CASE STUDY: PERFORMANCE OF THE OPERATING DEMONSTRATION-SCALE CONSTRUCTED WETLAND TREATMENT SYSTEM AT MINTO MINE

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ABSTRACT

The Minto Mine is following a phased approach for the design and implementation of a Constructed Wetland Treatment System (CWTS) for water treatment at closure. The CWTS is currently in the demonstration-scale and optimization stage preceding full-scale implementation. The CWTS has successfully treated constituents of potential concern in the mine site's sub-arctic continental climate. *Carex aquatilis* (aquatic sedge) and aquatic mosses (bryophytes) from natural wetlands onsite were used for planting, while water mine-impacted seepage water was used as feed water. The CWTS was designed to target specific physicochemical parameters for treatment (confirmed and refined through off-site pilot-scale testing), which enable denitrifying, selenium-, and sulfate-reducing bacteria to treat nutrients, metals and metalloids in the water. The CWTS treated targeted constituents of potential concern in the following extents and percentages (averages): cadmium 80% (from 0.0261 µg/L to 0.0092 µg/L), copper 65% (from 49.1 µg/L to 17.3 µg/L), molybdenum 58% (from 6.3 µg/L to 2.7 µg/L), selenium 89% (from 4.0 µg/L to 0.5 µg/L), zinc 98% (from 49.2 µg/L to 1.9 µg/L), and nitrate as N 97% (from 6.5 mg/L to 0.19 mg/L). Continued trials are underway in 2018 to investigate treatment under a wider range of operational conditions.

KEY WORDS

Semi-passive water treatment, sustainability, biogeochemistry, microbial community profiling, constructed wetland treatment systems, mine closure management.

INTRODUCTION AND BACKGROUND

The Minto Mine is an open pit and subsurface copper mine located 240 km northwest of Whitehorse in the Yukon Territory. As a result of mining activities, cadmium, copper, molybdenum, selenium, zinc, and nitrate are slightly elevated beyond background concentrations and have been identified as constituents of potential concern (CoPCs) in the Reclamation and Closure Plan for the Minto Mine. As part of the

Reclamation and Closure Plan, a constructed wetland treatment system (CWTS) is being implemented at the Minto Mine with the objective of attaining suitable semi-passive water treatment at closure.

For a CWTS to be effective, it must be designed, piloted, optimized, implemented, and maintained in a site-specific manner (Rodgers et al., 2008, Haakensen et al., 2015). The Minto Mine CWTS followed this process, allowing for site-specific improvement and optimization through modifications at each step. The approach used at Minto Mine includes the following phases: 1) site assessment and information gathering, 2) technology selection and conceptual design development, 3) pilot-scale testing and optimization in a controlled environment, 4) on-site demonstration-scale confirmation and optimization, and 5) full-scale implementation. Minto Mine is currently in phase 4, and the operation and performance at this phase is the focus of this paper.

The phased approach for Minto Mine was initiated with a site assessment in 2013 that identified local plants suitable for a CWTS as well as biogeochemical treatment processes that were naturally occurring on-site (Contango Strategies, 2014). Following the site assessment, pilot-scale testing was undertaken with the purpose of determining which local plants and substrate types should be used in the CWTS for remediation of mine effluent and runoff water. The demonstration-scale CWTS was constructed at Minto Mine in August 2014 and commissioned from 2015 through mid-2017. The demonstration-scale CWTS was designed to target conditions favorable for the establishment of microbial populations, including denitrifying, selenium-reducing, and sulphide producing bacteria. These bacteria are the driving force of many treatment pathways that target the CoPCs for Minto Mine at closure, including cadmium, copper, molybdenum, selenium, zinc, and nitrate.

The commissioning period is defined as the period between the construction of the CWTS and confirmation of expected treatment performance. During the commissioning period, operational adjustments were performed, including changes to water depth and outflow patterns, and plant and microbial populations established and matured. The demonstration-scale CWTS passed all commissioning criteria by mid-August 2017 and was monitored for operational performance until freeze-up mid-September 2017. The system was monitored according to a regimented schedule in 2017, the results of which are detailed in this report, including: operating conditions, water treatment performance, fate, and distribution of treated metals, and microbial community characterization.

METHODS

Demonstration-Scale Design and Construction

The construction of the demonstration-scale CWTS was completed in 2014 and includes two series in parallel with two cells in each series and a common downstream catchment for return to the site wide water management system (Figure 1).

