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Special Series

An integrated knowledge synthesis of regional ambient monitoring in Canada's oil sands

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EDITOR'S NOTE:

This article is part of the special series "A Decade of Research and Monitoring in the Oil Sands Region of Alberta, Canada." The series documents the history of monitoring in the region and critically reviews a synthesis of monitoring results published within key environmental theme areas to identify patterns of consistent responses or effects; significant gaps in knowledge; and recommendations for improved monitoring, assessment, and management of the region.

Abstract

The desire to document and understand the cumulative implications of oil sands (OS) development in the ambient environment of northeastern Alberta has motivated increased investment and release of information in the past decade. Here, we summarize the knowledge presented in the theme-based review papers in this special series, including air, surface water, terrestrial biology, and Indigenous community-based monitoring in order to (1) consolidate knowledge gained to date, (2) highlight key commonalities and gaps, and (3) leverage this knowledge to assess the state of integration in environmental monitoring efforts in the OS region and suggest next steps. Among air, water, and land studies, the individual reviews identified a clear focus on describing stressors, including primarily (1) contaminant emission, transport, transformation, deposition, and exposure, and (2) landscape disturbance. These emphases are generally partitioned by theme; air and water studies focus heavily on chemical stressors, whereas terrestrial monitoring focuses on biological change and landscape disturbance. Causal attribution is often stated as a high priority objective across all themes. However, studies often rely on spatial proximity to attribute cause to industrial activity, leaving causal attribution potentially confounded by spatial covariance of both OS- and non-OS-related stressors in the region, and by the complexity of interacting pathways between sources of environmental change and ecological receptors. Geospatial and modeling approaches are common across themes and may represent clear integration opportunities, particularly to help inform investigation-of-cause, but are not a replacement for robust field monitoring designs. Cumulative effects assessment remains a common focus of regional monitoring, but is limited in the peer-reviewed literature, potentially reflecting a lack of integration among monitoring efforts beyond narrow integrated interpretations of results. Addressing this requires greater emphasis on a priori integrated data collection and integrated analyses focused on the main residual exposure pathways, such as atmospheric deposition. *Integr Environ Assess Manag* 2022;18:428–441. © 2021 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Cumulative effects, Environmental monitoring, Integration, Oil sands

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INTEGRATED ENVIRONMENTAL MONITORING

The status of the environment surrounding oil sands (OS) operations in northeast Alberta, Canada, is a topic of global profile, and the associated environmental monitoring represents a substantial effort to determine the extent and magnitude of regional environmental change in the context of local OS industrial activity. Since 2010, the intensity of interest has increased across multiple stakeholders, particularly as multiple program reviews criticized the then-existing monitoring approach, highlighting the need for greater attention from industry and the federal and provincial governments (e.g., AEMP, 2011; Gosselin et al., 2010). Soon after, several large-scale monitoring initiatives were launched, including the joint Canada and Alberta Governments' Oil Sands Monitoring Program (OSM; Dubé et al., 2021; Environment Canada, 2011), efforts by OS companies to collaboratively address collective issues (COSIA, 2012), government policy development and implementation such as the Lower Athabasca Regional Plan (LARP; Government of Alberta, 2012), the raising of concerns and sponsoring of research by neighboring Indigenous communities (e.g., Candler et al., 2010; Davidson & Spink, 2018), the development of Indigenous community-based monitoring (ICBM) programs (Beausoleil et al., 2021), as well as focused research that has been both industry-funded (e.g., Hall et al., 2012; Shotyk et al., 2014) and independently funded (e.g., Kelly et al., 2009; Timoney & Lee, 2009).

The result of this investment has been hundreds of published papers, datasets, reports, and other media—much from the past decade—examining potential environmental impacts of the OS industry, but few consolidated outputs. Although this work has produced a significant body of literature, calls have persisted to increase the integration among regional environmental monitoring programs (Environment Canada, 2011; Hopke et al., 2016) to implement an adaptive monitoring approach focused on stressor–response pathways, particularly across environmental media for assessments of cumulative effects and to overcome the familiar challenge of drawing an inference and making decisions despite lingering scientific uncertainties (Suter, 2007).

Conceptually, integration is straightforward and has clear benefits. In practice, however, integration is challenging (Arciszewski et al., 2021). At its simplest, integration consists of the consideration of one's own results in the context of the results of others, as in peer-reviewed paper discussions, and although straightforward to do, has limitations. In contrast, combining otherwise independent datasets in integrated analyses can facilitate addressing a wider range of hypotheses and monitoring questions, but such approaches must often contend with many challenges, such as data compatibility. Integrated programs that oversee coincidental data collection, potentially within standardized monitoring frameworks and experimental designs, have the capacity to maximize the breadth of scientific and monitoring questions that can be addressed, but also risk becoming methodologically inflexible or administratively burdensome (Arciszewski et al., 2021). In the context of environmental monitoring, integration is scale dependent, ranging from synthesis of information within or across disciplines, to coordinated and coincident data collection, to assessments that incorporate multiple knowledge systems and ways of knowing. Unsurprisingly, the complexity of environmental interactions that operate at multiple scales, disagreements among specialists regarding the selection of indicators, and the attribution of cause in the context of multiple pressures, can make an integrated design difficult to implement.

The charge to regional ambient environmental monitoring, including in the oil sands region (OSR; Figure 1), is substantial. Ambient environmental monitoring in the OSR must distinguish among multiple pressures whose influences have accumulated across the landscape, and often when a predevelopment comparison is unavailable. A desire to document and understand the implications of these pressures has motivated increased investment and release of scientific knowledge in the past decade. Although some topic-specific reviews of this material are available on, for example, landscape disturbances (e.g., Dabros et al., 2018; Venier et al., 2014) or contaminants (e.g., Harner et al., 2018), a comprehensive review of literature reporting the status of environmental indicators in the ambient environments of the OSR is lacking. To address this, we undertook a critical review series to consolidate this information to compile and synthesize information contained in the peer-reviewed literature, with the objectives of (1) assessing and cataloging monitoring effort and, by proxy, environmental knowledge, in the OSR; and (2) identifying knowledge gaps in the monitoring literature or opportunities for future effort or monitoring focus.

We have reported on this review in this special series by organizing the material into overlapping environmental themes of atmospheric emissions and atmospheric deposition (Horb et al., 2021), surface water and aquatics (Arciszewski et al., 2021), and terrestrial biology (Roberts et al., 2021b). We have also presented an introduction to environmental monitoring in the OSR (Dubé et al., 2021) and a critical review of ICBM programs (Beausoleil et al., 2021). Considered together, these documents report on the breadth and depth of knowledge of environmental condition in the OSR, identify both accumulations and gaps in knowledge, and provide guidance where efforts should align to increase knowledge acquisition within the region's ambient monitoring programs. As with the individual theme papers in this series, here we apply a conceptual model approach to organize the information.

Although this review paper series satisfies only the narrowest definition of integration (i.e., the collective interpretation of published results of individual studies), it remains a useful and appropriate approach to integrated reporting, given the monitoring knowledge resources available from the OSR. The informal weight of evidence approach employed here demonstrates how studies can be nested within pathways and ultimately within a program-scale conceptual effects model as an evaluation of hypotheses about the influence of development on ecological responses and, ideally, on meaningful indicators of change that can inform decision-making at various levels.

The conceptual model

A conceptual model is a tool for organizing and communicating knowledge, and a useful model will create opportunities for mutual understanding among holders of

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FIGURE 1 The location of the three main subregions (Peace, Athabasca, and Cold Lake) of the larger oil sands region in northeastern Alberta, Canada. The extent of the surface minable area is shown in gray, and the remainder of the bitumen reserves within the region is accessible only via in situ approaches. Protected areas are shown in green

Traditional, local, and scientific environmental knowledge (Suter, 2007). Development of a robust conceptual model is essential to implementing sound scientific monitoring and management by anchoring monitoring activities in a common understanding of the system. As such, it is not testable, but postulates the principal question about the relationship between development-related pressures and ecosystem values. Rather, the model provides the framework around which monitoring questions are formulated and facilitates designing appropriate approaches to address these questions (Lindenmayer & Likens, 2009). Delineating complex change requires an understanding of relationships between the various pathways of stressors, observed effects, and valued components, and many subhypotheses that are themselves the subject of monitoring inquiry are nested within the conceptual model. A commitment to adaptation in a monitoring program demands constant model revision as hypotheses are tested.

Conceptual models describe the expected linkages between a human activity and environmental receptors (Suter, 2007). The complex pressures from a variety of OS-related industrial activities, including both surface mining and in situ bitumen extraction (Dubé et al., 2021), exist in the context of other anthropogenic (e.g., forestry, urbanization, recreation) and natural (e.g., wildfire, flooding) pressures. Climate change also represents an anthropogenic pressure driving changes in natural disturbance regimes, such as the frequency and magnitude of natural phenomena. Although this complex of natural and anthropogenic processes may seem discouragingly large, visual tools such as conceptual models can assist the organization of knowledge and understanding of such environmental systems.

