Evidence of low toxicity of oil sands process-affected water to birds invites re-evaluation of avian protection strategies

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Exposure to water containing petroleum waste products can generate both overt and subtle toxicological responses in wildlife, including birds. Such exposure can occur in the tailings ponds of the mineable oil sands, which are located in Alberta, Canada, under a major continental flyway for waterfowl. Over the 40 year history of the industry, a few thousand bird deaths have been reported following contact with bitumen on the ponds, but a new monitoring programme demonstrated that many thousands of birds land annually without apparent harm. This new insight creates an urgent need for more information on the sublethal effects on birds from non-bitumen toxicants that occur in the water, including naphthenic acids, polycyclic aromatic hydrocarbons, heavy metals and salts. Ten studies have addressed the effects of oil sands process-affected water (OSPW), and none reported acute or substantial adverse health effects. Interpretive caution is warranted, however, because nine of the studies addressed reclaimed wetlands that received OSPW, not OSPW ponds per se, and differences between experimental and reference sites may have been reduced by shared sources of pollution in the surrounding air and water. Two studies examined eggs of birds nesting >100 km from the mine sites. Only one study exposed birds directly and repeatedly to OSPW and found no consistent differences between treated and control birds in blood-based health metrics. If it is true that aged forms of OSPW do not markedly affect the health of birds that land briefly on the ponds, then the extensiveness of current bird-deterrent programmes is unwarranted and could exert negative net environmental effects. More directed research on bird health is urgently needed, partly because birds that land on these ponds subsequently migrate to destinations throughout North America where they are consumed by both humans and wildlife predators.

Key words: Birds, oil sands, oil sands process-affected water, review, tailings ponds, toxicology

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Introduction

Exposure to oil commonly occurs in terrestrial, freshwater and marine environments, and the toxic properties of oil have been documented in numerous plant and animal taxa, including birds (Albers, 1998). Water-associated birds are at particular risk from oil that spills or seeps into aquatic habitats. Mortality is common when birds are exposed to large amounts of oil, primarily because it coats feathers, thus compromising thermoregulation, flight and foraging abilities (Leighton, 1993;
Mortality of avian embryos is also likely following eggshell exposure during incubation (Leighton, 1993). The ingestion of oil products by adults typically results in sublethal rather than acute effects, although these can affect bird populations and communities for many years (Hennan and Munson, 1979; Leighton, 1993). In addition to large marine oil spills, exposure of birds to oil products occurs routinely at inland oil-production facilities, including in the tailings pits throughout the USA (e.g. Trail, 2006) and in the tailings ponds of the oil sands industry of Alberta, Canada (Timoney and Ronconi, 2010; Smits and Fernie, 2013; St Clair, 2014).

Tailings ponds produced by the oil sands mining industry present numerous environmental challenges, one of which is the hazard posed by their constituents to water-associated birds. The necessity of protecting birds from exposure to tailings ponds was anticipated by both industry and government biologists decades ago (Hennan and Munson, 1979; Yonge and Christiansen, 1979). They reasoned that the ponds could attract waterfowl travelling to and from the Peace-Athabasca Delta, an internationally recognized staging area 200 km north of the oil sands that attracts more than one million birds twice annually (Hennan and Munson, 1979; Butterworth et al., 2002). These biologists predicted that large numbers of migrating water birds would be especially likely to land on tailings ponds during early spring, when adjacent water bodies might still be frozen, and late autumn, when winter storms might force abrupt landings.

Such harm to wildlife is regulated by three pieces of legislation, which oblige oil sands operators to prevent exposure of birds to all forms of water that has been affected by oil sands processing; hereafter OSPW (oil sands process-affected water). The Alberta provincial Environmental Protection and Enhancement Act states that hazardous substances must be stored in a manner that ensures they do not directly or indirectly come into contact with any animals (Alberta Government, 2010). The federal Migratory Birds Convention Act prohibits operators from depositing substances harmful to migratory birds in any location that might be used by said birds or from killing migratory birds (Government of Canada, 1994). Finally, the Species at Risk Act prohibits the harm of wildlife species listed as extirpated, endangered or threatened (Minister of Justice, 2002). Associated regulations currently prevent the release of OSPW into the environment, with the exception of experimental wetlands, either constructed or naturally situated to receive OSPW as a form of reclamation (reviewed by Allen, 2008b).

These legislative requirements oblige the oil sands industry to design and implement bird protection programmes to deter birds from landing on ponds via one or both of visual (e.g. effigies of humans and predatory birds, flashing lights, reflective tape, lasers) and auditory stimuli (e.g. propane cannons, electronic noise makers; reviewed by Ronconi and St Clair, 2006; St Clair and Ronconi, 2009; Cassidy, 2015). Deterrent devices may be deployed continuously or may be triggered by the approach of birds after detection via marine radar systems (Ronconi and St Clair, 2006; Loots, 2014). If birds land, they are further deterred by workers employing aversive stimuli, such as flares, cracker shells and boat-based chases. Over the past 10 years, traditional deterrent systems consisting mainly of propane cannons and human effigies have been supplemented with very loud acoustic devices capable of achieving comparable sound intensity over radii of several kilometres (St Clair et al., 2010). Additional deterrence occurs passively through the removal of habitat features (e.g. beaches, vegetation and prey habitat) that potentially attract birds (Yonge and Christiansen, 1979).

The bird protection programmes operating in the oil sands received implicit public approval until recently, when three separate mortality events occurred, each causing the death of between a few and several hundred migrating birds. The first of these landing events occurred on a tailings pond that was not protected by deterrents, resulting in a criminal conviction (R. v. Syncrude Canada Ltd, 2010), sustained media attention (Nelson et al., 2014) and a new standardized monitoring programme to determine rates at which birds make contact with and die from OSPW ponds (St Clair et al., 2013). Over the first 3 years of its existence, this programme revealed that tens of thousands of birds land on tailings ponds annually, but few (0.1–1%) appear to suffer acute or subacute mortality as a result (St Clair, 2014). Landings have been observed for dozens of species that subsequently migrate in flyways throughout North America, including several federally listed species at risk (St Clair et al., 2013).

These recent monitoring results create a paradox for the environmental regulation of OSPW. Either pond toxicity has been overestimated and existing deterrent programmes are far too expansive, potentially subjecting entire landscapes to unnecessary stressors (St Clair, 2014), or brief exposure to OSPW causes sublethal effects that subsequently play out in diverse ways, time periods and destinations. If the former is true, the current goal of deterring birds from all OSPW ponds may prevent deterrents from succeeding where they are needed most, i.e. in the areas containing residual bitumen (St Clair et al., 2010; St Clair, 2014). If the latter is true, the sublethal effects of OSPW will complicate the assessment of the overall impact of petroleum products on birds, which are undeniably negative but so complex that they will always be uncertain (Leighton, 1993).

Resolving this regulatory paradox will require greater knowledge of the toxicological effects of OSPW. Specifically, it is essential to know the extent to which birds may be harmed by the contact with OSPW that occurs when birds land briefly while migrating. Although there have been comprehensive reviews of the chemical constituents of OSPW (e.g. Headley and McMartin, 2004; Clemente and Fedorak, 2005; Allen, 2008a; Brown and Ulrich, 2015) and the more general impacts of oil sands development (e.g. Gosselin et al., 2010; Council of Canadian Academies, 2015), surprisingly few studies have addressed the effects of exposure to OSPW on birds.
Moreover, there has been no comprehensive review of that work despite its potential to provide insights into ecosystem sustainability (Smits and Fernie, 2013). The objectives of this review article are as follows: (i) to review the production and toxic constituents of processed water in the oil sands; (ii) to synthesize the literature specific to the toxic effects of OSPW on birds; (iii) to identify explicitly the most important missing information; and (iv) to recommend research that will reduce ambiguity about the toxicity of common types of OSPW. This information will make it possible for government to align regulatory requirements and bird protection better for the oil sands industry, and has potential for application to the dozens of other industries that produce waste water.

Production and composition of process-affected water in the oil sands

The oil sand deposits of northeast Alberta, Canada comprise one of the largest petroleum reserves on Earth, and one, the Athabasca Deposit, is shallow enough to support surface mining (Gosselin et al., 2010). The process of surface extraction of oil sands ore (bitumen) from its surrounding mixture of sand, clay and water generates copious waste water (ratio of 9:1; Chataluruky et al., 2002), but recycling of the water reduces the net ratio of freshwater needed during extraction (ratio of 3:1; Allen, 2008a). Continued use of recycled water in extraction processes concentrates the toxics contained in both the water and the associated solids (sand, silt and clay; Allen, 2008a). Given that the oil sands companies are not currently permitted to discharge the waste water, the number and size of containment ponds, also referred to as tailings or OSPW ponds, has grown rapidly over the past 40 years. By 2013, there were 64 ponds, ranging in size from 0.01 to over 10 km² (St Clair, 2014) and covering an area of roughly 182 km² (Alberta Environment and Sustainable Resource Development, 2014).

