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Methodology for the Reclamation of Phosphogypsum Stacks in Canada Using Afforestation

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The Canadian Wood Fibre Centre (CWFC) explores and deploys targeted, effective, and environmentally responsible solutions to the challenges facing the Canadian forest sector. The knowledge, tools and approaches developed by the CWFC aim to grow resilient forests, mitigate the impacts of climate change, and reduce the risks surrounding the wood fibre supply in Canada.

Additional information on Canadian Wood Fibre Centre research is also available online at cwfc.nrcan.gc.ca. To download or order additional copies of this publication, visit the Web site Canadian Forest Service Publications at cfs.nrcan.gc.ca/publications.

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Introduction

The goal of this operations guide is to assist those who seek to establish and manage fast growing, high-yield afforestation plantations for the vegetation of phosphogypsum (PG) stacks. The approach offers an innovative reclamation option that makes beneficial use of PG rather than treating it as waste. CWFC operational researchers envisioned an opportunity to use the industrial waste in situ as a vital input to a favourable environment for the growth of trees. In likely the first effort of its kind, CWFC in partnership with Nutrien Inc. has established and grown a forest on a PG stack. Protocols developed for the establishment and management of the short rotation woody crops on these industrial sites provide industry with a cost-effective method for growing high value crops, combatting climate change, and producing feedstock for the generation of green energy. There are multiple long-term benefits of establishing mixedwood forests on PG stacks. These benefits include increasing carbon sequestration, improving long-term ground water quality, increasing wildlife habitat and ecosystem biodiversity, and enhancing long-term sustainability while reducing long-term maintenance costs.

Phosphogypsum is a gypsum by-product from the manufacturing of phosphate fertilizer. It is composed primarily of hydrated calcium sulfate ($CaSO_4.2H_2O$) produced when phosphate rock reacts with sulphuric acid to produce phosphoric acid, the main component of phosphate fertilizer. Approximately 5 tonnes of PG are produced for every tonne of fertilizer manufactured. The gypsum is typically stored in large stacks called "gypstacks." PG contains trace amounts of radium that was originally in the phosphate rock and is considered a NORM (Naturally Occurring Radioactive Material).

Nutrien is the world's largest provider of crop inputs and services (https://www.nutrien.com/). Since 2005, Nutrien has been working to contribute to the preservation of nature by developing innovative reclamation and reuse strategies for PG stacks in Alberta. Over 61 million tonnes of gypsum covering approximately 325 ha are stacked near Nutrien facilities northeast of Edmonton, AB. It is estimated that over 200 million tonnes of PG are produced annually in 33 countries around the world.

In Canada, agroforestry and afforestation plantations have been successfully established using a variety of native and exotic species that have growth consistent with or greater than species in the adjacent native forests. The treatments described in this guide may achieve high yields (8x native yields) over short rotations (12–20 years) as a means of rapidly producing fibre for use in the wood products industry and for energy. With intensive management treatments following appropriate site selection and site preparation, plantations of native species may achieve yields up to three-fold greater than typical native yields. With the incorporation of fast-growing species such as hybrid poplars, yields may attain up to eight times native yields. The information provided in this guide is a result of decades of operational research in establishing, managing, sampling, and harvesting high-yield afforestation plantations across Canada. Furthermore, the guide provides a synthesis of operational knowledge and information from numerous afforestation proponents and stakeholders with experience in all aspects of short rotation woody crop (SRWC) production.

Establishing an afforestation forest on PG stacks can reduce long-term maintenance costs while improving ecosystem biodiversity and wildlife habitat. Research also shows that the forest cover can reduce or eliminate rain and snowmelt infiltration, thereby improving long-term ground water quality through the phytoremediation of excess nutrients and water within the rooting zone. Nutrien began conducting research into alternative methods of reclamation. In 2014, the Canadian Wood Fibre Centre, Canadian Forest Service joined the collaboration to provide expertise in applying short rotation woody crop systems to industrial sites to improve PG stack reclamation procedures while sequestering carbon and producing woody biomass. In the revegetation of PG sites project, CWFC brought silvicultural knowledge and operational experience to build upon research previously conducted by Nutrien in partnership with the University of Alberta. The combined result provides an innovative solution, developed and validated to meet multiple issues facing the PG industry. The high-yield afforestation operational protocols developed and tested in Canada by Natural Resources Canada provide a "roadmap" that supplied the basis of information summarized in this document to guide work on industrial sites across Canada and around the world to increase carbon sequestration, produce woody biomass and restore ecosystems.

Site Engineering

Proper site engineering is crucial to the success of any plantation established for phytoremediation purposes. Establishing and managing afforestation plantations requires a large amount of physical and economic resources. Expending these resources on the correct site is vital to the success of any afforestation plantation. Understandably, not all PG stacks are able to be engineered to facilitate the establishment of afforestation plantations. Traditionally, PG stack reclamation involves contouring the PG stack, covering it with a layer of soil (with or without a synthetic liner), and seeding grasses.

