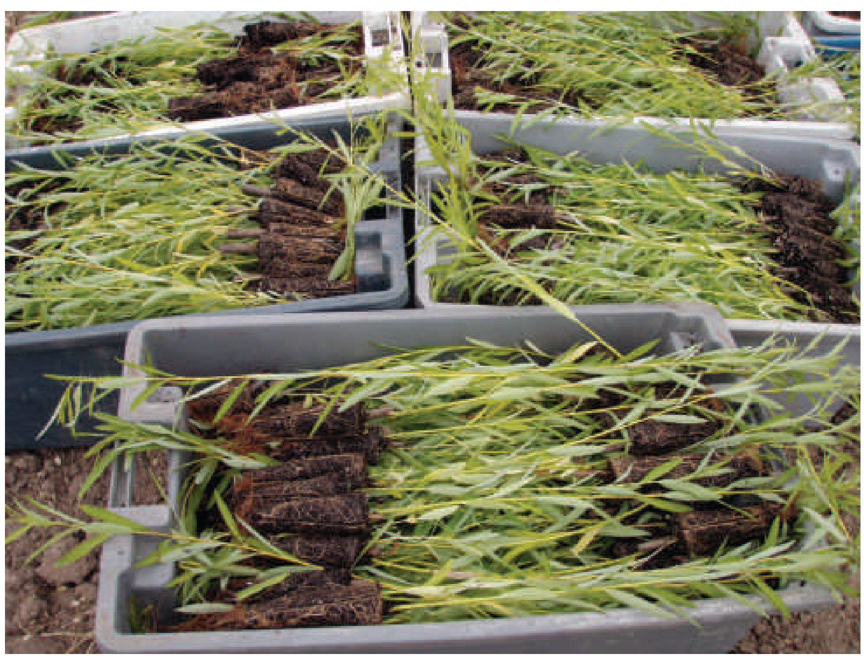
Rooted plugs

In the case of hybrid poplars and willows, planting taller stock that has been grown out in containers will give plants a head start over unwanted weeds and grass that they will usually maintain, making repeated vegetation control less critical. Although rooted plugs for hybrid poplars and hybrid willows are more expensive than cuttings to purchase and to plant, the cost may be offset in the long-run with reduced maintenance.

Herbicide

The effective, safe and legal use of herbicide is specific to each product, intended for specific plants and for specific applications, for example, orchards, field crops, nursery stock, and reforestation. To use a herbicide which has not been tested for specific applications and plants is considered "off label" for which there may be penalties. It is best to contact regulators or licensed applicators to confirm that a product under consideration is not an off label application in the site jurisdiction. If herbicide application for unwanted weeds

FIGURE 8. Hybrid willow plugs grown from cuttings.



is possible, oversight of the operation by a vegetation specialist on the project will ensure that the phytocover is not unintentionally sprayed as well.

Protect

All phyto installations, no matter what the size, should be fenced to protect from browsers, such as deer or moose, and grazers such as horses, and from intentional or unintentional human transgression, such as vandalism, parking of cars and equipment, and dumping.

Smaller tree-based installations should consider tree collars that protect from rodent girdling. With larger installations, there is unlikely to be enough damage to be significant, and tree collars eventually add to the on-site waste stream. Overplanting, discussed above, is a solution for this risk.

Fertilize

Adequate fertility for all soils must be assessed and augmented, if necessary, but the nutrient deficiency of brownfield anthroposols in particular must be addressed. Fertility tests geared to the type phytoremediating vegetation—such as trees, grasses or forbs—must be sampled at appropriate densities determined by a soil scientist. Strategies that favour the fertilizing of the phyto-cover over the competing vegetation must be determined, such as placing in the root zone at the time of planting, or in the case of trees, under the canopy or at the base of individuals. Various approaches can be considered, for example, slow release fertilizers or organic amendments such as alfalfa pellets that add nitrogen and contribute to soil organics.

