Special Series

A synthetic review of terrestrial biological research from the Alberta oil sands region: 10 years of published literature

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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

In the past decade, a large volume of peer-reviewed papers has examined the potential impacts of oil and gas resource extraction in the Canadian oil sands (OS). A large proportion focuses on terrestrial biology: wildlife, birds, and vegetation. We provide a qualitative synthesis of the condition of the environment in the oil sands region (OSR) from 2009 to 2020 to identify gaps and progress cumulative effects assessments. Our objectives were to (1) qualitatively synthesize and critically review knowledge from the OSR; (2) identify consistent trends and generalizable conclusions; and (3) pinpoint gaps in need of greater monitoring or research effort. We visualize knowledge and terrestrial monitoring foci by allocating papers to a conceptual model for the OS. Despite a recent increase in publications, focus has remained concentrated on a few key stressors, especially landscape disturbance, and a few taxa of interest. Stressor and response monitoring is well represented, but direct monitoring of pathways (linkages between stressors and responses) is limited. Important knowledge gaps include understanding effects at multiple spatial scales, mammal health effects monitoring, focused monitoring of local resources important to Indigenous communities, and geospatial coverage and availability, including higher attribute resolution in human footprint, comprehensive land cover mapping, and up-to-date LiDAR coverage. Causal attribution based on spatial proximity to operations or spatial orientation of monitoring in the region is common but may be limited in the strength of inference that it provides. *Integr Environ Assess Manag* 2022;18:388–406. © 2021 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Athabasca, Biodiversity, Canada, Cumulative effects, Environmental monitoring

INTRODUCTION

The Canadian oil sands region (OSR) in the western Nearctic boreal forest holds almost a third of the world's hydrocarbon deposits and is a major driver of global economies and geopolitics (Bayoumi & Mühleisen, 2006; Giesy et al., 2010). However, this economic boon, as with all industrial development, comes at an environmental cost. Better understanding the residual and existing environmental impacts of oil sands (OS) development has been a priority for various ambient monitoring and research programs, including those run by independent researchers as
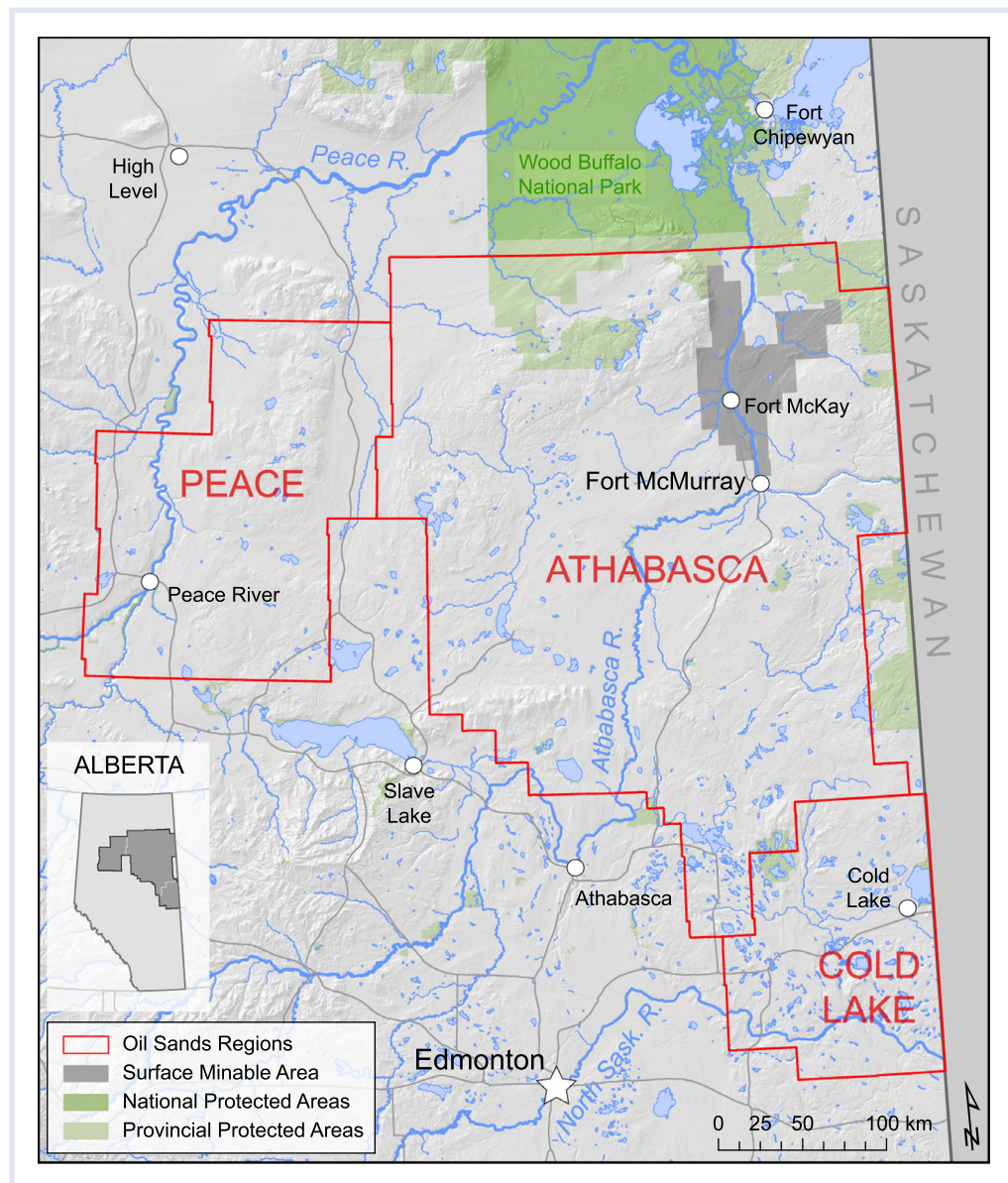
FIGURE 1 Map of the Canadian oil sands region in northeastern Alberta, Canada, identifying the three main OS regions (Peace, Athabasca, and Cold Lake) as well as urban centers, major hydrological features, the surface minable OS area (in dark gray), and protected areas (in green)