Contouring

Contouring of the PG stacks is completed to achieve the objective of preventing water ponding. For PG stacks engineered for afforestation plantations, contouring also provides the physical site characteristics needed to ensure operational effectiveness and equipment productivity required for the establishment and management of plantations. Contouring operations conducted to establish afforestation plantations should result in a site that is relatively flat and that is easily accessible for future treatments.

Establishing a Soil Cap

A soil layer 15-20 centimetres in depth is spread over the entire area and mixed deeply into the PG during site preparation treatments to provide a stable substrate and to improve the chemical and physical properties of the PG. To reduce the adverse impacts on operations and plantation growth, soil caps should:

1. have minimal stones or other impediments,
2. have a soil texture of loam, sandy loam, loamy sand, silty clay, clay loam, or silty clay loam
3. be non-saline (E.C. <2.5), and
4. have a pH of 5.5-8.0.

Whenever soil products are added to a landscape at this scale, there is risk of introducing noxious weed species to the site through providing resources that promote germination of latent seed. One option is to initiate a vegetation management plan following the establishment of an organic soil cap. Depending on the preference of the landowner, this site re-vegetation can be managed through either mechanical or chemical means prior to seeding a cover crop.

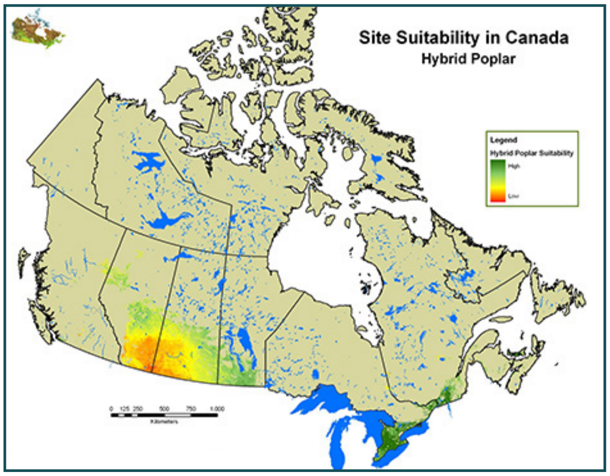
Seeding a Cover Crop

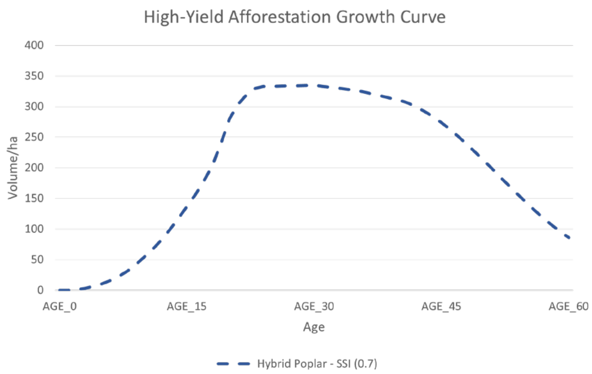
Cover crops help prevent wind and water erosion, reduce or eliminate infiltration of water, improve aesthetics, and minimize any exposure to radon or gamma emissions. Cover crop species should be chosen to minimize future competition on the afforestation seedlings with the understanding that the future site preparation treatments will result in disturbance to the seeded area. Some of the more commonly recommended species include ryegrass, clover, and fine fescues. Local agricultural proponents, service suppliers and government researchers are resources that can provide options and valuable insight for determining the appropriate cover crop option.

Evaluating the Suitability of SRWC

Vegetating PG stacks requires a significant amount of resources. Depending on your location, SRWC may or may not be a suitable option. The Canadian Forest Service developed an SRWC Site Suitability Index modelling system (Joss et al., 2008) to support decisions about where to establish crops, thus helping to manage finite financial resources. The model evaluates the natural fitness of land to support the establishment and growth of fast-growing tree species, such as hybrid poplar, for sequestering carbon. In this case, natural fitness refers to the environmental conditions (e.g., topographic, edaphic, and climatic conditions) conducive to the growth of fast-growing tree species. Combined with the fast-growing species growth trajectories, the model is one of the options available to predict SRWC growth and yields for agricultural lands in Canada (https://open.canada.ca/data/en/dataset/07668020-91d7-481a-bfbd-8ea07aace7b4).

Validation of the modelled results with actual high-yield afforestation site sampling has confirmed that better quality lands grow additional woody biomass for less cost when consistent and proven establishment and management protocols are utilized. The term "marginal lands" is often included when evaluating SRWC potential in Canada. When incorporating soils from a site deemed marginal, two important factors that require consideration are 1) that not all marginal lands are considered equal and each location may have a different reason for being designated as "marginal" and 2) depending on the parameters used to identify land as "marginal", growth expectations should be adjusted accordingly. Known parameters may be used in developing mitigation options to be costed in site preparation estimates.