Although the terms ‘OSPW’ and ‘tailings’ are used interchangeably in many contexts, there are several important differences among the types of OSPW that exist on the landscape. Differences result from variations in source material, extraction and processing methods (including chemical treatments) and pond characteristics, such as age, purpose and the surrounding environment (Fig. 1; Allen, 2008a, b). After initial extraction, much of the OSPW is contained on site in large settling or tailings ponds, which are usually surrounded by sand dykes and drainage collection systems (e.g. interceptor ditches and wells; Gosselin et al., 2010). A typical tailings pond consists of 70–80% water, 20–30% solids (i.e. sand, silt and clay) and only 1–3% residual bitumen (Allen, 2008a). Over time, the tailings de-water to produce ‘mature fine tailings’. Water that is destined for reuse in the extraction process is held in ‘recycle water ponds’. Finally, as part of tailings pond reclamation, some operators use tailings to fill pits that result from earlier excavation. These so-called ‘end-pit lakes’ are capped with freshwater and are anticipated to resemble natural wetlands over time, although none has been reclaimed to date and their ecological value is debated (reviewed by Council of Canadian Academies, 2015). Additional reclamation techniques include the addition of aerobic bacteria to speed the breakdown of organic contaminants, the addition of plants for phytoremediation, and decanting of OSPW to existing wetlands (reviewed by Council of Canadian Academies, 2015).

Exposure to OSPW by birds can occur in several ways. Most obviously, birds may land on ponds that are designated as containing OSPW and are being monitored as part of the standardized programme. However, birds may contact OSPW in at least four other ways. First, even in ponds that have been capped with freshwater, birds may encounter OSPW via diving or water mixing. Second, some OSPW seeps from containment ponds into adjacent areas (e.g. Ferguson et al., 2009; Ross et al., 2012; Frank et al., 2014), mixes with groundwater and may enter adjacent watercourses, such as the Athabasca River (reviewed by Council of Canadian Academies, 2015). Third, OSPW is sometimes pumped into surrounding areas, including existing wetlands, as a means of reclaiming mature OSPW (as described above). Finally, birds may contact OSPW on ponds that were not designated for monitoring in the standardized programme, such as some of the recycled water ponds (St Clair, 2014). This variety of sources and concentrations of OSPW creates very different mixtures and concentrations of toxicants included under the broad description of OSPW exposure.

The highly variable composition of OSPW ponds was comprehensively reviewed by Allen (2008a, b). As toxicants of primary biotic concern, he named aromatic hydrocarbons (including polycyclic aromatic hydrocarbons (PAHs), benzene, phenols and toluene), naphthenic acids (NAs) and dissolved solids. Although many of the components in OSPW also occur naturally in adjacent landscapes, the mining process increases their concentrations (reviewed by Gosselin et al., 2010) and, consequently, several of their specific toxicological effects.

Bitumen, like all petroleum, is composed almost entirely of hydrocarbons but, unlike conventional crude oils, bitumen is extremely heavy and viscous at room temperature. Residual bitumen may be present in tailings ponds both on the surface and at depth, but concentrations are difficult to quantify because its distribution changes both horizontally and vertically, and in response to mining practices as well as environmental factors. The recycled water from tailings ponds typically contains bitumen at concentrations of 25–7500 mg/l, significantly higher than the environmental guidelines of the Environmental Protection and Enhancement Act (10 mg/l; reviewed by Allen, 2008a). However, the volume in surface OSPW might more typically be between 0.63 and 3.1 g/100 g of water (0.6–3%; Holowenko et al., 2000). Fouling of feathers and resulting mortality of birds appears to occur only when birds directly contact mats of bitumen that have accumulated near discharge sites or from wind and wave action (St Clair, 2014).

Polycyclic aromatic hydrocarbons are a large family of naturally occurring aromatic hydrocarbon compounds found
Figure 1: Examples of ponds containing oil sands processed-affected water (OSPW) and freshwater on or adjacent to oil sands lease sites. Operators are required to deter birds from tailings ponds (a) and many other ponds containing OSPW, including some recycle water ponds (b), but not freshwater reservoirs or lakes (c). Vegetation, and sometimes nest boxes, attracts birds to wetlands and ponds that have received OSPW via seepage from dykes surrounding tailings ponds (d) or reclamation via diversion of mature fine tailings (e) and end-pit lakes (f), for which mature fine tailings have been capped with freshwater. Photograph sources: David Dodge (top), Judit Smits (middle) and Louis Helbig (bottom).
in oil deposits, which are released during combustion of fossil fuels (Eisler, 1987). Polycyclic aromatic hydrocarbons are composed of hydrogen and carbon atoms arranged as two or more fused benzene rings (Eisler, 1987). There are thousands of PAHs, which gives the group a broad range of physical and chemical characteristics and, therefore, toxicities. Although concentrations of PAHs in OSPW can be reduced by volatilization, dilution and degradation, an average concentration has been estimated to be around 0.01 mg/l, substantially exceeding environmental guidelines of 0.00001–0.00006 mg/l and thus creating the potential for toxicity (Allen, 2008a).

Many PAHs have teratogenic, mutagenic and carcinogenic effects in fish, amphibians, mammals and birds (Eisler, 1987) and have been identified as endocrine disruptors that are also immunotoxic (Lintelmann et al., 2003; Fairbrother et al., 2004).

Other types of hydrocarbons found in OSPW are also capable of causing adverse effects on health, particularly the simpler aromatic hydrocarbons, including benzene, toluene, ethylbenzene and xylene, collectively known as BTEX (Cruz-Martinez and Smits, 2012). These compounds are both water soluble and volatile and can cause both acute and chronic toxic effects via inhalation, dermal contact or ingestion. Resulting effects can be minor (ethylbenzene) or extensive, and include haematotoxicity and leukaemia (benzene), neurotoxicity (toluene), and narcosis, leukocytopenia, thrombocytopenia, cyanosis and dyspnoea (xylene; reviewed by Cruz-Martinez and Smits, 2012).

Naphthenic acids, which consist of polar organic carboxylic acids, occur naturally in bitumen deposits (~2% of total weight; Headley and McMartin, 2004) as a result of biodegradation of mature petroleum (Kindzierski et al., 2012; Brown and Ulrich, 2015). Background concentrations in the surrounding Athabasca region (typically <1 mg/l) occur at a small fraction of the concentrations in OSPW, which vary substantially depending on the source of the sample and the test method (reviewed by Brown and Ulrich, 2015) but may be as high as 110 mg/l (Headley and McMartin, 2004; Allen, 2008a). Naphthenic acids are presumed by some researchers to be one of the primary drivers of acute toxicity for many taxa in fresh tailings and, because they become concentrated in aged and recycled OSPW, they also challenge the reclamation of industrial sites (Headley and McMartin, 2004; Kindzierski et al., 2012; Brown and Ulrich, 2015). Exposure to high concentrations of NAs can be lethal; other sublethal acute effects include cytotoxicity to both red and white blood cells and hepatotoxicity (Cruz-Martinez and Smits, 2012).

Trace amounts of metals also exist naturally in the environment, although their concentrations and distribution can change significantly with anthropogenic activities (Cruz-Martinez and Smits, 2012). Oil sands process-affected water contains common, low-toxicity metals, such as aluminum, iron, molybdenum, titanium and vanadium, in addition to metals listed as toxic and priority pollutants, including arsenic, cadmium, chromium, copper, lead, nickel and zinc (Allen, 2008a; United States Environmental Protection Agency, 2013). The toxic effects of metals vary immensely; whereas some are essential elements, others are found only in association with industrial activities. Some metals may elicit teratogenic effects (e.g. chromium) and others acute mortality (e.g. lead or mercury at high levels; Eisler, 2000). Despite evidence that several of these metals exceed toxicity guidelines in the environment surrounding the oil sands (e.g. Kelly et al., 2010), there is uncertainty about the extent to which they result from OSPW, emissions from upgraders or blowing dust (Kirk et al., 2014).

A final common source of contaminants in water associated with industrial development is the accumulation of salts, including sodium, chloride, sulfate and bicarbonate (Allen, 2008a), that alter both pH and hardness of water (Eisler, 2000). Sodium, in particular, can be 60–80 mg/l higher than in natural surface water in the region (Gosselin et al., 2010). The level of toxicity caused by salts varies with their concentration, which is influenced by the length of time since production and weather-associated evaporation and dispersion of lighter chemical fractions (Tully et al., 2009), as well as the physiological status of exposed animals. Toxic responses to the salinity of OSPW have been reported primarily from plant and plankton communities, but high salinity has also been shown to reduce duckling growth and survival in other contexts (Swanson et al., 1984). Moreover, this toxicity could be additive or synergistic based on the interaction between salts and naphthenic acids (Allen, 2008a).

**Factors associated with toxic exposure of birds landing on oil sands process-affected water ponds**

Beyond the types and concentrations of contaminant compounds contained in OSPW, their toxic effects on birds are dependent on several interacting operational, environmental and avian factors. This section reviews the impact of some of the most commonly described factors.