well as government agencies, such as through the Oil Sands Monitoring Program (OSM), run jointly by the Governments of Canada and Alberta (Dubé et al., 2021), as well as through Indigenous community-based monitoring (ICBM) programs.

Oil sands industrial operations necessitate a variety of facilities and developments on the landscape. Open-pit surface mining of shallow bitumen—the viscous hydrocarbon mixture extracted from OS—involves removing large tracts of topsoil and overburden, effectively removing all biomass from an area. Conversely, in situ operations—bitumen extraction from drilled wells—generate narrow forest cut lines (seismic lines) for exploration and cleared well-drilling pads. Both types of extraction necessitate large networks of roads, above- and below-ground pipelines, and industrial upgrading facilities

used to refine bitumen. Although major developments (surface mines, well pads, bitumen upgrading facilities) sit on land leased to private companies, the monitoring of which falls under regulatory guidelines, other OS-related footprints (e.g., roads, seismic lines, pipelines) and regional impacts (e.g., contaminant deposition) exist or occur off-lease, falling within the purview of ambient environmental monitoring programs (Dubé et al., 2021). Environmental monitoring within the OSR (Figure 1) beyond lease boundaries is important as, particularly for terrestrial ecology, many potential changes are likely to be observed at larger landscape scales, in regions both close to and far from OS facilities and on-lease operations. Further, scientific inconsistencies in regulatory processes such as environmental impact assessments have been recently identified (Campbell et al., 2020), emphasizing the

need for third-party monitoring of the larger condition of the environment in the OSR.

Substantial monitoring and research efforts in the OSR have resulted in a large body of peer-reviewed literature examining the potential environmental impacts of oil and gas resource extraction. Monitoring priorities in the OSR must be guided by a conceptual understanding of the biotic and abiotic systems in the boreal forest of northern Alberta and hypotheses describing how industrial development may influence these systems. Oil sands-related publications can be organized into discrete but overlapping theme areas of air, water, and land, and generally consider a wide breadth of anthropogenic and natural stressors, the associated responses to those stressors, and the pathways connecting them. Although reviews are available on specific topics such as seismic lines (Dabros et al., 2018) or more general forest disturbance (Venier et al., 2014), the information in these publications has not been synthesized to examine the condition of the environment in the OSR, inhibiting the progression of larger cumulative effects assessments. Ambient terrestrial monitoring in the OSR includes assessments of potential effects of industrial activities on a variety of taxa, including those of social and cultural importance, species of concern, and ecological resources of value to local communities.

Here, we present a synthetic review of the last decade of peer-reviewed literature focused on monitoring the potential terrestrial biological effects of OS industrial development, with the objectives being to (1) synthesize knowledge from the OSR via a synthesis of relevant published literature; (2) identify consistent trends in the focus and effort within the reviewed literature; and (3) pinpoint knowledge gaps and opportunities for greater monitoring or research effort. To represent known or suspected environmental relationships, we implement a conceptual modeling approach—a box and line diagram to visualize environmental monitoring components (e.g., stressors, pathways, responses; Box 1) and the links between them. Conceptual models are fundamental tools to inform monitoring foci within environmental monitoring and cumulative effects assessment. We outline major conclusions from the literature, organized by key pressures, and include notable gaps and opportunities. We identify overarching challenges, such as issues of scale. We close with a discussion of specific monitoring and research opportunities in the OSR offered by emerging geospatial methods, which represent a substantial focus in the methodological literature.