Site Preparation

Proper site preparation is vital to the success of growing any type of crop in an agricultural environment and is equally important for afforestation plantations. The correct site preparation treatments create environments in which "trees love to grow", thereby facilitating successful and cost-effective vegetation management programs. SRWCs require (and love to grow in) adequately mixed soils that will enable them to thrive for their entire 12-25-year rotation to reach their growth potential, bringing economic benefits to stakeholders and landowners. Studies have validated that SRWC plantations require a suitable rooting environment over the entire plantation site to allow seedlings to extend their roots deeper into the soil to be better prepared to deal with the effects of periodic climatic events such as drought and flooding.

Deep Mixing

PG stacks that have been contoured and covered with a soil cap usually have a compacted PG layer that is considered a "hardpan" that will inhibit the rooting ability of seedlings. The goal of deep mixing is to penetrate and destroy the top layer of this hardpan allowing for a 25-30 centimetre layer of mixed PG/organic soil. Trees may push their roots deeper into the mixed soil as they grow to be better prepared for the effects of periodic climatic events.

To break this hardpan and create a deep mixing of the soil, a set of large, heavy breaking discs are recommended. They should have a maximum width of 4.3 metres or 14 feet, large 90 centimetre or 36-inch discs and be equipped with extensive down force capabilities. Site preparation treatments should be initiated as early as the soil conditions will allow in the spring prior to planting. It is recommended that the site be treated using a two-pass system, with the second pass being completed perpendicular to the initial treatment immediately following the initial pass. The goal of the two heavy discing treatments is to create a crudely mixed PG/soil layer anthrosol, 25-30 centimetres in depth, which will enhance the rooting ability of the planted trees. Depending on the success of the two heavy discing treatments, an additional pass may be required and completed perpendicular to the previous treatment.

There are numerous examples of trees planted in an afforestation environment that have not reached their full potential. In many instances, the reduced long-term growth is a result of inadequate site preparation treatments. Attempts to reduce costs of SRWC plantations through selective site preparation along planting rows (either by intermittent deep mixing using a narrow ripper tooth or by limiting mixing depth by using improper discing attachments) have proven to result in reduced long-term growth and increased vegetation management costs. A failure to create a 25-30 centimetre mixed soil layer over the entire site risks increased mortality and reduced yields, increasing the production costs of the woody biomass.

Levelling the Site to Facilitate Future Treatments

Deep mixing treatments result in uneven site terrain, which limits equipment operability and the consistency of subsequent treatments. To deal with such inconsistencies and to create a finer soil mixture in the top 10-15 centimetres, a field discing treatment is required. The field discing may immediately follow the deep discing treatments, using a wide set of field discs (7.3 metres or 24 feet). The goal of field discing is to create a consistent and level site that does not limit the travel of equipment and the consistency of future treatments. To ensure the desired results are achieved, a second pass of the field discs may be required.

Initiating the Site Vegetation Management Program

Prior to the planting of any seedlings, competing vegetation must be controlled. Discing treatments can increase risk of exposing latent seed to the resources needed for germination. There tends to be a flush of competing vegetation following discing treatments. The timing of the field discing treatments is often sufficient to control the vegetation prior to planting. However, in certain circumstances, the timing of the treatments results in a vibrant growth of vegetation that requires action prior to the initiation of planting. Depending on the preferences of the landowner, this site re-vegetation can be managed through either mechanical or chemical means.

Mechanical

Managing competing vegetation through mechanical means requires close monitoring and timely action. It is vital to control the vegetation at an early stage before germinates develop a sustainable rooting base. It must be realized that the competing vegetation could go from the 3-5 leaf stage to the 30 centimetre stage in a relatively short time.

Pre-planting vegetation control can be completed through field discing, consistent with the previous treatment. It can also be completed through shallow cultivation (5-10 centimetre depth) or harrowing. Either treatment can use equipment similar to the previous treatments or a smaller scale tractor equipped with the desired attachment. Depending on the length of time between the field discing treatment and the planting operations, more than one treatment may be required.

Chemical

Dealing with the competing vegetation through chemical means requires less monitoring. The vegetation is permitted to grow unimpeded until 7-10 days prior to the initiation of planting operations. At this time, a broadcast herbicide application of the required chemical or mixture of chemicals is applied to the entire site. Local agricultural proponents, service suppliers and government researchers are resources that can provide options and valuable insight for determining the appropriate chemical vegetation management option. Depending on the success of the initial treatment, a second application may be required.

In addition to the field discing and pre-planting vegetation management treatments, some sites may require the removal of stones or other impediments that could impede future treatments. These impediments may exist on-site or become exposed during the site preparation treatments. Once the site is free of vegetation and other impediments, it is now ready for the initiation of planting operations.

Site Design and Layout

Afforestation establishment designs and layout have a lasting impact on operations and long-term success of plantations. Creating a suitable site design that ensures accessibility, enhances operations productivity, and reduces risks will provide the basis to create the framework for successful operations and plantation establishment. It is important to incorporate all future facets of plantation management and harvesting when developing the site design and layout to avoid problems and delays throughout the life of the plantation. Some of the main parameters that require consideration include plantation size and accessibility, multiple clones and/or species, block-style planting, and operational buffers.