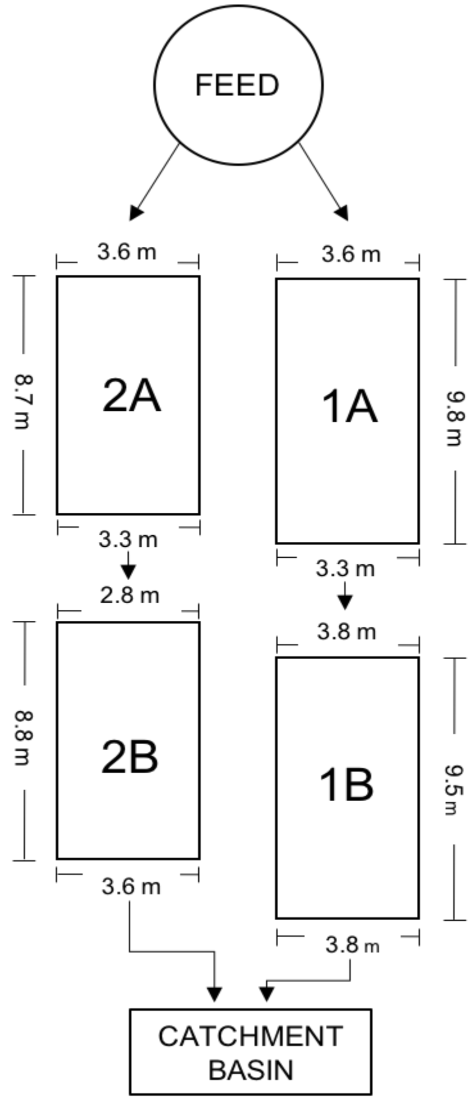

Figure 1: Diagram of Demonstration-Scale CWTS.
Dimension measurements are indicated at soil surface at time of construction. Water flow direction is indicated with black arrows. Series 1 and series 2 flow independently of each other, and serve as replicates for comparison of variable modifications.

Water flows from the feed tank through the A cells, through the B cells and into the final combined catchment basin. Series 1 and series 2 flow independently of each other and are intended as replicates for analytical testing and operation confirmation, as well as comparison of when variables are modified (Figure 1). Water for the demonstration-scale CWTS was sourced from a sump that collects mine-impacted seepage water from waste rock, dry stacked tailings, and construction-grade fill rock, and resembles the chemistry of predicted closure water quality. The recommended substrate for the CWTS was sand with 2-7% v/v organic material (e.g., woodchips). However, the material used in demonstration-scale CWTS construction was an organic peat taken from stockpiled material that originated from the construction of an open pit on site as this was the material available at the time of construction. The soil used also had much higher available copper concentrations (between 148-608 µg/L) than the material that had originally been tested and sourced for use (between 5.46-29.6 µg/L). This constituted a 95% increase in available copper compared to the originally selected substrates. These elevated concentrations have been taken into consideration regarding wetland performance as copper treatment in the CWTS has been masked by leaching from the substrates into the water. However, copper leaching has now been mostly remedied through treatment of copper into more stable sulphide forms in the substrate (Contango Strategies, 2016).

Substrate used in construction was also a different particle size distribution, higher in organic content, and lower in sand than substrate used in pilot-scale testing (and construction specifications). These changes affected the constructability, hydrology, and interactive pore space of the CWTS. The targeted overlaying water depth is 20 cm (+/- 5 cm) and is designed to have a uniform flow field to prevent potential hydrology issues. Each level cell of the CWTS was constructed at a lower grade than the previous, thereby flowing the influent water passively through the system.

Plants used in both the pilot- and demonstration-scale CWTS were *Carex aquatilis* (sedge) and mosses found at the Minto Mine site during the 2013 site assessment. *C. aquatilis* was selected for the CWTS at Minto Mine as it was the only emergent macrophyte growing abundantly in the area. While vegetation does not directly treat the CoPCs (other than some minimal nitrate uptake as a nutrient) it provides: food for the microbial populations that catalyze the targeted reactions, structural stability, and enhances accessibility of substrates, and therefore treatment capacity, through evapotranspiration. Aquatic mosses (bryophytes) were also added to the CWTS as they are endemic to the area and can assist in removing metals and metalloids from water through sorption, leading to a coupled process of biomineralization. As such, higher concentrations of metals and metalloids are expected to be found in CWTS moss. Because moss is not a significant food source for any known fauna (Haines and Renwick, 2009; Longton, 1997; Suren and Winterbourn, 1991), its use in the CWTS is a safe mechanism to transfer elements from water into stable mineral forms. Five sedges were planted per square meter, with moss initially tied to stakes that outline the 1 m^2 grid and moss later supplemented in between grids (Contango Strategies, 2015). The system matured as expected through commissioning, with plants becoming more established and abundant, and microbial communities maturing and acclimating to targeted conditions as seen in vegetation sampling.

