Oxygen migration through a cover with capillary barrier effects colonized by roots.

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Title: Oxygen migration through a cover with capillary barrier effects colonized by roots

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Abstract:

Covers with capillary barrier effects (CCBE) are multilayered oxygen barrier covers used in humid climates to reclaim reactive mine tailings and limit the generation of acid mine drainage. Once constructed, CCBEs are colonized by surrounding plants. Roots modify water storage and respire oxygen. The performance of CCBEs could evolve over time due to root colonization. Twenty-five plots with varying vegetation were investigated at a seventeen-year-old CCBE in the mixed forest of Québec, Canada. Geotechnical parameters and root colonization of the moisture-retaining layer (MRL) of the CCBE were characterized. The performance of the MRL to control oxygen migration was assessed using oxygen consumption tests and numerical modeling. Despite root colonization at the surface of the MRL, oxygen fluxes generally complied with the CCBE’s design criteria. Roots presence created oxygen consumption in the MRL, which could be expressed with a reactivity coefficient ($K_r$). A positive correlation ($R^2 = 0.65$) was found between root length density and $K_r$. Oxygen consumption by root respiration helped to lower oxygen fluxes by 0.5 to 76 g/m²/yr with an average of 13 g/m²/yr. These results will help to better understand the influence of roots on CCBEs’ performance to control oxygen migration.

Key words: Oxygen barrier cover in forest environment, root respiration, oxygen consumption test, acid mine drainage, vegetation impact, numerical modelling
1. Introduction

One of the most significant environmental risks in mine tailings storage facilities (TSF) is the formation of acid mine drainage (AMD). AMD occurs due to the oxidation of sulfide minerals when they are exposed to water and atmospheric oxygen. The AMD is generally characterized by low pH values and high metal concentrations (Kleinmann et al. 1990; Blowes et al. 2003; Demers et al. 2009). In humid climates such as that of Québec, where the average annual precipitation is around one meter per year (Government of Canada 2016), preventing water infiltration into tailings can be challenging. Therefore, limiting oxygen migration to the reactive tailings is usually the preferred reclamation approach in such regions (Aubertin et al. 2000; Johnson and Hallberg 2005).

Several techniques currently exist for controlling oxygen migration, including: water covers (e.g. Aubertin et al. 1999; Yanful et al. 2004; Awoh et al. 2012) and engineered soil covers (Yanful et al. 1999; Aubertin et al. 1995) such as monolayer covers with elevated water table (e.g. MEND 1996; Ouangrawa et al. 2006; Demers et al. 2008), geosynthetic clay liners (Adu-Wusu and Yanful 2006; Renken et al. 2005) and covers with capillary barrier effect (CCBE) (Nicholson et al. 1989; Yanful et al. 1993a,b; Wanful et al. 1999; Aubertin et al. 1995; Aubertin et al. 1999; Lundgren 2001; MEND 2001; MEND 2004; Bussière et al. 2003; Bussière et al. 2006; Molson et al. 2008).

A CCBE is an oxygen barrier cover that is comprised of a minimum of three layers (Aubertin et al. 1995). Its effectiveness as an oxygen barrier is based on its capacity to maintain a (fine-grained) moisture-retaining layer (MRL) at a high degree of saturation (Sr). Because oxygen migrates $10^3$ to $10^4$ times more slowly in water than in air (Hillel 1998; Chapuis and Aubertin 2003), the saturation of the MRL limits oxygen fluxes. High saturations are maintained in the MRL by placing layers of coarse-grained materials above [protection layer (PL)] and below [capillary break layer (CBL)] the MRL (Aubertin et al. 1995; Bussière et al. 2003; Morel-Seytoux 1992).
reported in the literature typically aim to maintain $S_r$ values in the MRL greater than 85% and have
O$_2$ fluxes below 20 to 40 g.m$^{-2}$.yr$^{-1}$ (Nastev and Aubertin 2000; Ricard et al. 1997; Dagenais et al.
2001). CCBE design is performed using the hydrogeological properties of the cover materials (e.g.,
porosity, saturated hydraulic conductivity, and water retention curves) and the boundary conditions
applied to the cover system (e.g., precipitation, evaporation, transpiration and water table level).
Studies on the design and in situ testing of CCBEs have been documented in numerous
publications (e.g., Nicholson et al. 1989; Yanful et al. 1993a,b; Yanful et al. 1999; Aubertin et al.
1995; Aubertin et al. 1999; Lundgren 2001; MEND 2001; MEND 2004; Bussière et al. 2003;
Bussière et al. 2006; Molson et al. 2008).
Following construction, CCBEs can support vegetation, which can be established either through
active revegetation that is part of a reclamation design (Tordoff et al. 2000), or through natural
recolonization (Guittonny-Larchevêque et al. 2016; Smirnova et al. 2011). It has been
demonstrated that CCBEs meet or exceed performance expectations in the short and medium term
(<10 years) (Dagenais et al. 2001; Bussière et al. 2006; Bussière et al. 2009; Mbonimpa et al.
2011), despite possible influences from vegetation. In the longer term, roots could have significant
and contrasting impacts on important parameters controlling the effectiveness of CCBEs. For
example, root colonization could modify the porosity of the cover’s material (Bodner et al. 2014;
Sasal et al. 2006; Angers and Caron 1998), create preferential pathways (Scanlon and Goldsmith
1999), change the materials’ water retention curve (Jotisankasa and Siritannachat 2017), decrease
the degree of saturation or increase suction through water pumping (Yan and Zhang 2015), and
finally consume oxygen via respiration (Lambers et al. 2008). However, the overall influence of
vegetation on the performance of CCBEs has not yet been documented, thus there is a strong need
to better understand potential long-term impacts.
The effect of plants on CCBE effectiveness likely could change with plant type and species. Since most herbaceous plants have shallow root systems located in the first 50 cm of soil (Jackson et al. 1996), a thick protection layer at the surface of a CCBE should be able to limit the impacts of such species. In contrast, trees and shrubs grow deeper root systems (Jackson et al. 1996) that can reach depths of 75 to 200 cm in dry soils of the boreal forest (Strong and La Roi 1983). Thus, woody roots could potentially penetrate the MRL of a CCBE in forested environments. However, some root growth can be limited by highly saturated soils (Boggie 2016). In such cases, species with tolerances to high saturations, such as willows and poplars (Jackson and Attwood 1996; Gong et al. 2007), could still be considered as threats to the MRL. Fine roots (< 2 mm diameter) will absorb most of the water (Lambers et al. 2008), and their total length in a given soil volume is a good indicator of overall water consumption (Zhang et al. 2009). Oxygen consumption rates generally increase with root length density (RLD) (Cook et al. 2007) but respiration rate of roots decreases while in highly saturated soil (Cook and Knight 2003).