METHODS

Our qualitative synthetic review followed advice derived from systematic reviews (Haddaway et al., 2015; Xiao & Watson, 2019) in that we searched for papers using defined terms and rigorously adhered to delineated criteria for exclusion, and then subjected the result to reviews by the body of authors. Note, however, that this is not a systematic review; we did not use a vote-counting approach (Berger-Tal et al., 2019; Xiao & Watson, 2019) or strictly constrain our content to the search criteria, which would overlook publications lacking target keywords but providing critical context. Allowing flexibility in inclusion provides the opportunity to pursue additional relevant literature missed in the original searches. Further, though gray (all non-peer-reviewed) literature can hold important information for reviews (Haddaway et al., 2015), we excluded it; such a review would be a massive undertaking worth its own effort. We instead focused on peer-reviewed literature to begin the knowledge synthesis process for the OSR using the most scientifically credible information available and acknowledge that this subjects us to publication bias (Westgate & Lindenmayer, 2017).

In our synthetic review, we considered all peer-reviewed papers published from 2009 to 2020 that fulfilled three criteria: (1) covered a terrestrial topic or focal indicator; (2) collected data inclusive of or specific to the OSR; and (3) were relevant to OS industrial operations. Initial searches for literature were performed using general OS-related search terms within Scopus and Google Scholar. We also consulted reference lists from these publications for literature missed in initial searches. We read all selected papers and recorded predetermined details for each study including monitoring location and dates, focal taxa or topic, stressors, pathways, effects, key findings, and any environmental change reported (Appendix S1). We summarize these findings in this article, with more detailed summaries and discussion provided in Appendix S2. Much has been written about biological monitoring (Ims & Yoccoz, 2017; Yoccoz et al., 2001) and much debate exists around the best approaches, including some approaches adopted within the OSM (Haughland et al., 2010; Lindenmayer & Likens, 2009). Although a rigorous, systematic review that generates new conclusions (like a meta-analysis) will be of value for the future of research and monitoring in the OSR, the state of the science does not yet lend itself to this meta-analytical approach; hence, our focus was to critically synthesize what is known, so that future efforts may target what remains unknown.

We excluded papers based solely on three designated, predelineated criteria (Haddaway et al., 2015): (1) laboratory-only studies; (2) field research specific to land reclamation, recovery, or remediation; and (3) methods development research. All others were retained and exclusion was checked by all authors, lending confidence that we avoided entraining unconscious bias (Haddaway et al., 2015). Reclamation and recovery of disturbed land is an important ecological and economic activity in the OSR (e.g., Caners & Lieffers, 2014; Filicetti et al., 2019; Z. Zhang, 2019) and should be the subject of a dedicated future review. We do not consider the exclusion of reclamation literature as a risk to undermine our conclusions, as our scope is limited to impacts of OS operations, not the reversal of those impacts. It is noteworthy that we did retain monitoring papers with data collection within reclaimed habitats when studies offered knowledge applicable to the larger boreal forest ecosystem. We also retained papers that included the recovery status of features (e.g., amount of regrowth on disturbance features), an environmental covariate explaining variance in terrestrial species responses (e.g., Tattersall et al., 2020a).

Further, our scope was restricted to terrestrial biology. Wetland environments combine qualities of both terrestrial and aquatic systems, and so do not fall squarely into either this review or others (Arciszewski et al., 2021). We divided wetland literature between the terrestrial and surface water themes: terrestrial taxa (e.g., birds, vegetation, etc.) were included even if they were wetland habitat specialists, whereas aquatic taxa (including amphibians) were included in the accompanying surface water review (Arciszewski et al., 2021). A recent review of wetland literature from the OSR has also been completed by Ficken et al. (2021), separate from this Special Series. Artificial divisions of holistic ecosystems (e.g., into terrestrial, aquatic, and air themes) compromise interpretability to some extent, but they are pragmatic; they reflect the thematic divisions of current monitoring efforts in the OSR and parallel natural divisions in expertise among scientists and authors. In effect, the thematic breakdown of this Special Series is largely a product of the structure of the OSM Program, more than an independent decision among all the Special Series authors.