Commissioning

The commissioning period was separated into 2 parts, named A and B. Commissioning period A ran from 2015 to July 2016 (Contango, 2017), and focused on evaluation of construction and the effectiveness of *C. aquatilis* and moss transplantation. Since performance expectations were not met during the first year, commissioning period B then occurred from July 2016 to August 2017 and was focused on treating the additional copper load from the substrates through the addition of organics (additional electron donors for sulphide mineralization of the oxidized copper in the substrates). The added organics (straw and woodchips) represented an amount of organic material similar to what would be produced by the CWTS once fully established with *C. aquatilis.*

Hydraulic Retention Time

Hydraulic retention time (HRT) is a calculation of the duration of time water is retained in the CWTS from inflow to outflow. The HRT was purposefully varied during the commissioning of the demonstration-scale CWTS to target the desired conditions needed for CWTS establishment. To obtain equivalent HRT between the two series, flow rates for cells in series 1 were set faster than series 2 as the cells in series 1 are slightly larger due to construction variances. Flow is regulated by adjustable valves at the feed tank and monitored with an inline flow meter. For the operational period, the targeted HRT for series 1 and series 2 was five days. This was the longest HRT possible with the flow meters used and was a desirable HRT to aid in generating reducing conditions in the CWTS.

Microbial Processes

The demonstration-scale CWTS was designed to target conditions favorable for the establishment of microbial populations, including denitrifying, selenium-reducing, and sulphide producing bacteria. These bacteria are the driving force of many treatment pathways that target the CoPCs for Minto Mine at closure, including cadmium, copper, molybdenum, selenium, zinc, and nitrate. Therefore, denitrifying and selenium-reducing and sulphide-producing microbial populations were monitored for abundance and diversity. Diversity and proliferation of these desired subsets of the overall microbial population is considered beneficial to treatment and enhances the overal robustness of the CWTS.

Nitrate is a CoPC during mine operations and early closure conditions. Nitrate concentrations can inhibit selenium and sulphate treatment (and associated metals and metalloids requiring sulphide for treatment). However, many denitrifying microorganisms also reduce selenium, thereby making it easier to decrease high concentrations of selenium (which do not exist at the Minto Mine), but more difficult to achieve low aqueous selenium concentrations in the presence of nitrate.

The design of the CWTS targets the proliferation of selenium-reducing bacteria, including both selenate- and selenite-reducing bacteria. The pathway for removal of selenium species can be directly performed on soluble selenate and selenite, or by a coupled reaction including sorption to mosses and organics, followed by the reduction to the insoluble elemental selenium (Se).

Sulphides, which are essential for the treatment of calcophile forming metals and metalloids such as Cu, Cd, Mo, and Zn, can be produced through reduction of sulphur-containing compounds, such as sulphate (SO_4^{2-}), sulphite (S^{2-}), thiosulphate ($S_2O_3^{2-}$) and elemental sulphur (S).

CWTS Performance Monitoring

Explanatory parameters are quantifiable aspects of a CWTS environment that can be used to explain and assess performance and treatment mechanisms. These include dissolved oxygen (DO), pH, oxidation-reduction potential (ORP), and soil oxidation-reduction potential (soil redox). These are specifically targeted by the design of the system and used to guide operations, being modifiable through defined actions for optimization or corrections (Haakensen et al., 2015). Conductivity and temperature were also monitored, as they help explain observed results (e.g., dilution, evaporation, freezing, etc). Monitoring of explanatory parameters in the demonstration-scale CWTS followed a planned schedule.

Monitoring of the CWTS performance is coordinated through a planned sampling and monitoring schedule. Water samples analyzed for total metals, dissolved metals, anions, and ammonia were collected weekly from the feed tank, outflow of each cell, and catchment. Water samples for total and dissolved metals were also collected at cell inflow and mid-locations monthly to assess dissolution of copper and other elements from the substrates, and a more comprehensive suite of analytes was collected from the outflow.

