VEGETATION MANAGEMENT ON TAILINGS IMPOUNDMENTS RECLAIMED WITH COVERS WITH CAPILLARY BARRIER EFFECTS.

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ABSTRACT

Under humid climates, covers with capillary barrier effect (CCBE) can control oxygen migration down to reactive mining wastes to limit acid generation and water contamination. Their functioning relies on a high moisture content in one (or more) of its layers to prevent oxygen migration down to the underlying wastes.

After construction, plants coming from adjacent ecosystems may rapidly colonize CCBEs placed on tailings impoundments. If plant roots reach the water-retention layer of a CCBE, they could affect its performance by absorbing water and creating preferential paths for oxygen diffusion, at the cost of environmental pollution. Deep large diameter roots of woody species may be more threatening to CCBE functioning. Thus, trees are routinely pulled out on CCBEs. However, this woody species control may not kill the root system of resprouters (ex. poplar, willow) from which new shoots could regenerate and allow roots to survive.

This study aimed at examining the efficiency of a woody species' removal done in 2012 on a 17 years old CCBE in Northwestern Quebec, which is surrounded by mixed boreal forest. Vegetation cover and woody species density were characterized on twelve 50m transects in 2015. We also investigated the age of woody above- and below-ground parts to determine if the woody species control allowed root survival of resprouting species. Finally, the occurrence of woody species was compared before and after vegetation control.

Woody species were dominant on the site since they accounted for more than 51% of total plant presences, but total aerial cover of the vegetation remained low (38 to 67%). Woody species mean density reached 5 to 8 individuals by square meter, broadleaved species accounting for more than 70% of the individuals. Several woody individuals were clearly older than the year of the vegetation control, which demonstrated that the control did not fulfill its goal. Woody vegetation colonization increased on the CCBE, especially that of broadleaved and resprouters, despite the control.

In conclusion, the control technique used to remove woody species on CCBE should be improved or CCBEs should be considered as dynamic systems, including interactions with woody species, to predict their long-term performance.

Keywords: Acid mine drainage, Cover integrity, Roots, Vegetation control, Woody species.

INTRODUCTION

Engineered covers are used worldwide to confine reactive wastes in landfills, hazardous waste sites, and mine sites [1]. Mine wastes can contain sulphide minerals, like pyrite, which react with water and oxygen when exposed to atmospheric conditions to produce sulfuric acid, and generate acid mine drainage. The mitigation of acid mine drainage is one of the main environmental issues associated to the restoration of mine waste disposal areas [2] [3]. In particular, mine tailings, which have a great surface contact with water and oxygen due to their fine grain size, are prone to the generation of acid mine drainage. Mine tailings consist of the finely crushed ore (70% to 80% of particles between 2 µm and 80 µm) [4] that remains after valuable products are removed.

Under humid climates, different approaches are available to control AMD from tailings storage areas [5]. One of these approaches is called covers with capillary barrier effect (CCBE, [6]) and aim at controlling oxygen migration down to the reactive wastes to limit acid generation and water contamination. CCBE functioning relies on the ability to maintain a nearly water-saturated layer (i.e. water-retention layer) through which oxygen diffusion down to the underlying wastes is limited [7]. CCBEs achieve satisfactory performance at the short and medium term in laboratory and in real conditions [8], [9] [10]. However, at the longer term in situ, their physicochemical properties may be modified by interactions with the natural environment, especially plants, which could affect their functioning.

After construction, plants coming from adjacent ecosystems, in particular trees from adjacent forests (boreal forest in many mining regions in Canada), may rapidly colonize CCBEs built on tailings impoundments [11]. If plant roots reach the water-retention layer of a CCBE, they could affect its performance by absorbing water and creating preferential paths for oxygen migration, at the cost of environmental pollution. For example, in humid climates, plant transpiration can account for half the soil water loss from covers [12] while cracking due

to enhanced wetting-drying cycles [13], [14] and root biopores can increase saturated hydraulic conductivity of barrier covers by as much as three order of magnitudes [15], [16].

Deep large diameter roots of woody species [17] may be more threatening to CCBE functioning than thin and shallow roots of herbaceous species [18]. Thus, trees are routinely pulled out on CCBEs. However, this vegetation control may leave alive roots in the CCBE from which some tree species, called resprouters (ex. poplars, willows), may have the ability to regenerate shoots. If resprouting occurs after tree pulling, it could maintain old root systems alive in CCBEs, decreasing the control efficiency.