Weather, especially temperature, is a critical contributor to the distribution and concentration of several compounds in OSPW because warmer oil has lower surface tension, specific gravity and viscosity (United States Environmental Protection Agency, 1999). In the northern latitudes where OSPW occurs, fresh tailings are highly aerated and usually warmer than ambient temperature, which causes the bitumen to float and form mats (Masliyah et al., 2004). On some ponds, operators corral residual bitumen with booms comparable to those used to contain oil spills at sea (St Clair, 2014). As the bitumen cools, it condenses, increases in density and, eventually, sinks (Camp, 1977), but it sometimes resurfaces or remains on the surface in association with other compounds (Allen 2008a). Wind and wave action can change the distribution of bitumen on the pond surface very rapidly, particularly during storm events when winds change direction over a few hours (St Clair et al., 2010). Historically, corralling was applied mainly to recover bitumen,
but the difficulty of securing booms against strong winds and the low quality of recovered bitumen has reduced its use (D. Martindale, Shell Canada, personal communication, 2014).

In addition to temperature, pond age contributes to the abundance, distribution and concentration of toxic constituents. The age of OSPW is typically referred to as ‘fresh’ (i.e. recently produced) or ‘aged’ (for a number of years, typically 3–5 years, in inactive waste-water ponds or pit lakes; Kindzierski et al., 2012). The influence of age on toxicity is not straightforward; while recycling of OSPW for multiple extraction cycles can concentrate some toxicants (reviewed by Allen, 2008a), others (e.g. phenols, cyanide, ammonia, oil and grease) degrade significantly over time via naturally occurring biological, physical and chemical actions (MacKinnon and Boeger, 1986). Even when OSPW is aged, whether naturally (e.g. when filtered through wetlands) or experimentally (e.g. through chemical additives), it has been shown to elicit toxic effects in amphibians (e.g. Pollet and Bendell-Young, 2000; Herskorn and Smits, 2011), fish (e.g. van den Heuvel et al., 1999, 2000; Nero et al., 2006) and birds (e.g. Smits et al., 2000; Gurney et al., 2005; Gentes et al., 2006, 2007a, c; Harms et al., 2010). Likewise, although metals tend to adsorb and settle into the sediment over time (Sauer and Tyler, 1996), some are maintained in the water column in association with fine particulate matter, both organic and inorganic (Sengupta et al., 1997). The tremendously slow rate at which these fine particles settle has been recognized for decades as a central problem in tailings management (e.g. Camp, 1977; Chalaturnyk et al., 2002; Allen, 2008b).

For the birds that land on OSPW, exposure to contaminants can occur by three major routes, namely external contact (dermal or egg), ingestion and inhalation. The severity of exposure by any route is presumed to be greater for resident species than for migrants, particularly if exposure occurs during life stages that are critical to growth, development and reproduction (Cruz-Martinez and Smits, 2012).

Ultimately, bitumen kills birds from hypothermia, drowning or starvation through loss of thermoregulation, waterproofing, flight and foraging after the interlocking structure of the feather and, therefore, feather function is destroyed (Tully et al., 2009). Beyond the mechanical effects of oil on feathers, transfer of oil from the feathers of incubating birds to the egg is acutely toxic via shell penetration and absorption by the embryo (reviewed by Leighton, 1993).

Ingestion of bitumen and other constituents may occur through either preening or consumption of contaminated food or water. Ingestion of petroleum products can cause direct damage to the gastrointestinal system, which may manifest as ulcers, diarrhea and dehydration (Tully et al., 2009). When glaucous-winged gulls (Larus glaucus) and mallards (Anas platyrhynchos) ingested petroleum hydrocarbons, more than 50% was absorbed into the circulatory system and distributed into body tissues (McEwan and Whitehead, 1980). Although this assimilation can compromise most body systems, a primary target is red blood cells, resulting in haemolytic anaemia (Leighton et al., 1983). Consumption of contaminated food is especially significant for birds in higher trophic positions; bioaccumulation of aromatic hydrocarbons has been shown in captive redhead ducks (Aythya americana; Tarshis and Rattner, 1982). The ingestion of oil sands process-affected material as grit can result in significant exposure to compounds such as oil and grease (King and Bendell-Young, 2000).

A final route of exposure occurs through inhalation of the volatile components of oil, which can lead to respiratory irritation and inflammation (e.g. pneumonia), emphysema, suffocation, and degradation of the central nervous system (United States Environmental Protection Agency, 1999). In the oil sands region, air quality is affected by several toxicants (including hydrogen sulfide, sulfur dioxide, nitrogen dioxide, ozone and particulate matter) that can compromise the health of wildlife (Cruz-Martinez and Smits, 2012). Negative effects of air pollution have recently been reported for both captive birds exposed to airborne pollutants from the oil sands (Cruz-Martinez et al., 2013b) and wild tree swallows nesting near the oil sands (Cruz-Martinez et al., 2015a). Inhaled toxins are not considered in additional detail in this review, which is focused on OSPW.

**Evidence of toxic effects of oil sands process-affected water to birds**

It is well established that acute, lethal effects of exposure to refined oil always involve mechanical disruption of feather structure following direct contact between the birds and the oil (Leighton, 1993; Tully et al., 2009). The available evidence suggests the same principle applies to the bitumen contained within OSPW ponds. Consistent with this evidence, there is a widespread belief in the oil sands industry that OSPW is not acutely toxic to birds if it does not contain fresh tailings or bitumen. Three years of data from the recent standardized monitoring programme support this belief. That programme reported between 100 and 200 bird mortalities annually in association with OSPW, most of which were found covered in bitumen and were either dead or moribund (St Clair et al., 2013; St Clair, 2014). These numbers are comparable to mortality rates reported by government and industry over many years (Timoney and Ronconi, 2010). Bitumen exposure characterized the three recent events in which hundreds of birds died after landing on tailings ponds during or immediately after severe weather (St Clair, 2014). However, it is possible that more birds land, become oiled, sink in the ponds and are not found by oil sands operators. Rates of mortalities, landings and oiling have been extrapolated to suggest there are between 458 and 5029 mortalities each year (Timoney and Ronconi, 2010) and even as many as 100 000 (Wells et al., 2008). However, this high estimate from Wells et al. (2008) was derived from an extrapolated estimate of the landings at all ponds, with an assumption that 90% of landed birds die, and differs vastly from the <1% mortality reported by the standardized monitoring programme. Although undesired,
even the highest of these estimates is relatively negligible in comparison to the recently estimated 269 million human-related avian mortalities that occur in Canada alone, each year (Calvert et al., 2013).

The subacute effects of contact with OSPW are much more variable and difficult to measure, typically requiring extended monitoring of exposed individuals. These effects are especially difficult to measure for the migratory birds that frequent the region, which could become sick or die later in another location. When individuals can be captured, assessment of exposure to toxicants typically includes physiological metrics of health related to endocrinology, immunology, haematology, blood biochemistry and major organ systems (Tully et al., 2009). When it is not possible or desirable to measure physiological metrics, evidence of exposure to toxicants that the birds logically may encounter is sometimes inferred from measurements of individual fitness (e.g. reproductive performance, chick growth and survival), population ecology (occupancy and abundance) and community ecology (species composition and evenness; reviewed by Fairbrother, 2003).

A literature search for direct assessments of toxicity to birds from OSPW exposure revealed 10 studies; nine in the peer-reviewed literature and one MSc thesis (Tables 1 and 2). Six studies compared reproduction, growth, survival and health of tree swallows (Tachycineta bicolor) that nested in boxes adjacent to either reference ponds or wetlands that had received OSPW as a means of reclamation (Smits et al., 2000; Gentes et al., 2006, 2007a, b, c; Harms et al., 2010). Three studies used captive mallards that were either held on reclaimed wetlands (King and Bendell-Young, 2000; Gurney et al., 2005) or subjected to water from OSPW from a recycle water pond (Beck et al., 2014). The unpublished MSc thesis compared occupancy rates and abundance of avian species on and near different OSPW wetlands with results from initial surveys in 1976–83 (Dagenais, 2008). We did not include in Tables 1 and 2, although they will be described in text, two studies that were based on evaluation of mercury concentrations in eggs of wild gulls (Larus spp.) and terns (Sterna spp.) that were collected during different periods at sites down-stream from the oil sands (Hebert et al., 2011, 2013). Although the industry potentially contributes mercury contamination to the adjacent river (Kelly et al., 2010), it is likely to originate mostly as aerial pollution from combustion exhaust and pollutes water following deposition with precipitation (Wang et al., 2004). Studies were reviewed by synthesizing the evidence associated with the types of assessment described above, beginning with the physiological metrics, followed by those related to reproduction, growth and survival and, finally, those that scale to the population or community level.

**Endocrinology**

Three studies provided evidence of endocrinological change in response to exposure to OSPW via assessment of one or both of the thyroid hormones and the stress hormone, corticosterone. In tree swallow nestlings, Gentes et al. (2007a) found elevated triiodothyronine (T3) in plasma and thyroxine (T4) in thyroid glands of birds in boxes adjacent to reclaimed OSPW wetlands, compared with birds on nearby reference sites. The authors speculated that this disruption in normal thyroid function could compromise the subsequent survival and fitness of birds through increased energy expenditure from a higher basal metabolic rate, or by altering moulting patterns or affecting reproductive behaviour (Gentes et al., 2007a). Likewise, Beck et al. (2014) found that the plasma ratio of T3/T4 was higher in male (26%), but lower in female (14%), juvenile pekin ducks (Anas platyrhynchos domestica) exposed to recycled OSPW, relative to those treated with well water, suggesting that the treated water may have induced some chronic physiological stress (Scanes, 2015).