The main goal of this study was to characterize the geotechnical and root colonization properties of a 17-year-old CCBE at a mine site in Québec, Canada. The performance of the CCBE was evaluated with respect to its ability to limit oxygen fluxes passing through the cover to values lower than the established design criteria of 20 to 40 g of O₂/m²/year (Nastev and Aubertin 2000). Oxygen consumption tests (OCTs) were used to estimate oxygen fluxes. Following its construction, the CCBE was gradually recolonized by the surrounding vegetation of the mixed forest. The impacts of different vegetation types and species (i.e., herbaceous, broadleaf, coniferous) are considered here, with a focus on woody species. The relationships between the morphological parameters of roots colonizing the MRL (i.e., RLD, biomass, and diameter) and the parameters influencing O₂ diffusion into the materials [i.e., degree of saturation (Sᵢ), reactivity...
coefficient ($K_r$), effective diffusion coefficient ($D_e$), and porosity ($n$) are also studied. The present work links geoenvironmental engineering with plant biology and will enable better integration of the effects of vegetation into the design of CCBEs.

The main research hypotheses were: i) roots exist primarily in the upper portion of the MRL due to the high $S_r$ in deeper parts of the MRL, and under typically deep-rooted species like Salix sp.; ii) a negative correlation exists between RLD, and the $S_r$ of the MRL; iii) roots colonizing the MRL consume oxygen, resulting in increases in observed $K_r$ values; iv) a positive correlation exists between RLD and $K_r$.

2. Materials and methods

2.1. Experimental site

The Lorraine mine site is located near Latulipe-et-Gaboury in the Témiscamingue region of Québec (47° 24' 00' N, 79° 00' 00' W). Gold, silver, copper, and nickel were extracted for a total of four years (from 1964 to 1968), after which the mine was abandoned leaving behind approximately 600,000 tons of acid-generating tailings over an area of 15.5 ha (Dagenais et al. 2001; Genty et al. 2016). In 1999, the Québec Ministry of Energy and Natural Resources decided to reshape the tailings storage facility, build a CCBE over the tailings, install limestone drains to passively treat acidic effluents (Nastev and Aubertin 2000; Potvin 2009), and implement a monitoring program (Dagenais et al. 2001). Since then, the site has returned to a seminatural state, with native vegetation growing over the CCBE. The site is in the Balsam fir-yellow birch domain and is surrounded by a mixed forest (MFFP 2016). A mature jack pine plantation can be found nearby (Guittonny-Larchevêque et al. 2016). Colonization of the CCBE by native vegetation was studied from 2003 to 2008 (Smirnova et al. 2011) and later in 2015 (Guittonny-Larchevêque et al.)
2016a) to identify the dominant plant species as well as their cover and density levels. The average monthly precipitation at the site varies between 36 mm (February) and 96 mm (August) for a yearly total of 837 mm. The water table is close to the surface in the northern portion of the CCBE, but can reach up to 2 m deep in the southern portion (Bussière et al. 2009). The average daily temperature ranges between -15 °C in January and +18 °C in July (Government of Canada 2016). The main technical objectives for the CCBE were to maintain a minimum Sr of 85% in the MRL at all times, and to have maximum oxygen fluxes reaching the tailings of 20 to 40 g/m² year (Dagenais et al. 2001). The materials used in the construction of the CCBE were characterized for their grain-size distribution (GSD), Effective diffusion coefficient (Dₑ), saturated hydraulic conductivity (k_sat), water retention properties, and dry density. Using these properties, a three-layered design was selected that was comprised, from bottom to top, of: (1) a 30-cm thick uniform sand (SP) (according to the USCS classification; Bowles 1984) capillary break layer; (2) a 50-cm thick non-plastic inorganic silt (ML) moisture-retaining layer; and (3) a 30-cm thick sand and gravel protection layer used to minimize the effects of evaporation and erosion on the MRL (Dagenais et al. 2001) (Table 1). More information on the design and the configuration of the CCBE can be found in Nastev and Aubertin (2000), Dagenais et al. (2001), Dagenais et al. (2005) and Bussière et al. (2009).

2.2. Vegetation

In 2012, most of the woody vegetation was removed from the CCBE using an excavator. In 2015, a monitoring study found that herbaceous species (e.g.: Poaceae), Cyperaceae, Ericaceae, shrubs and trees were present on the site (Guittonny-Larchevêque et al. 2016). Overall, 15 different woody species were found during the study, accounting for 51 to 75% of the total plant cover. Of these
species, five of them each accounted for more than 10% of the number of woody individuals per square meter: balsam poplar, \textit{Populus balsamifera} L. (28%); alder, \textit{Alnus rugosa} (Du Roi Spreng) (22%); willows, \textit{Salix} Sp. (16%); black spruce, \textit{Picea mariana} (Mill.) (14%); trembling aspen, \textit{Populus tremuloides} Michx (12%). Four of these species were selected for the present study, including one per genus. \textit{Populus balsamifera} was selected over \textit{tremuloides} due to a higher number of individuals on site. The mean measured age of individuals was, in 2016, over seven years old, despite the 2012 efforts to control the vegetation (Guittonny-Larchevêque et al. 2016).