Our review criteria resulted in a final selection of 85 peer-reviewed papers (Appendix S1), though we cite many others in this review as part of contextual, methods, or other related discussions. A cross-theme synthesis and complete bibliography of all papers reviewed for water, air, terrestrial biology, and ICBM are provided in the cross-theme synthesis paper within this Special Series (Roberts et al., 2021a).

RESULTS AND DISCUSSION

We organized key research findings by major stressors (e.g., landscape disturbance and contaminants), as well as specific methodological approaches and challenges. Extended results and discussion, including additional background and references, are provided in Appendix S2. To visualize the effort from the reviewed literature, we allocated the reviewed papers to a terrestrial biological conceptual model for the OSR, where the individual papers supported the inclusion of a model component (i.e., pressure, stressor, pathway, or response) (Figure 2).

Key pressures

Landscape disturbance. Landscape disturbance—removal of mature forest or wetland and creation of an anthropogenic feature—is arguably the most widespread stressor in the OSR, with roughly 13.8% of the land base qualifying as "disturbed" habitat (2012 data) in the form of agriculture (7.4%, largely concentrated in the Cold Lake and Peace River OS regions), forestry (2.9%), and energy exploration and extraction (2.2%) (Alberta Biodiversity Monitoring Institute [ABMI], 2014) (Figure 3). Publications addressing landscape disturbance were the dominant focus of the literature from the OSR that we reviewed (Figure 2). This focus may be a result of landscape disturbance being highly visible, directly quantifiable (both on the ground and geospatially), and discrete in its distribution on the landscape.

It can be challenging to separate terrestrial impacts of OS-specific landscape disturbances (e.g., 3D seismic lines common to in situ development, surface mines, OS roads) from non-OS landscape disturbances (e.g., agriculture, forestry, urban development, conventional oil and gas, non-OS roads). For example, very few papers that considered landscape disturbance as a stressor specifically investigated responses to features identifiable as OS related. Individual disturbance features may be attributable to a specific industry when classified one by one in focused monitoring studies, but the more typical approach of utilizing geospatial human footprint layers (e.g., Burton et al., 2014) complicates attribution to specific industries (especially OS vs. conventional oil and gas).

Habitat alteration from OS development can be divided into two categories, each with different associated environmental responses: (1) linear disturbance (narrow and long clearings, such as seismic lines and roads) and (2) polygonal disturbance (more contiguous clearings, such as well pads, agricultural clearing, and forestry cut blocks). Although linear disturbances cover less total area at the local scale relative to polygonal disturbances, they can extend across vast distances and are ubiquitous within the OSR ($\geq$1 km/km^2 in most of the OSR, Figure 3), making them the main source of forest edges (Dabros et al., 2018). They also naturally regenerate slowly enough to remain on the landscape for decades, and features with ongoing human access (e.g., roads, seismic lines accessible to off-highway vehicles; OHVs) may persist on the landscape indefinitely (Finnegan et al., 2019; Pigeon et al., 2016; Van Rensen et al., 2015).