Plantation Size

Animal browse could have a significant impact on the long-term survival and success of any afforestation plantation. Deer, moose, elk, hares, mice, and voles all have the ability to cause mortality or long-term growth impacts within afforestation plantations. To alleviate the risk of widespread mortality and reduce long-term growth and yield impacts, it is recommended that site plantings should have a minimum area of 10 hectares, whenever possible, so that the plantation has the best potential to withstand browsing pressures from various wildlife species. In some instances, physical PG stack characteristics may result in size constraints. This means that options other than minimum size limits are required to minimize the impacts of browsing pressures.

Plantation Accessibility

Establishing and managing afforestation plantations requires multiple treatments scheduled throughout the growing season. Initial site preparation treatments are conducted during the fall (September-October) and/or spring (April-May) seasons. Planting operations are completed in May-June and vegetation management activities occur from June-September. Having all-season access to the site will reduce overall establishment and management costs and reduce long-term biomass costs.

Multiple Clones and/or Species

The risks associated with insects, pests, and diseases vary with each species and clone. Creating a site design that incorporates multiple species and/or clones will reduce these risks and provide the best protection from a catastrophic outbreak.

Block-Style Plantings

Growth characteristics (e.g., crown diameter and height-to-crown diameter ratio) vary with each species and clone. For example, the early growth (1-5 years) of hybrid poplar clones such as Walker, Assiniboine, and NM-6 have a larger portion of their growth contained in their main stems with narrow crowns that seldom overlap. Other hybrid poplar clones such as Northwest, Hill, and DN-34 have a larger portion of their growth contained in much wider crowns that will overlap. Crown closure represents a point of reduced pressure from competing vegetation and an opportunity for enhanced growth. Hence, growth traits of each clone affect the time required to manage competing vegetation. Establishing and managing each clone individually in a block-style design will ultimately result in reduced management and long-term plantation costs while providing the opportunity to manage each block independently, if needed.

Operational Buffers

Afforestation plantations require suitable buffers to allow for equipment access and movement, including turning, around the perimeter of the planted blocks. The goal is to incorporate a buffer large enough to ensure the planted stems do not suffer damage from equipment during the life of the plantation. Individual landowners and afforestation stakeholders can determine the perimeter buffer requirements based on their equipment availability. A general rule is that a buffer of 10–15 metres around the entire perimeter of the plantation and 5–10 metres between clonal blocks is suitable to allow for the positioning and turning of equipment during operations.

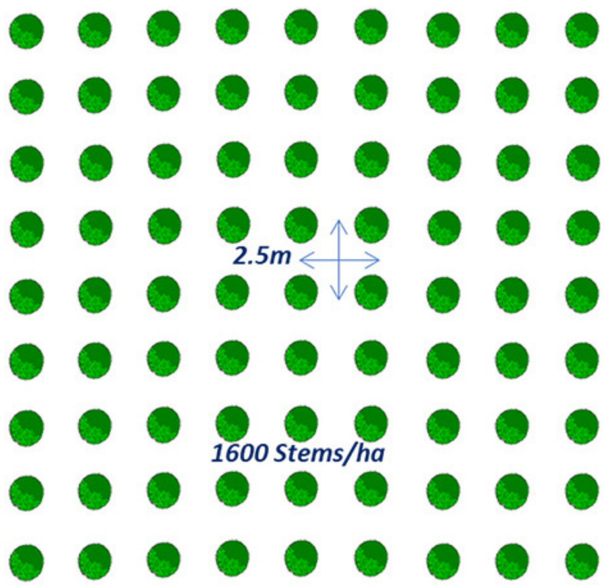
Planting Operations

While the costs of planting material and associated labour and equipment costs are significant, landowners and stakeholders should not regard planting as the most important part of the process of plantation establishment. Planting takes its place, along with site preparation and post-planting vegetation management, in assuring the overall success of establishment that favours a positive return on investment.

Afforestation planting operations require a carefully coordinated, well-designed plan that ensures the meshing of components such as planting density and design, mechanical site marking, species/clone and stock type selection, planting material preparation or conditioning, and planting methodology.

Planting Density and Design

Selecting a planting density for afforestation plantations is ultimately the responsibility of the landowners and project stakeholders and is often based on preference and equipment availability for post planting vegetation management. The goal for plantation density is to ensure an even distribution of stems over the entire area so that each tree can take equal advantage of the site's resources for rapid attainment of crown closure. Once crown closure is achieved, the reduced sunlight reaching the understory decreases vegetation management requirements. It is recommended to combine clonal growth traits and plantation density to achieve crown closure by Year 5 without limiting post crown closure growth due to overstocking. In Canada, a density of 1600 stems per hectare (2.5 metre X 2.5 metre spacing) has been successful in meeting these parameters in most locations. Various locations have been successful in meeting crown closure by Year 5 or earlier with less stems per hectare. For example, certain clones in Southern Ontario have achieved crown closure with 1111 stems per hectare (3.0 metre X 3.0 metre spacing).



