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Assessment of wetland/upland vegetation communities and evaluation of soil-plant contamination by polycyclic aromatic hydrocarbons and trace metals in regions near oil sands mining in Alberta

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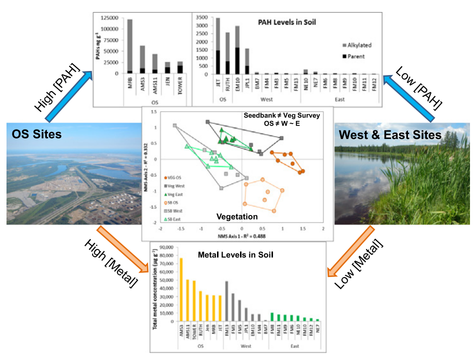
HIGHLIGHTS

- Sites closer to oil sands mining (OS sites) differed in their vegetation and seedbank.
- Most species were native perennials in all sites with some non-native in OS sites.
- Elevated levels of parent and alkylated PAHs were measured in soils of OS sites.
- Elevated levels of several trace metals were found in soils of OS sites.
- Uptake and translocation to native plants were limited in most cases.

GRAPHICAL ABSTRACT



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ABSTRACT

Oil sands mining in Alberta, Canada, has been steadily increasing over the last 50 years. The extent to which the surrounding vegetation has been altered/contaminated by pollutants released during bitumen extraction has not been a focus of oil sands environmental monitoring efforts. The objectives of this study were to assess plant species richness and composition in wetlands and uplands in the vicinity of oil sands mining areas and to measure levels of contamination of trace metals and polycyclic aromatic hydrocarbons (PAHs) in soils and plants. Twenty-two sites were selected in three locations: near to (OS, $n = 7$), West ($n = 7$), and East ($n = 8$) of oil sands mining operations. Aboveground plant species were inventoried and soil was collected for a seedbank study. Soils and plants were collected for analyses of 28 metals and 40 parent and alkylated PAHs. Plant species richness and composition differed significantly among locations. More species were found in the OS sites, many of them being non-native, than in East and West sites, which contained almost exclusively native perennials. PAH levels were significantly higher in OS sites, and were mostly comprised of alkylated PAHs. Patterns of PAH distribution indicated contamination from bitumen/petroleum in four sites; other combustion types may have affected five additional sites at different levels. Metals were also elevated in OS sites. Metal levels were significantly correlated with distance to upgrader facilities. Ratios of some metals in soil vs. above- and belowground plant parts were significantly higher in West and East than in OS sites, likely due in part to pH as soil was acidic at the East and West locations but alkaline at OS sites. This study showed that sites located near oil sands mining operations were contaminated with PAHs and metals, and that the vegetation composition at these sites greatly differed from less disturbed areas.

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1. Introduction

The boreal forest in northern Canada extends from the Yukon in the West to Newfoundland and Labrador in the East and covers over 50% of the country (http://www.nrcan.gc.ca/forests/boreal). It is interspersed with numerous lakes and vast wetlands with a distinctive native flora and fauna (Turchenek, 1990). In fact, wetlands comprise 30% of the Canadian boreal ecosystem and over 50% of that ecosystem within Alberta (Graf, 2009). Canada's boreal region is also extensively exploited for timber products, as well as for mineral and energy resources, including oil sands activities in Northern Alberta (Timoney and Lee, 2009). Oil sands production in Alberta has expanded considerably since its inception at the end of the 1960s. The mineable area of bitumen extraction comprises 4800 km^2, and it is entirely within the boreal forest (Weinhold, 2011 and references therein). In 2014, over 2.4 million barrels of oil per day were produced via surface mining or by in situ extraction (http://www.energy.alberta.ca/OilSands/) and this value will likely double in the coming years. However, this area of the boreal forest is also subjected to disturbance and/or contamination from other activities that are directly associated with bitumen extraction including: the construction of seismic lines (Kemper, 2006; Lee and Boutin, 2006), roads, power transmission lines and well pads; the building of processing facilities and upgraders; as well as many other events linked to oil sands exploitation (vehicular traffic, waste and residue disposal, etc.) (Turetsky and St. Louis, 2006). Specifically, the release of contaminants including polycyclic aromatic hydrocarbons (PAHs) and trace metals has been directly associated with oil sands extraction and processing (Wayland et al., 2008; Kurek et al., 2013; Kelly et al., 2009) along with other industrial activities (Scientific Committee on Food, 2002).

PAHs are a group of persistent organic compounds with two to seven aromatic, fused benzene rings comprising hundreds of individual substances (Douben, 2003). They occur naturally as a by-product of incomplete combustion during natural fire events and can be released as a result of anthropogenic activities (Ahad et al., 2015). PAHs occur naturally in bituminous fossil fuels and are released into the environment when these fuels are extracted or burned, often in the form of alkylated PAHs (with attached alkyl substituents) (Olson et al., 2004). PAHs can be transported via airborne emissions or in water (including snow deposition) to other environmental compartments (Kelly et al., 2009; Allen, 2008; Jautzy et al., 2013). It has been shown that PAH concentrations in sediments of the Athabasca River in Alberta have increased at a rate of 0.05 mg kg^{-1} per year between 1999 and 2009 (Timoney and Lee, 2011).