Linear disturbances affect biota in two main ways. First, they create extensive forest edges and associated edge effects. These ecological changes—including those in behavior, abundance, and community—manifest where two distinct habitats meet (e.g., forest and clearings, old and
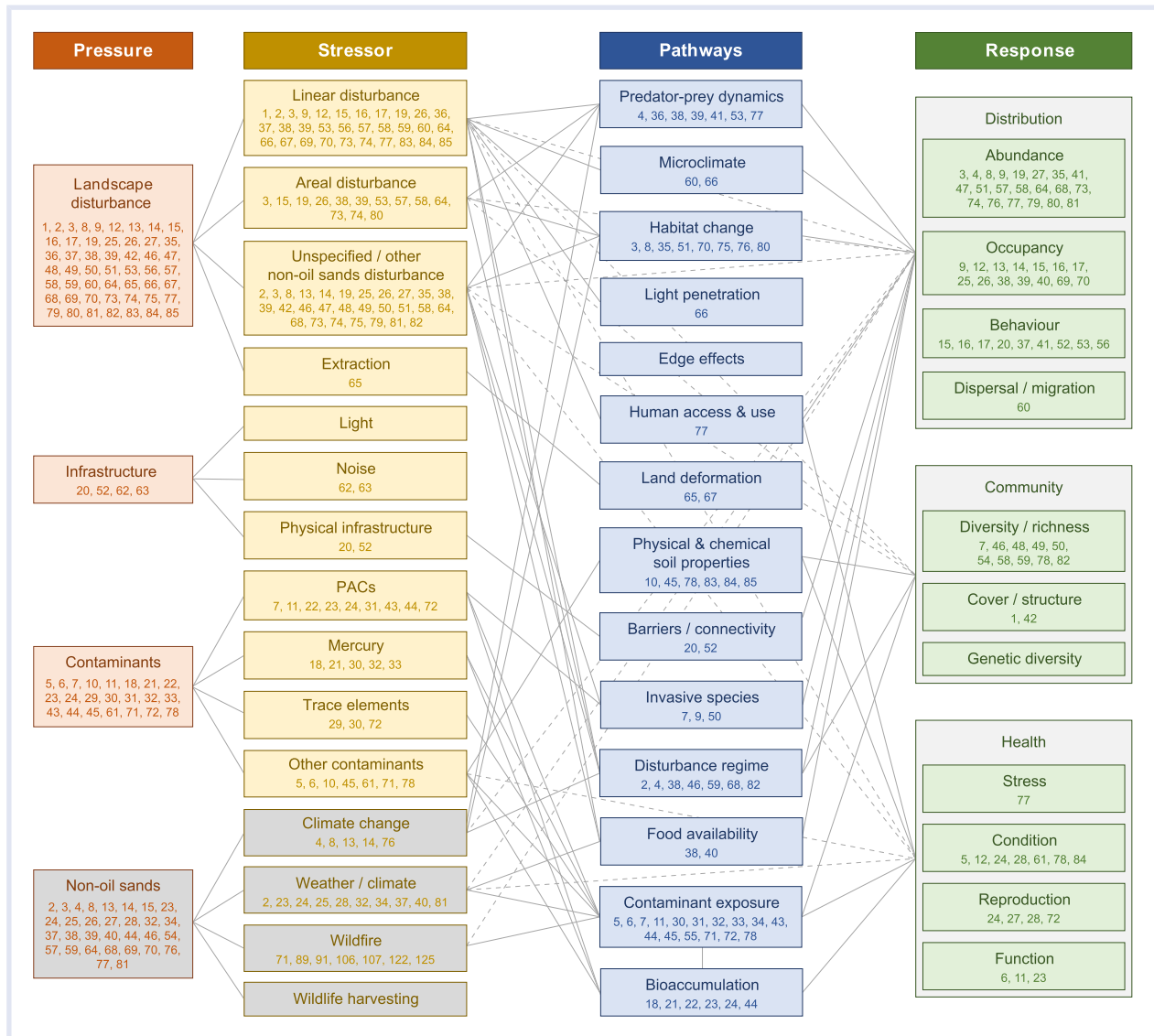
FIGURE 2 Terrestrial biological conceptual model for the oil sands region, showing pressures, stressors, pathways, and responses. For reference, papers included in our review that demonstrated evidence for that model component are shown in the respective boxes by a number corresponding to the review tables (Appendix S1) and numbered bibliography (Appendix S3). Boxes are connected by gray lines if we found evidence of their connection in the reviewed literature (i.e., if a paper appears in multiple boxes, they are connected). Dashed lines represent stressor–response relationships in the literature that did not have a defined pathway

young growth forest) (Murcia, 1995). Polygonal disturbances, while larger and contiguous, produce fewer forest edges and habitat transitions per unit area. Therefore, when buffering effects around disturbances are considered, the ubiquitous linear features that segment the OSR landscape may represent a much larger area of disturbance than what is directly reported (ABMI, 2014) (Figure 3).

Second, linear features create networks of interconnected low-vegetation corridors that facilitate movement for some species such as wolf (*Canis lupus*) (Dickie et al., 2017; Latham, Latham, Boyce, & Boutin, 2011). This has indirect impacts on other species by increasing predator–prey encounters (Mckenzie et al., 2012) and wolf hunting efficiency (Dickie et al., 2017), which consequently leads to avoidance of these features by prey species (Latham, Latham, Boyce, &

Boutin, 2011). Such altered predator–prey interactions have, in combination with changes in deer (*Odocoileus virginianus*) habitats and populations (Dawe et al., 2014; Dawe & Boutin, 2016; Fisher et al., 2020; Fisher & Burton, 2021), been implicated in the decline of woodland caribou (*Rangifer tarandus*) in the OSR (S. Boutin et al., 2012).