Monitoring

Measuring remediation

Measuring performance must occur at the biomass level for the phyto-cover, and at the environmental level for contaminant remediation. Ideally plant growth as indicated by increase in biomass, will be correlated to a decrease in CoC. The latter is well understood practice of conventional site remediation, involving soil and water sampling protocols, as well as ground water elevation monitoring, to name the principle methods.

Measuring biomass and transpiration

Mensuration for tree phyto-covers can follow any of the well established protocols for forestry, agroforestry, agriculture and landscape trades. The following tools and methods are examples of how to measure biomass and processes, however, it is not exhaustive or complete.

Tree growth can be measured by diameter at breast height (DBH) from year to year which will also allow for a number of further stand-level calculations, such as basal area, a measure of biomass. Height is measured using clinometers and canopy closure using densiometers. These and other tools and methods are well known among professional foresters.

Perennial and annual grasses and forbs used, especially for phyto-sequestration, may be harvested in a standardized bale and biomass accounted for by number and average weight.

Transpiration monitors that measure the amount of water taken up by an individual tree can support estimates of volatilization for the phytoremediation of light VOCs and for hydraulic control of groundwater plumes. These data can also be used in conjunction with measurements of groundwater elevations to examine mass balance equations, and with groundwater monitoring to determine remediation.

FIGURE 9. Measuring diameter at breast height (DBH) of hybrid poplar with a DBH tape.

Aside from biomass measurements, consider excavation of a representative individual to explore root development, distribution and depth. There is variety of diagnostics that can be determined by a plant pathologist that are helpful in managing the phyto-cover. Excavation may find that roots have not developed to the desired depth, or conversely, may show colonization by beneficial symbiotic mycorrhizae that enhance their growth and remediation capacity. Excavation may also show pathogens or root-boring insects as the cause of mortality, and not phytotoxicity.

Since phytoremediation is often a function of root growth, looking at growth that is normally invisible below ground will reveal many unanticipated insights into the process and the soil media. For example, excavation revealed that, in the case of hybrid poplars, root systems do not mirror the tree canopy in a symmetrical dome as depicted in much of the phytoremediation literature. Tree roots are constructed cell by cell according to the path of least resistance and the best return on carbon and water resources for their effort, making them surprisingly assymetrical.

Pathology

A qualified pathologist should undertake a plant health assessment for symptoms of pathology and whether they are related to phytotoxicity. For example yellowing leaves (chlorosis) have many causes: drought, nitrate deficiency, trace mineral deficiency, and/or toxic compounds in soils. Whether it is across all individuals in the phyto-cover or just one or a few is also diagnostic. Identifying the reasons may inform future management regimes, for example, sampling for specific parameters such as micronutrients, and subsequent adjustment of fertilization requirements.

Reporting

Annual reporting should include measurements against milestones, as described above, measures for adaptive management and revised milestones, if necessary.

A third party review of the monitoring results is an invaluable tool for the client, the practitioner and the phytoremediation community at large. It can assist in explaining recalcitrant reactions and suggest adaptations that can set the project back on track. These must be done in the spirit of professional conduct that shares lessons learned and allow the greater community of practitioners to benefit, providing a positive feedback loop to the industry.

CONCLUSION

These BMPs have been developed mostly for hybrid poplars and hybrid willows, however, many of the principles are the same across plant species, sites, and geography. But the practitioner must always be alert to the ways in which their application differs, and be prepared to look to the established plant trades first for solutions but ultimately to be observant, inquisitive and innovative to find solutions and increase the knowledge base of BMPs.

With BMPs shared widely and freely, it is hoped that a positive feedback will begin to take place, instilling widespread confidence in a technology that is applied with expertise and rigour on the abundance of sites for which phytoremediation is suitable.

Once basic BMPs for phytoremediation are well understood, the next step is to experiment and report on techniques that optimize plant performance, increasing predictability and reliability. In the future, we can look beyond monocultural phyto-covers to opportunities to design complex phytoremediating novel ecosystems that remediate or phytostabilize over the term of decades or centuries.

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