Soil redox potential was used to monitor CWTS maturation and confirm targeted reducing conditions in the soil of the CWTS. The targeted soil redox potential was -100 mV to -250 mV, based on fundamental principles of biogeochemistry, and reined by information gathered through pilot-scale testing. In these ranges, bacterial denitrification, selenium-reduction, and sulphide-production are expected. Sulphide production directly results in metals and metalloid treatment for CoPCs such as cadmium, copper, molybdenum, nickel, lead, and zinc by precipitation as metal sulphides (Equation 1). As soil redox potential stabilizes within the targeted range, the proportion, abundance, and activity of denitrifying, selenium- reducing, and sulphide-producing microbes increases. During CWTS construction, each cell was equipped with six platinum tip electrodes (copper wired probes) permanently installed in the soil to measure the relative oxidation-reduction (redox) potential of the soil (Faulkner, Patrick, & Gambrell, 1989). Vegetation samples of *C. aquatilis* and mosses were collected annually, and analyzed for metals content.
Soil samples were analyzed seasonally (three times per year) for a suite of soil parameters to inform biogeochemical processes and mineral stability. Microbial samples were also collected seasonally, with samples of each cell comprising detritus, moss, soil, and plant roots. Microbiology samples were assessed for the quantity and identity of organisms present and classified into groupings of those relevant to the targeted treatment processes. The total abundance of microbes and beneficial microbes was also characterized from these samples. The analysis of multiple sample types allowed for better understanding of biogeochemical processes occuring in the CWTS.

$$\text{Organic Carbon} + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$$

$$HS^- + M \leftrightarrow MS + H^+$$

M = metals (e.g., Cd, Cu, Fe, Mo, Ni, Pb, Zn)

Equation 1: Example equation of sulphate reduction and resultant metals mineralization and treatment. Demonstrates sulphate reduction with creation of alkalinity and sulphides, which can then form metal sulphide complexes. Adapted from Contango, 2016.

RESULTS AND DISCUSSION

Explanatory Parameters

As expected, conductivity remained relatively stable through commissioning into operations and pH remained circumneutral (Table 1), while temperature experienced typical seasonal fluctuations. DO concentrations in the CWTS during the operational period were on average 5.3 mg/L, which is within aerobic ranges (> 2 mg/L). Elevated DO in the water column is likely the result of photosynthesis by algae and mosses. Despite the elevated DO, stable reducing conditions were achieved in CWTS substrates (Table 1). Reducing conditions are needed for nitrate and selenium treatment processes, and for creating metal sulphides that remove copper and cadmium from the water. Water ORP also decreased compared to 2016, which is also indicative of reducing conditions in the CWTS.

Soil redox is a key explanatory parameter used to confirm that reducing conditions are being achieved in the CWTS. The soil redox decreased on average during the commissioning periods and stabilized by the end of commissioning-B. Stable soil redox measurements contributed to the transition into the operational period. At the end of 2016, the demonstration-scale CWTS had begun achieving soil redox values that are conducive to sulphide production due to the decomposition of the organics that were added on July 28, 2016 (Contango, 2017). By the end of 2017, soil redox values had decreased to within the targeted range (-100 to -250 mV), even without additional organics added. It is therefore evident that the commissioning period was successful and the CWTS had matured and become self-sufficient in producing organic matter to provide electrons to generate reducing conditions upon decomposition. Soil redox will continue to be monitored throughout operation in 2018.

Table 1: Average In-Situ Measurement from Pilot-Scale to Demonstration-Scale CWTS.

Testing Period		DO (mg/L)	ORP (mV)	Soil Redox (mV)	Conductivity (µS/cm)	pH
Demonstration-Scale 2015		10.0	147.9	-52	817.9	8.11
Demonstration-Scale 2016	Commissioning-A	15.9	143.7	-85	890.9	7.79
	Commissioning-B	8.4	157.6	-89	1020	7.59
Demonstration-Scale 2017	Commissioning-B	4.3	18.7	-162	795.9	7.43
	Operational Period	5.3	124.9	-152	879.7	7.36