Knowledge of wolf–caribou predator–prey dynamics is unique among mammal monitoring in its completeness and consistency. Findings among most mammal monitoring studies are generally more variable and often contradictory (Appendices S2 and S4). This may be an artifact of different sampling methodologies, different spatial or temporal scales of measurement, or simply due to large uncertainties associated with quantifying wildlife responses across large multistressor areas (i.e., science is hard). In fact, a central
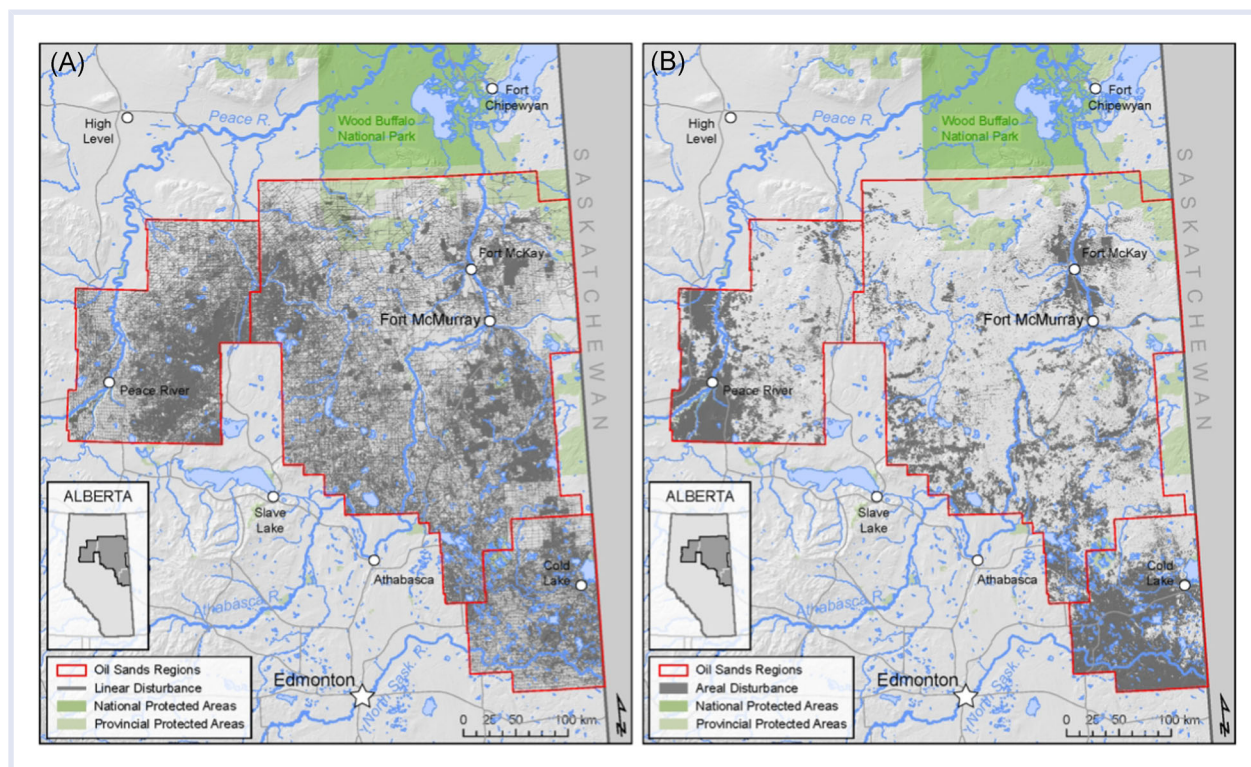
FIGURE 3 Extent of landscape disturbance in the oil sands region of northeastern Alberta (ABMI, 2017), showing the extent of human footprint in the area as (A) mapped linear disturbance features and (B) mapped polygonal disturbance features

consistency within the literature is that mammal responses to anthropogenic landscape features and other changes in forest seral stage in the OSR are complex and idiosyncratic across species (Fisher & Burton, 2018; Wittische et al., 2021).

While landbird species also respond to landscape disturbance idiosyncratically, they tend to do so more predictably, in alignment with their habitat preferences (Mahon et al., 2019). Generally speaking, in the boreal forest, landbird species distribution and communities are related to a combination of climate, forest structure, and human disturbance, to varying degrees of importance depending on the specific species guild (J. Zhang et al., 2013). Species preferring open or early seral habitats are generally found in greater abundance on disturbed sites, while the most negatively affected species are those commonly associated with older forest stages or shrublands, as well as habitat generalists (Bayne et al., 2016; Foster et al., 2017); this is a consistent pattern across the larger boreal forest (see review by Schieck & Song, 2006). Future projections of industrial development trends in the OSR suggest that old growth habitat specialists may be at risk of population decline through the next century (Mahon et al., 2014).

Further, cumulative effects on boreal birds may be underestimated, as additive and interactive effects may have a larger influence on bird abundances and communities than previously recognized. For many species, habitat and either single or multiple disturbance variables interact when accounting for species abundances, suggesting complex functional relationships between landbirds and their environments, including anthropogenic disturbance (Mahon et al., 2019). The implication of this complexity, likely extending beyond birds to other taxa, highlights the necessity of considering not just individual responses to specific stressors but also cumulative effects resulting from the multistressor OSR environment (Roberts et al., 2021a). Most landbirds are also migratory and the boreal is their breeding habitat, so disturbance effects in the rest of their ranges may compound those of OS activity.

