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Review

Characterization and distribution of metal and nonmetal elements in the Alberta oil sands region of Canada

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HIGHLIGHTS

- Metal and nonmetal contamination in the Alberta Oil Sands Area (AOSR) was reviewed.
- Contaminants found in air, river water, river sediment, soil and aquatic birds eggs.
- Oil sands development leads to inorganic contamination within the AOSR and beyond.
- More stringent treatment of air and water emissions is needed to limit impacts.

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ABSTRACT

This review covers the characterization and distribution of metals and nonmetals in the Alberta oil sands region (AOSR) of Canada. The development of the oil sands industry has resulted in the release of organic, metal and nonmetal contaminants via air and water to the AOSR. For air, studies have found that atmospheric deposition of metals in the AOSR decreased exponentially with distance from the industrial emission sources. For water, toxic metal concentrations often exceeded safe levels leading to the potential for negative impacts to the receiving aquatic environments. Interestingly, although atmospheric deposition, surface waters, fish tissues, and aquatic bird eggs exhibited increasing level of metals in the AOSR, reported results from river sediments showed no increases over time. This could be attributed to physical and/or chemical dynamics of the river system to transport metals to downstream. The monitoring of the airborne emissions of relevant nonmetals (nitrogen and sulphur species) was also considered over the AOSR. These species were found to be increasing along with the oil sands developments with the resultant depositions contributing to nitrogen and sulphur accumulations resulting in ecosystem acidification and eutrophication impacts. In addition to direct monitoring of metals/nonmetals, tracing of air emissions using isotopes was also discussed. Further investigation and characterization of metals/nonmetals emissions in the AOSR are needed to determine their impacts to the ecosystem and to assess the need for further treatment measures to limit their continued output into the receiving environments.

Contents

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1. Introduction

The oil sands bitumen reserves in northern Alberta, Canada, are considered to be one of the largest in the world containing 293 billion m^3 of initially in-place crude bitumen (Alberta, 2012, 2014; Hudson, 2013). Of this total, about 28 billion m^3 are considered to be established reserves that are recoverable using current technology and anticipated economic conditions (Kelly et al., 2010; Alberta, 2014). By 2013, the cumulative production from these reserves had exceeded 1.53 billion m^3 (Alberta, 2014). Although only a small portion of these reserves have been extracted thus far, the estimated industry investment in Alberta's oil sands had already reached over $21.6 billion in 2011 (Alberta, 2012). By 2023, the bitumen production is projected to double the 2013 production and anticipated to reach 121 million m^3 per year (Alberta, 2014). Overall, the Albertan oil sands industry has the ability to benefit Canada financially while also providing a wide variety of cross-disciplinary scientific studies that are targeted mainly at increasing bitumen extraction efficiencies and decreasing environmental impacts (Giesy et al., 2010; Tolton et al., 2012; Small et al., 2015). Of these targets, the environmental impacts are a primary concern for the oil sands industry due to the negative impacts of the invasive mining activities on the ecosystems of the affected region and beyond. The impact of the extraction processes are spread over lakes and rivers that go through the current oil sands development regions in northern Alberta as shown in Fig. 1 (Gueguen et al., 2011; Ross et al., 2012; Schwalb et al., 2014).

The Alberta oil sands region (AOSR) developments release a variety of pollutants via wastewaters and airborne stack emissions (Jack et al., 1979; Platt et al., 2012; Blaesing et al., 2014). These pollutants comprise of contaminants of concern including toxic metals (Headley et al., 2005; Kelly et al., 2010; Gueguen et al., 2011; Kirk et al., 2014), nonmetals (primarily airborne SO_2 and NO_x) (Simpson et al., 2010; Davies, 2012; Percy et al., 2012; Proemse et al., 2012b), and a wide variety of organic pollutants including naphthenic acids (NAs) (Headley et al., 2002; Headley and McMartin, 2004; Nyakas et al., 2013; Pereira et al., 2013) and polycyclic aromatic hydrocarbons (PAHs) (Kelly et al., 2009; Kurek et al., 2013). However, industry and government related agencies claim, based in part on the results from a Regional Aquatic Monitoring Program (RAMP), that environmental and human receptors are not at risk from oil sands development (Alberta, 2000) and that many sources of elevated pollutants of concern are naturally occurring in the AOSR (Alberta, 1999). Overall, much of the focus of previous research has been targeted on the organic pollutants that have known toxicity in the environment (Hagen et al., 2012; He et al., 2012; Scarlett et al., 2013; Wang et al., 2013). Much less focus has been on the metals despite their being on the United States Environmental Protection Agency (USEPA) list of priority pollutants (PPE) and known risks towards the health of many species (Kelly et al., 2010; Gueguen et al., 2011; Puttaswamy and Liber, 2012). Toxicological effects have been reported for currently considered metal elements including Hg (Sweet and Zelikoff, 2001; Clarkson and Magos, 2006; Rooney, 2007), Pb (Hsu, 2002; Canfield et al., 2003; Flora et al., 2012), As (Hindmarsh, 2000; Xia et al., 2009; Hughes et al., 2011), Cd (Perfus-Barbeoch et al., 2002; Nordberg, 2009), Cr (Katz and Salem, 1993; Levina et al., 2002), Be (Wagoner et al., 1980), Sb (Gebel, 1997), Se (Spallholz, 1994), Tl (Cerwenka and Cooper, 1961), Cu (Welsh et al., 1996), Ni (Oller et al., 1997), Ag (Hollinger, 1996), and Zn (Eisler and Gardner, 1973). Among these, Hg, Pb, and As have received the most attention, while enhanced synergistic toxicological effects have been reported in the presence of multiple elements (Leber, 1976; Pillai et al., 2003; Hu et al., 2013). In addition, currently reviewed nonmetals of concern include SO_2 and NO_x which are known to negatively affect ecosystems via acidification and eutrophication impacts (Stasik and Wendt-Potthoff, 2014; Fenn et al., 2015).

This review consolidates the previous literature studies involving the characterization and distribution of toxic elements (metals and nonmetals), primarily via air and water emissions, in the AOSR region. It should be noted in advance that studies have been performed with varying sample types and methodologies, and numerous analytical techniques. Thus, numerical comparisons between study measurements are currently not made directly. Metals studies were reported according to the sampled matrix including airborne, river water, river and lake sediments, soil, fish tissues, and aquatic bird eggs; while nonmetals studies include air, plant, and soil sampling. Despite the previous development of treatment measures for waterborne metals of the AOSR, (Mahdavi et al., 2012, 2013; Pourrezaei et al., 2014) the aim of this review is to call-to-attention the environmental concerns of inorganic contamination from the oil sands industry developments and indicate the necessity for more stringent treatment of airborne and waterborne emissions to safeguard the receiving environment health. It is also recommended that future studies, in addition to regulatory guidelines, should consider using measurement methodologies that can accurately determine the presence of metals in different phases (e.g., dissolved or particulate metals, nonlabile and labile dissolved metals) to allow for future comparisons between studies.

2. Distribution of metals in the AOSR

The AOSR metals concentrations have been investigated through air (i.e., atmospheric deposition), river water, river sediments, terrestrial soils, fish tissues, and aquatic bird eggs (Table 1). In addition to metals, the nonmetals arsenic (As) and selenium (Se) are typically considered along with the metals in the literature, thus their analysis was included herein grouped under 'metals'. Table 1 shows a summary of each study including metals, sampling sites, year and season of sampling, sample type, instruments used for analysis, and an overview of findings.