A density of 1600 stems per hectare provides a safety net to achieve crown closure regardless of the clonal traits outlined in the previous "Block-Style Plantings" section. Failure to match clonal growth traits with plantation density could result in extended vegetation management requirements, increased costs, and reduced growth. This would reduce the economic feasibility of the afforestation plantation.

Mechanical Site Marking

Prior to planting, mechanical site marking ensures that the grid-style plantations are established uniformly over the site. The goal of mechanical site marking is to identify planting sites so that all trees are planted in a parallel manner with consistent spacing. This enables subsequent vegetation management treatments in a manner that does not damage planted stems. Site marking also reduces planter uncertainty in selecting the correct location and increases planter productivity. This ensures that planting operations are completed in a timely manner. Failure to conduct mechanical site marking prior to planting can create inconsistent tree spacing. Inconsistent tree spacing hinders vegetation management treatments, increases costs, and reduces growth and plantation performance.

Mechanical site marking is completed using an 80-120 horsepower tractor equipped with a specially designed marker or a cultivator/harrow that has been adapted so that only the required tines enter the soil at the desired spacing. The entire site is marked using a two-stage process to create a grid-style pattern. The first pass creates parallel marks in the soil at the desired spacing. The second pass operates in a direction perpendicular to the initial pass, again creating parallel marks in the soil at the desired spacing. This two-stage system creates a grid pattern over the entire site with the desired planting spots where marks intersect.

Species and Clone Selection

In Canada, agroforestry and afforestation plantations have been successfully established using a variety of native and exotic species that have growth consistent with the adjacent native forests. High-yield afforestation plantations are established as a means of rapidly producing fibre for use in the wood products industry and for energy to achieve high yields (8x native yields) over short rotations (12-20 years). The use of site-appropriate hybrid poplar or hybrid aspen clones provides the best option for meeting growth and yield objectives.

Operational research conducted by SRWC proponents consistently confirms the value of linking the appropriate clones to the climate and site characteristics of the plantation location. In jurisdictions across Canada, there are examples of successful high-yield afforestation plantations that provide valuable insight on clonal suitability for future high-yield afforestation projects. Local afforestation landowners, proponents, service suppliers, and government researchers are additional resources that can provide options and valuable insight for determining the appropriate clones and species. Failure to do the required “homework” associated with selecting suitable clones for the location in Canada can negatively influence the longevity and growth of afforestation plantations.

Stock Selection and Preparation

Selection of the type of planting material or stock-type requires landowners to evaluate several factors and choose the best option based on their situation. Hybrid poplar planting material is grown through vegetative propagation and is available in three forms: a) non-rooted cuttings, b) bareroot seedlings, and c) rooted container seedlings. Other species, such as hybrid aspen and conifer are grown almost entirely from seed. They are available in bareroot and rooted container seedlings. Each stock-type represents a variation in cost and risk associated with hardiness and survival.

a) Non-rooted cuttings

Non-rooted cuttings represent the least expensive stock-type option for establishing afforestation plantations. This type is produced from stems that have grown during the previous year's growing season and were harvested during the late fall and winter when the stems are dormant. The stems are processed into cuttings a minimum of 25 centimetres in length, with a minimum top diameter of 5 millimetres, and stored at -2 to -5 degrees Celsius until needed for planting.

Prior to planting, the cuttings are removed from the freezer and "conditioned" (i.e., soaked at room temperature for 24–48 hours prior to planting to break dormancy and initiate growth). It is very important that the conditioning of the planting stock be closely coordinated with the planting operations to avoid bud flush prior to planting. Within 2-4 days following planting, a viable cutting will use its stored resources to flush and begin growth. At the same time, below ground, the cutting will grow small feeder roots to collect nutrients and moisture. If cuttings "flush" during the conditioning phase prior to planting, there is a high probability of damage to the feeder roots and newly developed growth. This reduces growth and potentially increases mortality.

Once planted, non-rooted cuttings are much more vulnerable to local climatic impacts such as drought. If the feeder roots are unable to obtain the required resources within 4–7 days, it is common for the cutting to expire, a risk to be weighed against the cost savings of this lowest-cost stock type.

b) Container and bareroot seedlings

Planting operations for container and bareroot seedlings can begin when the soils reach 8-10 degrees Celsius at a depth of 15 centimetres. The objective is to plant the seedlings with a minimum of 2 centimetres and a maximum of 7 centimetres of soil on top of the container and/or all roots. To plant the seedling, first create a suitable opening with a shovel. Then place the rooted portion of the tree vertically in the hole at the required depth and compact the soil lightly atop the roots or container.

For afforestation activities, it is recommended that planting operations be stopped once the soil temperatures reach 20 degrees Celsius at a depth of 15 centimetres unless available moisture for the planting stock is not limited. The window of opportunity to complete operations is relatively short, calling for good planning and coordination.