Most vegetation monitoring papers focus on richness or other community-level responses at various scales. Species-level responses to various footprint types, and the pathways by which those responses are aggravated, are poorly understood by comparison. Responses may be complex (e.g., interactions between abiotic factors like light and biotic factors like pollinator movements), and evidence from the boreal region outside the OSR suggests idiosyncratic variation among species, as has been seen with other taxa (Dabros et al., 2018). Broadly, the majority of vegetation studies in the OSR have focused on linear features, including conventional (wider) seismic lines and 3D (narrower, denser) seismic lines. Roads are also unique as a "hard" linear feature in the OSR that alters the hydrology of forested peatlands, thus affecting canopy and understory species and communities (Miller et al., 2015; Saraswati et al., 2020).

The physical and chemical properties of soils are changed in disturbance features, representing an important pathway for vegetation community change. This specifically includes changes in soil chemistry resulting from changes in organic

cover and decomposition rates (S. J. Davidson, Goud, et al., 2020), in soil water from winter road use (Strack et al., 2018), in soil temperature (Finnegan et al., 2019), and in microtopographic simplification (Stevenson et al., 2019). A small body of literature on terrestrial invertebrates from the larger boreal region often considers the effects of forest harvesting in addition to those of conventional oil and gas or OS effects specifically. Exceptions to this include monitoring responses to energy-related disturbances of a few native butterflies (Riva et al., 2018a, 2018b) and nonnative earthworm species (e.g., Cameron et al., 2007), though most knowledge on the latter comes from pre-2010 publications and from boreal habitats outside the OSR specifically.

Idiosyncratic species responses to landscape disturbance are a common thread across taxa in monitoring studies from the OSR, and mammal monitoring work has demonstrated that consideration of a complexity of covariates may be required when assessing the impacts of landscape disturbance. For example, various levels of seismic line regeneration, snow cover, human use, line density, and line width can differentially alter the magnitude and direction of occupancy rates for different species (Tattersall et al., 2020a), and the effect of these covariates likely changes at different temporal and spatial scales (Beirne et al., 2021; Tattersall et al., 2020b). Consequently, while species-level focused monitoring may be useful for indicator or focal species, this approach may be too resource-intensive for widespread application. Instead, OSR monitoring would benefit from multispecies monitoring using tools that measure responses of multiple species simultaneously, such as remote cameras for mammals (Burton et al., 2015) and autonomous recording units for birds and amphibians (Shonfield & Bayne, 2017a), or for other taxa community-level indicators (e.g., richness, diversity) that can assess biodiversity and ecosystem health. Such multitaxa approaches would be further strengthened by an increase in integrated monitoring designs with colocated and coincidental data collection across known stressor gradients.

Finally, from a conservation perspective, it is spurious to interpret idiosyncratic species responses to disturbance as a zero-sum game in which losses in one species are offset by gains in another. The decline in the abundance of some species in parallel with increases in others will result in a net loss of diversity, and potentially ecosystem function, over time and, if disturbance continues under consistent trends, local extirpation of some species, likely those favoring intact late-stage forests, may be the result.

Landscape disturbance: gaps and opportunities. The complexity of the boreal environment and the multistressor nature of the OSR introduce challenges when determining responses of terrestrial biology to landscape disturbance. Species and taxa (e.g., birds, mammals, insects, and vegetation) respond idiosyncratically and differences in observed responses may depend, for example, on the type and nature of disturbances, the habitat preferences of the individual species, or the spatial scale of measurement (Fisher & Burton,

2018; Toews et al., 2018; Venier et al., 2014). High-latitude boreal systems have a well-known low diversity and a lack of functional redundancy (Cooke et al., 2019; Hillebrand, 2004), so a spectrum of unique responses is entirely expected.

Still, there are opportunities to refine monitoring approaches to bring more consistency to and comparability between observations. We observed few consistent monitoring approaches or designs among taxa, with research instead tailored to targeted questions. This yields important specific knowledge but undermines multitaxa syntheses and inhibits understanding of whole-ecosystem connections (such as between mammals, birds, and plants, as in trophic cascades) (Terborgh & Estes, 2010). Standardizing monitoring designs across taxa, colocating and integrating monitoring across the region at nested spatial and temporal scales, using sample sizes derived from power analyses, and encouraging consistency in field methods would generate more consistent results and stronger inference with respect to species responses to landscape disturbance.