This study aimed at examining the consequences of a woody species' removal done in 2012 on a 17 years old CCBE in Northwestern Quebec, which is surrounded by mixed boreal forest. Vegetation cover and woody species density and occurrence were measured in 2015, and compared to data before control. We also investigated the age of woody above- and below-ground parts to determine if the vegetation control allowed root survival of resprouting species.

MATERIAL AND METHODS

Experimental site

The study took place on the reclaimed tailings facility of the abandoned Lorraine mine (Cu and Ni) in Quebec (47° 24' 00' N; 79° 00' 00' W) whose surface is approximately 15 ha. The Ministère de l'Énergie et des Ressources naturelles (Québec, Canada) was in charge of the tailings facility reclamation. In 1999, the acid generating tailings were covered with a CCBE made with sand and silt materials (Fig. 1). The details of its design and construction are provided in [19] [20]. CCBEs are multilayered covers minimally composed of three layers: a fine grain sized water retention layer above a coarse grain sized capillary break layer and below a protection layer against erosion, evaporation and biointrusion [9]. The CCBE was designed to account for local climatic conditions and water table levels. At this site, mean monthly precipitation varies from 35.7 mm (February) to 96.4 mm (August), and total annual precipitation is 837 mm. Mean daily temperature varies from -15°C (January) to 18.3°C (July) [21]. A gradient of water table depth is observed from the north (leveled water table) to the south (more than 2m deep water table). The site is surrounded by mixed boreal forest and a mature jack pine plantation. The CCBE was colonized by non-woody vegetation as well as eleven woody species (*Salix sp.*, *Abies balsamea* L. (Mill.), *Larix laricina* (Du Roi) K. Koch, *Alnus rugosa* (Du Roi) Spreng, *Populus balsamifera* L., *Pinus banksiana* Lamb., *Pinus resinosa* Aiton, *Populus tremuloides* Michx, *Betula papyrifera* Marshall, *Picea mariana* (Mill.) Britton and *Prunus pensylvanica* L. f.) as soon as the first year after its construction [11]. In 2012, the woody vegetation on the CCBE was controlled by pulling out woody species with a mechanical shovel.

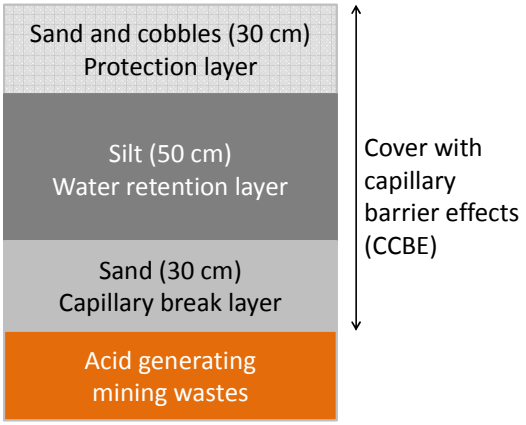

Fig. 1 Configuration of the cover with capillary barrier effect constructed at the Lorraine abandoned mine site in 1999.

Vegetation monitoring

Vegetation measurements were all performed in 2015 at maximal aerial development of the vegetation (July). Vegetation cover was evaluated along 12 north-south transects of 50-m distributed over the site area (4 transects in high water table zone, 4 transect in intermediate water table zone, and 4 transects in low water table zone). Vegetation presence was noted along 500 measurement points by transect (one point each 10 cm) using the point intercept method [22]. Plants were pooled in several groups: trees, shrubs, and others. All woody species were identified. Total vegetation cover (%) on one transect was calculated as the number of plant contact occurrence / 500 x 100. The vegetation cover was also calculated for each plant group and woody species, as well as their contribution (%) to total cover (number of occurrence for the species or group / total number of plant occurrence x 100).

Woody species number was evaluated for each species on 6-m^2 circular plots placed each 5 m along transects (10 plots by transect) to calculate their density (number / m^2) and their contribution (%) to

woody species density (number of individuals of one species / total number of woody individuals x 100). Woody species occurrence (%) was also calculated by species on each transect as the number of plots where the species was present / 10 x 100. Occurrence data were compared with data collected with the same methods before the vegetation control in 2012 (see [11]). Woody species were also segregated by functional groups, i.e. resprouters vs seeders, and broadleaved vs conifers to calculate their respective occurrence and density.