Post-planting Vegetation Management

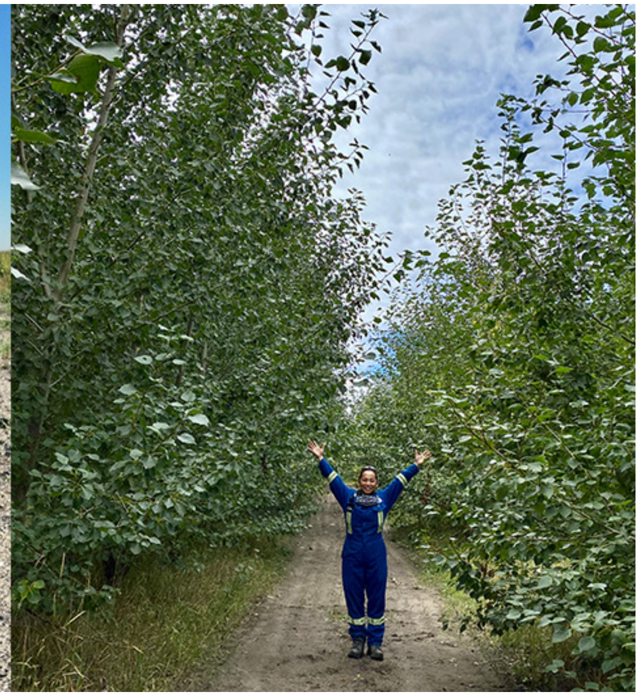
Proper vegetation management is key in reducing long-term mortality and achieving growth and yield goals for maximal potential return on investment and economic feasibility of the afforestation plantations. The objective of vegetation management treatments is to control competing vegetation in a timely manner, starting 10–14 days following planting and continuing until the first frost in the fall of each year, until the stands achieve crown closure. As the plantation grows, the amount of sunlight reaching the soils is limited. As the annual leaf litter increases, the need for vegetation management decreases.

Afforestation plantation managers can choose to complete vegetation management treatments through mechanical or chemical applications. Chemical vegetation management treatments require the use of contact-based herbicides to control the competing vegetation. Most, if not all, contact-based herbicides available in Canada are also lethal to the planted deciduous seedlings. To reduce the risk of mortality associated with accidental contact with the planted seedlings, a shrouded zero drift implement is required. Depending on the nature of the competing vegetation, multiple applications and multiple contact-based herbicides or "tank mixes" may be needed each growing season to successfully manage competing vegetation. Several factors contribute to the high cost of chemical treatment including availability and cost of zero-drift equipment, the cost of contact-based herbicide, and the costs associated with mortality risk to planted trees.

A more common approach to controlling competing vegetation in afforestation plantations is mechanical vegetation management through shallow cultivation or tillage. The added benefit of mechanical vegetation management is the incorporation of the competing vegetation into the soils, reducing emissions during decomposition and increasing organics and nutrient availability to the developing root systems of the planted seedlings. This method requires 4–5 treatments during the first two or three years of the plantation. It can then be reduced to 2–3 treatments per year until the site reaches crown closure. Mechanical vegetation management treatments require a small tractor (30–40 horsepower) equipped with either a pssive (shallow cultivator or rotary harrow) or a PTO-driven (rotary or tiller) attachment. The width of the tractor and attachment is to be limited so that neither contacts the planted seedlings. Contact with the planted seedlings can damage and/or create scars that can result in stems breaking in the future, increasing the risk of mortality. To ensure that the treatments minimize damage to establishing root systems, all equipment needs to be configured to ensure a maximum disturbance depth limited to 3–7 centimetres. The grid style design of afforestation plantations supports conducting vegetation management operations in multiple directions to maximize the treatment's effectiveness.

Occasionally, events may limit the completion of vegetation management activities resulting in the competing vegetation becoming too large for productive mechanical vegetation management activities. In this situation, a suitable option is to conduct a mowing treatment, immediately followed by a mechanical vegetation management treatment. Mowing treatments stimulate below ground growth and can increase below ground competition from competing vegetation root systems. Mowing treatments, if not immediately followed by mechanical vegetation management treatments, can also create an insulating layer atop the soil. The insulating layer can slow the soil warming processes during the spring and reduce the length of the growing season, resulting in reduced growth of the planted seedlings.

The goal is to achieve crown closure by Year 5, or earlier, at which time the plantation can control competing vegetation without treatment. Failure to manage competing vegetation throughout the growing season can result in aggressive competing vegetation concealing the planted seedlings. This results in reduced growth and increases the potential of seedling mortality.