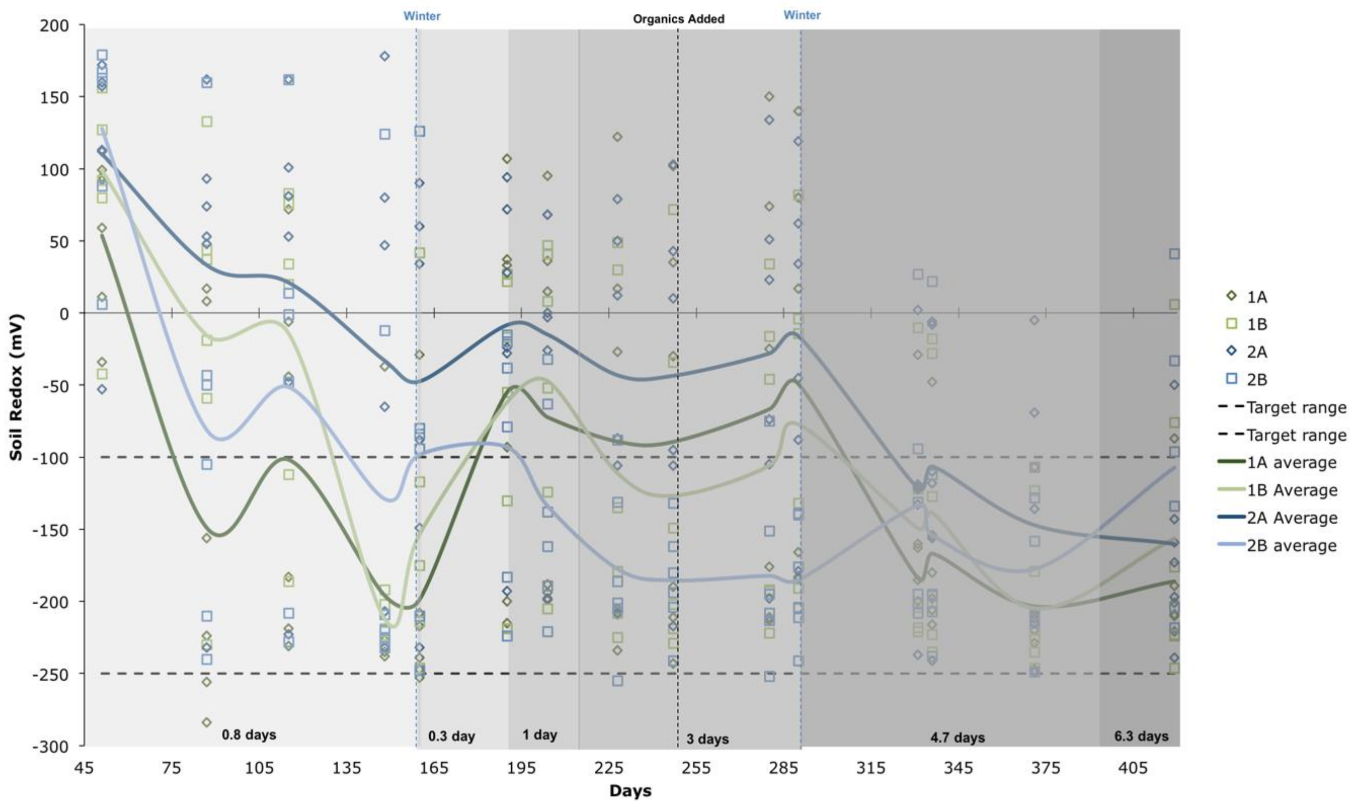

Figure 2: Soil redox potential of each CWTS cell over time (Contango, 2017). All demonstration-scale CWTS soil redox measurements are plotted. Targeted soil redox values based on pilot-scale testing are indicated with dotted lines. The blue dotted line indicates break in measurements for winter 2015 and 2016. Days and associated grey indicate the HRT (average of series 1 and 2).

Water

The operational period ran from August 18 to September 22, 2017 and achieved levels of treatment that were designed for dissolved cadmium, copper, selenium, and zinc. Dissolved metal concentrations are used for discussion purposes in this report, as total concentrations were highly variable and not representative of the metals concentrations in the CWTS. The variability of the total metal concentrations is due to the grab sample collection method where particulate material containing metals may have been present. During the operational period the CWTS treated targeted constituents of potential concern in the following extents and percentages (averages): cadmium 80% (from 0.0261 µg/L to 0.0092 µg/L), copper 65% (from 49.1 µg/L to 17.3 µg/L), molybdenum 58% (from 6.3 µg/L to 2.7 µg/L), selenium 89% (from 4.0 µg/L to 0.5 µg/L), zinc 98% (from 49.2 µg/L to 1.9 µg/L), and nitrate as N 97% (from 6.5 mg/L to 0.19 mg/L). Percentage removals have been corrected to account for the detection limit since the percent removals were artificially low for some CoPCs (such as cadmium) because the analytical detection limit was routinely reached, thereby making it impossible to have a further extent of removal (Figure 3). Additionally, inflow concentrations were generally low, making it difficult to achieve a large percent removal. However, the percent removal of molybdenum and selenium in 2017 is notable, as it has increased from 0% removal during commissioning in 2015 and 2016 (Contango, 2017). These results indicate that the commissioning periods were successful in establishing beneficial conditions for the removal of CoPCs in the CWTS and treatment of these CoPCs should continue through 2018. Additionally, removal rates for molybdenum and selenium showed dramatic increases after the addition of organics and the beginning of the commissioning-B period as the sulphide demand of the copper is no longer overwhelmed by the electrons available to the system.