Additional hormonal evidence of health effects emanating from exposure to OSPW was through elevation of corticosterone, which is indicative of a stress response in birds (Palme et al., 2005). Higher plasma corticosterone was found in the adult male, but not female, captive ducks exposed to OSPW (Beck et al., 2014). Given that plasma corticosterone has a very short half-life (within minutes), it could have reflected in part more ephemeral forms of stress, such as capture and restraint (Scanes, 2015), although these birds were regularly handled. A more reliable index of chronic stress (days to months) may exist in feathers because they incorporate circulating corticosterone during development (Bortolotti et al., 2008). Harms et al. (2010) used this method to assess the effects of OSPW on nestling tree swallows and found corticosterone levels to be significantly higher in male nestlings, but only on the younger, more contaminated OSPW wetlands compared with the reference wetland. Given that the birds were still pre-fledging and presumably experienced comparable social stress on all three sites, this study provides more compelling evidence that exposure to OSPW can contribute to chronic physiological stress.

**Immunotoxicity**

Immunotoxic effects, which can reflect detrimental effects of environmental pollutants on immune system components and function (Briggs et al., 1996), were measured in several studies of tree swallows exposed to OSPW. Smits et al. (2000) examined the adaptive, cell-mediated immune response of nestling tree swallows through the phytohaemagglutinin skin test, which measures the proliferative response of T lymphocytes following a short-term, local inflammatory response. The authors compared the responses of birds from several reclaimed wetlands receiving OSPW with reference sites. A decreased cell-mediated immune response of nestlings from one of the OSPW wetlands was identified in year 1, but not the second year of study at the same sites, although differences in liver ethoxyresorufin-O-deethylase (EROD) among these birds confirmed that they were being exposed to contaminants (Smits et al., 2000). Using a different, more integrated measure of cell-mediated immune function, Harms et al. (2010) found that nestling tree swallows on one of the wetlands...
Table 1: Summary of studies with relevance to the effects of oil sands processed-affected water on birds. Summary information describes study design (species, authors, response variables, sample size, study duration, and location), core results (toxicological, health, and reproductive metrics), and implications for wild bird populations

| Study design | Results | Implications |
|--------------|---------|--------------|
| Mallard (Anas platyrhynchos) | Grit turnover rates: ducklings consumed an average of 2 g grit/day | Grit consumption may increase exposure to toxicants above that predicted by trophic position |
| King and Bendell-Young (2000): grit consumption was measured in captive ducklings (n = 71) over 15 days | | |
| Gurney et al., (2005): captive ducklings (n = 135) were held for 33 days in pens on two experimental (NW, HU) and one reference wetland (SI) | Growth: ducklings on experimental sites were smaller (skeletal size), with lower body mass Plasma metabolites (glycerol, triglyceride): no effect EROD activity (surrogate for HAH exposure): no effect Toxicant exposure: higher PAH metabolites in bile | Exposure to PAHs on OSPW wetlands may reduce growth rates in ducklings Differences may have been obscured by OSPW seepage into the reference site |
| Pekin duck (Anas platyrhynchos domestica) | Mass, survival, biochemistry, endocrinology, haematology, and meteals (19, 4, 7 and 21 standard measures each): blood vanadium levels were higher in treated birds; all other parameters were within biological reference ranges | There was little evidence of toxic effects resulting from repeated, but brief, exposure to OSPW from a recycled water pond |
| Beck et al., (2014): captive birds were repeatedly exposed to experimental (Shell Canada’s MRM recycled water) or reference (well) water as ducklings and as adults (n = 36, 29) | Reproduction (female age, clutch, hatch, nesting skeletal size, ninth primary feather length, survival and mass: no effect EROD activity: increased at experimental sites Immune function (T cell): no effect | Slight exposure to toxicants in food was assumed for experimental sites |
| Tree swallows (Tachycineta bicolor); sample size generally refers to the number of boxes | Reproduction (female age, clutch, hatch, nesting skeletal size, ninth primary feather length, survival and mass: no effect EROD activity: increased at experimental sites Immune function (T cell): no effect | Exposure to OSPW reduced reproductive success, but results were heavily influenced by weather and by year |
| Gentes et al., (2006): wild adults and nestlings were monitored in nest boxes (n = 92) in 2003 and 2004 (53, 54 BP) on three experimental (CT, NW, DP; n = 25, 21, 20) and one reference wetland (PC; n = 26) | Reproduction, growth, survival (female age, clutch, hatch, egg mass, nesting mass/wing length, F/SNS): smaller broods and fledglings and higher nesting mortality at experimental sites EROD activity: elevated at experimental sites | Potentially indicative of exposure to toxicants, especially PAHs |
| Gentes et al., (2007a): wild nestlings were monitored in nest boxes on three experimental (DP, CT, NW; n = 20, 25, 21) and one reference wetland (PC; n = 26) | Endocrinology [triiodothyronine (n = 62), thyroxine (n = 63), thyroid weight (n = 64)]: thyroid hormone levels slightly elevated at experimental sites | |
| Gentes et al., (2007b): wild nestlings living on a reference wetland (PC; n = 26 boxes) were dosed daily (days 7–13) with 1.5 mg of naphthenic acids or saline solution or were not treated (n = 20 each) | Growth (mass, wing length): no effect Haematology, biochemistry (packed cell volume, total protein): no effect EROD activity: no effect Organ health (mass, SI, pathological change): hepatocyte changes, including vacuolation and glycogen accumulation; extramedullary EPO in treated birds | Birds can tolerate brief exposure to high levels of naphthenic acids |
| Gentes et al., (2007c): wild birds were monitored on three experimental (CT, NW, DP; n = 25, 21, 20) and one reference wetland (PC; n = 26) | Reproduction, growth and survival (clutch initiation, brood size, nestlings weight/wing length, survival); decreased nestling mass at experimental sites Immune function (skin lesion, number of blowfly pupae/empty puparia, mean nesting load): infestation double at experimental sites | OSPW in reclaimed sites may decrease host resistance to and increase populations of blowflies |
| Harms et al., (2010): wild birds were monitored on three experimental wetlands at various stages of maturity (CT, NW, DP/SW; n = 13, 13, 14) | Reproduction, growth, body condition (clutch, egg number/mass, hatch, nestling mass/wing and head–bill length, FS): greater nestling mass and wing length at day 6 on one site Immune function (adaptive and innate): higher DTH responses present in larger birds. Feather corticosterone associations varied with sex | There was no negative effect on the immune system or body condition of nestlings Reclaimed wetlands can support populations in favourable environmental conditions |

Abbreviations and terminology: BP, breeding pair; clutch, includes clutch initiation date, size and/or mass; DTH, delayed-type hypersensitivity; E, experimental; EPO, erythropoiesis; EROD, ethoxyresorufin-O-deethylase; FS, fledging success (fledgedlings/eggs hatched); HAH, halogenated aromatic hydrocarbons; hatch, includes date, number hatched and/or hatchig success (eggs hatched/laid); mean nesting load, total puparia/brood size; MRM, Muskeg River Mine; NS, nest success (fledgedlings/eggs laid); OSPW, oil sands process-affected water; R, reference; skeletal size, includes wing cord, tarsal length and bill length/depth; SI, somatic index, (organ weight/body mass) × 100. Abbreviations for pond names and types (DP, HU, PC, RL, S1, and SW) are spelled out in Table 2.
created with oil sands process-affected material had a subtle, but significantly greater delayed-type hypersensitivity response than those nesting on the reference wetland; a difference attributed to exposure to OSPW. They evaluated the innate immune responses of the same birds through a chemiluminescence assay, which measures the release of reactive oxygen species by circulating heterophils, a type of white blood cell that responds to any foreign antigen, which was not different across sites. This test of the very generic innate immune response may be less sensitive than immunotoxicity tests involving the more highly evolved, adaptive immune response. Indirect tests of immune status, such as microbial infections or parasitic infestations, may provide more relevant information about the immunocompetence of birds exposed to OSPW (Smits and Fernie, 2013). Gentes et al. (2007c) used this approach when they examined larval blow flies (Protocalliphora spp.) in nests and on tree swallow nestlings. Nests on reclaimed wetlands had 60–72% more parasites, and nestlings had double the parasite load relative to those on the reference site, supporting the interpretation of an immunotoxic effect of OSPW for young tree swallows.