On each transect, two individuals with mean representative height were randomly sampled for four woody species (*Picea mariana*, *Populus basalmifera*, *Populus tremuloides* and *Salix sp.*). The age of the root system (first roots under the hypocotyl) and the main shoot (just above the hypocotyl) was determined by counting the annual growth rings on cross-cuts.

Statistical analyses

Each woody species or functional group occurrence was compared among measurement years with a one-way ANOVA (year factor). When year effect was significant, a Tukey-Kramer test was applied to compare means. For each considered species, a Student test was used to compare mean age of shoot vs root. All analyses were performed with the JMP software (version 12) with an overall significance set at alpha = 0.05.

RESULTS AND DISCUSSION

CCBE colonization by woody species from the adjacent boreal forest was succesful since in July 2015, fifteen different woody species were present on transects *Salix sp.*, *Abies balsamea* L. (Mill.), *Larix laricina* (Du Roi) K. Koch, *Alnus rugosa* (Du Roi) Spreng, *Populus balsamifera* L., *Pinus banksiana* Lamb., *Pinus resinosa* Aiton, *Populus tremuloides* Michx, *Betula papyrifera* Marshall, *Picea mariana* (Mill.) Britton, *Prunus pensylvanica* L. f., *Pinus strobus* L., *Comptonia peregrina L.*, *Vaccinium* sp., *Kalmia* sp.). Moreover, woody species were dominant in the vegetation, accounting for 51 to 75% of total plant presences (Table 1), which means that they are well adapted to CCBE habitat colonization. Woody species deep roots may provide them access to the water saturated part of the CCBE, allowing them to survive to water shortage. Indeed, previous studies showed that the roots of several woody species were able to colonize the water retention layer of the CCBE at the Lorraine mine site before the vegetation control [11]. In comparison, non-woody plants with shallower roots may lack water on the fast-drainage surface layer of the CCBE (sandy protection layer).

Woody species mean density reached 5 to 8 individuals by square meter, *Populus balsamifera*, *Alnus rugosa*, *Populus tremuloides*, *Salix* sp., and *Picea mariana* contributing each more than 10% to density. Except *Picea mariana* that was well represented on the site, broadleaved species seemed more adapted to CCBE colonization than conifers, since they accounted for 86 to 88% of the woody individuals.

Even if the CCBE was successfully colonized by woody species, the total vegetation cover in 2015 remained low due to the small size of the trees. Vegetation cover varied between 38 and 67% depending on the water table depth (Table 1). However, the study of shoots and roots age of four woody species revealed that this low vegetation cover was not due to the young mean age of woody species, that was greater than 6 years (Table 2). This result may rather illustrate that aerial growth of woody species was limited on the CCBE. Yet on mineral substrates like the sandy protection layer of the CCBE, woody species colonization is possible but seedling growth can be restricted by nutrient limitations, especially nitrogen [23].

Contrarily to what was expected, the control of the CCBE vegetation performed in 2012 did not result in a mean age of woody species populations lower than 3 years (due to their establishment between 2012 and 2015). Indeed, we found woody individuals which were clearly older than the year of the control, some dating from the first years of the CCBE construction (16 and 17 years) (Table 2). These results highlight that the vegetation control did not remove efficiently all the woody plants from the CCBE.

Table 1 Vegetation cover (%) and density (Number of individuals by m^2) in July 2015 on the cover with capillary barrier effect of the abandoned Lorraine mine among zones of differing water table level (high, intermediate, low), as well as contribution to cover and density (%). Mean, N=4.

		High	Interm.	Low
Total vegetation cover	%	67	48	38
Tree contribution to vegetation cover	%	16	31	18
Shrub contribution to vegetation cover	%	35	38	57
Woody species density	$Nb.m^{-2}$	6	8	5
Broadleaved contribution to woody species density	%	86	86	88

Table 2 Mean and maximal ages of the shoot and root systems of four woody species occurring in July 2015 on the cover with capillary barrier effect constructed on the Lorraine abandoned mine site. Mean (SE), N=24. Similar letters indicate means that do not differ at the 0.05 level among shoots and roots.

