RESULTS OF VEGETATION SURVEY AS A PART OF NEUTRALIZING LIME SLUDGE VALORIZATION ASSESSMENT

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ABSTRACT

The use of the lime neutralization process is a common technique to treat acid mine drainage (AMD) generated by sulphidic mine wastes. The AMD-contaminated water collected on the mine site is neutralized by addition of air, lime and flocculant. The sludge generated by the treatment is stored in specifically designed storage ponds. A multidisciplinary project is being conducted to investigate if sludge may be valorized as a material for mine site reclamation. The Doyon-Westwood mine site, operated by IAMGOLD, has two sludge ponds which were colonized by vegetation shortly after sludge deposition. One objective of the study was to investigate metal bioaccumulation risk by plants, to evaluate the sludge's suitability as vegetation growth medium. Ten functional groups of plants were found on the sludge ponds. Arborescent species were among the most frequent vascular plants on the sludge ponds. Chemical analyses of tissues from three arborescent species (leaves, branches, wood and roots) have indicated that the trees growing on the sludge were not affected by the deficit of major nutrients. The metal concentrations in the plant tissues sampled on the sludge ponds fit in the range of those from a control site. Chemical analyses of plant tissues did not reveal any bioaccumulation. The sludge shows a significant potential as a vegetation growth medium.

Key Words: Sludge Valorization, Bioaccumulation, Vegetation Succession, Mine Site Reclamation, Trace Elements.

INTRODUCTION

Lime neutralization is an efficient and worldwide technique used to treat acid mine drainage (AMD) generated by sulphidic mine wastes (MEND 2013). The AMD-contaminated water collected on the mine site is treated by lime addition, which increases alkalinity and promotes precipitation of metal ions as hydroxides. The precipitated metals form a sludge, which also contains significant amounts of gypsum and unreacted lime. This sludge is generally stored in ponds for dewatering and permanent disposal. According to Zinck and Aubé (2000), approximately 7 million cubic metres of sludge are produced annually in Canada. For example, the Doyon-Westwood mine site, operated by IAMGOLD in the Abitibi (Quebec) region, has two closed sludge ponds. The observation of natural vegetation succession on the sludge ponds inspired a research project, which consists of evaluating the possibility of using the sludge as a material for mine site rehabilitation. No studies of the vegetation succession on the sludge and sludge effects on living organisms, particularly focused on the bioaccumulation risks, have been conducted previously. The potential use of sludge as a reclamation material highlights the need to investigate these questions. A multidisciplinary team of researchers from URSTM – Unité de recherche et de services en technologie minérale (UQAT), which includes specialists in the fields of geochemistry, geotechnique, hydrogeology and biology, is involved in this project.

For the projected usage of sludge as rehabilitation material, it was necessary to determine if sludge as a growth medium has an effect on plant status and contaminant bioaccumulation. Indeed, if the vegetation starts growing naturally on the sludge a few years after deposition in the ponds, this indicates that sludge may be a suitable substrate for plant growth. Also, it was observed that the sludge ponds are actively used by local fauna. However, sludge contains considerable concentrations of chemical elements (e.g., As, Co, Cd, Cu, Ni and Zn), that might be harmful for living organisms (Adriano 2001).

The principal objective of the part of the project herein presented focused on the evaluation of the influence of the sludge on the spontaneous vegetation development. The specific objectives were (1) to survey vegetation on the sludge storage ponds (SSP), focusing on arborescent species; and (2) to evaluate the risk of metal bioaccumulation by the vegetation due to the elements present in the sludge that represent a risk for the organisms.

STUDY AREA

IAMGOLD is one of the leading gold mining companies in the Abitibi region; the Doyon-Westwood Mine is a gold producing operation located 40 km east of Rouyn-Noranda, Quebec, Canada (Figure 1). It has been in operation since 1978, and is now the property of IAMGOLD Corporation. Because the ore and wastes (waste rocks and tailings) contain sulphides with minimal neutralising potential, acid mine drainage is produced by the waste rock piles, tailings impoundments, underground mine workings, and site infrastructure (roads) built with AMD-generating rocks.