A conceptual model for OS environmental monitoring was developed through collaborative, in-person consultation with Western scientists, policy-makers, and industry and Indigenous community representatives (Dubé et al., 2021; Swanson, 2019). In this review series, we have organized this program-scale conceptual model into a Pressure-Stressor-Pathway-Response structure (Figure 2), associating actions that potentially drive environmental change (stressors) and their origins (pressures), resulting changes within the environment (responses), and mechanisms (pathways) linking sources (pressures or stressors) to responses. This approach contextualizes responses into corresponding categories of environmental concern and identifies more complex components affected by change in a single or group of receptors that reflect environmental and related cultural values (valued components).

In this special series, we have expanded this model within several monitoring foci, including air (Horb et al., 2021), water (Arciszewski et al., 2021), land (Roberts et al., 2021b), and ICBM (Beausoleil et al., 2021), prior to recombining these media-specific models into a program-scale model that we also use to summarize monitoring effort. Note that the valued components identified in this program-scale conceptual model are an interpretation of community and ecosystem values, and are still being validated through ongoing dialog with Indigenous communities and other stakeholders in the OSR (Dubé et al., 2018).

Integrated interpretation of OS monitoring

Monitoring efforts in the ambient environments surrounding OS developments have produced more than 300 peer-reviewed publications over the past decade. At the same time, reports and studies conducted by regional multi-stakeholder organizations provide another large body of knowledge specific to the OSR. These are not systematically included in the air, water, or terrestrial reviews, but form a large portion of the ICBM literature, where such reports are significant contributions to the state of the knowledge otherwise not represented in the peer-reviewed literature. Our review effort in this special series divides knowledge products by theme to simplify the task. Among the themes, different monitoring objectives, discrepancies in spatial and temporal resolution in collected data, and natural divisions of scientific expertise are apparent, and it can be a challenge to present work that links these themes together. To help span the boundaries among individual theme areas and theme-centered reviews, we present in this paper an integrated synthesis of the major findings, gaps, and challenges across themes, from an integrative perspective.

To visualize the focus of monitoring effort and resulting evidence from the past decade based on the published

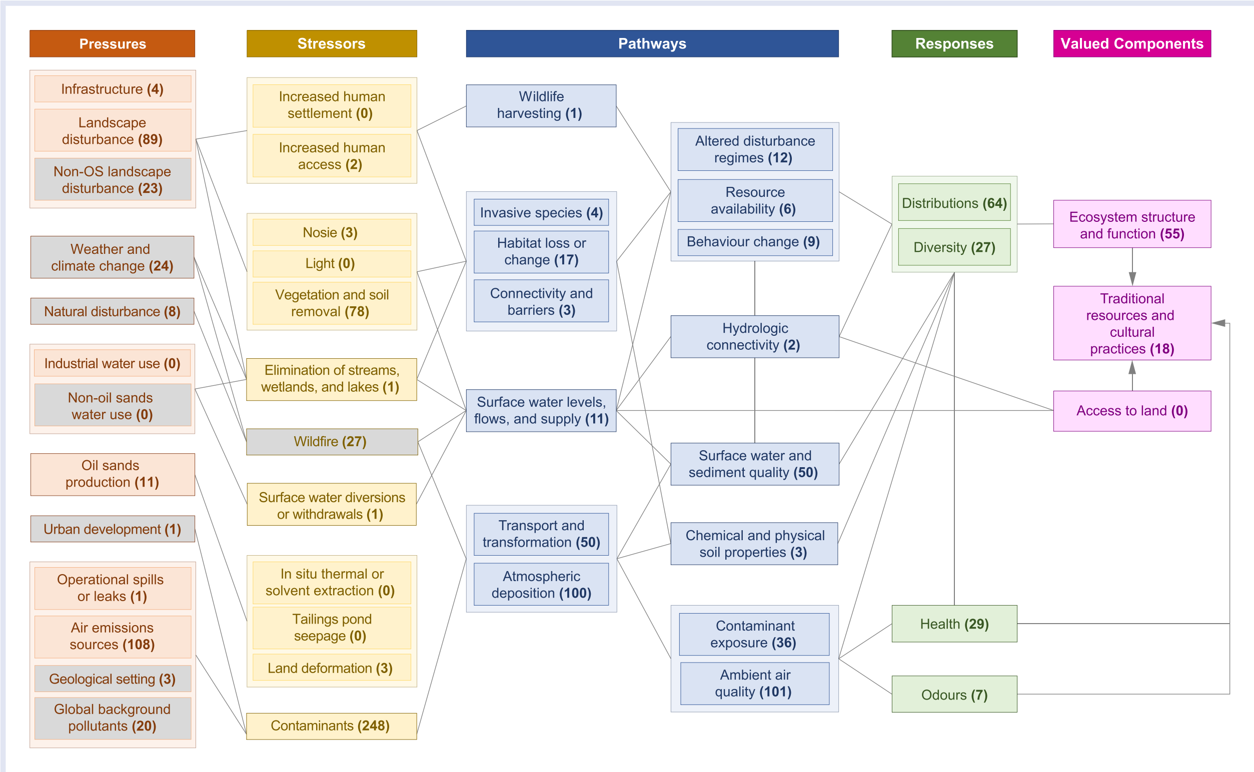

FIGURE 2 The conceptual model for the oil sands region is a system-scale visualization of the known and/or suspected relationships between development-related pressures and valued components. Pressures, including non-oil-sands pressures (left; gray shading) are conceptually related to valued components (right) via pathways (middle) that represent intermediate processes, stressors, or ecological components. Numbers in parentheses represent the counts of peer-reviewed papers published between 2009 and 2020 providing evidence of a particular model component (i.e., if a paper investigated a component but found no evidence of it, it was not counted). Individual publications may be counted in multiple boxes. References associated with each box are listed in Supporting Information Appendix S1

literature, we consolidate the information from individual conceptual models from the papers in this series here (Figure 2). Papers on the conceptual model were counted if the results support the inclusion of a model component or pathway. Most papers fall into multiple boxes on the model, as they address multiple conceptual components. If a paper considers a conceptual model component but finds no evidence for it, the paper is not included in the conceptual model in Figure 2. Although not all papers are represented on the conceptual model, summary tables reporting on key findings of each paper are provided in the Supporting Information for each of the individual theme papers in the series (Arciszewski et al., 2021; Beausoleil et al., 2021; Horb et al., 2021; Roberts et al., 2021b).

Because environmental effects are generally monitored within living organisms, most of the literature considering environmental responses (i.e., the right side of the conceptual model) fell under the terrestrial theme. Although some biotic responses are included in aquatic indicators (e.g., fish and benthos), a much larger range of terrestrial indicators is monitored in the OSR (e.g., mammals, birds, amphibians, vegetation, etc.). Although this imbalance is largely a construct of compartmentalizing monitoring into themes of air, water, and land, it does suggest that integrating monitoring knowledge across these traditional environmental and expertise boundaries remains a challenge, potentially undermining the understanding of complete stressor–response pathways in the OSR and thus limiting cause–effect inference. Because Indigenous perspectives tend to be holistic in nature, much ICBM literature is integrative across the other theme areas of air, water, and land.

Although there are similarities between ICBM and Western science-themed monitoring programs, these similarities arise largely from integrating science-driven multimedia monitoring at a regional scale, designed to assess impacts on the environment. ICBM programs do assess impacts on the environment, but are driven by the necessity of assessing environmental impacts on the exercise of Aboriginal and Treaty rights (Beausoleil et al., 2021). Although not directly linked to a conceptual model, much ICBM literature in this report series focuses on key principles and frameworks for developing ICBM programs, and subsequently how ICBM programs can fill knowledge gaps in the OSR. Most ICBM programs focus on water (e.g., depth, quality, aquatic biota) and air (e.g., quality, odors), with more limited documentation of land (including wetlands) and wildlife impacts. This does not characterize land and wildlife as less significant, but rather suggests ICBM approaches currently support regional monitoring efforts where data are more easily captured in regional scale

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models, such as air and water quality analyses (Beausoleil et al., 2021). Indigenous communities have monitored their lands through their oral histories for centuries. Some communities in the region have also led and implemented community-based monitoring in the region. Data and knowledge exist, but are not commonly reported in the peer-reviewed literature. This is a limitation of our paper and this review series in general.

Monitoring for change

Natural environments are dynamic. When combined with climate change, natural disasters, increasing industrial development, constantly changing human land use, and industrial activity, both OS and non-OS-related pressures, and the mosaic of the OSR landscape, are constantly in flux. Stressors arising from these changes have ecological consequences and are manifest in observed biotic and abiotic responses. To tease apart the various influences of natural change and anthropogenic change, the reviewed literature often documents changes across stressor gradients or vis-à-vis some "reference" or "baseline" condition, often defined by one or more sites from a spatially distant location from inferred sources.