### Haematology and biochemistry

Haematology and biochemistry provide powerful tools for assessing the health of organisms because blood contains information about gas exchange (via red blood cells), immune function (via white blood cells), clotting capacity (via platelets or thrombocytes) and numerous biochemical building blocks contained in the plasma (Tully et al., 2009). Three studies have reported haematological differences following exposure to OSPW, but their results are equivocal. In a study conducted by Gentes et al. (2007b), tree swallows treated with naphthenic acids exhibited higher total proteins than control birds; however, the birds with higher total protein also exhibited higher hematocrit, which suggested that the differences were related to hydration status rather than toxicant exposure (Gentes et al., 2007b). Using mallard ducklings held in water-based enclosures, Gurney et al. (2005) found higher glycerol in 13-day-old birds on the reclaimed wetlands compared with a reference site, but no difference was seen at 33 days, and no difference in its derivative triglycerides occurred at either age. This result suggests a transient negative effect of exposure to OSPW; triglycerides are the primary form of lipid storage in the blood, and high levels of glycerol alone can be indicative of starvation (Ritchie et al., 1994).

Only one study examined both haematological and biochemical constituents of blood in the context of OSPW exposure. Beck et al. (2014) repeatedly exposed pekin ducks for ~6 h at a time as juveniles and, a year later, as adults to either recycled OSPW or well water. They found several differences...
between groups that were statistically significant, but most interacted with bird age and/or sex. For example, OSPW-treated juveniles had higher potassium following the last of the block of exposures, which could be manifestations of electrolyte imbalance or renal disease. Treated adults had higher levels of plasma bicarbonate, potential evidence of salt imbalance, but lower levels of γ-glutamyl transferase; elevation of γ-glutamyl transferase is associated with liver damage (Ritchie et al., 1994). Among the OSPW-treated birds, adult females exhibited higher concentrations of globulins, bile acids and molybdenum. Heightened globulins are mainly associated with immune system activation (γ-globulins are produced by B lymphocytes), with lower amounts of α- and β-globulins synthesized in the liver. Elevation of bile acid concentrations is also seen with liver damage and is suggestive of toxicant exposure (Tully et al., 2009). On the contrary, molybdenum is an essential micronutrient that more often causes health problems through deficiency (Eisler, 2000). Little can be made of any of these differences because, despite their statistical significance, all mean values fell within avian reference ranges, indicating minimal toxicological effects (Beck et al., 2014). The only blood constituent that was higher in all the birds exposed to OSPW was vanadium, a pollutant of concern in the oil sands region (Wiklund et al., 2014). Vanadium oxides are released by the burning of fossil fuels (Barceloux, 1999), but the mineral also appears to be heightened in natural sediments of the region (Wiklund et al., 2014). Vanadium is thus an interesting, potential biomarker of exposure to OSPW.

### Examination of tissues

Damage to the functional capacity of organ systems following exposure to contaminants can be revealed in post-mortem examination by organ weights, histology and evidence in liver tissue of detoxification effort. One such detoxification metric is the relative EROD activity, which responds primarily to organic pollutants (Walker, 2001). Three studies have measured EROD in tree swallows nesting in boxes for evidence of exposure to compounds requiring detoxification. Two of these studies found higher EROD activity in nestlings exposed to OSPW at reclaimed wetlands (Smits et al., 2000; Gentes et al., 2006), but no such increase occurred when tree swallows were dosed daily with NAs over approximately half their nestling period (Gentes et al., 2007b). Likewise, the treatment with NAs, which included doses reflecting worst-case scenarios of potential environmental exposure, had no adverse effects on the weights or histology of major organs, including the liver, heart and spleen, or in the bursa of Fabricius (an organ specific to birds that contributes to the immune system; Gentes et al., 2007b; Scanes, 2015).

In addition to studies of organs and tissues, eggs of nesting birds can provide evidence of exposure to pollutants via shell thickness and internal constituents (Scanes, 2015). Hebert et al. (2011) collected eggs of gulls and terns from nesting colonies north of the oil sands (~300 km downstream) to measure levels of mercury, arsenic and PAHs. As expected (biomagnification has been shown to occur with mercury; Gray, 2002), they found that mercury levels were higher in species at higher trophic levels, but also within trophic levels in eggs from two areas receiving water from the oil sands mining region (Athabasca River), compared with a third site, Peace River, which does not flow through any industrial area (Hebert et al., 2011). For one site in Lake Athabasca, the authors reported a 40% increase in mercury from eggs collected in 2009 vs. 1977. Subsequent work showed evidence of increased mercury levels even between 2009 and 2012 for both gulls and terns, but the concentrations were highly variable and generally below the thresholds associated with impairment of avian reproduction (Hebert et al., 2013). The authors speculated that the most parsimonious explanation for these trends was changes in oil sands-related atmospheric emissions. Such aerial sources are believed to be responsible for the vast majority of mercury pollution in water (Wang et al., 2004), but mercury and other heavy metals are likely also to be contained in mining dust in the oil sands (Council of Canadian Academies, 2015), which may enter surrounding water bodies. Although the overall importance of mercury as a biological contaminant to birds in this region remains inconclusive, ongoing studies are addressing this issue because of the recognized importance of mercury in the aquatic food chain.

### Reproduction, growth and survival

Several studies of tree swallows sought evidence of toxic effects of OSPW through the conventional fitness metrics of reproduction, growth and survival. Smits et al. (2000) found no differences in the clutch size, mass or hatching success of birds nesting on reclaimed wetlands used to detoxify OSPW in comparison to reference sites. A subsequent study evaluated similar metrics at the same sites and found dramatic interannual differences. As a result of a severe, sustained spell of cold, rainy conditions in 2003, all sites exhibited high rates of mortality, but they were significantly higher on the reclaimed sites. In 2004, when the weather was more moderate, mortality of chicks was consistently low, but chicks on the reclaimed sites were smaller, which the authors suggested could compromise post-fledging survival (Gentes et al., 2006). Later still, and again during years of moderate weather, investigators found no differences among three reclaimed wetlands of different ages in clutch size, egg mass, hatching success or fledging success (Harms et al., 2010). This range of detectable impacts over different years in the same populations points to the importance of local weather, food and energy-related factors in reproduction and survival in these sentinel passerines.

Two studies addressed growth in captive ducks exposed to OSPW. Gurney et al. (2005) enclosed mallard ducklings in pens on two reclaimed OSPW wetlands and one reference site for slightly longer than 1 month. Although all birds had access to supplemental feed, the body mass of birds on both reclaimed sites was significantly lower than those on the reference site for the first half of the experimental period. This difference was no longer significant by the end of the study, although the trend of smaller size remained. The authors speculated that smaller size could compromise survival in the wild.
because homeothermy in very young mallards is strongly affected by body size. In the study of captive pekin ducks conducted by Beck et al. (2014), duckling growth was not recorded, but there was no difference in the adult sizes or survival of birds exposed to recycled OSPW relative to the control birds.

**Population and community effects**

Population health variables in oil-affected species are often inadequately documented because of the scale over which they occur (Votier et al., 2005). Extensive mortality can reduce local population sizes, but exposure to oiled water can also decrease avian reproductive rates that accumulate over time to cause population and community effects (Crawford et al., 2000). No published study has addressed the population or community effects on birds of exposure to OSPW in the oil sands region. However, an MSc thesis by Dagenais (2008) compared the abundance and diversity of avian species on various wetlands, as well as providing a historical comparison to wetlands surveyed between 1977 and 1983. She found no evidence that bird abundances were negatively affected by existing OSPW wetlands but did find an overall reduction in species richness between the 1976 and 1983 surveys and those she conducted in 2006–07. She also documented changes in community composition, particularly for avian guilds that nest in trees, in cavities or on the water. The only other publication on the effects of OSPW on birds is based on estimates of habitat loss, which are extrapolated to estimate the concomitant loss of several hundred thousand birds, mostly songbirds (Wells et al., 2008).

**Conclusions and research recommendations**

Attention to the toxicity of waste water produced by the oil sands industry has risen in recent years, partly because of three widely reported events in which several hundred birds died after landing on OSPW ponds and contacting bitumen (Nelson et al., 2014). The first of these events resulted in the implementation of a standardized monitoring programme that has determined that tens of thousands of birds land on the ponds annually, but that <1% of these appear to die as a result (St Clair, 2014). Meanwhile, federal and provincial legislation that obliges operators to prevent landings has encouraged the installation of hundreds of deterrent devices that create noise pollution throughout the region, which has well-known detrimental effects on birds (Bayne et al., 2008). These energy-intensive systems also contribute to greenhouse gas emissions; the most significant environmental issue associated with the industry (Council of Canadian Academies, 2015). Counterproductively, widespread and frequent use of deterrents causes habituation by birds (Conover, 2001), lessening their responsiveness at the locations and times that pose the highest danger to them. This apparent mismatch between the problem and its solution creates an urgent need to determine the toxicological effects of landings by birds that do not contact bitumen.