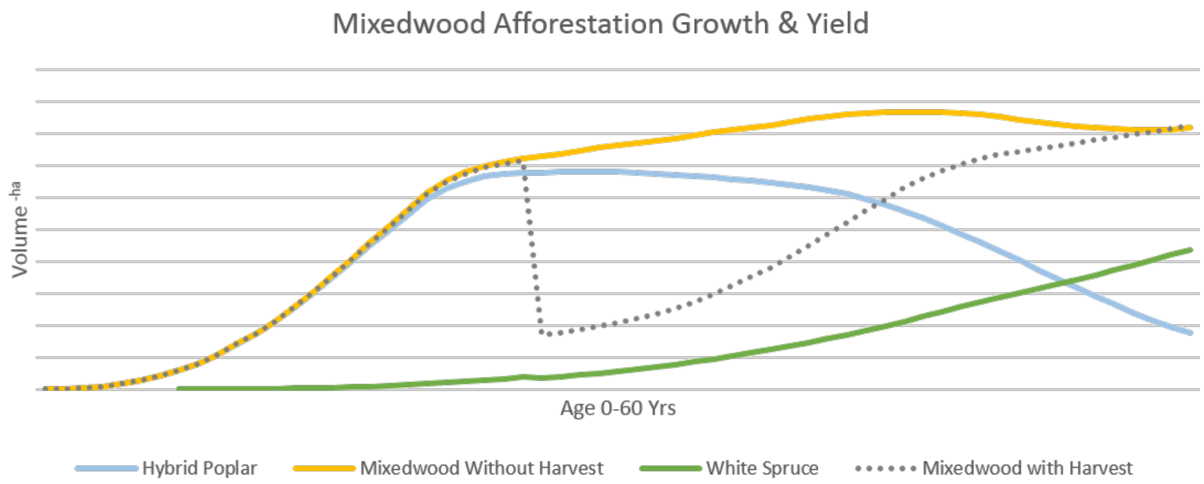
Post-Crown Closure Maintenance

Vegetation management activities to enhance growth of afforestation plantations are no longer needed once the stands have achieved crown closure. From this point forward, plantation maintenance focuses on the reduction of potential risks and aesthetic values. It targets the buffers established around the perimeter of the plantations and the buffers established between the clones, if they exist. To reduce the potential risk of fire or to limit weed encroachment from adjacent properties, a common practice is to create a non-vegetated strip around the circumference of the plantation using the equipment previously used to conduct the mechanical vegetation management treatments. Many landowners may also choose to mow the established buffers for aesthetic purposes.

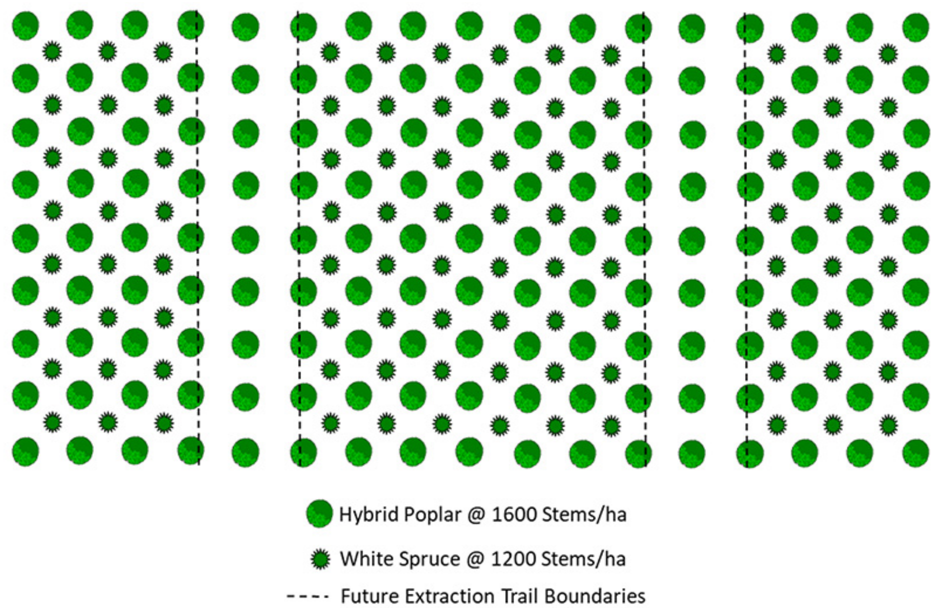
Mixedwood Afforestation Plantations

Sampling of historic afforestation plantations in Canada has shown that the plantations can continue to grow productively long after the stands have reached maximum mean annual increment (MAI). An example of this is hybrid poplar plantations exceeding 50 years of age. Many landowners, whether initially or later, may choose to augment an afforestation plantation with tolerant softwood species as an option to extend the timeframe of the afforestation plantation and/or create an afforestation plantation that mimics natural mixedwood forests.

Adding a softwood component to afforestation plantations is a proven option for increasing growth and yields, diversifying potential end-product options, and extending forest cover timeframes. To ensure that the added softwood component does not impede vegetation management operations, it is best to complete the augmentation of tolerant softwoods after the afforestation plantation reaches the crown-closure stage. The established overstory will act as a nurse crop and provide protection for the newly planted softwood trees. The scheduling of adding a tolerant softwood component to an afforestation plantation is flexible and depends on the objectives of the landowner and/or stakeholders. For best results, scheduling should ensure that vegetation management treatments have been completed and that the planted softwood seedlings have had the opportunity to establish themselves on-site prior to the harvesting of the overstory trees.



Selecting a planting density and design for augmenting afforestation plantations with tolerant softwoods is ultimately the responsibility of the landowners and project stakeholders. It is often linked to the original planting density and future harvesting operations. For example, one option is to plant the softwood seedlings at the mid-point of the "grids", creating rows of softwood between the rows of overstory trees. This results in a planting density consistent with the original plantation. To facilitate future harvesting operations to remove the overstory, it is common practice to "skip" or opt not to plant a row at 15–20 metre intervals to allow for harvesting equipment access and to reduce damage to the residual softwood trees during harvesting operations.