Monitoring data from a true baseline condition (e.g., from the same location but in a largely undisturbed condition) is limited in the OSR, because the OSR was disturbed decades ago, before the importance of environmental monitoring was recognized. Measurement technologies have also evolved in some cases, potentially stranding some preexisting data. This is neither unique to Alberta nor to the OS industry. Except for some paleolimnological methods, baseline conditions in OSR research are often inferred either by substituting space for time (i.e., reference sites spatially removed from stressors of interest), by backfilling with predictive empirical models, or by monitoring across gradients of stressors to quantify their relationships with responses. Integrating Indigenous Knowledge, with the objectives of (1) informing historic environmental conditions, and (2) gathering first-hand insight into environmental change and drivers of that change, would contribute to an informed and integrated monitoring system that assesses cumulative impacts holistically and a move closer to addressing Indigenous concerns collaboratively (e.g., Bill et al., 1996).

Changes can be observed at the most fundamental level simply by monitoring stressors (i.e., stressor-based assessments). However, changes in stressors may not be reliably informative of resulting environmental effects (i.e., through the linkages of the conceptual model). Stressors may exist on the landscape without observable ecological consequence, but elevate risk so responses must also be monitored. Of greater concern, especially to local Indigenous communities, are changes in progressively larger scale environmental components (e.g., abiotic chemical and physical changes) or biological responses (e.g., changes in organisms, populations, or entire ecosystems), which take longer to observably manifest and are generally more irreversible in their consequence (Munkittrick & McCarty, 1995). These changes cannot be inferred from stressors alone so must be monitored directly. Such environmental effects are also often observed by Indigenous communities, either informally in daily life or more formally as part of ICBM programs, and represent potential effects on traditional lands, quality of traditional resources, and the exercise of their constitutionally guaranteed rights.

As responses grow in scale and breadth (from the biochemical, physiological to the population to the ecosystem), irreversibility (and thus risk) increases. This progression may take time as toxicological responses in populations from exposure to contaminants progress from biochemical effects through to the level of the individual. Responses across multiple individuals can manifest as population changes, whereas responses across multiple taxa can manifest as community changes, eventually potentially undermining basic ecosystem function. Effects from individual stressors may be exacerbated by exposure to multiple chemical and nonchemical stressors, but they may also be ameliorated by detoxification processes, selection of hardy individuals, or by the sequestering, degradation, or removal of harmful compounds.

Because environmental systems operate at multiple spatial and temporal scales, in order to properly observe and quantify phenomena therein, monitoring systems must do the same. Spatially, this includes both extent (how much landscape to cover) and grain (how close together or at what resolution to monitor) of monitoring and analysis. On the temporal side, this includes monitoring intervals (i.e., how often to return to the same site) and periods of record (i.e., for how many years should a monitoring site be maintained). Scientists can always implement power analyses to calculate the monitoring effort required to detect changes of a given magnitude. However, the appropriate balance of effort to achieve adequate knowledge of all priority indicators within given time frames, particularly when resources are limited, is impossible to know a priori.

Current monitoring in the OSR at multiple spatial scales to capture responses at various scales of biological organization is sometimes achieved in some capacity, but seldom intentionally or with consistent methodologies. Few indicators are well-represented across a meaningful breadth of scales. In the aquatic theme, for example, this ranges from measurements of local fish health to larger population-level monitoring at the regional scale (Arciszewski et al., 2021). In terrestrial monitoring, responses, such as wildlife behavior or vegetation community changes, contribute to local-scale monitoring, whereas larger scale population-level monitoring is in the form of wildlife abundance responses to regional landscape disturbance rates (Roberts et al., 2021b). Across themes, geospatial methods often contribute to regional or larger scale analyses.

The manifestation of stressors and responses at different spatiotemporal scales necessitates that (1) priority indicators be clearly identified, and (2) monitoring program designs be developed at the appropriate scale(s) to detect change in priority indicators within a reasonable period and with appropriate power and resolution. Adaptive monitoring components, such as baselines and monitoring triggers, must also be spatially appropriate and matched to indicators. With the exception of some legislated toxicological limits for air and water, triggers remain largely undefined, which represents a critical challenge to timely initiation of investigations of cause. In this respect, terrestrial and other biotic triggers are a notable gap and, if developed, are best informed by both Western science and Indigenous Knowledge. Inclusion of Indigenous perspectives, for baselines, triggers, or otherwise, is uncommon in the examined peer-reviewed literature. Western scientists and Indigenous Knowledge holders from Indigenous communities view change through different lenses and approach monitoring through different methodologies (Baker, 2017).

The ICBM process involves early engagement of Indigenous peoples to improve integration of community priorities in research projects from the onset to completion (Wong et al., 2020), a step missing in virtually all reported Western science. Despite this, some overlap exists in the types of monitoring indicators used in Western science and ICBM programs, including changes in biotic distributions (e.g., occupancy, abundance), diversity (e.g., community composition), and health (e.g., condition, reproduction). However, whereas these different philosophical approaches may have common indicators, observational approaches can differ greatly. For example, whereas Western science may assess wildlife health via quantitative metrics of physiological function, local communities may prioritize accessibility and abundance of land and resources, such as metrics of food quality reflecting traditional use, including odor, taste, and texture (e.g., Baker, 2017; Bill et al., 1996; Candler et al., 2010; Parlee et al., 2012). These differences reflect the values of each community—although quantitative metrics may resonate with Western scientists—they are less valuable to local communities more concerned with, for example, the perceived quality and availability of traditional foods and water within the context of their historical knowledge (Beausoleil et al., 2021).

Indigenous participation in monitoring has traditionally taken the form of researchers gathering information from Indigenous communities to be analyzed within an existing Western science framework. This practice decontextualizes the position of Indigenous Knowledge from the larger land management ethic. Indigenous people wish to be involved in monitoring not to further Western science, but to improve land management and the health of their inextricably linked landscapes and cultures (Baker, 2017). For this reason, meaningfully including Indigenous perspectives and values in monitoring is complicated by the lack of link to management decisions. Ethical inclusion of Indigenous people in environmental monitoring requires codevelopment of research and a recognition that monitoring should improve Indigenous peoples' ability to access, manage, and trust the landscapes in which they live (Beausoleil et al., 2021; Wong et al., 2020).

CONDITION OF ENVIRONMENT IN THE ALBERTA OSR

Contaminants

Oil sands operations are highly regulated and are prohibited from the release of process-affected water. However, there are releases of depressurization water, domestic wastewater, a single recorded industrial water discharge, and stormwater runoff from industrial sites. Atmospheric emissions from point sources such as stacks are also regulated by facility, but emissions are released to the atmosphere from several sources during bitumen extraction, transport, and upgrading processes, including facility stacks, heavy vehicle fleet, and machinery operation. Additionally, exposure of the mine faces and tailings pond surfaces generates evaporative emissions in open-pit operations and, given the nature of surface mining operations and bitumen processing, significant amounts of fugitive dust can be emitted (Horb et al., 2021). Other fugitive emissions, such as leaks from seals, welds, or other sources, also occur from the substantial industrial infrastructure (Horb et al., 2021). The published literature identifies challenges in quantifying certain emissions, especially those from fugitive sources that tend to be diffuse and variable. However, new technology and innovative methods, including geospatial applications, are being developed and applied to address this gap (Horb et al., 2021). In addition, much relevant information remains in on-site compliance reporting and data. Although emissions databases (such as the Canadian National Pollutant Release Inventory) exist, they may not adequately record fugitive or nonpoint source emissions, offering opportunities for additional facility-specific monitoring to contribute to integrated monitoring and analyses in the OSR. In these instances, other industry-reported facility data may overcome some challenges.

After release to the atmosphere, substances are further transported and transformed in the air and eventually deposited to the earth's surface. Measurements of deposition indicate that contaminants are transferred from air to the surface and enter aquatic and terrestrial ecosystems. Surface aquatic environments are end receivers for several contamination pathways: surface discharges, air deposition onto aquatic surfaces, contaminated precipitation, surface runoff associated with rainfall events and snowmelt, and contaminated groundwater discharges (Arciszewski et al., 2021). However, the specific rate and pathways of uptake and response in organisms is not well understood (Arciszewski et al., 2021; Horb et al., 2021; Roberts et al., 2021b). To address this gap, effort is required to integrate air deposition monitoring with other themes, specifically aquatic and terrestrial, to begin to connect our understanding of air emissions and deposition with potential responses in organisms in aquatic and terrestrial environments. A notable exception is Forest Health Monitoring, which is designed to detect specific types of environmental effects (acidic and eutrophying deposition) on the terrestrial environment using colocated deposition and terrestrial monitoring (Davidson et al., 2020). Some other efforts have also been made through the use of ICBM programs, integrating air-quality deposition data from culturally important plants, wetlands, and surface-water quality to better assess confounding hydrological and land disturbance stressors within the OSR (Beausoleil et al., 2021). Finally, industry-reported data may be valuable and underutilized resources for integrated analyses.