Oil sands process-affected water ponds are known to contain many constituents with potential toxicity to birds, including residual bitumen, PAHs and other hydrocarbons (e.g. BTEX), NAs, metals and salts (reviewed by Allen, 2008a, b). Surprisingly few studies have addressed the rates of exposure to these components and their toxicological effects on wild birds. Work involving known exposure to OSPW is limited to a narrow spectrum of the wetlands receiving OSPW as a form of reclamation and one recycled water pond. These relatively benign sources of OSPW show some evidence of health impacts on birds in the forms of EROD activation (Smits et al., 2000; Gentes et al., 2006), reduced growth and reproductive performance (Gurney et al., 2005; Gentet et al., 2006), disrupted hormone levels (Gentes et al., 2007a; Harms et al., 2010; Beck et al., 2014), increased intensity of parasitism (Gentes et al., 2007c) and immunomodulation (Harms et al., 2010; Table 1). All of these effects were either modest, inconsistent among years and metrics, dependent on exacerbating weather conditions, or all three. The single study that exposed birds directly and repeatedly to OSPW did not find a single health metric that was consistently elevated in blood from treated birds, although these birds exhibited slightly higher levels of the metal vanadium (Beck et al., 2014) and had elevated $T_3/T_4$ ratios, which can be indicative of long-term stress (Scanes, 2015).

Far from throwing open the doors to avian exposure to OSPW, we suggest an urgent need for more directed research. The existing literature is both small and equivocal. Much of the evidence of minor or absent effects of OSPW comes from six studies of tree swallows that nested in boxes placed beside wetlands receiving aged OSPW. This exposure is not comparable to the exposure experienced by birds that land on the OSPW ponds directly. Moreover, recent evidence from stable isotopes revealed that swallows nesting adjacent to OSPW wetlands do not consistently forage on prey derived from those wetlands (Farwell et al., 2014). This means that the results on avian health reported in these studies are indicative only of the general effects of the region on aerial insectivores and do not address the effects of direct exposure to OSPW.

There is, however, evidence of toxicant exposure to large numbers of birds 200–300 km downstream of the oil sands; higher levels of mercury were detected in the eggs of gulls and terns (Hebert et al., 2011, 2013), corresponding to similar detections in water samples from the Athabasca River (Kelly et al., 2010). There is ongoing debate about the source of the toxicants in the river, with some authors attributing them to industrial activity (e.g. Kelly et al., 2009, 2010) and others emphasizing natural sources in the region (e.g. Wiklund et al., 2014). Many contaminants, including mercury, result mostly from industrial emissions that may be transported long distances before deposition (Wang et al., 2004), but this source of pollution in the oil sands has only been identified recently as a source of toxicants for birds (Cruz-Martinez et al., 2015a, b). Of course, the pond surfaces themselves present vast collection areas for airborne pollutants, separate from those contained in mining effluent. No study has yet examined the health of wild,
water-associated birds that land on OSPW ponds, although bird carcasses have been collected from operators for the purposes of post-mortem analyses of pollution exposure (B. Pauli, Environment Canada, personal communication, 2015). The lack of direct assessment of the effects of OSPW on water-associated birds is surprising given the well-known importance of the region to waterfowl (Hennen and Munson, 1979; Butterworth et al., 2002) and several years of data indicating that tens of thousands of birds land on these ponds annually (St Clair et al., 2013) while migrating to and from destinations throughout the continent. Despite the uncertainty about this and other environmental effects, there remains no technology that can either eliminate or completely reclaim oil sands tailings ponds, which are projected to double or triple in volume by 2030 (Council of Canadian Academies, 2015).

A better understanding of the important thresholds for toxic effects of OSPW on birds will require studies that control exposure to specific types and concentrations of OSPW. It is likely that many of the reported effects of OSPW exposure are correlated with other environmental variables and may reflect cumulative manifestations of environmental conditions (e.g. weather, food availability and habitat suitability) and the physiological responses of birds to them. Ongoing environmental change, including climate change, will further alter these relationships. Thus, even data from controlled exposure studies must be interpreted with consideration of both environmental (e.g. time of year, location and proximity to operations) and avian variables (e.g. age, sex and species). To provide the information necessary to manage exposure of birds to OSPW, we propose the development of a coordinated framework for assessing toxic effects on birds, identifying specific and ecologically relevant thresholds that provide different levels of bird protection, and a more integrated approach to wildlife and human health. Assessment of effects on birds should ideally begin with baseline data prior to mine development and continue with ongoing risk assessment and management throughout the life of the project (sensu Fairbrother, 2003). Specifically, we make the following suggestions.

(i) Oil sands process-affected water should be divided into toxicological categories (e.g. fresh tailings, aged tailings, recycled water, ephemeral run-off and OSPW in reclaimed wetlands), based on pond purpose, water constituents, associated environmental factors and regulatory standards (sensu Allen 2008b).

(ii) Appropriate standards of bird protection should be assigned to each level of risk associated with OSPW, comparable to the standards that have been developed for protection of birds from marine oil spills (Transport Canada, 2015).

(iii) Ongoing assessment of all components (i.e. water constituents, risk to birds, efficacy of existing and alternative protection systems) should be evaluated and refined via adaptive management (sensu Walters, 1986).

(iv) All steps of study and programme development should be published to support comparable, evidence-based and transparent assessment (sensu Sutherland et al., 2004).

(v) Policy-makers should incentivize industry to work more cooperatively and speed the development and adoption of environmental technology (Council of Canadian Academies, 2015).

At a minimum, such a programme should explicitly and consistently separate the types of water ponds that are already managed as if they pose little risk to birds (e.g. recycled water ponds), ensure that management is consistent among operators and regularly evaluate their effects on bird health. Identification of safe thresholds of contaminants in water samples might subsequently support specific deterrent practices in different regions of large ponds, particularly when toxic fresh tailings have consistent and controlled inputs and bitumen is segregated with the use of traditional booms or more sophisticated devices to separate oil from water (Cheng et al., 2011). Identifying or creating safer landing areas within large ponds could compensate for the low proportion of freshwater that is available in the region (St Clair, 2014).

Within a toxicological framework, traditional areas of investigation should extend beyond blood-borne metrics of physiological stress to include evaluation with complementary modalities, such as behaviour and morphology. Greater use could be made of non-invasive tools, especially remote photography via unmanned aerial vehicles, to document potential evidence of toxicity via both traditional metrics, such as changes in abundance, and more subtle metrics, such as anomalous mating behaviour (e.g. Pérez et al., 2010) or the colouration of sexually selected ornaments (e.g. Bortolotti et al., 2003). Early detection of responses to toxins and toxicants with these more subtle and non-invasive metrics could reduce the cost of monitoring with more invasive techniques, increase the appeal of the monitoring to industrial partners and increase the specificity of interpretation. All three attributes could increase the potential to identify problems early enough to promote cost-effective management actions.

Equally important to our proposed framework are the long-term studies needed to detect latent, subtle or cumulative effects of pollutant exposure, which are especially valuable for detecting neurotoxins and carcinogens. Authors differ in the recommended duration of field studies for measuring toxicity. At the bare minimum, 2 years are necessary to account for the usual variability among typical seasons (Cruz-Martinez and Smits, 2012), but the detection of population trends and interacting effects will typically require many years. Only three of the studies in our review compared metrics of toxicant exposure over more than 2 years (Dagenais, 2008; Hebert et al., 2011, 2013).

The absence of a standardized protocol for monitoring birds on OSPW ponds over most of the last 40 years is difficult to fathom given the centuries-old role of canaries in coal mines. The capacity of birds to be reliable indicators of environmental quality at the level of individuals, populations and
communities is well recognized (reviewed by Smits and Fernie, 2013). More directed study of wildlife health in the oil sands could probably reveal broader information about environmental and human health that is critically needed in this region (Gosselin et al., 2010; Cruz-Martinez and Smits, 2012) and in other jurisdictions with oil-producing facilities. The link between bird and human health is particularly poignant for waterfowl, which are consumed by people in the region, but also throughout the continental flyways that emanate from the delta immediately north of the oil sands.

In our opinions, it is illogical to regulate environmental protection from OSPW for birds with a single implicit category of toxicity that makes compliance so difficult. Without explicit standards, bird protection could focus deterrents much more effectively in the places and times where they are essential to bird protection (e.g. at tailings deposition sites, during storm events). Such an evidence-based approach to the management of OSPW could increase avian protection as well as the social licence of the industry while reducing deterrent costs and the collateral damage to workers and ecosystems. The achievement of this triple bottom line defines modern sustainability (Scerri and James, 2010) and could be practised better by the oil sands industry and many other industries.

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References

Albers PH (1998) An Annotated Bibliography on Petroleum Pollution. USGS Patuxent Wildlife Research Center, Laurel, MD, USA, 360 pp.

Alberta Environment and Sustainable Resource Development (2014) Oil Sands Information Portal. http://osip.alberta.ca/map/.

Alberta Government (2010) Environmental Protection and Enhancement Act. Chapter E-12. http://www.qp.alberta.ca/documents/acts/e12.pdf.

Allen EW (2008a) Process water treatment in Canada’s oil sands industry: I. Target pollutants and treatment objectives. J Environ Eng Sci 7: 123–138.

Allen EW (2008b) Process water treatment in Canada’s oil sands industry: II. A review of emerging technologies. J Environ Eng Sci 7: 499–524.

Barceloux DG (1999) Vanadium. J Toxicol Clin Toxicol 37: 265–278.

Bayne EM, Habib L, Boutin S (2008) Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. Conserv Biol 22: 1186–1193.