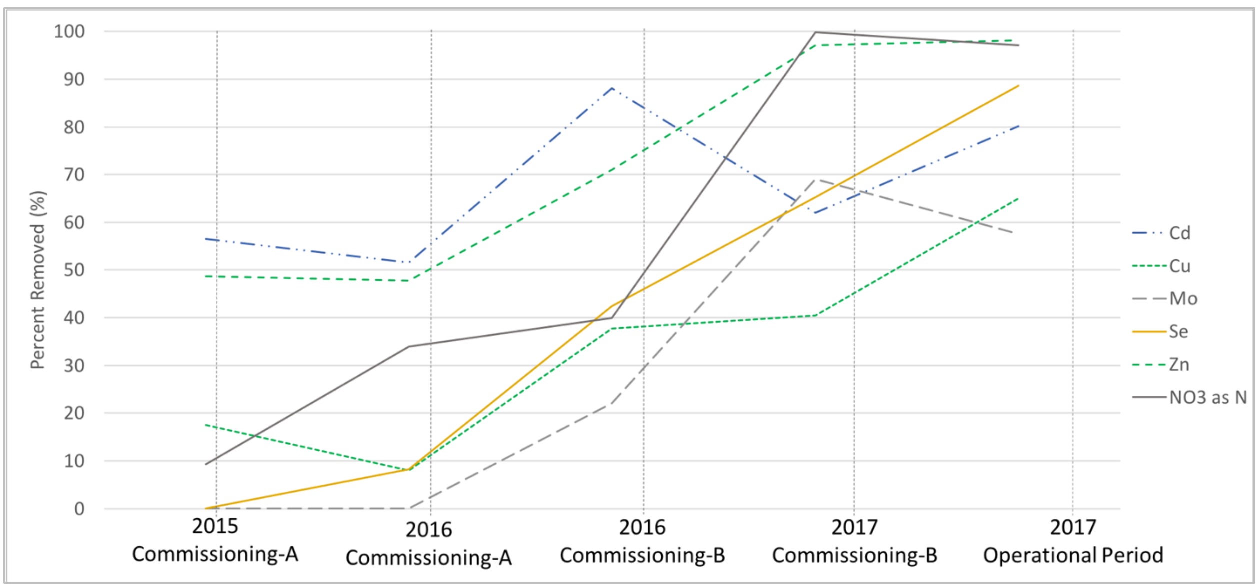

Figure 3: Average Percent Metal Removal by CWTS over Time. Percentage removals have been corrected to account for the detection limit since the percent removals were artificially low for some CoPCs (such as cadmium) because the analytical detection limit was routinely reached, thereby making it impossible to have a further extent of removal.

Vegetation

As per the CWTS design, uptake of metals in above ground *C. aquatilis* was low, whereas concentrations in aquatic mosses was higher. Both moss and *C. aquatilis* in the demonstration-scale CWTS showed higher copper concentrations compared to the pilot-scale (Contango, 2017). This is likely due to the higher concentrations of bioavailable copper contained in the substrates used for construction of the demonstration-scale CWTS. Over time, CoPCs sorbed to mosses will form reduced minerals, rendering them less bioavailable.

Substrate

Because the substrates used for construction of the CWTS were from overburden sources, copper was in oxidized form rather than in mineral form which would typically be found in a reducing CWTS (i.e., substrates with negative soil redox). Therefore, there was some initial leaching of copper from the substrates into the water in early 2017. When compared to early 2016 results, leachable copper concentrations in 2017 substrates decreased throughout the CWTS while total copper concentrations temporarily increased as copper shifted in the soils from its leachable to a treated and stable reduced mineral form. In general, substrates in the demonstration-scale CWTS appear to be reaching a steady-state with concentrations of leachable copper changing little throughout 2017. We expect leachable copper to decrease further in 2018. It should also be noted that copper that leached from the original substrate into the water put additional treatment demands on the CWTS.

Microbiology

Microbes are the driving force of many treatment pathways that are targeted in a CWTS. The beneficial microbes catalyze biogeochemical processes that remove specific CoPCs from the water column. Careful design of a CWTS can create the environmental conditions needed to enhance the abundance and metabolic activity of these beneficial microbes. Accordingly, complimentary methods of genetic and growth-based testing were used to characterize the microbial populations associated with a range of microbial habitats in the demonstration-scale CWTS (e.g., substrates, sediment, biofilms, aquatic mosses, and plant roots).