Mammals, birds, and vegetation can be affected by contaminants transported through the atmosphere. The contaminants can originate from local industrial development, but also from other sources, including wildfire, urban activities, and global emissions (Horb et al., 2021; Roberts et al., 2021b). These same contaminants can also affect aquatic organisms. However, in the aquatic case, the delivery mechanisms can be augmented by additional processes, such as overland flow, and can thus be more challenging to estimate than in the terrestrial environment. Studies suggest that, although signals of industrially derived materials are found in lake sediments, the same is not true in flowing waters, suggesting the deposited substances are retained in the landscape (Arciszewski et al., 2021). Although some point-source discharges occur in the region (e.g., domestic wastewater effluents), they are not common and many are not continuous. In contrast, other influences are uncertain (e.g., seepage of OS process-affected waters from tailings ponds) or diffuse (e.g., influences of geology), and undermine the clear detection of effects related directly to OS industrial activity (Arciszewski et al., 2021).

Despite an inability to specifically identify the source of the agonists, there is evidence of exposure to bituminous compounds and physiological or biochemical changes in resident organisms. Detoxification enzymes in fish are commonly elevated in areas adjacent to OS mines (McMaster et al., 2020; Pilote et al., 2018; Tetreault et al., 2020) and comparisons of upstream and downstream tributaries have identified changes in both benthic communities (Culp et al., 2020) and fish populations (Tetreault et al., 2020). The exact sources and consequences of these exposures are, however, not certain. For example, the strength of bacula in river otters (*Lontra canadensis*) was statistically lower than greater concentrations of some petrogenic compounds in liver tissue, but in some cases the inverse effect was also observed (Thomas et al., 2021), which highlights the complexity of such relationships and the challenges associated with working with limited sample sizes in complex environments. Although the spatial trends are consistent, it should be noted that causal relationships have not been demonstrated in these studies, and other contaminant-related work has identified other important natural covariates contributing to observed responses (Godwin et al., 2019; Hebert, 2019; Tetreault et al., 2020). However, preliminary analyses in the water review suggest some influence of industrial activity in fish captured in the high deposition zone (Arciszewski et al., 2021). These analyses further suggest that additional work should be done to explore this potentially potent source of information.

The overwhelming concentration on contaminants as a stressor in the OS-related literature from the past decade also likely reflects the widespread concerns around toxicity issues both within local Indigenous communities and within the larger public. Local concerns related to contaminants are most often associated with food safety, including traditional foods and clean water. For example, observed elevated mercury concentrations in gull eggs led to a 2014 Alberta Health consumption advisory of this traditional food source (Government of Alberta, 2014). Oil sands activities are a source of mercury (Horb et al., 2021). However, their relative potential to elicit related ecological responses compared with non-OS activities is still unknown. Regardless, this health consumption advisory contributed to an erosion of trust in some wild resources. Through this lens of Indigenous communities, there may be little difference between the safety of food or water consumption and the state of the environment itself. For this reason, most ICBM projects focus on contaminant pathways and responses, including fish health, berry quality, and terrestrial wildlife ecotoxicology (Beausoleil et al., 2021).

Defining baselines has been an ongoing challenge. For example, although the data from some lake sediments suggest the onset of industrial influence shortly after the commercial opening of the first OS mine (Great Canadian Oil Sands, 1967), other data suggest the potential influence of petrogenic sources before this date (Arciszewski et al., 2021). Studies have suggested the influence of construction at some locations, but few studies have considered the construction of the GCOS plant from 1964 to 1967 on indicators of ecosystem status. There may also be influence of precommercial activities, including Abasand, Bitumount, and Cold Lake (Arciszewski et al., 2021).

The lack of preindustrial understanding of contaminant burdens in the OSR undermines the ability to detect change. Although contaminants occur in the ambient environment, they are often, but not always, reported below relevant environmental quality guidelines. These results, however, are based on three assumptions: (1) all potentially toxic contaminant concentrations are known and measured, (2) all compounds that need them have exceedance guidelines, (3) guidelines consider implications of chemical interactions, and (4) below these guidelines consumption is safe and above them it is not. These assumptions are unlikely to be consistently met in practice, and certainly not across all contaminants, undermining confidence that no effects will occur and thus local uses are safe. Further, although consumption guidelines may sometimes be exceeded for some biota, such as walleye or colonial waterbirds (eggs), there remains only indirect spatial association with OS industrial operations, leaving source attributions largely undefined (Arciszewski et al., 2021; Roberts et al., 2021b).

In addition to assessments of chemical effects on water and wildlife, considerable monitoring effort has also been spent on air-quality metrics. Ambient air quality is monitored continuously in the OSR via dozens of permanent monitoring stations within the Athabasca, Peace, and Cold Lake OS regions, and via time integrated samples collected on variable schedules (e.g., 1-in-6 day, monthly) in a ca. 150 km radius from the mineable OS region and across the Cold Lake OSR. Both monitoring and modeling approaches find OS industrial operations to be a major contributor of both emitted and chemically transformed atmospheric contaminants, including SO_x, NO_x, particulate matter, volatile organic compounds (VOCs), polycyclic aromatic compounds (PACs), trace elements, base cations, and reduced sulfur compounds (Horb et al., 2021). Odors are of local concern in Fort McKay, a Cree, Dene, and Métis community close to extensive OS industrial development. Air quality throughout the OSR is generally consistently reported as below thresholds set by the Alberta government for the protection of human health with consideration of socioeconomic factors. However, thresholds do not exist for all compounds potentially contributing to air-quality issues in the OSR, including reduced sulfur and some VOCs and PACs. The Air Quality Health Index is also reported in many OSR communities; however, it was developed for urban regions and it also does not include all compounds potentially contributing to air-quality issues in the OSR (Horb et al., 2021). The Fort McKay Air Quality Index is a community-driven metric that includes compounds that contribute to regional odor issues (Dann, 2016). Some monitoring stations have previously reported air-quality levels (based on $PM_{2.5}$) within the orange zone for Canadian Ambient Air Quality Standards (CAAQS; www.ccme.ca), a ranking that triggers active air management for the prevention of exceedances. However, the two most recent CAAQS assessments (2014–2016; 2015–2017) indicate that ambient $PM_{2.5}$ and O_3 levels are in the yellow zone (which requires actions for continuous improvement, but does not require active air management). Under the LARP for NO_2 and SO_2, the latest assessment (for 2018) indicates that nine stations exceeded triggers for NO_2 and SO_2, including one exceeding an SO_2 trigger for proactive management.

The atmospheric deposition of contaminants can potentially affect biotic and abiotic components of terrestrial and aquatic ecological systems. Concerns around soil acidification caused by contaminant deposition prompted the design of monitoring programs aimed at acid-sensitive lakes and the impacts of acid deposition in forests. These programs have found that acidifying deposition tends to be neutralized by the concurrent deposition of fugitive dust containing high amounts of base cations. However, although deposition and critical load exceedance modeling has also predicted a region of base cation neutralization within 140 km of the sources, northern Alberta and Saskatchewan are predicted to undergo acidification over an area of 334 000 km^2 if emission levels are maintained at 2013 levels (Makar et al., 2018). Although these monitoring programs were originally designed to detect acidification, they have instead observed local eutrophication in forests and wetlands within roughly 50 km of OS operations caused by enhanced N deposition levels (Horb et al., 2021).

Landscape disturbance

Landscape disturbance forms a major focus within the conceptual model for the OSR and includes components of vegetation removal, soil disturbance, natural disturbance regimes, increased human access, and habitat loss. Although landscape disturbance as a stressor may be a relevant covariate for surface-water or atmospheric deposition studies, its treatment in the literature is largely confined to terrestrial biological topics. Although there are some specific topics that integrate with other theme areas, such as fugitive dust contaminants from mine sites or erosion from larger land clearings leading to increased sedimentation in surface waters, these have received relatively limited consideration in the peer-reviewed literature. In publications where landscape disturbance is the focal stressor, we find that pathways are less often considered and, when they are, they are often related to resource availability (e.g., microhabitats, food, light) or altered organism behaviors (e.g., movement, dispersal). Landscape disturbance-associated responses tend to focus on changes in species distribution (e.g., occupancy, abundance) and diversity (e.g., community composition), with most focus on mammals and birds as receptors (Roberts et al., 2021b).