Beck EM, Smits JEG, St Clair CC (2014) Health of domestic mallards (Anas platyrhynchos domesticas) following exposure to oil sands process-affected water. Environ Sci Technol 48: 8847–8854.

Bortolotti GR, Fernie KJ, Smits JE (2003) Carotenoid concentration and coloration of American kestrels (Falco sparverius) disrupted by experimental exposure to PCBs. Funct Ecol 17: 651–657.

Bortolotti GR, Marchant T, Blas J, German T (2008) Corticosterone in feathers is a long-term, integrated measure of avian stress physiology. Funct Ecol 22: 494–500.

Briggs KT, Yoshiida SH, Gershwin ME (1996) The influence of petrochemicals and stress on the immune system of seabirds. Regul Toxicol Pharmacol 23: 145–155.

Brown LD, Ulrich AC (2015) Oil sands naphthenic acids: a review of properties, measurement, and treatment. Chemosphere 127: 276–290.

Butterworth AE, Leach A, Gendron M, Pollard B, Stewart GR (2002) Peace-Athabasca Delta waterbird inventory program: 1998–2001 Final Report. Ducks Unlimited Canada, EDMONTON, ALBERTA, CANADA, 51 pp.

Calvert AM, Bishop CA, Elliot RD, Krebs EA, Kydd TM, Machants CS, Robertson GJ (2013) A synthesis of human-related avian mortality in Canada. Avian Conserv Ecol 8: 11.

Camp FW (1977) Processing Athabasca tar sands—tailings disposal. Can J Chem Eng 55: 581–591.

Cassidy F (2015) The potential of lasers as deterrents to protect birds in the Alberta oil sands and other areas of human-bird conflict. MSc thesis. University of Alberta, EDMONTON, ALBERTA, CANADA.

Chalaturnyk RJ, Scott JD, Özüm B (2002) Management of oil sands tailings. Petrol Sci Technol 20: 1025–1046.

Cheng MJ, Gao YF, Guo XP, Shi ZY, Chen JF, Shi F (2011) A functionally integrated device for effective and facile oil spill cleanup. Langmuir 27: 7371–7375.

Clemente JS, Fedorak PM (2005) A review of the occurrence, analyses, toxicity, and biodegradation of naphthenic acids. Chemosphere 60: 585–600.

Conover MR (2001) Resolving Human-Wildlife Conflicts: the Science of Wildlife Damage Management. Lewis Publishers, Boca Raton, FL, USA.

Council of Canadian Academies (2015) Technological prospects for reducing the environmental footprint of Canadian oil sands.
The Expert Panel on the Potential for New and Emerging Technologies to Reduce the Environmental Impacts of Oil Sands Development, Council of Canadian Academies.

Crawford RJM, Davis SA, Harding RT, Jackson LE, Leshoro TM, Meijer MA, Randall RM, Underhill LG, Ufop L, Van Dalsen AP et al. (2000) Initial impact of the Treasure oil spill on seabirds off western South Africa. S Afr J Mar Sci 22: 157–176.

Cruz-Martinez L, Smits JEG (2012) Potential to use animals as monitors of ecosystem health in the oil sands region. Report no. TR-18. OISR, University of Alberta, Edmonton, Alberta, Canada.

Cruz-Martinez L, Fernie KJ, Soos C, Harner T, Getachew F, Smits JEG (2015a) Detoxification, endocrine, and immune responses of tree swallow nestlings naturally exposed to air contaminants from the Alberta oil sands. Sci Total Environ 502: 8–15.

Cruz-Martinez L, Smits JEG, Fernie K (2015b) Stress response, biotransformation effort, and immunotoxicity in captive birds exposed to inhaled benzene, toluene, nitrogen dioxide, and sulfur dioxide. Ecotoxicol Environ Saf 112: 223–230.

Dagenais L (2008) Effects of oil sands extraction activities on breeding birds in the Athabasca oil sands region. MSc thesis. University of Alberta, Edmonton, Alberta, Canada.

Eisler R (1987) Polycyclic aromatic hydrocarbon hazards to fish, wildlife, and invertebrates: a synoptic review. Biological Report 85 (1.11). US Fish and Wildlife Service, Laurel, MD, USA.

Eisler R (2000) Handbook of Chemical Risk Assessment: Health Hazards to Humans, Plants, and Animals. Lewis Publishers, Boca Raton, FL, USA.

Fairbrother A (2003) Lines of evidence in wildlife risk assessments. Hum Ecol Risk Assess 9: 1475–1491.

Fairbrother A, Smits J, Grasman KA (2004) Avian immunotoxicology. J Toxicol Environ Health B 7: 105–137.

Farwell A, Harms N, Smits J, Dixon D (2014) Stable nitrogen isotopes of nestling tree swallows indicate exposure to different types of oil sands reclamation. J Toxicol Environ Health A 77: 415–425.

Ferguson G, Rudolph D, Barker J (2009) Hydrodynamics of a large oil sand tailings impoundment and related environmental implications. Can Geotech J 46: 1446–1460.

Frank RA, Roy JW, Bickerton G, Rowland S, Headley JV, Scarlett A, West CE, Peru KM, Parrott J, Conly M et al. (2014) Profiling oil sands mixtures from industrial developments and natural groundwaters for source identification. Environ Sci Technol 48: 2660–2670.

Gentes ML, Waldner C, Papp Z, Smits JEG (2006) Effects of oil sands tailings compounds and harsh weather on mortality rates, growth and detoxification efforts in nestling tree swallows (Tachycineta bicolor). Environ Poll 142: 24–33.

Gentes M-L, McNabb A, Waldner C, Smits JEG (2007a) Increased thyroid hormone levels in tree swallows (Tachycineta bicolor) on reclaimed wetlands of the Athabasca oil sands. Arch Environ Contam Toxicol 53: 287–292.

Gentes M-L, Waldner C, Papp Z, Smits JEG (2007b) Effects of exposure to naphthenic acids in tree swallows (Tachycineta bicolor) on the Athabasca oil sands, Alberta, Canada. J Toxicol Environ Health A 70: 1182–1190.

Gentes M-L, Whitworth TL, Waldner C, Fenton H, Smits JEG (2007c) Tree swallows (Tachycineta bicolor) nesting on wetlands impacted by oil sands mining are highly parasitized by the bird blow fly Protocalliphora spp. J Wildl Dis 43: 167–178.

Gosselin P, Hrudey SE, Naeth M, Plourde A, Therrrien R, Van Der Kraak G, Xu Z (2010) Environmental and health impacts of Canada’s oil sands industry. Royal Society of Canada Expert Panel, Ottawa, Ontario, Canada.

Government of Canada (1994) The Migratory Birds Convention Act. Chapter 22. http://laws-lois.justice.gc.ca/PDF/M-7.01.pdf.

Gray JS (2002) Biomagnification in marine systems: the perspective of an ecologist. Mar Poll Bull 45: 46–52.

Gurney KE, Williams TD, Smits JEG, Wayland M, Trudeau S, Bendell-Young L (2005) Impact of oil-sands based wetlands on the growth of mallard (Anas platyrhynchos) ducklings. Environ Toxicol Chem 24: 457–463.

Harms NJ, Fairhurst GD, Bartolotti GR, Smits JEG (2010) Variation in immune function, body condition, and feather corticosterone in nestling tree swallows (Tachycineta bicolor) on reclaimed wetlands in the Athabasca oil sands, Alberta, Canada. Environ Pollut 158: 841–848.

Headley JV, McMartin DW (2004) A review of the occurrence and fate of naphthenic acids in aquatic environments. J Environ Sci Health A 39: 1989–2010.

Hebert CE, Weleshov DVC, Macmillan S, Campbell D, Nordstrom W (2011) Metals and polycyclic aromatic hydrocarbons in colonial waterbird eggs from Lake Athabasca and the Peace-Athabasca Delta, Canada. Environ Toxicol Chem 30: 1178–1183.

Hebert CE, Campbell D, Kindopp R, MacMillan S, Martin P, Neugebauer E, Patterson L, Slothoff J (2013) Mercury trends in colonial waterbird eggs downstream of the oil sands region of Alberta, Canada. Environ Sci Technol 47: 11785–11792.

Hennan EG, Munson B (1979) Species distribution and habitat relationships of waterfowl in northeastern Alberta, LS 22.1.2. Canadian Wildlife Service, Edmonton, Alberta, Canada.

Hersiskorn BD, Smits JE (2011) Compromised metamorphosis and thyroid hormone changes in wood frogs (Lithobates sylvaticus) raised on reclaimed wetlands on the Athabasca oil sands. Environ Pollut 159: 596–601.

Holowenko FM, MacKinnon MD, Fedorak PM (2000) Methanogens and sulfate-reducing bacteria in oil sands fine tailings waste. Can J Microbiol 46: 927–937.

Kelly EN, Short JW, Schindler DW, Hodson PV, Ma M, Kwan AK, Fortin BL (2009) Oil sands development contributes polycyclic aromatic compounds to the Athabasca River and its tributaries. Proc Natl Acad Sci USA 106: 22346–22351.