Figure 1. Study area location (Demers et al., 2010).

All the acidic water is collected and treated using standard high-density sludge process, which includes neutralization of acidic water by lime addition, thereby precipitating metal ions as hydroxides. In the past, AMD neutralization sludge was deposited in two, now closed, dedicated storage ponds. The sludge ponds, filled during the last decade, contain nearly 1 million cubic metres of sludge with calcium (18%), iron (9%) and sulfur (7%) as main components, mostly as gypsum and ettringite (Bouda et al. 2012).

METHODS

To study the influence of the precipitated sludge on the spontaneous vegetation development, the chemical properties of the sludge, a survey of the vegetation and an evaluation of element concentrations in plant tissues were conducted on the northern sludge pond of Doyon-Westwood mine site. The study focused on one of the two closed ponds, i.e., the north SSP.

Chemical Properties of the Sludge in SSP

The chemical properties of the sludge sampled in the north SSP were analysed by ICP-AES, atomic absorption. Concentrations of 60 elements were measured (12 replicates). In this paper, we focus on the concentrations of macroelements (Ca, K, Mg) and of hazardous elements for the organisms in the case of bioaccumulation: As, Cu, Co, Zn. Concentrations provided by MDDEP (Ministère du Développement Durable, de l'Environnement et des Parcs 2013) and Biological Test Method (BTM) (2007) in the forest soils are considered as a reference level (Table 1).

Vegetation Survey

At the end of the fall season in 2011 and 2012, a vegetation survey was conducted. Based on visual observation, two ecotopes (lake and forest) were distinguished on the SSP. The forest ecotope is characterized by dense arborescent vegetation, while the lake ecotope includes three depressions filled with water during periods of excessive precipitation. Also, the lake ecotope is distinguished by characteristic vegetation consisting mainly of cyperaceous species and willows.

Eight transects of 45 m were delimited systematically across the study site. Five transects crossed the forest ecotope. In the lake ecotope three transects were started at the water border along the radius pointing to the centres of each lake. Study plots of 1.3 m in diameter were established along the transects at 5 m intervals. Within these circular plots, floristic composition was identified (Marie-Victorin 1964); species absence (0) or presence (1) was noted. Vegetation composition was assessed by a cluster sampling method (Hoshmand 2006). The occurrence per ecotope was evaluated as the percentage of plots where the species were found (n = 40). Mean occurrence per transect was calculated, and then mean occurrence per zone was assessed. All species documented on site were classified into functional groups (Bloom and Mallik 2006). The species of the same functional group in the boreal zone (the major functional groups are: herbs, graminoids, trees and shrubs, ericaceous and cyperaceous species) share ecological characteristics and play an equivalent role in the community. Also they are characterised by similar growth forms and general life history strategies. Hence, the litter properties, i.e., nutrient concentrations, decomposition rate, etc., of the species belonging to the same functional group are similar (Wardle et al. 1997).

Arborescent species represent a particular interest in this project because they stay for a long period on the site in addition they produce considerable biomass and are often consumed by large herbivores (e.g., moose). Thus, they need to be investigated more meticulously to evaluate the magnitude of heavy metal bioaccumulation in this functional group. To determine the age of the arborescent species establishment on the SSP, these taxa were sampled (discs) in three replicates per taxon at three locations along the SSP. The discs were sanded, and then age was determined by year ring counting.

The characteristics of arborescent species (with basal diameter greater than 1 cm) were documented according to the following variables: height, basal diameter, live status and species abundance per square metre. Based on the results of vegetation survey, three dominant arborescent taxa were identified: balsam poplar, paper birch and willow.

Element Concentrations in Plant Tissue

To evaluate the risk of bioaccumulation, plant tissues of the three tree species were analysed. Plant material was sampled in three replicates in the two ecotopes and in a control site that was selected 10 km away from the SSP. Four plant fractions were sampled: leaves, previous year branches, stems and roots. Concentrations of major nutrients (K, Ca, Mg, P) were measured in leaves and branches, and Ca and Mg in all four fractions. Furthermore, the elements representing a potential risk for the organisms (As, Co, Cu, and Zn) were analysed.