Landscape disturbance encompasses a wide breadth of specific stressors, from very narrow linear disturbances to large polygonal clearings, and from relatively natural (e.g., minimally disturbed or regenerating) features to highly transformed landscapes (e.g., mine sites, roads, or agriculture). Further, terrestrial taxa that tend to be affected by landscape disturbance are also not homogenous in their habitat preferences, with some preferring disturbed or young stage forest habitats and others thriving in intact old-growth forests. Consequently, responses among indicator species to landscape disturbance tend to be mixed, producing "winners and losers," largely in line with habitat preferences of focal taxa (Fisher & Burton, 2018; Roberts et al., 2021b). Generally speaking, disturbances tend to benefit generalists or young forest stage species, while challenging old-growth or intact forest specialists. However, habitat relationships are not always straightforward, and some complex interactions are notable. For example, caribou populations are negatively associated with linear disturbance, but not because they are intact forest specialists per se. Rather, this negative response is largely the consequence of increased predation by wolves, itself largely a consequence of increased deer populations throughout the OSR, caused both by climate change and agricultural conversion (Boutin et al., 2012; Roberts et al., 2021b).

Monitoring of landscape disturbance represents a key opportunity for the continued development of geospatial methods, given that the stressor can be quantified from satellite imagery or other remote sensing approaches. Other future work on landscape disturbance should include increased feature resolution or similar enhancement of

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geospatial layers and continued focused monitoring to clarify the quantitative and qualitative attributes of disturbance that cause change in indicators of concern, with the goal of informing restoration priorities or other management actions.

Water quantity

Also largely unaddressed in the published literature are related cross-theme topics such as local alteration of topography and potential resulting changes to runoff pathways, and resulting water availability in wetland habitats, potentially in combination with climate change and local surficial dewatering in mining operations. Such investigations would be of particular interest, as issues of surface-water quantity have been identified by local communities as being of high importance, because navigable waterways are critical to transportation and land access, ensuring the practice of traditional lifestyles based on hunting and fishing (Beausoleil et al., 2021; Candler et al., 2010).

Further, although ICBM programs and Indigenous Knowledge holders have identified negative trends in water depths, water flows, ice jam floods, ice thickness, and changes in abundance of aquatic mammals such as muskrat in the Peace–Athabasca Delta (PAD) region, the attribution of cause to these trends is complicated by climate change and extensive hydroelectric development on the Peace River. Most investigations into causes of drying in the PAD have focused on stressors on the Peace River (e.g., Beltaos, 2018; Prowse et al., 2006), whereas the limited literature on the effects of OS operations have focused on the effects of current water withdrawals, finding little evidence of an effect (Arciszewski et al., 2021). However, the potential impacts of hydrologic alteration caused by extensive landscape disturbance and, potentially, much greater future withdrawals during reclamation activities have not been assessed.

Attributing cause to OS industrial operations

Because a range of activities occur at or near OS industrial operations, disentangling the multiple and co-occurring OS-related activities along with accounting for natural or other non-OS anthropogenic sources of environmental change can be challenging. This is partly the result of the overlapping spatial structure of both OS and non-OS-related stressors within the OSR, and partly the result of the level of difficulty in delineating clear pathways between sources of environmental change and ecological receptors, as interactions among natural and anthropogenic mechanisms along stressor–response pathways may negate, attenuate, or aggravate ecological responses.

Monitoring of bitumen-associated contaminants in flowing waters exemplifies this challenge. Water sampling of tributaries in the OSR has historically been focused on reaches near their confluence with the Athabasca River. Although these areas are adjacent to development, they are also where natural bitumen outcrops are common, confounding the upstream–downstream, time-for-space designs (Arciszewski et al., 2021). Other spatially confounding influences, such as upstream urban development and bitumen-rich geology, introduce spatial autocorrelation when variables such as "proximity to" or "upstream vs. downstream of" OS industrial development are used as analytical predictors or explanatory model components. Although diagnostic ratios can generally differentiate between, for example, pyrogenic (i.e., combustion derived, as from wildfire) and petrogenic (i.e., bitumen or other petrochemical derived) PACs in sediment, source profiling techniques for other contaminants of concern, such as naphthenic acids originating from OS process water occurring outside mine site containment in surface and groundwater have proven to be less effective or are still in development and less tested (Arciszewski et al., 2022).

Although the coincidental location of bitumen-rich geologic formations and OS operations can undermine strong inference of source attribution, in other cases, the spatial autocorrelation of stressors centered on the active mining areas of the OSR can be helpful if spatial gradients away from OS operations are in themselves stressor gradients. For example, source attribution of ambient air contaminants or atmospheric deposition are more straightforward, at least for some contaminants. Deposition patterns tend to follow predictable patterns of exponential decline in deposition away from emissions sources such as active operations, although this does not necessarily hold true for secondary pollutants produced in the atmosphere (Arciszewski et al., 2021; Horb et al., 2021). In such cases, the strategy of using spatial proximity to OS facilities or operations as a proxy for exposure may be useful. However, ecosystem sensitivity varies widely, and monitoring for specific effects should consequently be designed and implemented in parallel with existing ecosystem knowledge, modeling, and monitoring of stressor pathways, compared with monitoring designs using proximity to OS industrial operations as a proxy for cause, which may be of more limited utility. Going forward, it is advisable that monitoring, including modeling or the use of facility production and fuel use data, be focused on specific source–effect pathways designed to clearly delineate cause. The potential impact of a diffuse pathway such as atmospheric deposition is the clearest example of the need for such a strategy.

For stressors such as habitat alteration and landscape disturbance, quantifying source attribution of development (i.e., allocating disturbances to specific industries) may not be possible with the current level of feature resolution of most geospatial data, though refinement of monitoring designs, geospatial methods, and finer resolution analytical approaches may improve this going forward (Roberts et al., 2021b). This is only partly a matter of data resolution, however. Individual disturbance features may have multiple uses, preventing attribution of features to specific industries or activities, and thus complicating management. For example, a single road originally built along a conventional seismic line for forestry operations may see heavily increased traffic when OS operations increase nearby or when used by the public.

The exception to this is human footprint from ongoing and active industrial use with restricted access, such as land cleared for surface mines and other physical infrastructure. In these cases, landscape disturbance was approved via regulatory processes such as Environmental Impact Assessments, implying a socially acceptable, but also likely conditional change. By contrast, the focal question for ambient monitoring is limited in these cases to whether the systems regulating these known disturbances are functioning in expected ways and if the regional environment is or is not within those previously agreed limits.

Cumulative effects in the OSR

Cumulative effects encompass any impacts on the environment resulting from the incremental, accumulating, and interacting impacts of an action, when combined with other past, present, and future actions, both natural and anthropogenic (Dubé, 2003). These effects may not only be directly additive, but may also interact in compounding or synergistic ways, and may represent some of the more serious environmental effects of any industrial development (Clark, 1994; Dubé, 2003). Although stressors tend to be considered individually in the monitoring literature, no stressor (natural or anthropogenic) acts in isolation, and biota can be simultaneously influenced by, for example, landscape disturbance, infrastructure, natural bitumen exposure, and other anthropogenic contaminants, to say nothing of changing natural disturbance regimes and (closely related) climate change. Indeed, even individual disturbance features may provide multiple pathways to effects, from facilitating increased predation to increased browsing to increased traffic and human use. Cumulative effects are therefore distinguished from singular effects not by consequence or manifestation, but by cause.

Nearly every component of the conceptual model is affected by both OS and non-OS pressures. These cumulative pathways converge on the conceptual model under responses of valued components, reflecting the difficult reality that, by definition, all effects within the OSR are cumulative effects. However, the difficulty in understanding and teasing apart cumulative effects cannot be used as an excuse for not investigating cause. There is a risk that cumulative effects can be interpreted as a black box through which undesirable environmental outcomes occur. Instead, environmental monitoring must accept and work within the reality that cumulative effects emerge from multiple stressors on a heavily industrialized landscape, requiring rigorous monitoring and assessment.

As environmental monitoring in the OSR continues, the broad integrated structure of the conceptual model can inform what questions need additional work, as well as what monitoring efforts may have been sufficiently explored. Consistent methodologies and experimental design that clearly assesses relative impacts of covariates will help ensure that (1) goals of identifying environmental change are defined, (2) existing links between observed changes and OS development are identified, and (3) the appropriate policy and regulatory efforts are informed. There currently exist worthwhile monitoring opportunities to address stressors that we know (1) to be impactful drivers of change in the OSR, (2) to have (at least in part) been attributed to OS operations, and (3) to have a great deal of knowledge about already: namely contaminants and landscape disturbance. Local communities many also identify other priority stressors, particularly those related to human and ecosystem health, or those directly affecting the extent to which Indigenous communities can exercise rights.

Climate change is an example of a global pressure that must be constantly considered as a driver of change, operating as a background process onto which all other cumulative stressors must be overlaid. Despite climate change potentially altering every facet of the natural environment, from hydrology to natural disturbance regimes to habitat quality and resource availability, its consideration in the peer-reviewed literature from the OSR remains peripheral (Arciszewski et al., 2021; Roberts et al., 2021b). Certain stressors driven by climate dynamics are often included as a key driver in OSR monitoring studies, such as extreme weather events, natural disturbance regimes, or even simple interannual variability, all of which are projected to change into the future. Despite this widespread impact (or perhaps because of it) climate change is not often directly addressed in the OSR literature, though it is often included peripherally in discussions of results. Seldom are direct effects of climate change incorporated into analyses of monitoring data within the literature.