2.3. \textit{Experimental design}

Five squares monitoring zones (50×50m) were randomly selected in the southern portion of the CCBE (Figure 1). The southern part was selected because the water table is below the CCBE, while in the northern part the water table is inside the MRL. Thus, in the northern part the performance of the CCBE may be independent of the presence of vegetation. In each zone, five plots corresponding to five different vegetation types were randomly selected. The five vegetation types corresponded to one of the four dominant woody species (\textit{Populus balsamifera}, \textit{Alnus rugosa}, \textit{Salix} Sp. and \textit{Picea mariana}) or to dominant herbaceous vegetation. Young woody individuals were occasionally found on the herbaceous plots, but this was assumed to have no impact on the MRL. All plots dominated by a woody species needed to have at least one individual of the selected species with a minimum age of five years old. Other species could also be found on each plot, but the targeted species were clearly dominant (> 50%) in terms of aerial biomass.

2.4. \textit{Oxygen consumption tests}

Oxygen consumption tests were first developed by Elberling et al. (1994). They consist in a closed and monitored gas chamber over tailings and are used as a rapid and precise method for
determining instantaneous sulfide oxidation rates. This method assumes that the oxygen migration into tailings is mainly due to diffusion (Nicholson et al. 1989). Fluxes entering tailings are therefore modeled using Fick’s second law with first order reaction kinetics (Eq. 1).

$$D_e \frac{d^2C}{dz^2} - K_r C = 0 \quad (Eq. 1)$$

where $D_e$ is the effective diffusion coefficient of oxygen, $C$ is the oxygen concentration, $z$ is depth, and $K_r$ is the reactivity coefficient of the material. Assuming the boundary conditions $C(z) = C_0$ at $z = 0$ and $C(z) = 0$ as $z \to \infty$, the steady-state oxygen flux at the top of the tailings can be estimated by Eq. 2 (Elberling et al. 1994).

$$F_{so} = C_0 \sqrt{K_r D_e} \quad (Eq. 2)$$

where $C_0$ is the initial concentration of oxygen in the chamber’s headspace. When the area ($A$) and volume ($V$) of the headspace are known, $K_r D_e$ can be obtained from the slope of the plot of $\ln\left(\frac{C}{C_0}\right)$ vs. time ($t$). For further details on this OCT method, the interested reader is referred to Elberling et al. (1994) and Elberling et al. (1996).

In the present study, OCTs were performed to assess the impact of roots on the oxygen fluxes migrating through the CCBE at Lorraine. Whereas the original OCT method proposed by Elberling et al. (1994) was intended to determine oxygen fluxes passing through reactive tailings at the surface, Mbonimpa et al. (2003) and Dagenais et al. (2012) proposed a modified method to evaluate oxygen fluxes reaching reactive tailings underneath oxygen barrier covers, such as CCBEs. Their method uses longer cylinders to penetrate through the depth of a cover, as well as longer measurement periods (typically from 3 to 5 days). Since longer measurement periods usually violate the assumption of a steady-state flux, oxygen fluxes must then be calculated using...
a numerical model instead of the simplified Fick’s second law (Eq. 2). At the Lorraine site, OCTs
were performed using a 10-cm diameter aluminum cylinder that was inserted into the CCBE such
that the whole depth of the MRL was penetrated (Figure 2). The cylinder was then sealed with a
cap to create a headspace with a height between 1 and 10 cm. Decreases in the concentration of
oxygen in the headspace were monitored over a period of 3 to 5 days just after cylinder insertion
(Proteau et al. 2019). Eventual roots enclosed in the cylinder were assumed to respire O₂ during
the test at the same rate as before cylinder placement. However, after the aerial part of the plant
was removed and roots were cut, in this case by the cylinder placement, the rate of oxygen
consumption could vary. Nevertheless, it has been shown to remain the same (Makita et al. 2013)
or to decrease slowly during the first couple of days after the section of roots (Lipp and Andersen
2003; Marshall and Perry 1987). The assumption of constant respiration by roots despite cylinder
placement thus produces realistic yet slightly conservative results for oxygen consumption by roots
in the MRL.

Oxygen and CO₂ concentrations in the headspace were measured periodically using a syringe and
a portable gas chromatograph (GC; HDT5 3000 Micro GC Gas Analyzer, ± 10 ppm). Volumetric
water contents (θ\textsubscript{w}; VWC) were measured using an ECH\textsubscript{2}O EC-5 probe (± 0.03 m\textsuperscript{3}/m\textsuperscript{3}) that was
inserted vertically at the surface of the MRL (0 - 5 cm). A matrix-specific calibration was
performed on the EC-5 probe in the lab using a soil sample from the CCBE. The volumetric water
content was measured every 5 minutes, and CO₂ and O₂ concentrations were measured every 2
hours. For each zone, five OCTs were performed and each test was conducted in plots with
different vegetation types. This process was repeated for the five zones (25 OCT in total). The
plots were named according to the vegetation type [A: Alnus rugosa, E: Picea mariana (“Épinette”
in French), H: Herbeacous only, P: Populus balsamifera, S: Salix Sp.] and the zone’s number from
1 to 5. (eg. Plot P4 was the *Populus balsamifera* containing plot of the fourth zone where the OTCs where made). Oxygen flux through the CCBE was determined by using the POLLUTE software (Rowe et al. 1998). This software solves the second Fick’s law, with oxygen concentration data from the headspace and the MRL’s material properties as the input data. The following parameters were also required: equivalent porosity ($\theta_{eq}$), Darcy’s velocity ($v = 0$), the half-life degradation ($t^{*1/2}$), and the coefficient of hydrodynamic dispersion ($D^{*} = D_e \theta_{eq}^{-1}$). The equivalent porosity (Eq. 3) is a parameter that was introduced to account for the oxygen transport that occurs in both air- and water-filled pores (Aubertin et al. 1999; Aubertin et al. 2000).

$$\theta_{eq} = \theta_a + H \theta_w \quad \text{(Eq. 3)}$$

where $\theta_a$ is the volumetric air content, $\theta_w$ is the volumetric water content and $H$ is the dimensionless Henry’s equilibrium constant ($\sim 0.03$ at 20 °C). The $D_e$ parameter was estimated using a semi-empirical expression (developed by Aachib et al. 2004) that is based on the porosity and the volumetric air and water contents of the material (Eq. 4).

$$D_e = 1/n^2 \left( D_a^0 \theta_a^P + H D_w^0 \theta_w^P \right) \quad \text{(Eq. 4)}$$

where $D_a^0$ and $D_w^0$ are the O₂ diffusion coefficients in air and water, respectively; and $p_a$ and $p_w$ are related to the tortuosity of the interstitial gas and liquid phases, respectively. As suggested by Aachib et al. (2004) values, $p_a = p_w = 3.4$ were used.