Harvesting Afforestation Plantations

High yield afforestation plantations are designed to produce large diameter (20–30 centimetre diameter at breast height) stems at maturity. By design, afforestation plantations are established with uniform spacing resulting in consistent stem size and spacing, which commonly result in higher harvesting operational productivity and reduced harvesting costs. Harvesting equipment required to fell and utilize the stems is consistent with harvesting equipment used in conventional harvesting operations within natural forests. Afforestation landowners can contact local service suppliers to determine the availability and applicability of harvesting equipment options for their jurisdiction.

The large diameter stems grown in high-yield afforestation plantations can be processed and used in the production of conventional forest products, such as lumber, oriented strand board, cross-laminate timbers, veneer, etc., to increase long-term carbon storage. Other product options include feedstock to make pulp for paper production and woody biomass for heat and power production. Residues resulting from the harvesting and processing operations may also be utilized to produce woody biomass that could be used for landscape mulch, industrial wood pellets, biochar, etc. depending on the availability of local processing facilities and markets.

Discussion

Afforestation using fast-growing species has been recognized worldwide as an option for carbon sequestration and ecosystem rehabilitation. Adding an afforestation component to revegetating PG stacks can also create value and provide other benefits. These benefits include biomass for green energy or wood chips, reduced maintenance costs through the elimination of mowing treatment once plantations are established, and improved aesthetics and ecosystem diversity. Research conducted on afforested PG stacks indicates that trees can utilize residual nutrients present in the PG and are able to close canopy after 2–3 growing seasons with no rain or snowmelt infiltration beyond the tree-rooting zone.

These preliminary findings provide the proof of concept for mixing a small amount of soil into PG to create a fabricated soil mixture (anthrosol). When forested, the anthrosol can limit or eliminate water infiltration beyond the tree-rooting zone. The concept of establishing afforestation plantations on PG is a more cost effective option than the historical barrier approach to reclamation, which, once proven, can reduce stack closure costs and potentially replace the use of synthetic liners in arid and semi-arid environments.

As a cover that reduces erosion and improves water quality, forests grown on PG stacks can create habitat for a wildlife (mammal and bird) species. They can also improve long-term sustainability by reducing human pressures on native forests as an adaptation and mitigation approach to address the impacts of a changing climate. SRWC can create woody biomass feedstock options for energy production through heat, power, or renewable natural gas production.

Plantations are often perceived as temporary, short-term solutions to existing issues based on their fast growth. However, sampling of historic afforestation plantations in Canada has shown that, once established, high-yield afforestation plantations have the potential to grow and remain a viable carbon storage option for 50 years and potentially longer. Plantations are continuously evaluated for benefits in rehabilitation of ecosystems, reduction of hydrological impacts, and the incorporation of tolerant conifers to extend carbon sequestration potential for 100 years or more.

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Definitions

Afforestation

The act or process of establishing a forest especially on land not previously forested.

Phosphogypsum

A gypsum by-product produced during the manufacture of phosphate fertilizer. It is composed primarily of hydrated calcium sulfate ($CaSO_4.2H_2O$) and is produced when phosphate rock is reacted with sulphuric acid to produce phosphoric acid, the main component of phosphate fertilizer.

High-Yield Afforestation

Establishing plantations to grow wood fibre and woody biomass at rates 8–10 times the growth of "native forests" on previously non-forested lands to create significant carbon sinks and produce feedstock for an evolving green or renewable energy industry, contributing to a low-carbon economy.

Phytoremediation

The treatment of pollutants or waste (as in contaminated soil or groundwater) by the use of green plants that remove, degrade, or stabilize the undesirable substances (such as toxic metals).

Short Rotation Woody Crops

A "silvicultural approach to establishing and managing fast growing plantations on previously cleared lands" established as a means of rapidly producing fibre for use in the wood products industry and for energy. They require appropriate site selection and preparation, suitable clonal planting stock and intensive management to achieve high yields over short rotations (3–20 years).

Agroforestry

Land management involving the growing of trees in association with food crops or pastures.

Anthrosol

A soil that has been formed or heavily modified by long-term human activity.

Cutting

A plant section originating from stem, leaf, or root and capable of developing into a new plant.

Vegetative Propagation

Asexual reproduction occurring in plants in which a new plant grows from a fragment or cutting of the parent plant.

Mean Annual Increment (MAI)

Average growth per year for a tree or stand of trees to a specified age.

Overstory

The upper portion of a community of plants, above the understory.

Stool Beds

A plot of ground in which plants are grown for the specific purpose of producing vegetative propagation planting stock.

Lateral Branching

Any secondary branch that grows off of the main stem.

Diameter at Breast Height

Outside bark diameter measured 1.3 metres above the ground level for regular or normal stems.

Feedstock

Raw material supplied to a machine or processing plant.

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