A two-way analysis of variance (ANOVA) with a general linear model (GLM) procedure (Legendre and Legendre 1998) was used to determine the influence of the ecotope and species on the concentrations of Ca, Mg, As, Co, Cu and Zn (SAS 1999). The objective of this analysis is to ensure that there is no significant interaction between ecotope and species. Preliminary tests confirmed that the data respond to the normality requirements. In the analyses, the location of sampling was randomized. The analyses were applied for each fraction separately. Afterwards, Tukey's multiple comparison tests were used to assess the difference in element concentrations in plant tissue between the two ecotopes and control locations for each species and fraction separately.

RESULTS AND DISCUSSION

Chemical Properties of Sludge

A characteristic feature of the SSP is the absence of soil stratigraphy and the absence of the forest floor, hence very low organic matter content. Concerning the major nutrients, Table 1 shows that the total concentration of macroelements (Ca, K, Mg) in the sludge is dramatically low compared to typical forest soil (approximately 80, 2000 and 100 times lower than in the reference soil, respectively). Although these are total concentrations and plant available concentrations do not necessarily correlate with total concentrations, the results allow concluding that the sludge has an oligotrophic status.

Arsenic is one of the elements representing a bioaccumulation risk. The analyses of the sludge show that the concentration of As is below the detection level of the analytical method. Low As concentrations in the sludge allow eliminating the toxic effect of this element for the site studied. Other elements related to the bioaccumulation risk, Co, Cu, and Zn, are present in high concentrations in the sludge compared to the reference soil (by MDDEP and BTM).

Table 1. *Total element concentrations in SSP of Doyon site (ppm)*

Element	Reference concentrations: criteria of MDDEP and BTM	SSP Doyon average (minimum-maximum) concentrations
Ca	963	11.98 (16.60 - 3.43)
K	250	0.14 (0.60 - 0.01)
Mg	192	1.82 (2.24 - 1.50)
As	5	<0.01
Co	20	130.63 (185.00 - 82.30)
Cu	50	598.83 (1030.00 - 297.00)
Zn	120	205.08 (321.00 - 114.00)

Co and Cu concentrations are more than six and ten times higher, respectively, compared to the reference soil, and Zn concentration is twice the reference. These concentrations allow anticipating high plant available forms of these elements, which may lead to their accumulation in plant tissue and high possibility to be translocated along the food chain.

Vegetation Survey

Species belonging to ten functional groups are found on Doyon SSP: arborescent species (trees and shrubs), lycopodiaceae, herbs, graminoids, cyperaceous species, equisetaceae, bryophytes, lichens and mushrooms (occurrence was not documented) (Figure 2). Among these groups, the bryophytes and cyperaceous are the most frequent species on the SSP. Lichens and lyciopodiaceae were found only in the forest ecotope, while thypaceae is limited to the lake ecotope. Cyperaceae is four times more abundant in the lake ecotope. Occurrence of other groups is rather equal in both ecotopes.

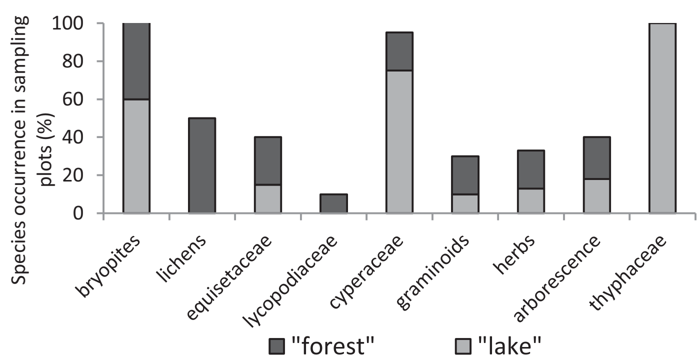

Figure 2. Species occurrence by major functional groups in two ecotopes (forest and lake) on the Doyon north SSP.