A barrier to including climate change in more OSR monitoring studies may simply be issues of scale. As climate change represents a global phenomenon with projected impacts typically quantified at the continental or larger scale, incorporating climate change projections at the regional, landscape, or local scale within specific OS monitoring work is challenging. These challenges are common for Indigenous-led environmental initiatives that collect holistic data over time, space, and media. The sheer complexity of quantifying and delineating complex change over time, especially in sensitive regions such as the PAD, which is highly subject to multiple influencing factors, is exacerbated by the additional stress of a changing climate and often cannot be separated completely from climate attribution. That said, any analysis within the OSR that considers climatic covariates—particularly work with hydrological, species habitat, or other predictive models—should also be considered in the context of change in those covariates over time. There may be opportunities to formally incorporate climate change projections, either as raw meteorological variables or as secondary ecological predictions of, for example, altered species ranges or predicted habitat changes, directly into monitoring designs and analyses. There already exist in the literature a plethora of species distribution models for Alberta, Canada, or North America for a wide range of taxa, and considering such projections, particularly in the context of cumulative effects, represents an opportunity.

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Moving towards comprehensive cross-theme evaluations of cumulative effects is a critical next step, as this has been largely absent from the peer-reviewed literature, which has instead favored reporting on focused monitoring and specific topics. The peer-review process and associated journal preferences (i.e., research article formats) may not lend themselves well to cumulative effect assessments, so there are likely gaps identified here that may be filled by an extended review of the gray literature, particularly arising from multiple years of multi-stakeholder-driven research in the OSR. Further, although primarily limiting our scope to the peer-reviewed literature adds a measure of objectivity and credibility to our findings, it also introduces issues associated with publication bias, favoring positive over negative results—although we did review many papers reporting, at least partially, on negative results also.

THE FURTHER NEED FOR INTEGRATION

In this review, we considered many individual research papers that identify a wide breadth of change in both stressors and effects. However, among these publications are limited studies integrating data or knowledge along a complete and specified pathway. Efforts to increase integration among regional environmental monitoring programs are driven by the desire to ask more useful scientific questions and address the multiple demands of an educated audience seeking to understand the (potentially personal) consequences of a set of results and assess threats. Supplying all information to satisfy all possible inquires and standards of all interested parties, particularly across environmental media for assessments of cumulative effects in an area such as the OSR, remains challenging. Although integrated interpretation is common among the peer-reviewed studies from the OSR (e.g., discussions of results in the context of other research), integrated analyses, which combine data from two or more studies, are much rarer, and integrated data collection is nearly nonexistent, particularly across different theme areas. For example, literature on contaminants spans all three major theme areas: air, water, and land. Despite this, monitoring and reporting on contaminants tend to be both compartmentalized within these themes, with little overlap. The contaminant interfaces between some theme areas are recognized processes, such as atmospheric deposition onto land or water and transport there from into waterways via snowmelt or runoff. However, these processes exist in parallel with global background and local natural sources of contaminants (e.g., wildfire, local bituminous geology) and, if we are to clarify causal connections within the OSR, for contaminants or any other stressors, we require the capacity to trace, forwards or backwards, through the conceptual model, the linkages of contaminant transport and transformations. Although ICBM and terrestrial effects monitoring can identify health or other responses, and whereas air monitoring can identify emissions stressors and chemical transformations occurring in the atmosphere, filling in the pathways remains critical to establishing causal attribution. These issues are challenging but not insurmountable.

Investigations of cause require thoughtful experimental design, the complementary use of more refined data analysis and, in some cases, further technological development (e.g., chemical signatures, regional chemical transport modeling, and remote sensing). Integrated data collection—the monitoring of multiple stressors and effects at coincident locations—is required and should supplant using spatial proximity to OS operations as a covariate of response. Thus far in the literature, only a single program in the OSR satisfies the definition of integrated monitoring across multiple theme areas: The Forest Health Monitoring program measures deposition of acidifying and eutrophying compounds, tissue and soil concentrations, physiological responses and community responses colocated in ecosystems known to be sensitive to acid deposition (Foster et al., 2019). Within individual themes, integrations of monitoring and modeling can also provide a quantitative estimate of cumulative impacts. For example, regional air-quality modeling and model-measurement fusion provide means by which source emissions may be linked via chemical transformation through to acidifying deposition (Makar et al., 2018). Such approaches can provide much stronger inference and more confident attribution of cause than simply measuring contaminant burdens on spatial gradients away from (sometimes arbitrary) center points of OS industrial development. Even when strong spatial correlations exist between responses and stressors, mechanisms of causality (i.e., pathways) may still require validation in controlled environments, such as in laboratory toxicology experiments. Such integrated designs need to be expanded within the OSR.

Within the recent literature from the OSR, methodological developments within geospatial science are becoming more common, including remote sensing, GIS, and landscape-scale modeling applications. Although the focus of most of these developments is on air and terrestrial topics, they also have important applications for a wide breadth of monitoring applications, both within and outside the OSR. Geospatial developments generally focus on improving the quality and availability of spatial data, consistency in spatial data used for modeling, and mismatches between spatial resolution of monitoring and stressor data. There are also opportunities to use remote sensing and GIS for regional scale monitoring and integrated cumulative effects assessments, though these applications are less common in the recent literature.

Methodological advancements in geospatial sciences, including GIS and remote sensing applications, have improved the cataloging of surface disturbance in the OSR. However, although accounting for landscape disturbance may be straightforward, providing the attribute resolution to enable meaningful analyses—particularly with respect to causal attribution—remains challenging. Efforts are underway to refine remotely sensed human footprint data layers (i.e., anthropogenic landscape disturbance) and map land use change over time to identify specific OS contributions. Similarly, continued engagement with industry and the increased utilization of industry data resources and knowledge remains critical. For example, industry data, such as estimates of emissions or effluent release and estimates of mine fleet and tailings ponds emissions, although potentially invaluable for modeling, may not be readily available. Accurate and timely facility location data, industrial production data, or spatial operational intensity data can be difficult to access and so may not be used to their fullest potential.

Valuable integration opportunities for Indigenous communities and ICBM also exist here, particularly with respect to aligning or validating geospatial products with community-based observations of near-real-time environmental change, identifying meaningful indicators of change, and informing pathways of cause. Equally important, when assessing impacts on land, is the need for Western scientists to understand community perspectives; what constitutes an impact; and how methods, indicators, and thresholds should also be community-driven and/or culturally appropriate. Further to this, ICBM requires timely reporting and increased capacity and support if communities are to direct specific monitoring questions and integrate within a larger monitoring framework. Also critical are increased communication and ethical information sharing, improved data repositories, and data mapping utilizing innovative geospatial technologies. In this context, these technologies must also be user-friendly and must conform to culturally sensitive principles of ethics, ownership, control, and access. It must be recognized, however, that the barriers to meaningful inclusion of Indigenous perspectives are not solely technological, but also arise from early challenges in developing an equitable governance structure for monitoring in the OSR (Dubé et al., 2021). Fundamentally, what is required to achieve and maintain credibility is an integrated knowledge translation approach where local Indigenous communities are involved in all aspects of monitoring design, analysis, and reporting.

FINAL THOUGHTS

The ongoing need for a monitoring framework for the OS

The spatial scale of OS industrial developments in northern Alberta is vast, as is the scope of the monitoring undertaken in the region. In this final paper of this special series, we have summarized the peer-reviewed literature available from the past decade to inform the condition of the environment in the OSR of northeastern Alberta. We have taken the conceptual model approach, loading the cross-theme model with the publication counts from the past decade. In doing so, we have identified model components and linkages receiving comparatively high and low attention. The published literature reveals the clear emphasis of existing work on chemical stressors and their association with atmospheric emissions, transport, transformation, and deposition. Also clear is the emphasis on the effects of landscape disturbance and the almost complete occurrence of this work within the terrestrial monitoring theme.

At the same time, some topics of regional concern, particularly to local Indigenous communities, such as water quantity have received notably less attention. Our approach of mapping results to conceptual models has also revealed additional system-wide gaps. Primary among them is the disconnect between theme areas, such as links between atmospheric emissions and implications for rivers and aquatic ecosystems. Gaps in complete knowledge of functional linkages is problematic as, in general, knowledge amassed in the outer columns of the conceptual model (stressors and responses) at the expense of the center (pathways) limits the ability to inform regulatory and policy assurance. Combining the results of papers that were not explicitly designed together creates interpretative and analytical challenges.