In the model, a parameter is included to define the reactivity of a soil called the reactivity coefficient ($K_r$). Because the MRL is made of an inert silty material, in the initial model $K_r=0$ was used. Roots, on the other hand, could consume oxygen during their respiration (Lambers et al. 2008), thus creating a biologic-based $K_r$. Since respiration also produces CO₂, oxygen depletion from respiration should be coupled with an increase in CO₂ concentrations. After the initial
simulation of the OCTs using $K_r = 0$, an iterative method was used to find a $K_r$ to explain the
differences between the in situ measurements and modeled values. In POLLUTE, $K_r$ cannot be
directly inserted but is related to a half-life constant as shown in Eq. 5.

$$t_{1/2}^* = \ln 2 / K_r^* = \theta_{eq} \frac{\ln 2}{K_r} \quad (\text{Eq. 5})$$

Using these parameters and Eq. 6, it is possible to calculate the oxygen flux reaching the tailings
at the bottom of the MRL (Mbonimpa et al. 2003).

$$F_{SR,L} = F_{S,L} + 2K_r^*F_{S,L} \sum_{i=1}^{\infty} \left[ \frac{(-1)^i}{i^2\pi^2D^* + K_r^*} \right] \quad (\text{Eq. 6})$$

where $F_{S,L}$ is defined by Eq. 7, $K_r^*$ is defined in Eq. 8, $D_e^*$ is defined in Eq. 9, and $L$ is the depth of
the MRL.

$$F_{S,L} = \frac{C_0 D_e}{L} \quad (\text{Eq. 7})$$

$$K_r = \theta_{eq} K_r^* \quad (\text{Eq. 8})$$

$$D_e = \theta_{eq} D^* \quad (\text{Eq. 9})$$

2.5. Soil characterizations

After the OCTs, three samples with a diameter of 8 cm and height of 10 cm were taken directly in
the cylinder at depths of 0-10 cm, 20-30 cm, and 35-45 cm (Figure 2). These samples were washed
and sieved to collect the roots. Roots were scanned and the images were analysed using
WinRHIZO (regular version, Regent Instruments, Inc., Sainte-Foy, Québec). This software
provides the root volume density (total root volume / volume of soil sample) and root length
density (RLD = total root length / volume of soil sample) of the sample, which are indicators of
root colonization (Guittonny-Larchevêque et al. 2016b). Roots were also oven-dried for 48 h at
65 °C to measure the dry root mass of the samples (normalized to the soil volume). Soils were also sampled at two locations in each plot that were 50 cm from the center of the plot (Figure 3). Three samples were collected at depths of 0-10 cm, 20-30 cm, and 35-45 cm (R samples), for a total of nine samples per plot (including the three cores inside the OCT cylinder). These samples were processed the same way as those taken from the OCT cylinders.

Additionally, a double-cylinder core sampler of 100 cm$^3$ was used to take eight undisturbed samples per plot at four different depths (0-5 cm, 10-15 cm, 25-30 cm, and 40-45 cm from the top of the MRL; P samples; Figure 3). The variation of porosity as a function of depth in the MRL was measured by saturating the samples with water under vacuum, then fully drying the samples in an oven at 100 °C. The total porosity of each sample was calculated using Eq. 10.

\[
\frac{Saturated\ sample\ mass - dry\ sample\ mass}{Sample\ volume} = n \quad (Eq.\ 10)
\]

Six bulk samples per plot were collected with an auger at depths of 0 cm, 20 cm, and 35 cm (L samples; Figure 3). These samples were used to determine GSD (Malvern Mastersizer 2000 Laser Diffraction, ± 0.02 μm, ASTM designation: D422-63) and gravimetric water content (oven drying for 48 hours at 60 °C; ASTM D2216-10). Degrees of saturation (S_r) were calculated at various depths using mass-volume relationships. Organic matter (OM) contents were also measured using the calcination method (burning at 375 °C for 16 hours and weighing before and after; MA. 1010 – PAF 1.0). This method had a limit of detection of ~ 1%. All samples used for OM analyses were taken at 50 cm from the center of each plot.
2.6. **Statistical analyses**

Linear relationships were analysed with Pearson correlation tests with a p-value < 0.05 significance level between root parameters (RLD, root biomass density, and root volume density) and soil parameters (K_r, n, and S_r). The effects of sampling depth on the soil parameters used in the CCBE performance assessment with POLLUTE (n and S_r) and root length density were tested with one-way ANOVA analyses using depth as the fixed factor and zone as the random factor. Analyses were performed with XLSTAT with an α of 0.05.

3. **Results**

3.1. **Soil properties of the MRL**

Of the 25 OCTs that were performed, 18 produced data that were interpreted. Table 2 shows the values obtained from the various characterizations performed on the 18 plots. In those plots, the porosity varied from 0.29 to 0.38 (\(\bar{x} = 0.34 \pm 0.03\) 1SD). The D_{10} and D_{60} varied from 1.87 mm to 3.57 mm (\(\bar{x} = 2.47 \text{ mm} \pm 0.42\) 1SD) and 10.68 mm to 23.44 mm (\(\bar{x} = 16.46 \text{ mm} \pm 3.39\) 1SD), respectively, across all plots. Due to the low variability in porosity and GSD, the plots were considered to be similar from a hydrogeological perspective. The volumetric water content was measured at the top of the MRL and varied from 0.22 to 0.37 (\(\bar{x} = 0.32 \pm 0.04\) 1SD). The degree of saturation ranged from 0.76 (at plot S1; only four measurements were < 0.85) to 0.99 (at plots A2, E2, H2, P3, S2). The mean S_r was 0.93 ± 0.07 (1SD). The S_r values used for each plot were the average value measured by the ECH2O EC-5 probe during the whole OCT. The root length density was highly variable, with a minimum of 17 m/m³ and a maximum of 5303 m/m³ (\(\bar{x} = 1653 \pm 1700\) 1SD).
3.2. Oxygen consumption tests

After comparing the results of field measurements with the results obtained by numerical modelling (using the measured soil properties), the plots were separated into two distinct groups (A and B). Plots in Group A, which included A2, A5, E1, E2, E5, H1, H2, H3, H5, P1, P3, P5, S2, and S5, generally showed slower or similar modeled rates of oxygen consumption with respect to the field measurements. In contrast, Group B, which included plots A3, E3, S1, and S3, had modeled oxygen consumption rates that were faster than those calculated from field measurements. Further details on each group are provided below.