In the context of the Minto Mine CWTS, beneficial microbes include those that are involved in the reduction of selenium (i.e., selenate and selenite), nitrate, and sulphur compounds. Reduced sulphur can in turn treat copper, cadmium, molybdenum, and zinc through geochemical interactions. Information on each of these mechanisms and the associated microbial populations in the demonstration-scale CWTS is outlined in the following sections.

Populations of sulphide producing bacteria (SPB) were highest in the operational period, with greater abundances of SPBs in soil and root samples compared to moss and detritus samples. The overall abundance in the operational period was greater than in the pilot-scale system, indicating successful commissioning prior to the operational period and speaking to the diversity that comes with an outdoor system. As soil redox levels decreased and stabilized in the operational period, SPB populations increased and diversified, as shown in Figure 4.

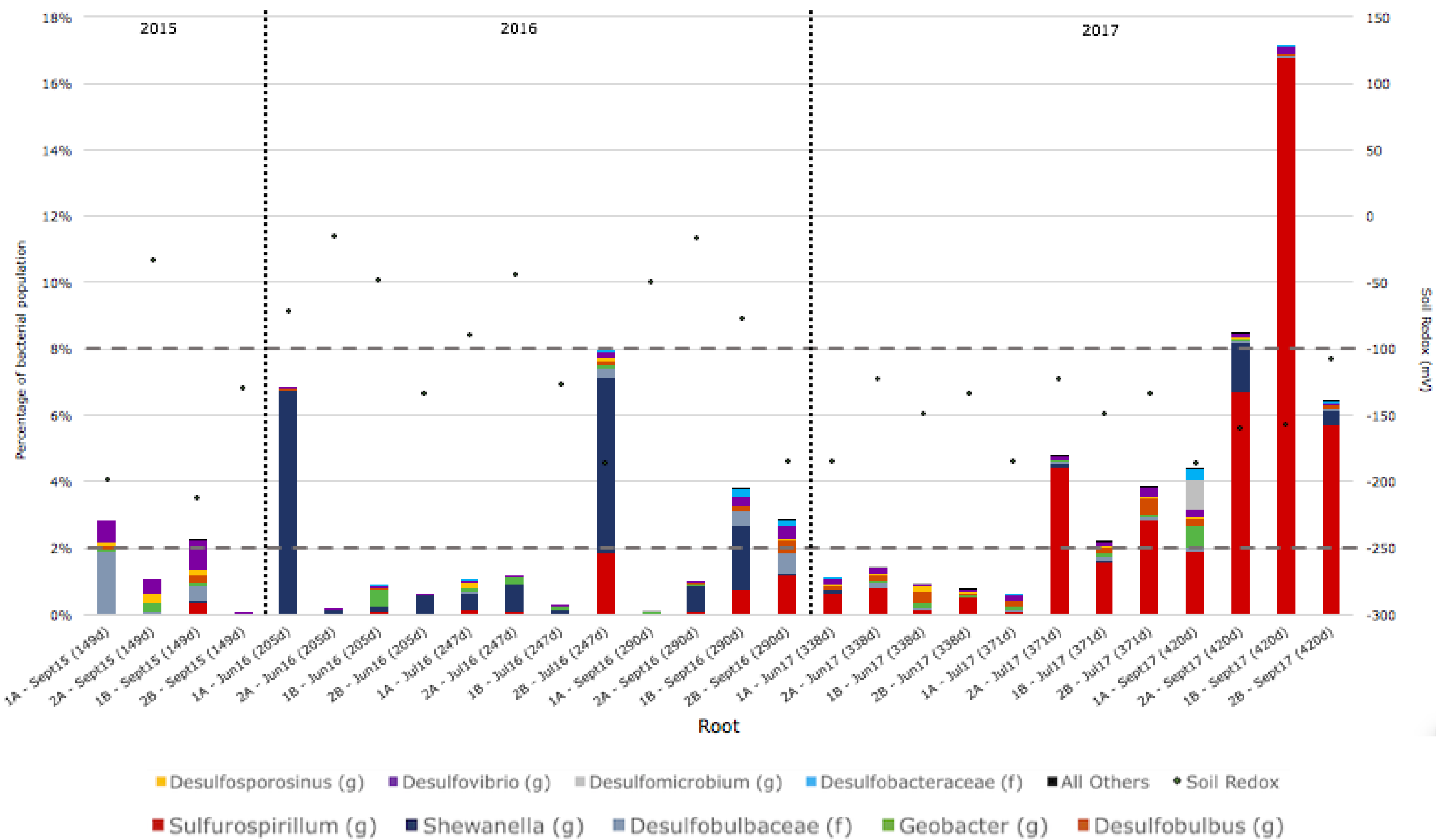

Figure 4: Average Number of Different Types of Sulphide-Producing Bacteria (SPB) in roots vs. Soil Redox Over Time. Percentage of bacterial population is on primary y-axis while soil redox is on the secondary y-axis.