Overcoming these gaps may include future optimization of and integration between targeted monitoring projects (integrated data collection and integrated analysis) and entire theme areas (an integrated program). There are, however, implications of any optimization, including the potential for greater efficiency through a reduction in field monitoring effort. Other novel approaches may also be introduced. Where the introduction of new core monitoring efforts may be justified, achieving efficiency and integration may also result in the cessation of some existing monitoring efforts. Although as scientists we may wince at the thought of ceasing the collection of long-term data, adaptive monitoring dictates that, if we are willing to add or increase critical monitoring components to the program to fill knowledge gaps, we must also be willing to subtract or scale back those for which knowledge is established, and confidence in the consistency of measured changes is high. Periodic optimization is necessary to maintain relevance and utility of a monitoring program in the OSR.

Although the use of conceptual models to organize information is useful, the approach also has limitations. While the emphases on the monitoring and research may be clear from the conceptual model, the reasons for them are not. Are these topics of greatest public or local community concern? Are they of greatest scientific interest? Are they topics with historic scientific inertia? Or do they merely reflect what is easy and/or economical to monitor? The alignment of monitoring effort (and by extension, it is to be hoped, knowledge) with priority indicators for multiple stakeholders is a foundational challenge for any ambient monitoring program. Such decisions can be guided by a monitoring framework for the OSR, emphasizing integrated data collection and integrated analysis, and progressing from a posteriori techniques, such as conceptual mapping of existing information, to a priori methods: based on four discrete and ordinal components: (1) an evolving conceptual model, (2) principal questions, (3) testable hypotheses, and (4) adaptive monitoring. This process should follow a deductive model of question articulation, hypothesis formulation, prediction, analysis, adjustment, and iteration by incorporating a scoping, inference, and analysis phase, culminating in characterization of the accumulated environmental state.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHOR CONTRIBUTION

David R. Roberts and Roderick O. Hazewinkel wrote the first draft of the manuscript. All authors provided manuscript content and revisions.

DATA AVAILABILITY STATEMENT

No new data were generated by this literature review.

SUPPORTING INFORMATION

APPENDIX S1. Complete bibliography of published literature consulted in the review series, organized by where they fall on the conceptual model.

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REFERENCES

Alberta Environmental Monitoring Panel (AEMP). (2011). *A world class environmental monitoring, evaluation and reporting system for Alberta*. Alberta Environmental Monitoring Panel Report No.: June, 2011. https://wbea.org/wp-content/uploads/2018/06/a_world_class_environmental_monitoring_evaluation_and_reporting_system_for_alberta_the_report_of_the_alberta_environmental_monitoring_panel.pdf

Arciszewski, T. J., Hazewinkel, R. R. O., Ussery, E. J., & Dubé, M. G. (2021). A critical review of the status of lakes and rivers from Canada's oil sands region. *Integrated Environmental Assessment and Management*, *18*(2), 361–387.

Arciszewski, T. J., Roberts, D. R., Munkittrick, K. R., & Scrimgeour, G. J. (2021). Challenges and benefits of approaches used to integrate regional monitoring programs. *Frontiers in Environmental Science*, *9*, 666698. https://doi.org/10.3389/fenvs.2021.666698

Baker, J. (2017). Research as reciprocity: Northern Cree community-based and community-engaged research on wild food contamination in Alberta's oil sands region. *Engaged Scholar Journal: Community-Engaged Research, Teaching, and Learning*, *2*(1), 109–124. https://doi.org/10.15402/esj.v2i1.201

Beausoleil, D. L., Munkittrick, K. R., Dubé, M. G., & Wyatt, F. (2021). Essential components and pathways for developing Indigenous community-based monitoring: Examples from the Canadian oil sands region. *Integrated Environmental Assessment and Management*, *18*(2), 407-427. https://doi.org/10.1002/ieam.4485

Beltaos, S. (2018). Frequency of ice-jam flooding of Peace-Athabasca Delta. Canadian Science Publishing. www.nrcresearchpress.com/cjce

Bill, L., Crozier, J., & Surrendi, D. (1996). *A report of wisdom synthesized from traditional knowledge component studies* (Northern River Basins Study, project synthesis report 12). http://www.barbau.ca/content/report-wisdom-synthesized-traditional-knowledge-component-studies-1

Boutin, S., Boyce, M. S., Hebblewhite, M., Hervieux, D., Knopff, K. H., Latham, M. C., Latham, A. D. M., Nagy, J., Seip, D., & Serrouya, R. (2012). Why are caribou declining in the oil sands? *Frontiers in Ecology and the Environment*, *10*(2), 65–67. https://doi.org/10.1890/12.WB.005

Candler, C., Olson, R., & DeRoy, S., Firelight Group Research Cooperative. (2010). *As long as the rivers flow: Athabasca River use, knowledge and change*. Parkland Institute. http://www.barbau.ca/content/long-rivers-flow-athabasca-river-knowledge-use-and-change

Clark, R. (1994). Cumulative effects assessment: A tool for sustainable development. *Impact Assessment*, *12*(3), 319–331. https://doi.org/10.1080/07349165.1994.9725869

COSIA. (2012). *Charter for Canada's Oil Sands Innovation Alliance*. Canadian Oil Sands Innovation Alliance (COSIA). https://cosia.ca/about/charter

Culp, J. M., Brua, R. B., Luiker, E., & Glozier, N. E. (2020). Ecological causal assessment of benthic condition in the oil sands region, Athabasca River, Canada. *Science of the Total Environment*, *749*, 141393. https://doi.org/10.1016/j.scitotenv.2020.141393

Dabros, A., Pyper, M., & Castilla, G. (2018). Seismic lines in the boreal and arctic ecosystems of North America: Environmental impacts, challenges and opportunities. *Environmental Reviews*, *26*, 214–229. https://doi.org/10.1139/er-2017-0080

Dann, T. 2016. *Integration of 2015 Odour Data for the Wood Buffalo Environmental Association (WBEA) Human Exposure Monitoring Program (HEMP)*. Wood Buffalo Environmental Association (WBEA). https://wbea.org/wp-content/uploads/2018/03/integration_odour_data_hemp_2015_nov_10th_2016_final.pdf

Davidson, C. J., Foster, K. R., & Tanna, N. (2020). Forest health effects due to atmospheric deposition: Findings from long-term forest health monitoring in the Athabasca oil sands region. *Science of the Total Environment*, *699*, 134277. https://doi.org/10.1016/j.scitotenv.2019.134277

Davidson, C. J., & Spink, D. (2018). Alternate approaches for assessing impacts of oil sands development on air quality: A case study using the First Nation Community of Fort McKay. *Journal of the Air & Waste Management Association*, *68*, 308–328.

Dubé, M., Cash, K., Wrona, F., Enei, G., Cronmiller, J., Abel, R., Andreeff, W., Berrade, D., Davidson, C., Dawson, J., Dersch, A., Dertien, K., Donald, G., Evans, M., Fayant, K., Gladue., B., Gosselin, J., Ilesanmi, Y., … Ladouceur, B. (2018). *Oil sands monitoring program letter of agreement and operational framework*. Alberta Environment and Parks. https://open.alberta.ca/publications/9781460142363

Dubé, M. G. (2003). Cumulative effect assessment in Canada: A regional framework for aquatic ecosystems. *Environmental Impact Assessment Review*, *23*(6), 723–745. https://doi.org/10.1016/S0195-9255(03)00113-6

Dubé, M. G., Dunlop, J. M., Davidson, C. J., Beausoleil, D. L., Hazewinkel, R. R. O., & Wyatt, F. (2021). History, overview and governance of environmental monitoring in the oil sands region of Alberta, Canada. *Integrated Environmental Assessment and Management*, *18*(2), 319-332. https://doi.org/10.1002/ieam.4490

Environment Canada. (2011). *An integrated oil sands environmental monitoring plan*. Ottawa, ON, Canada. http://publications.gc.ca/site/eng/396679/publication.html

Fisher, J. T., & Burton, A. C. (2018). Wildlife winners and losers in an oil sands landscape. *Frontiers in Ecology and the Environment*, *16*(6), 323–328. https://doi.org/10.1002/fee.1807

Foster, K. R., Davidson, C., Tanna, R. N., & Spink, D. (2019). Introduction to the virtual special issue monitoring ecological responses to air quality and atmospheric deposition in the Athabasca Oil Sands Region the Wood Buffalo Environmental Association's Forest Health Monitoring Program. *Science of the Total Environment*, *686*, 345–359. https://doi.org/10.1016/j.scitotenv.2019.05.353

Godwin, C. M., Barclay, R. M. R., & Smits, J. E. G. (2019). Tree swallow (*Tachycineta bicolor*) nest success and nestling growth near oil sands mining operations in northeastern Alberta, Canada. *Canadian Journal of Zoology*, *97*(6), 547–557. https://doi.org/10.1139/cjz-2018-0247

Gosselin, P., Hrudey, S. E., Naeth, A. M., Plourde, A., Therrien, R., Kraak, G. V. D., & Xu, Z. (2010). *Environmental and Health Impacts of Canada's*