**Group A**

For Group A (N = 14), it appeared that oxygen was migrating on par with or slightly faster than what was predicted by POLLUTE (see Figure 4). All group A plots had Sr values above 0.85 (see Table 2). One assumption to explain these discrepancies could be the consumption of oxygen by roots. Including a Kr value > 0 in the numerical model to take into account oxygen consumption by roots improved the fit of the model with respect to measured O2 concentrations (Figure 4). The Kr values were inferred and varied between 1.2E-8 sec⁻¹ and 1.0E-5 sec⁻¹, with a mean value of 1.4E-6 sec⁻¹. The De values were calculated and varied between 1.94E-11 m²sec⁻¹ and 4.09E-9 m²sec⁻¹ with a mean value of 7.14E-10 m²sec⁻¹ (Table 3). These values for De are close to what was expected and previously measured (Dagenais et al. 2001) whereas Kr values imply an oxygen reactivity. Those results are discussed further in the discussion.

CO₂ production in the OCT cylinders was used to validate that the observed reactivity was due to biological activity, whether from the respiration of roots or decomposition of organic matter. Results from four stations typical of Group A are presented in Figure 5. The CO₂ concentrations
increased significantly from atmospheric values (≈ 400 ppm) to values between 3000 and 8000 ppm after 40 hours, thus confirming the presence of biological activity. The production of CO₂ did not appear to be due to the presence of organic matter in the soil since the OM concentrations in the MRL were lower than the detection limit of the method, regardless of the sampling depth. Only two plots had OM concentrations that were slightly over the detection limit: 1.11% for E3 and 1.02% for P1. Therefore, the variability in OM concentrations could be attributed to methodological factors and regarded as insignificant. Root length density at the top of the MRL (0-10cm) had the strongest linear correlation with calculated Kᵣ values (R² = 0.65, p < 0.01) (Figure 6).

Group B

Plots in Group B (N = 4) showed modelled oxygen consumption rates that were faster than what was observed from field measurements (Figure 7). Almost all of the plots in Group B were from Zone 3, and all of the plots had Sᵣ values < 0.85. Because Sᵣ values were only measured near the surface of the MRL, and since a desaturation can be observed at the interface between the PL and the MRL, one possible explanation for the discrepancies between the predicted rates and empirical observations is that the Dᵣ values could be overestimated if the Sᵣ values in the entire MRL were underestimated. It has been shown in other work that the deeper parts of the MRL are usually highly saturated (Dagenais et al. 2001)

Measurements of porosity and water content outside the cylinder were used to calculate the Sᵣ and to validate this hypothesis for plots in Group B. Porosity was approximately the same across both groups and along the depth of the CCBE, with mean values by depth between 0.34 and 0.37 (Figure 8). Degree of saturation values calculated using the samples taken outside the OCT cylinders at
different depths showed no significant variation along depth or across groups, with all values
> 0.85, except for the top portion of the MRL for samples in Group B where $S_r$ values were
typically < 0.80 (Figure 8). To explain the lower $\theta_w$ values measured near the top of the MRL in
Group B, comparisons of the presence of roots along depth profiles of the MRL were performed.
In both groups, RLD was clearly greater at the 0-10 cm interval than in deeper parts of the MRL
at a 0.95 confidence interval (p-value < 0.0001) for both groups, as shown in Figure 9. At the
Lorraine site, these measurements showed that root impacts were mainly limited to the first 10 cm.
The linear correlation analysis revealed that RLD and $S_r$ were negatively related (Figure 10) at the
surface of the MRL (0-10cm).

Since the RLD of Group B (3286 m/m³) was three times higher than that of Group A (1018 m/m³),
$S_r$ values measured at the top of the MRL were lower in group B than in group A. It is thus fair to
assume that the readings of the ECH2O probe placed in the OCT cylinder were accurate.

However, those readings were only from the top 10 cm of the MRL and not representative of the
overall saturation of the MRL. Numerical modeling of the group B OCTs’ was therefore redone
using $S_r$ more indicative of the whole MRL. Because the observed oxygen consumption rates were
relatively low in Group B (especially at plots A3 and S3), the upper end of the standard deviation
bracket of Group B’s $S_r$ at depth 35-45 (= 0.93 – see Figure 8) was used for modeling the OCTs
performed on Group B. Inferred $K_r$ values for Group B (1.40E-7 to 1.82E-6 sec⁻¹), which resulted
in improved fits with respect to the observed results, were similar to those measured in Group A
(see Table 4).

As was the case with Group A, CO2 was produced during the OCTs for Group B. Results from the
four plots of Group B are presented in Figure 11. CO2 concentrations increased significantly from
atmospheric values (≈ 400 ppm) to values between 3000 and 12000 ppm after 40 hours, suggesting
the consumption of O₂ by root respiration.

Oxygen fluxes

Oxygen fluxes at the base of the MRL were calculated using the $D_e$ and $K_r$ determined through
umerical modeling of the OCTs (Table 3 and 4; Eq. 5). Calculated fluxes represent the
effectiveness of the CCBE in terms of controlling oxygen migration into the Lorraine tailings. It
is also possible to remove $K_r$ from Eq. 6 to obtain the expected flux if no roots were present. As
shown in Figure 12, the flux of O₂ at the base of the MRL stayed under the design objective of 20
to 40 g O₂/m²/year for every plot, except for plot A5, which had a flux of 45.3 g O₂/m²/year. The
minimum calculated flux was of 2.3E-5 g O₂/m²/year, and the mean was 2.86 g O₂/m²/year (± 4.80
g O₂/m²/year, 1SD). In contrast, when fluxes were calculated without any reactivity ($K_r = 0$) the
minimum flux was 0.38 g O₂/m²/year and the maximum was 79.81 g O₂/m²/year ($\bar{x} = 16.18$ g
O₂/m²/year ± 24.74, 1SD). Two plots, H5 and A5, had calculated fluxes that exceeded the design
criteria when $K_r$ was not included in the model. However, in all other cases the flux was either
within or lower than the target range.