The results suggest that, regardless of the oligotrophic edaphic conditions, primary vegetation succession is occurring on the SSP. It is known that primary succession starts with pioneer non-vascular plants (lichens and bryophytes) followed by gramineas and perennials, finally arborescent species appear (Johnson 1992). The succession observed on Doyon SSP is different because it started by pioneer arborescent species, while the understory layer is poorly developed.

Characteristics of Arborescent Species

Ring counting of tree discs showed that the oldest tree specimen is a 25 year-old willow (Table 2). Considering that the sludge was deposited less than 15 years ago, this age indicates that trees were already present on the future SSP basin, and sludge deposition has not inhibited their growth.

Table. 2 Age of four arborescent species on the Doyon north SSP

Tree species	Average tree age (minimum-maximum),years
Willows	21.6 (18-25)
Balsam poplar	18.6 (16-21)
Trembling aspen	17.6 (16-20)
Paper birch	14.3 (12-16)

In the methodology section we reported that willows are the most abundant arborescent species in the lake ecotope, while in the forest ecotope high arborescent diversity is documented. Balsam fir, tamarack, paper birch, trembling aspen, balsam poplar, black spruce, jack pine and willows are found on the SSP. The study of tree and shrub occurrence showed that trembling aspen, paper birch, balsam poplar and willows are the most abundant species in the forest ecotope. The same species, except paper birch, are the most abundant species in the lake ecotope (Figure 3).

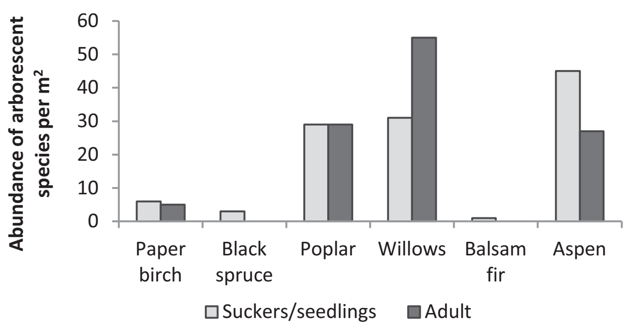

Figure 3. Age structure of arborescent species on the Doyon SSP

The analyses of arborescent species structure (Figure 3) showed that the abundance of arborescent seedlings and suckers is equal to the abundance of adult trees on the SSP. This suggests that arborescents successfully propagate on the site.

Element Concentrations in Plant Tissue

The analyses of variance suggest that there is no significant interaction between plant species and sampling location (ecotope and control), while the difference in terms of concentrations for As, Co, Cu and Zn is due to the ecotope and species (Table 3).

Significant differences in terms of element concentrations are observed in the foliar tissue compared to the branches, wood and roots. Generally, roots accumulate higher trace-element concentrations than other fractions. Surprisingly, plant metal concentrations in the control tissues are in most cases similar or even higher compared to the ones observed on the Doyon SSP. This difference may be explained by high As and metal concentrations in the bedrock of the Cadillac fracture, where the mine site is located.

*Table 3. Analyses of variance performed on main chemical element concentrations in three ecotopes for three species; statistically significant differences (p <**0.05**) are indicated with boldface italic fonts.*