Sixteen parent PAHs have been designated as chemicals of concern due to their known toxicity to mammals and aquatic organisms (USEPA, 1986). The vast majority of PAHs released into the environment, however, occur primarily as a mixture composed of parent and alkylated compounds (Meador, 2003). The phytotoxicity of PAHs varies with the number of benzene rings and carbon chains attached (Greenberg, 2003). Two to three ring PAHs are known to be more water soluble and therefore their uptake and accumulation by plants may be higher than 4–6 ring PAHs, although this is not always the case (Plaza-Bolaños et al., 2010). Due to their ubiquity in the environment, PAHs are able to enter the food chain through various exposure routes and across all trophic levels. Furthermore, uptake and accumulation by primary producers, such as plants, provides an additional entry for contamination to the upper trophic positions. However, the effects of PAHs on native vegetation at the individual, population and community levels have yet to be investigated.

Recent studies have indicated that atmospheric transport of metals from the oil sands development area extends beyond 50 km and up to 90 km from upgrader facilities (Kelly et al., 2010). Several metals have been detected at elevated levels in tailing pond water (Allen, 2008) while others were found to decline in the sediments of the Peace-Athabasca Delta, which is situated 200 km north of oil sands industrial activities (Wilklund et al., 2012). Measurements of oil sands pollutants on primary producers have been reported for lichens (Addison and Puckett, 1980; Studabaker et al., 2012). These authors showed a clear link between distances from oil sands activity and measured metal concentrations in lichens. In addition, lichen health was found to be adversely affected by some metals (Addison and Puckett, 1980). More recently, vanadium (V) was the only metal that was found to be elevated in *Sphagnum* spp. L. sampled near oil sands extraction regions within Alberta; however, this was expected given that V is the most enriched metal in bitumen (Shotyk et al., 2014). Renault et al. (2000) observed phytotoxic effects on the germination of several native boreal plant species of Alberta when they were treated with tailings materials originating from oil sands processing activities. However, limited information exists on the uptake and accumulation of trace metals in the vegetation near oil sands industrial operations.

In this study we examine and inventory the vegetation communities found within and around the Fort McMurray, Alberta, oil sands area, as well as perform an initial assessment of potential contamination in the region as it pertains to plant health. The objectives were: 1) to assess species composition and diversity in wetland and upland plant communities situated in three different regions around the oil sands mining area through both site vegetation surveys and soil seedbank studies and 2) to measure the level of contamination of PAHs and heavy metals in soils and wild plants within these areas.

2. Materials and methods

2.1. Site selection

This study was conducted in the boreal forest of Alberta from 56.53996 to 58.0582 latitude and from −110.2263 to −112.87983 longitude. Elevation ranged from 230 to 760 m a.s.l. The region typically has long, severe winters with an average temperature of −14.3 °C in the coldest months and short summers (16.5 °C during the warmest month). The mean annual precipitation is approximately 475 mm (Government of Canada, Historical Climate Data, 2016 - http://weather.gc.ca). Sites were selected in three regions within the study area surrounding Fort McMurray, Alberta (Fig. 1). In total, 22 sites (12 in 2013 and 10 in 2014) were surveyed: seven sites (all road access) were situated in close vicinity to the oil sands extraction area near Fort McMurray (OS sites), seven sites (all helicopter access) were selected to the west of the oil sands extraction zone (West sites) and an additional eight sites (all helicopter access) were selected to the east of the oil sands mining area (East sites) where dominant westerly winds may contaminate habitats (Jautzy et al., 2013). The average distance from the closest oil sands upgrader facility was 13.1 ± 4.4 km for OS sites, 42.2 ± 4.5 km for the East sites, and 53.4 ± 9.4 km for the West sites, and was significantly shorter for OS sites than for both East and West sites (ANOVA: $df_{2,19} = 14.649$, $p < 0.001$). Sites with wetlands and upland areas near waterbodies (small ponds, lakes, or rivers) were chosen.

2.2. Vegetation survey

At each site, vegetation surveys were conducted along three transects that were positioned perpendicular to the edge of the waterbody (Supplementary Fig. S1). Each transect was divided into three distinct zones: wetland, intermediate, and upland. The wetland zone began at the start of the vegetation (distance = 0 m), which often included floating and emergent plant species, and extended to the approximate end of the aquatic vegetation where there was little standing water. The intermediate zone was the area located between the wetland and the upland, and was often characterized by open areas, with scattered shrubs and few trees. Finally, the upland was categorized as beginning just inside the edge of the forest or tree line where tree density significantly increased, and extended various distances into the woodlot depending on the site. For two sites, MRB and AMS3, due to the presence of a steep bank at the edge of the waterbody, the wetland portion for all