	Salix sp.	*Populus balsamifera*	*Populus tremuloides*	*Picea mariana*
Mean age of the roots	8.5 (0.6) a	7.4 (0.6) b	6.8 (0.6) a	8.0 (0.6) a
Mean age of the shoots	7.3 (0.6) a	5.6 (0.7) a	6.8 (0.5) a	10.7 (0.6) b
Maximal age of the roots	17	13	13	13
Maximal age of the shoots	14	11	13	16

Roots of *Populus balsamifera* population were nearly two years older than shoots, which means that resprouting occurred on the CCBE for this species (Table 2). The vegetation control may have participated to this age difference by allowing resprouting of new shoots from roots that were not killed by tree pulling. However, since our sampling included individuals with shoots older than three years, i.e. not impacted by the control operations, the older age of roots cannot only be associated to persistence of alive roots in the CCBE due to resprouting after vegetation control. Other causes can kill aerial parts of woody species and induce their resprouting from the root parts, for example herbivory, fire [24], and crushing by machinery [25]. The other considered species with resprouting abilities, *Salix sp*. and *Populus tremuloides*, did not show significant differences between shoots and roots age. Thus they may be less prone to resprouting on the CCBE environment than *Populus balsamifera*.

Picea mariana is not a resprouting species and was used only to study the efficiency of control operations on the CCBE. The mean age of the sampled population shoots was clearly older than 3 years (10 years, Table 2), which highlights that the success of control operations was low for this species. Its roots had a lower mean age than the shoots, probably because this species is known to develop new adventitious roots from the shoots that replace the original root system that was formed concomitantly to the main shoot [26].

The control operations did not appear efficient to decrease woody species occurrence. On the contrary, their occurrence was significantly greater after the vegetation control compared to years before the vegetation control, for both seeders and resprouters, as well as broadleaved ($p<0.0001$, Fig. 2). In particular, *Alnus rugosa*, *Picea mariana*, *Populus tremuloides* and *balsamifer*a, as well as *Pinus strobus* individually showed greater occurrence in 2015 compared to all other measurement years. This result shows that woody vegetation progresses on the CCBE, especially broadleaved and resprouters, despite the woody vegetation control. Increasing colonization may be due to progressive enrichment of the protection layer in organic matter along the 17 years of vegetation presence, that may be associated to improved water retention and nutrient reserves.

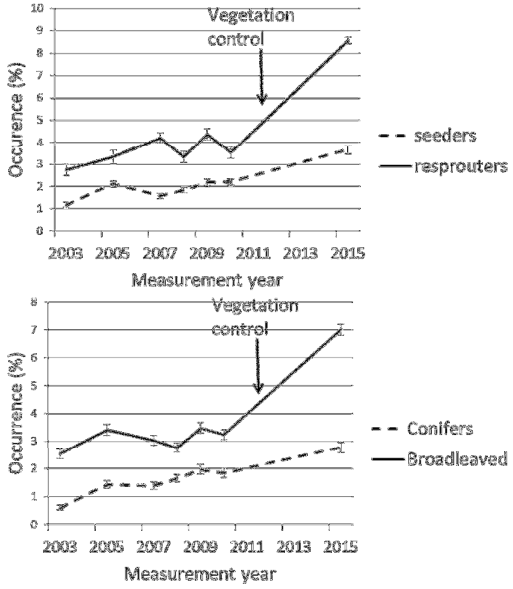

Fig. 2 Woody species occurrence before and after (July 2015) the vegetation control performed in 2012 on the cover with capillary barrier effects constructed at the abandoned Lorraine mine site. Species are pooled by functional groups: a) plants reproducing by seeds vs plants resprouting from roots; b) coniferous vs broadleaved plants. Mean (N=12).

CONCLUSIONS

In conclusion, the 17 years old cover with capillary barrier effect constructed at the Lorraine site constitutes a favorable habitat for colonization by woody species, especially broadleaved, but not for their aerial development at the medium term. Restricted development may reduce woody plants possible effects on the CCBE performance. However, low aerial growth is not always correlated to low root growth ('balanced growth' hypothesis, [27],

[28]), especially when resources associated to the substrate are heterogeneously distributed (like water in the CCBE). Caution would imply to quantify woody plants effects on CCBE functioning, especially root effects, and integrate it to their design since vegetation control operations did not succeed in removing them. CCBEs should be considered as dynamic systems, including interactions with woody species, to predict their long-term performance.

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