			Ca		Mg		As		Co		Cu		Zn	
Fraction	Source	*DF**	*F*	*P*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Leaf	Overall model	8	4,33	***0,01***	2,39	***0,05***	1,57	0,19	3,28	***0,01***	3,87	***0,01***	4,68	***0,01***
	Error	20												
	Ecotope	2	5,38	***0,01***	7,38	***0,04***	3,06	0,07	4,19	***0,03***	6,19	***0,01***	9,75	***0,01***
	Species	2	9,88	***0,01***	1,75	0,20	1,40	0,27	4,39	***0,01***	4,57	***0,02***	7,06	***0,01***
	Ecotope*species	4	1,02	0.42	0,21	0,93	0,90	0,48	2,01	0,13	1,22	0,06	0,95	0,46
Branch	Overall model	8	4,28	***0,01***	4,04	***0,01***	1,17	0,36	0,63	0,74	2,20	0,07	2,43	***0,05***
	Error	20												
	Ecotope	2	5,77	***0,01***	4,63	***0,02***	4,32	***0,03***	1,06	0,36	2,18	0,14	5,71	***0,01***
	Species	2	8,48	***0,01***	10,85	***0,01***	0,03	0,97	1,05	0,37	4,34	***0,02***	0,40	0,68
	Ecotope*species	4	1,43	0.26	0,34	0,84	0,17	0,95	0,21	0,93	1,15	0,36	1,81	0,17
Wood	Overall model	8	12,48	***0,01***	3,26	***0,02***	0.66	0,72	0,46	0,87	0,52	0,83	18,89	***0,01***
	Error	20												
	Ecotope	2	15,90	***0,01***	1,47	0,25	0,15	0,86	1,41	0,27	1,37	0,28	31,23	***0,01***
	Species	2	27,60	***0,01***	10,17	***0,01***	0,68	0,52	0,15	0,86	0,42	0,66	16,82	***0,01***
	Ecotope*species	4	1,22	0,06	0,70	0,60	0,91	0,48	0,14	0,96	0,15	0,96	1,25	0,06
Root	Overall model	8	3,28	***0,02***	1,12	0,40	2,50	***0,05***	0,82	0,59	0.95	0,50	6.99	***0,01***
	Error	20												
	Ecotope	2	11,08	***0,01***	3,49	0,05	0,34	0,71	0,86	0,44	1,67	0,22	15,43	***0,01***
	Species	2	1,52	0,25	0,66	0,53	4,67	***0,02***	1,30	0,30	0,52	0,60	5,13	***0,01***
	Ecotope*species	4	0,26	0,90	0,17	0,95	2,49	0,08	0,56	0,70	0,81	0,53	2,28	0,13

*DF: Degree of freedom

Figure 4 presents the average element concentrations (ppm) measured in plant tissues of arborescent species in the two ecotopes in the SSP Doyon site and the control site. P and K were measured only in branches and leaves. Willows accumulate higher macroelement and As, Co, Cu and Zn concentrations (Figure 4). This effect is expected since it is well known that most willows are metal hyperaccumulators (Kuzovkina et al. 2004). Due to that phenomenon, many willows are used as metal phytoextractors on contaminated sites.

More details on element accumulation by the three arborescent species are provided in Table 3.

Paper Birch

There is a difference in element accumulation by birch on the SSP, although the SSP has poor macronutrient content (Table 3). In birch tissues, macronutrient concentrations were generally higher in the lake ecotope compared to the control site and the forest ecotope (Figure 4), while in the forest ecotope As concentrations in the wood and roots were three times higher than the lake and control site.

The analyses showed metal accumulation in the wood and roots of birches, while metal concentrations in branches and leaves were similar in the three locations. Concentrations of Co, Cu and Zn in wood and roots were more than two times higher in the control than in the lake and forest ecotopes. Interestingly, Zn concentrations in the birch roots in the control were the highest among the three species in all locations.

Birch is classified as a pioneer species (Gallagher et al. 2011); it possesses plasticity and tolerance to a wide range of environmental conditions, however according to the literature birches are not considered a species with outstanding tolerance to soil contamination. The results of our study suggest that the SSP is a suitable habitat for this species and the risk of bioaccumulation by birches is minimal.

Balsam Poplar

Poplar had similar trends of macronutrient accumulation as birch (Figure 4). Major nutrients in poplar, except Ca, were twice or threefold lower in all fractions in the control compared to the forest and lake ecotopes. Concentration of As in poplar tissues did not differ significantly among locations. Poplar roots in the control contained the highest concentration of Co, which were more than five times higher than the concentrations in other fractions in the forest and lake ecotopes. The highest concentrations of Cu were found in poplar roots in the lake ecotope. Concentrations of Zn showed similar sequence between fractions: wood > roots > leaves = branches in all locations.