4. Discussion

Here will be discussed the colonization of the MRL by roots, its impact on $S_r$, $K_r$ and the overall
impact it has on the oxygen fluxes that go through the MRL.

4.1. Root colonization in the MRL

As suggested by our first hypothesis, root colonization that occurred in the MRL was mostly
limited to the upper 10 cm. The average measured RLD was of 1490 m/m³ in the top 10 cm, 130
m/m³ in the middle section (20 to 30 cm), and 97 m/m³ in the lowest section (35 to 45 cm).
However, roots were found in the MRL of all plots (regardless of the woody species present), including plots with only herbaceous vegetation. Based on our observations, surface vegetation was not a good indicator of the presence of roots in the MRL of this CCBE. Other studies in similar climates and environments (boreal forests) have demonstrated that most of the root biomass (83%) is limited to the upper 30 cm of a soil (Jackson and Attwood 1996). At the Lorraine site, this would suggest that most of the roots are confined to the CCBE’s protection layer. Some roots were found in the deepest part of the MRL but their average RLD was low. Other studies have shown that the maximum depth attained by plant roots in boreal climates is 2 m (Canadell et al. 1996). However, those observations were made on loamy and sandy soils where roots grow more easily than in fine, compacted materials with low porosities like the silt comprising the studied MRL (Dexter 2009; Lipiec and Hatano 2003). In fact, roots can also have a hard time growing in soils with a high degree of saturation, such as soil with high water-table (Boggie 2016). On the other hand, some studies made in boreal regions have shown that roots are present in soils with saturation levels similar to those found in the CCBE’s MRL (Gaumont-Guay et al. 2006). Some species are adapted to temporary flooding, including willows and poplars (Jackson and Attwood 1996; Gong et al. 2007). This justifies the finding of roots (in small quantities) in deeper parts of the MRL despite the high degree of saturation.

4.2. Root colonization and saturation of the MRL

Despite root colonization in the MRL, measured $S_r$ values appeared, in most cases, to be high enough to maintain the CCBE’s performance [$\geq 0.85$ (Bussière et al. 2009)]. However, the $S_r > 0.85$ criterion was not met at the surface (0 - 10 cm) of the MRL at four locations (plots S1, A3, E3 and S3). In plots where $S_r$ was above the targeted value (0.85), the average RLD in the top 10 cm was of 880 m/m$^3$, while in plots under the 0.85 threshold the average RLD in the top 10 cm was
4359 m/m^3. These observations confirmed the hypothesis that the degree of saturation would be negatively impacted by root length density ($R^2 = 0.71$). Linear correlations between $S_r$ and other root parameters, such as root biomass ($R^2 = 0.53$) and root volume ($R^2 = 0.49$), were also tested but were less significant. Root length density is a parameter that is commonly used to represent the extent of root colonization in soils (Angers and Caron 1998; Lipiec and Hatano 2003; Joslin et al. 2000). All roots that were analysed in the MRL were fine roots (diameter < 2 mm). Since water uptake by roots primarily occurs in fine roots (Lambers et al. 2008), the significant correlation between root colonization density and degree of water saturation could be expected. The mean RLD was 130 m/m^3 in the middle (20 to 30 cm) of the MRL and 97 m/m^3 in the lowest part of the MRL (35 to 45 cm); RLD values did not exceed 610 m/m^3 at these depths. Since these values were relatively low, it is unlikely that roots exerted a significant influence over the degree of saturation at the base of the MRL. Using direct measurements (i.e., gravimetric water contents), it was observed that $S_r$ values were indeed higher than the 0.85 threshold in the deeper parts of the MRL.

4.3. **Root colonization and reactivity coefficients ($K_r$)**

In previous studies of the Lorraine CCBE, OCTs were performed while not taking into account the potential for oxygen consumption since it was expected that only diffusion would be occurring in the first few years (Dagenais et al. 2012). Generally, calibration of the model used to interpret OCT results consists of fitting the modeled results to the observed results by manually adjusting the diffusion coefficients ($D_e$ and $D^*$). In the present study, some of the measured soil parameters were either too high ($S_r$) or too low ($D_e$) to explain the rate at which oxygen concentrations decreased during the OCTs. In fact, in some cases, an unrealistic adjustment of the $D^*$ of two orders of magnitude (from $10^{11}$ to $10^9$) would have been required to better fit the empirical data with the
model. Introducing a $K_r$ value to the model seemed to be a more realistic approach given that CO$_2$ effluxes were observed during the OCTs (indicating root respiration and O$_2$ consumption).

As mentioned previously, all roots in the MRL were fine, and such roots contribute the most to oxygen consumption by respiration (Lambers et al. 2008; Makita et al. 2009). Accordingly, a good level of correlation was observed between the RLD and $K_r$ ($R^2 = 0.65$), which was the fourth hypothesis. Soil biological oxygen consumption is primary driven by two processes: autotrophic respiration, which is performed by roots, and heterotrophic respiration, which is performed by microorganisms that break down organic matter (Bond-Lamberty et al. 2004; Chen et al. 2017; Olsson et al. 2005). In the present study, organic matter concentrations were too low to measure in the MRL silt (< 1%). This suggests that autotrophic respiration is likely dominant and would help to explain the high linear correlation between $K_r$ and RLD.