Kelly EN, Schindler DW, Hodson PV, Short JW, Radmanovich R, Nielsen CC (2010) Oil sands development contributes elements toxic at low concentrations to the Athabasca River and its tributaries. Proc Natl Acad Sci USA 107: 16178–16183.
Kindzierski W, Jin J, Gamal El-Din M (2012) Review of health effects of naphthenic acids: data gaps and implications for understanding human health risk. Report no. TR-20. OSRIN, University of Alberta, Edmonton, Alberta, Canada, 43 pp.

King JR, Bendell-Young LJ (2000) Toxicological significance of grit replacement times for juvenile mallards. *J Wild Manage* 64: 858–862.

Kirk JL, Muir DC, Gleason A, Wang X, Lawson G, Frank RA, Lehnerr I, Wrona F (2014) Atmospheric deposition of mercury and methylmercury to landscapes and waterbodies of the Athabasca oil sands region. *Environ Sci Technol* 48: 7374–7383.

Leighton FA (1993) The toxicity of petroleum oil to birds. *Environ Rev* 1: 92–103.

Leighton FA, Peakall DB, Butler RG (1983) Heinz-body hemolytic anemia from the ingestion of crude oil: a primary toxic effect in marine birds. *Science* 220: 871–873.

Lintelmann J, Katayama A, Kurihara N, Shore L, Wenzel A (2003) Endocrine disruptors in the environment (IUPAC Technical Report). *Pure Appl Chem* 75: 631–681.

Loots S (2014) Evaluation of radar and cameras as tools for automating the monitoring of waterbirds at industrial sites. MSc thesis. University of Alberta, Edmonton, Alberta, Canada.

McEwan E, Whitehead P (1980) Uptake and clearance of petroleum hydrocarbons by the glaucous-winged gull (*Larus glaucescens*) and the mallard duck (*Anas platyrhynchos*). *Can J Zool* 58: 723–726.

MacKinnon M, Boerger H (1986) Description of two treatment methods for detoxifying oil sands tailings pond water. *Water Qual Res J Can* 21: 496–512.

Masliyah J, Zhou ZJ, Xu Z, Czarnecki J, Hamza H (2004) Understanding mercury to landscapes and waterbodies of the Athabasca oil sands region. *Environ Sci Technol* 48: 7374–7383.

Palme R, Rettenbacher S, Touma C, El-Bahr S, Möstl E (2005) Stress hormones in mammals and birds: comparative aspects regarding metabolism, excretion, and noninvasive measurement in fecal samples. *Ann NY Acad Sci* 1040: 162–171.

Pérez C, Munilla I, López-Alonso M, Velando A (2010) Sublethal effects on seabirds after the Prestige oil-spill are mirrored in sexual signals. *Biol Lett* 6: 33–35.

Pollet I, Bendell-Young LJ (2000) Amphibians as indicators of wetland quality in wetlands formed from oil sands effluent. *Environ Toxicol Chem* 19: 2589–2597.

R. v. Syncrude Canada Ltd (2010) ABPC 229. [http://www.canlii.org/en/ab/abpc/doc/2010/abpc229/2010abpc229.pdf](http://www.canlii.org/en/ab/abpc/doc/2010/abpc229/2010abpc229.pdf).

Ritchie B, Harrison G, Harrison L, eds. (1994) *Avian Medicine: Principles and Application*. Wingers Publishing, Lake Worth, FL, USA.

Ronconi RA, St Clair CC (2006) Efficacy of a radar-activated on-demand system for deterring waterfowl from oil sands tailings ponds. *J Appl Ecol* 43: 111–119.

Ross MS, Pereira AS, Fennell J, Davies M, Johnson J, Sliva L, Martin JW (2012) Quantitative and qualitative analysis of naphthenic acids in natural waters surrounding the Canadian oil sands industry. *Environ Sci Technol* 46: 12796–12805.

Sauer PA, Tyler EJ (1996) Heavy metal and volatile organic chemical removal and treatment in on-site wastewater systems. *Water Air Soil Poll* 89: 337–350.

Scerri A, James P (2010) Accounting for sustainability: combining qualitative and quantitative research in developing ‘indicators’ of sustainability. *Int J Soc Res Meth* 13: 41–53.

Sengupta S, Tollefson EL, Dalai AK (1997) Recovery, characterization and conceptual modelling of non-bituminous organic materials from oil sands. *Can J Chem Eng* 75: 379–390.

Smits JE, Fernie KJ (2013) Avian wildlife as sentinels of ecosystem health. *Comp Immunol Microbiol Infect Dis* 36: 333–342.

Smits JE, Wayland ME, Miller MJ, Liber K, Trudeau S (2000) Reproductive, immune, and physiological end points in tree swallows on reclaimed oil sands mine sites. *Environ Toxicol Chem* 19: 2951–2960.

St Clair CC (2014) Final report of the research on avian protection project. University of Alberta, Edmonton, Alberta, Canada.

St Clair CC, Ronconi RA (2009) Review of Alberta Environment 2009 compliance inspection reports and avian deterrence in the oil sands region. University of Alberta, Edmonton, Alberta, Canada.

St Clair CC, Shore B, Habib T (2010) *Spatial and temporal correlates of mass bird mortality in oil sands tailings ponds*. A report prepared for Alberta Environment. University of Alberta, Edmonton, Alberta, Canada.

St Clair CC, Loots S, McCallum C, Thayer D, Fontaine T, Gilhooly P (2013) 2012 Report of the regional bird monitoring program for the oil sands. University of Alberta, Edmonton, Alberta, Canada.

Sutherland WJ, Pullin AS, Dolman PM, Knight TM (2004) The need for evidence-based conservation. *Trends Ecol Evol* 19: 305–308.

Swanson G, Adomaitis V, Lee F, Serie J, Shoemsmith J (1984) Limnological conditions influencing duckling use of saline lakes in south-central North Dakota. *J Wildl Manage* 48: 340–349.
Tarshis IB, Rattner BA (1982) Accumulation of $^{14}$C-naphthalene in the tissues of redhead ducks fed oil-contaminated crayfish. *Arch Environ Contam Toxicol* 11: 155–159.

Timoney KP, Ronconi RA (2010) Annual bird mortality in the bitumen tailings ponds in northeastern Alberta, Canada. *Wilson J Ornithol* 122: 569–576.

Trail PW (2006) Avian mortality at oil pits in the United States: a review of the problem and efforts for its solution. *Environ Manag* 38: 532–544.

Transport Canada (2015) National Oil Spill Preparedness and Response Regime. [https://www.tc.gc.ca/eng/marinesafety/oep-ers-regime-menu-1780.htm](https://www.tc.gc.ca/eng/marinesafety/oep-ers-regime-menu-1780.htm).

Tully TN, Dorrestein GM, Jones AK, eds. (2009) *Handbook of Avian Medicine*, Ed 2. Saunders/Elsevier, Edinburgh, UK.

United States Environmental Protection Agency (1999) Understanding oil spills and oil spill response. EPA 540-K-99-007. USEPA, Office of Emergency and Remedial Response. [http://www2.epa.gov/nscep/retrieving-ordering-and-printing-nscep-publications#ordering](http://www2.epa.gov/nscep/retrieving-ordering-and-printing-nscep-publications#ordering).

United States Environmental Protection Agency (2013) Appendix A – Priority Pollutants. Code of Federal Regulations. pp 423–126.

Van den Heuvel M, Power M, Richards J, MacKinnon M, Dixon D (2000) Disease and gill lesions in yellow perch (*Perca flavescens*) exposed to oil sands mining-associated waters. *Ecotoxicol Environ Saf* 46: 334–341.

Votier SC, Hatchwell BJ, Beckerman A, McCleery RH, Hunter FM, Pellatt J, Trinder M, Birkhead TR (2005) Oil pollution and climate have wide-scale impacts on seabird demographics. *Ecol Lett* 8: 1157–1164.

Walker CH (2001) *Organic Pollutants: an Ecotoxicological Perspective*. CRC Press/Taylor and Francis, London, UK.

Walters CJ (1986) *Adaptive Management of Renewable Resources*. MacMillan, New York, NY, USA.

Wang Q, Kim D, Dionysiou DD, Sorial GA, Timberlake D (2004) Sources and remediation for mercury contamination in aquatic systems—a literature review. *Environ Pol* 131: 323–336.

Wells J, Casey-Lefkowitz S, Dyer S, Chavarria G (2008) *Danger in the nursery: impact on birds of tar sands oil development in Canada’s boreal forest*. Natural Resources Defense Council, New York.

Wiklund JA, Hall RI, Wolfe BB, Edwards TW, Farwell AJ, Dixon DG (2014) Use of pre-industrial floodplain lake sediments to establish baseline river metal concentrations downstream of Alberta oil sands: a new approach for detecting pollution of rivers. *Environ Res Lett* 9: 124019.

Yonge KS, Christiansen ML (1979) A review of bird migration patterns and techniques for monitoring migration. *Syncrude Canada, Ltd, Fort McMurray, Alberta, Canada. Professional Paper 1981–2.*