Willows

Phosphorus concentrations in the tissue of willows did not differ among locations. Potassium concentrations were highest in the control, while the highest Ca and Mg concentrations were measured in the lake ecotope. In willows, the roots are the major As accumulators compared to other fractions. Willow roots in the control contained concentrations of As twice those in other locations. Cu root concentrations in the lake ecotope were ten times higher than the control site and twice higher than the forest ecotope. A similar trend was observed in poplar. Possibly more Cu is present in plant available form in the lake

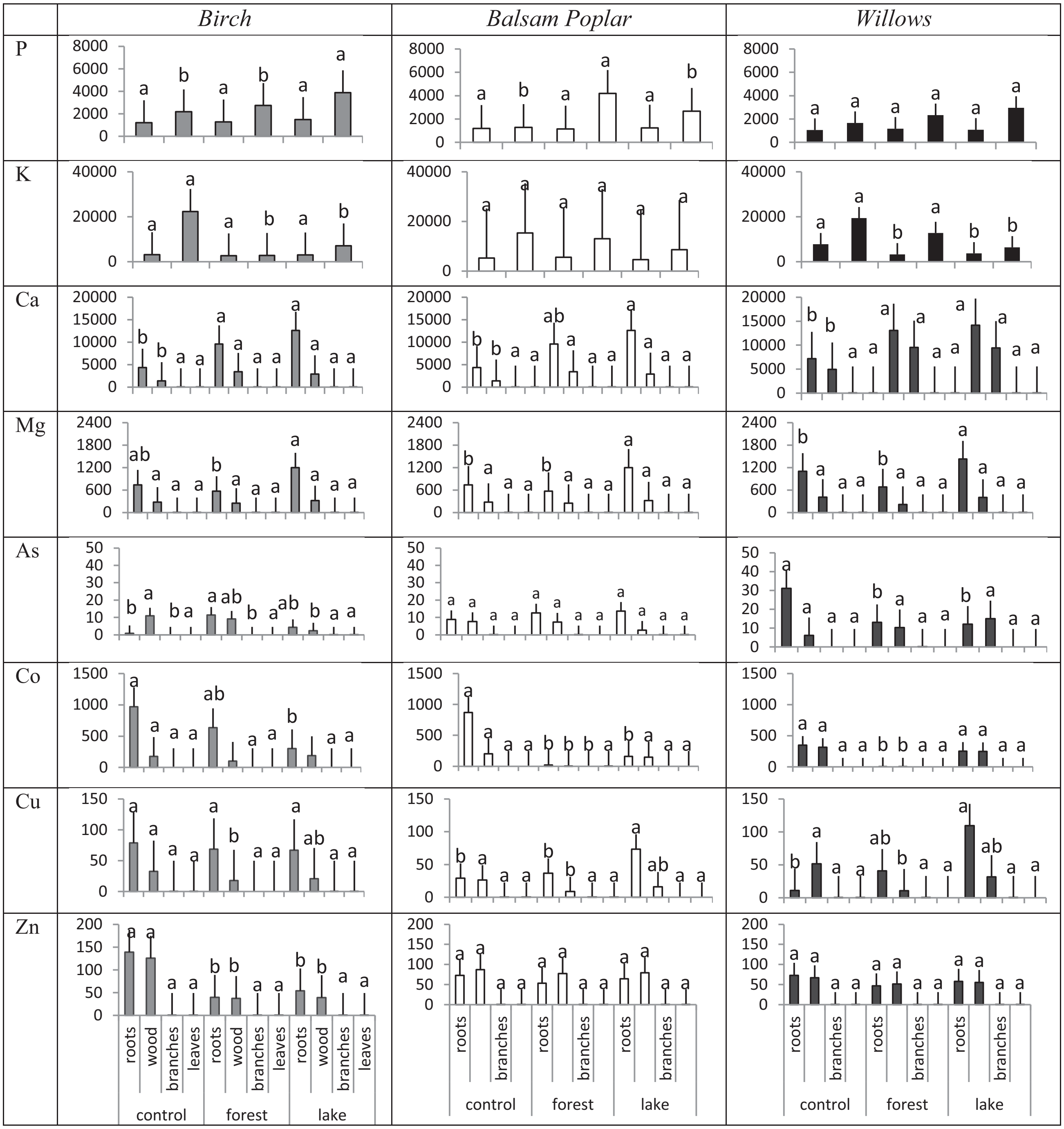

Figure 4. Average element concentrations (ppm) in plant tissue of arborescent species in two ecotopes of the SSP Doyon and in the control site. Tukey's test of element concentrations of the same plant fraction among three sampling locations. Columns with same letter are not significantly different according to the test. Bars indicate standard deviation.

compared to the other two locations, and the fact that willows and poplars are hyperaccumulators intensifies their capacity to accumulate Cu in this habitat. Cu concentrations in other fractions were similar and near the detection limit.

Concentrations of Zn and Co in different fractions of willows had similar distribution in different locations. It is worth noting that willow roots and wood contained equal concentrations of Co and Zn, which might be explained by the high translocation capacity of these elements within plants (Adriano 2001).

Balsam poplar and willows have many ecological similarities: they are fast growing and adapt to a wide range of ecological conditions, and can tolerate excessive metal concentrations in the soil. Therefore they are often used in phytostabilisation projects focused on phytoextraction (Kuzovkina et al. 2004) or contaminated site revegetation. The fact that As and other metal concentrations in the tissue of poplar and willows on the SSP do not surpass those of the control allow concluding that these species do not represent bioaccumulation risks by higher levels of the food chain.

CONCLUSIONS

In this investigation, a vegetation survey was performed on a sludge pond at the Doyon mine site. The bioaccumulation of contaminants by different fractions of three main arborescent species encountered has been investigated. Chemical analyses of plant tissues did not show any abnormal element accumulation compared to samples collected off the site, which indicate a possibility of using the sludge as a revegetation substrate for mine site reclamation. However, further detailed investigations, including analyses of plant available element concentrations and of other plant functional groups (e.g., lichens and perennial species) remain necessary to confirm the suitability of sludge as growth medium.