In the four plots where $S_r$ was under 0.85, it was not possible to measure a $K_r$ with the observed $S_r$ value. Since the degree of saturation measured at the top of the MRL was low, the expected diffusion coefficient was high, meaning that the expected measured oxygen depletion rate should have been high. However, the bulk consumption/diffusion rates of O$_2$ that were recorded on site at those four plots were similar to those modeled with a $S_r > 0.85$. This is mainly due to the high degree of saturation of the lower portion of the MRL. This portion of the MRL controls oxygen migration through the cover, with the less saturated upper portion having a negligible impact. Therefore, using a plausible $S_r$ value representing the whole MRL, it was possible to calculate a $D_e$ and then extract a $K_r$ value; values obtained using this method were in the same range as those modeled for the other plots.
4.4. **Impact of roots on oxygen flux and the overall performance of the CCBE**

Using the calculated $K_r$ values, it was possible to evaluate the oxygen fluxes through the CCBE. Root colonization appeared to have a noticeable impact on oxygen fluxes reaching the base of the MRL. Using eq.4 and considering a non-reactive silt (without the integrated $K_r$), calculated $O_2$ fluxes were lower than the performance criteria of 20-40 $g O_2/m^2/year$ (except for two plots where they were close). These results show that the CCBE works relatively well even if the vegetation is taken out of consideration. However, when considering reactivity due to root presence (with the calculated $K_r$), calculated oxygen fluxes are reduced further. Plant roots actually consume part of the oxygen that is slowly flowing through the MRL. For stations with an estimated oxygen flux greater than 10 $g O_2/m^2/year$, the average reduction in flux ($Flux \text{ without } K_r - Flux \text{ with } K_r$) was approximately 34.2 $g O_2/m^2/year$ due to root respiration.

It is important to take into account that increases in RLD were generally matched by decreases in $S_r$. Therefore, more significant root colonization could affect the degree of saturation of the MRL and be harmful to the CCBE’s performance. Nevertheless, 83% of root biomass is usually found in the top 30 cm of soil in boreal region (Strong and La Roi 1983). This shows the importance of having a thick protective layer that can help to lower evapotranspiration and confine plants roots to the upper layer of a CCBE. For the Lorraine CCBE, where root colonization occurred mainly in the top of the MRL (10 cm), vegetation did not impair the CCBE’s effectiveness, even 17 years after construction. Even if water uptake by roots could increase with greater RLDs (Zhang et al. 2009), it is not likely that roots would colonize the whole depth of the MRL in a boreal context. As mentioned earlier, plants have difficulties to elongate their roots in the absence of air in the soil where they grow (Grable and Siemer 1967) and deeper colonization of the MRL, where saturation remains high, is improbable. This means that the probability of significant root colonization as
deep as 80 cm is quite low. Another impact that roots could have had is a change of the MRL’s porosity. However, porosities measured in the present study were similar to those obtained by Dagenais et al. (2001) at a time when vegetation was not present on the CCBE. Thus, this possible impact was not observed in this study.

Overall the results of this study suggest a net positive impact on the CCBE’s performance as a result of more than 17 years of plant root colonization. By consuming oxygen, roots help the CCBE to control oxygen fluxes and lower the risk of tailings oxidation. By staying in the top part of the MRL, roots do not decrease the degree of saturation below the required threshold in the lower part of the MRL. Integrating biological effects like root colonization into the design of CCBEs could help to optimize their performance with respect to limiting oxygen migration. In a similar manner, low-sulfide tailings (< 0.3 % S) were used as construction materials for oxygen barriers like CCBEs or monolayer covers (Demers et al. 2008; Ethier et al. 2018). Those materials have been used to create slightly reactive covers that consume part of the O₂ migrating through an MRL. This was shown to further limit oxygen flux in covers, at least until the depletion of the sulfides. Similar modelling with POLLUTE was performed on such covers, and it is thus possible to compare their reactivity coefficients with those calculated in the present study. The calculated Kᵣ among all plots at the Lorraine CCBE varied from 1.2E-8 to 1.0E-5 s⁻¹, while low-sulfide covers have had Kᵣ values ranging from 1.0E-9 to 2.0E-5. Even if no pyrite was present in the Lorraine CCBE, the roots’ oxygen consumption created a Kᵣ that was similar to those of desulfurized tailings covers. However, unlike in desulfurized tailings covers, the reactivity of roots should not decrease with time.
5. Conclusion

Evaluating the effectiveness of engineered covers used to limit oxygen flow and control acid mine drainage production is essential to validating cover designs. In this study, some biological effects of plant roots were included for the first time in the evaluation of a CCBE’s effectiveness. The authors present a modified approach to the oxygen consumption test interpretation that considers the presence of roots in the cover. The main modification to the OCT was the relation of root colonization with the oxygen reactivity coefficient. Using POLLUTE to interpret the OCT made it possible to create a root-based oxygen reactivity coefficient. It was shown that it is possible to assess the impact of the quantity of roots present in a CCBE on the oxygen fluxes passing through it. Root length density showed strong positive correlations with $K_r$ and negative correlations with $S_r$, thus suggesting overall effects of root colonization on a CCBE’s effectiveness. Since the depth of root colonization remained limited 17 years after construction, it was concluded that the integrity and effectiveness of the CCBE was maintained. The results showed that the fluxes of oxygen through the CCBE stayed under the design target and that roots helped in lowering this flux. The presence of roots could be considered in future oxygen barrier cover designs and could help to limit oxygen fluxes. However, since roots could also have impacts on other soil parameters, such as hydrogeological properties, further research is necessary.

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Table 3. Calculated reactivity coefficient (K_r), effective diffusion coefficient (D_e), and water saturation level (Sr) for plots in Group A.

Table 4 Calculated reactivity coefficients, diffusion coefficients, and saturations for Group B plots.
Table 1. Properties of materials used in the Lorraine CCBE (Dagenais et al. 2001).

| Properties         | Silt       | Sand        |
|--------------------|------------|-------------|
| $D_{10}$ (mm)      | 0.001 to 0.002 | 0.06 to 0.15 |
| $C_u$              | 5.1 to 7.1  | 2.5 to 3.3  |
| $G_s$              | 2.8        | 2.7         |
| $k_{sat}$ (cm/s)   | $2.2 \times 10^{-6}$ to $1.1 \times 10^{-5}$ (n from 0.38 to 0.48) | $7.2 \times 10^{-3}$ (n = 0.38) |
| Suction at $S_r = 0.9$ (kPa) | 28.4 to 49.0 (n from 0.38 to 0.46) | 2.5 (n = 0.38) |
| $D_e$ (m$^2$/s)    | $3.1 \times 10^{-9}$ ($S_r = 0.91$, n = 0.39) | - |