Oil Sands Industry. Royal Society of Canada Report No.: December, Ottawa, ON, Canada. http://www.rsc.ca/documents/expert/RSC_ExP_ExecutiveSummary_ENG_Dec14_10_FINAL_v5.pdf

Government of Alberta. (2012). *Lower Athabasca Regional plan 2012–2022, Edmonton, AB, Canada*. https://open.alberta.ca/dataset/37eab675-19fe-43fd-afff-001e2c0be67f/resource/a063e2df-f5a6-4bbd-978c-165cc25148a2/download/5866779-2012-08-lower-athabasca-regional-plan-2012-2022.pdf

Government of Alberta. (2014). *Gull and tern egg consumption advisory, Edmonton, AB, Canada*. https://mywildalberta.ca/hunting/safety-procedures/gull-and-tern-egg-consumption-advisory.aspx

Hall, R. I., Wolfe, B. B., Wiklund, J. A., Edwards, T. W. D., Farwell, A. J., & Dixon, D. G. (2012). Has Alberta oil sands development altered delivery of polycyclic aromatic compounds to the Peace-Athabasca Delta? *PLoS One*, *7*(9), 9. https://doi.org/10.1371/journal.pone.0046089

Harner, T., Rauert, C., Muir, D., Schuster, J. K., Hsu, Y.-M., Zhang, L., Marson, G., Watson, J. G., Ahad, J., Cho, S., Jariyasopit, N., Kirk, J., Korosi, J., Landis, M. S., Martin, J. W., Zhang, Y., Fernie, K., Wentworth, G. R., Wnorowski, A., … Wang, X. (2018). Air synthesis review: Polycyclic aromatic compounds in the oil sands region. *Environmental Reviews*, *26*(4), 430–468. https://doi.org/10.1139/er-2018-0039

Hebert, C. E. (2019). The river runs through it: The Athabasca River delivers mercury to aquatic birds breeding far downstream. *PLoS One*, *14*(4), 1–19. https://doi.org/10.1371/journal.pone.0206192

Hopke, P. K., Alan, J., Johnson, D. H., Jana, K., Le, C., & Niemi, G. J. (2016). *Assessing the scientific integrity of the Canada-Alberta Joint Oil Sands Monitoring (2012–2015): Expert panel review*. https://open.alberta.ca/publications/assessing-the-scientific-integrity-of-the-canada-alberta-josm-2012-2015-expert-panel-review

Horb, E. C., Wentworth, G. R., Makar, P. A., Liggio, J., Hayden, K., Boutzis, E. I., Beausoleil, D. L., Hazewinkel, R. R. O., Mahaffey, A. C., Sayanda, D., Wyatt, F., & Dubé, M. G. (2021). A decadal synthesis of atmospheric emissions, ambient air quality, and deposition in the oil sands region. *Integrated Environmental Assessment and Management*, *18*(2), 333–360.

Kelly, E. N., Short, J. W., Schindler, D. W., Hodson, P. V., Ma, M., Kwan, A. K., Fortin, B. L. (2009). Oil sands development contributes polycyclic aromatic compounds to the Athabasca River and its tributaries. *Proceedings of the National Academy of Sciences*, *106*(52), 22346–22351. https://doi.org/10.1073/pnas.0912050106

Lindenmayer, D. B., & Likens, G. E. (2009). Adaptive monitoring: A new paradigm for long-term research and monitoring. *Trends in Ecology and Evolution*, *24*(9), 482–486. https://doi.org/10.1016/j.tree.2009.03.005

Makar, P. A., Akingunola, A., Aherne, J., Cole, A. S., Aklilu, Y., Zhang, J., Wong, I., Hayden, K., Li, S. M., Kirk, J., Scott, K., Moran, M. D., Robichaud, A., Cathcart, H., Baratzedah, P., Pabla, B., Cheung, P., Zheng, Q., & Jeffries, D. S. (2018). Estimates of exceedances of critical loads for acidifying deposition in Alberta and Saskatchewan. *Atmospheric Chemistry and Physics*, *18*(13), 9897–9927. https://doi.org/10.5194/acp-18-9897-2018

McMaster, M. E., Tetreault, G. R., Clark, T., Bennett, J., Cunningham, J., Ussery, E. J., & Evans, M. (2020). Baseline white sucker health and reproductive endpoints for use in assessment of further development in the Alberta oil sands. *International Journal of Environmental Impacts*, *3*(3), 219–237. https://doi.org/10.2495/ei-v3-n3-219-237

Munkittrick, K. R., & McCarty, L. S. (1995). An integrated approach to aquatic ecosystem health: Top-down, bottom-up or middle-out? *Journal of Aquatic Ecosystem Health*, *4*(2), 77–90. https://doi.org/10.1007/BF00044791

Parlee, B. L., Geertsema, K., & Willier, A. (2012). Social-ecological thresholds in a changing boreal landscape: Insights from Cree knowledge of the Lesser Slave Lake region of Alberta, Canada. *Ecology and Society*, *17*(2), art20. https://doi.org/10.5751/ES-04410-170220

Pilote, M., André, C., Turcotte, P., Gagné, F., & Gagnon, C. (2018). Metal bioaccumulation and biomarkers of effects in caged mussels exposed in the Athabasca oil sands area. *Science of the Total Environment*, *610–611*, 377–390. https://doi.org/10.1016/j.scitotenv.2017.08.023

Prowse, T. D., Beltaos, S., Gardner, J. T., Gibson, J. J., Granger, R. J., Leconte, R., Peters, D. L., Pietroniro, A., Romolo, L. A., & Toth, B. (2006). Climate change, flow regulation and land-use effects on the hydrology of the Peace-Athabasca-Slave system; findings from the Northern Rivers Ecosystem Initiative. *Environmental Monitoring and Assessment*, *113*(1–3), 167–197. https://doi.org/10.1007/s10661-005-9080-x

Roberts, D. R., Bayne, E. M., Beausoleil, D. L., Dennett, J. M., Fisher, J. T., Hazewinkel, R. R. O., Sayanda, D., Wyatt, F., & Dubé, M. G. (2021b). A synthetic review of terrestrial biological research from the Alberta oil sands region: Ten years of published literature. *Integrated Environmental Assessment and Management*, *18*(2), 388–406.

Shotyk, W., Belland, R., Duke, J., Kempter, H., Krachler, M., Noernberg, T., Pelletier, R., Vile, M. A., Wieder, K., Zaccone, C., & Zhang, S. (2014). Sphagnum mosses from 21 ombrotrophic bogs in the Athabasca Bituminous Sands region show no significant atmospheric contamination of “heavy metals”. *Environmental Science & Technology*, *48*(21), 12603–12611. https://doi.org/10.1021/es503751v

Suter, G. W. (2007). Ecological risk assessment (2nd ed.). CRC Press.

Swanson, S. (2019). *Oil Sands Monitoring Program: Integration Workshop Reports* (Part 1 of 2). Government of Alberta, Edmonton, AB, Canada. https://open.alberta.ca/publications/9781460144947

Tetreault, G. R., Bennett, C. J., Clark, T. W., Keith, H., Parrott, J. L., & McMaster, M. E. (2020). Fish performance indicators adjacent to oil sands activity: Response in performance indicators of slimy sculpin in the Steepbank River, Alberta, adjacent to oil sands mining activity. *Environmental Toxicology and Chemistry*, *39*(2), 396–409. https://doi.org/10.1002/etc.4625

Thomas, P. J., Newell, E. E., Eccles, K., Holloway, A. C., Idowu, I., Xia, Z., Hassan, E., Tomy, G., & Quenneville, C. (2021). Co-exposures to trace elements and polycyclic aromatic compounds (PACs) impacts North American river otter (*Lontra canadensis*) baculum. *Chemosphere*, *265*, 128920. https://doi.org/10.1016/j.chemosphere.2020.128920

Timoney, K. P., & Lee, P. (2009). Does the Alberta tar sands industry pollute? The scientific evidence. *The Open Conservation Biology Journal*, *3*(1), 65–81. https://doi.org/10.2174/1874839200903010065

Venier, L. A., Thompson, I. D., Fleming, R., Malcolm, J., Aubin, I., Trofymow, J. A., Langor, D., Sturrock, R., Patry, C., Outerbridge, R. O., Holmes, S. B., Haeussler, S., De Grandpré, L., Chen, H. Y. H., Bayne, E., Arsenault, A., & Brandt, J. P. (2014). Effects of natural resource development on the terrestrial biodiversity of Canadian boreal forests. *Environmental Reviews*, *22*(4), 457–490. https://doi.org/10.1139/er-2013-0075

Wong, C., Ballegooyen, K., Ignace, L., Johnson, M. J., & Swanson, H. (2020). Towards reconciliation: 10 calls to action to natural scientists working in Canada. *Facets*, *5*(1), 769–783. https://doi.org/10.1139/FACETS-2020-0005