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Overcoming Northern Challenges

Proceedings of the 2013 Northern Latitudes Mining Reclamation Workshop and

38th Annual Meeting of the Canadian Land Reclamation Association

Whitehorse, Yukon September 9 – 12, 2013

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Northern Latitudes Mining Reclamation Workshop

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Polster	Natural Processes: An Effective Model For Mine Reclamation
Dustin	Implementation of contaminated water management system upgrades to allow for dewatering of two open pits at the Vangorda Plateau, Faro Mine Complex, Yukon
Kempenaar, Marques and McClure	Tools for Arctic Revegetation: What's in Your Toolbox?
Smreciu, Gould, and Wood	Establishment of Native Boearl Plant Species On Reclaimed Oil Sands Mining Disturbances
Keefer	Twin Sisters Native Plant Nursery
Pedlar-Hobbs, Ludgate and Luchinski	Key Factors in Developing and Implementing a Successful Reclamation Plan
Chang, et.al	Effects of Soil Aggregates Sizes (paper not attached)
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Janin	Passive treatment of drainage waters: Promoting metals sorption to enhance metal removal efficiency
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Nadeau and Huggard	Restoration Planning and Application of Ecological Succession Principals
Simpson	Defining Disturbance and Recovery - the influence of landscape specific ecological responses to oil and gas linear disturbances in Yukon

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The first Workshop was held in Whitehorse, Yukon Territory, Canada in 2001 and it has been held every two years since, alternating between Canada and Alaska. The primary sponsors of the Workshop include the Yukon Geological Survey, Indian and Northern Affairs Canada, Natural Resources Canada, US Department of the Interior Bureau of Land Management, and the State of Alaska Department of Natural Resources.

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- To incorporate the advances from research and practical experience into land reclamation planning and practice.
- To collect information relating to land reclamation and publish periodicals, books and leaflets which the Association may think desirable.
- To encourage education in the field of land reclamation.
- To provide awards for noteworthy achievements in the field of land reclamation.

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