$D_{10}$ and $D_{60}$: grain diameter at 10% and 60% passing, respectively; $C_u$: uniformity coefficient corresponding to ratio of $D_{60}$ by $D_{10}$; $G_s$: specific gravity of the solid particles; n: porosity
Table 2. Porosity (N = 8 per plot), grain size properties (N = 6 per plot) Volumetric Water Content (VWC), Water Saturation level (Sr) and Root Length Density (RLD) of the MRL at plots used for the OCTs. VWC, Sr, and RLD were measured directly in the 0-10 cm samples from the inside of the OCT cylinders.

| Dom. Sp. Plot ID | Alnus Rugosa | Picea mariana | Herbaceous plants | Populus balsamifera | Salix sp. |
|-----------------|--------------|---------------|-------------------|---------------------|-----------|
| A2              | 0.33 ±0.02   | 0.29 ±0.04    | 0.29 ±0.03        | 0.29 ±0.03          | 0.29 ±0.02|
| A3              | 0.37 ±0.03   | 0.32 ±0.03    | 0.32 ±0.03        | 0.37 ±0.02          | 0.36 ±0.02|
| A5              | 0.38 ±0.02   | 0.30 ±0.02    | 0.33 ±0.02        | 0.35 ±0.02          | 0.36 ±0.02|
| A1              |              |               |                   |                     | 0.31 ±0.03|
| A2              | 0.37 ±0.03   | 0.30 ±0.02    | 0.33 ±0.02        | 0.34 ±0.03          | 0.37 ±0.02|
| A3              | 0.38 ±0.02   | 0.36 ±0.02    | 0.36 ±0.02        | 0.34 ±0.03          | 0.36 ±0.02|
| A5              | 0.36 ±0.02   | 0.36 ±0.02    | 0.36 ±0.02        | 0.35 ±0.02          | 0.36 ±0.02|

| Dom. Sp. Plot ID | VWC | Sr | RLD (m.m⁻³) | D₁₀ (µm) | 1SD | D₆₀ (µm) | 1SD |
|-----------------|-----|----|-------------|----------|-----|---------|-----|
| A2              | 0.33 | 1.00 | 556         | 2.49     | ±0.18| 17.62   | ±0.63|
| A3              | 0.33 | 0.99 | 2781        | 2.35     | ±0.02| 22.79   | ±0.17|
| A5              | 0.38 | 0.95 | 603         | 2.55     | ±0.12| 16.70   | ±1.16|
| A2              | 0.37 | 0.99 | 1118        | 2.45     | ±0.18| 17.37   | ±0.98|
| A3              | 0.38 | 0.99 | 4917        | 2.63     | ±0.02| 17.06   | ±1.08|
| A5              | 0.36 | 0.83 | 335         | 2.90     | ±0.23| 24.22   | ±0.61|
| A2              | 0.37 | 0.99 | 706         | 2.56     | ±0.13| 16.99   | ±0.61|
| A3              | 0.36 | 0.99 | 2864        | 2.53     | ±0.13| 17.10   | ±0.93|
| A5              | 0.36 | 0.95 | 225         | 1.95     | ±0.16| 17.73   | ±1.09|
| A2              | 0.34 | 0.99 | 436         | 2.54     | ±0.15| 11.21   | ±0.59|
| A3              | 0.33 | 0.96 | 744         | 2.47     | ±0.15| 15.63   | ±0.43|
| A5              | 0.31 | 0.90 | 5303        | 2.61     | ±0.17| 16.80   | ±1.12|
| A2              | 0.34 | 0.97 | 357         | 2.38     | ±0.17| 16.61   | ±1.76|
| A3              | 0.33 | 0.99 | 1764        | 2.47     | ±0.18| 16.46   | ±1.27|
| A5              | 0.31 | 0.99 | 4435        | 2.70     | ±0.18| 19.73   | ±1.40|
| A2              | 0.31 | 0.92 | 1587        | 2.54     | ±0.19| 13.55   | ±0.71|
| A3              | 0.31 | 0.93 | 1587        | 2.54     | ±0.19| 17.79   | ±0.62|
| A5              | 0.31 | 0.95 | 1587        | 2.54     | ±0.19| 17.79   | ±0.62|
Table 3. Calculated reactivity coefficient (K_r), effective diffusion coefficient (D_e), and water saturation level (S_r) for plots in Group A.

| Plot | S_r | D_e (m^2/sec) | K_r (sec^{-1}) |
|------|-----|---------------|----------------|
| A2   | 0.99| 2.0E-11       | 1.3E-06        |
| A5   | 0.90| 4.1E-09       | 6.2E-08        |
| E1   | 0.95| 4.6E-10       | 9.6E-08        |
| E2   | 0.99| 1.9E-11       | 7.5E-07        |
| E5   | 0.95| 3.7E-10       | 4.5E-07        |
| H1   | 0.98| 3.2E-11       | 1.9E-08        |
| H2   | 0.99| 2.2E-11       | 1.4E-06        |
| H3   | 0.96| 2.1E-10       | 1.0E-05        |
| H5   | 0.90| 4.0E-09       | 5.7E-07        |
| P1   | 0.95| 4.6E-10       | 1.2E-08        |
| P3   | 0.99| 2.3E-11       | 2.4E-06        |
| P5   | 0.97| 1.2E-10       | 4.2E-07        |
| S2   | 0.99| 2.2E-11       | 8.8E-07        |
| S5   | 0.97| 1.1E-10       | 8.1E-07        |
Table 4 Calculated reactivity coefficients, diffusion coefficients, and saturations for Group B plots.

| Plot | S<sub>r</sub> used | D<sub>e</sub> (m<sup>2</sup>.sec<sup>-1</sup>) | K<sub>r</sub> (sec<sup>-1</sup>) |
|------|------------------|------------------|------------------|
| S1   | 0.93             | 1.06E-09         | 1.82E-06         |
| A3   | 1.37E-09         | 1.40E-07         |
| E3   | 1.33E-09         | 4.53E-07         |
| S3   | 1.21E-09         | 2.48E-07         |
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