Selenium-reducing microbes are ubiquitous in nature and, as expected, were found in all sample types collected, including algae, biofilm, moss, soil, sediment, and roots. Although organisms that reduce selenate to elemental selenium (rather than intermediary selenium compounds) are generally less abundant in the environment, they were found associated with all sample types, indicating that the conditions conducive to their proliferation have been created within the CWTS. Moreover, the abundance of selenite- and selenate-reducing organisms generally increased or remained stable over time in the demonstration-scale CWTS through the commissioning and operational periods in 2017. Aquatic mosses were found to initially host the highest abundance of both selenate- and selenite-reducing organisms, affirming the importance of the inclusion of moss in the CWTS. Over time, as the vegetation has established, selenium-reducing bacteria have increased in abundance on the roots of *C. aquatilis.*

Microbiological data indicate the commissioning period was successful and the demonstration-scale CWTS established and maintained beneficial selenium-reducing microbes. Selenium is removed from water as it becomes sorbed to moss or detritus and/or by selenium reducing microbes interacting directly with selenium in water as it is drawn into the root zone of soils by vegetation. Abundance of selenium-reducing bacteria was similar to that found through pilot-scale soil testing, suggesting they have established as expected. Selenium-reducing microorganisms will continue to be monitored alongside performance testing.

As observed in commissioning, denitrifying organisms were found associated with all sample types in the demonstration-scale CWTS (Contango, 2017). Roots and detritus had a high abundance of denitrifying organisms, with soil being similar to or slightly less than what was found during pilot-scale testing. These results indicate denitrifying microorganisms have established in the CWTS during the commissioning period as expected. Denitrifying microorganisms will continue to be monitored in 2018, alongside performance testing.

CONCLUSION

When designed and implemented in a strategic and scientifically guided manner, CWTS can treat many CoPCs in mine impacted waters. A treatment plan that includes processes to precipitate insoluble minerals forms of these CoPCs for sequestration into the substrates are very desirable. These processes capture the CoPCs and stores them in stable form in the soil, rather than transferring the CoPCs to an indeterminate fate (e.g., through plant uptake that can potentially bio accumulate in wildlife or be re-released in plant decomposition). The phased approach taken for the Minto Mine CWTS has addressed several important design considerations, refining full-scale CWTS sizing and adaptive management strategies to guide the future treatment of CoPCs.

In order to achieve conditions conducive with the treatment of CoPCs, it was important that the demonstration-scale CWTS was commissioned appropriately. This commissioning period allowed plants and microbial populations to mature in the CWTS and to achieve targeted reducing conditions. As commissioning concluded and the operational period began, treatment for all CoPCs increased. Selenium concentrations were consistently treated to below 1 µg/L, and cadmium was routinely reaching the analytical detection limit, thereby making it impossible to have a further extent removal. Nitrate as N was also achieving notable treatment with 97% removal (6.5 mg/L to 0.19 mg/L). Leaching of copper and other CoPCs from the mineralized substrates used in the construction decreased by the end of 2017 with CoPCs showing a shift into stable reduced mineral forms in the soil. Additional positive results were also documented; plant uptake of CoPCs remained minimal throughout operation and high abundance of beneficial sulphide-producing bacteria for treatment of Cu, Cd, Zn, as well as denitrifying and selenium-reducing bacteria associated with plant roots.

The operational period of the demonstration-scale CWTS showed positive results and consistently proved to be an effective treatment for the targeted CoPCs under sub-arctic climate conditions at Minto Mine and has the potential to be an effective passive reclamation method for treatment of water at closure. The next steps for the CWTS program at Minto Mine in 2018 will be to assess performance under conditions that would be similar to the full-scale CWTS. As the 2018 operational phase continues, a range of HRTs will be implemented to predict how the full-scale system will react to natural variations in flow rates. Results from ongoing monitoring of the system in future years will be used to optimize performance and inform the designs for the full-scale CWTS.

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