Current gaps in disturbance research and monitoring exist with respect to species (e.g., mustelids, shrubs and forbs, invertebrates), methods (e.g., combining data sets, issues of scale), and ecological mechanisms generating observed patterns (i.e., pathways) (Figure 2). Causal attribution is limited by the complexity of attributing specific species responses to specifically OSR-generated disturbances—with the exception of 3D seismic lines, which are exclusive to OS operations. Enhanced geospatial human footprint layers with precise industrial attribution of anthropogenic features would bridge this gap, as would a design that captures the critical importance of scale when it comes to landscape disturbance response. Future monitoring must consider terrestrial biological responses at multiple scales, as these are often different and sometimes contrasting.

One of the most notable geospatial gaps in the OSR is that the regional human footprint data coverage, often implemented for landscape-scale analyses, does not include narrow 3D seismic lines, largely associated with in situ OS development (ABMI, 2017). Attribution of disturbance features and ecological response at fine scales is critical for accurately modeling responses and informing mitigation. Data enrichment efforts, such as adding greater attribute resolution to geospatial footprint layers, would help address this need. Even with such data improvements, however, the multistressor quality of the landscape in the OSR, where many habitat disturbances overlap in time and space, will continue to undermine causal attribution. To address this challenge, more causally inferential experimental designs are required, such as pre- and postconstruction monitoring to establish before–after stressor–response data. Geospatial approaches may offer support in this respect. For example, long-term remote-sensing data such as decades-long satellite imagery records can be used to develop time series of visible landscape changes (e.g., Chowdhury et al., 2017).

The comprehensive identification and characterization of landscape disturbance, including narrow 3D seismic features, within geospatial human footprint data sets will

facilitate local- and landscape-scale analyses of both responses and pathways related to landscape disturbance. Such data could also enable investigation into other potential pathways that are underrepresented or absent from the literature with respect to vegetation responses, including local changes in hydrology, microtopography, physical removal or disturbance effects such as soil compaction, or changes to larger mesoclimate patterns from larger-scale disturbance patterns. Polygonal features and their edge effects on plants, while assumed to be similar to linear disturbance effects, are less well understood and less often monitored.

While causal attribution is critical for the regulation and management of OS operations, the attributes required to attribute cause may not be the same as those required to refine ecological response analyses and models. For example, the ability to differentiate a linear disturbance as either a pipeline or a wide seismic line is likely less important in a wildlife distribution model than the ability to determine the width, vegetation cover, or other ecologically relevant variables of the feature itself. In many respects, the original human use of the feature is secondary to the ecological character of the feature, which can also be determined largely by human tertiary uses, such as OHV use of seismic lines that inhibits regeneration (Pigeon et al., 2016; Van Rensen et al., 2015). Moving beyond disturbance attribution to disturbance characteristic and use may produce stronger explanatory models where attributes are useful explanatory variables (e.g., Tattersall et al., 2020a) or serve to eliminate covariates as drivers of occupancy and abundance when they are not. Although the regeneration of disturbance features was beyond the scope of this review, it is an extensive and valuable body of knowledge that could provide relevant guidance in this context.

Oil sands disturbance features are unique. The most conspicuous polygonal features are, of course, active OS surface mines. While biodiversity on these sites is effectively zero, they represent a comparatively small area of actual landscape disturbance (<1% of Canadian OS deposits in 2018). The more ubiquitous and widespread OS-related landscape disturbances are networks of roads, aboveground pipes, wellsites, and seismic lines, and there is ample evidence to conclude that these features affect species distributions, and that they do so additively or synergistically with a variety of other anthropogenic landscape disturbances from a breadth of industries and activities (and, of course, climate change). Consequently, any causal attribution to OS-specific disturbance is extremely difficult. Idiosyncratic responses to disturbance between species, scales, and methodologies highlight the need for monitoring at multiple spatial extents and with consistent protocols whose assumptions and limitations are well understood. To evaluate a more comprehensive suite of species, especially among the smaller mammals, additional monitoring protocols may need to be considered. A larger, integrated experimental design across multiple research monitoring partners would be advantageous.

Contaminants. Contaminant research in the OSR can be broken down into three main components: (1) deposition of contaminants; (2) uptake by wildlife; and (3) effects of tissue burdens on species. While many studies quantify atmospheric deposition using biological organisms as indicators (Arciszewski et al., 2021; Horb et al., 2021), a few also investigate the biological or ecological responses to those depositions. This latter effort largely lies within the terrestrial effects monitoring literature, as well as being a notable focus of ICBM programs in the OSR (Beausoleil et al., 2021).

Plants, soils, and wildlife represent the three ecological endpoints of contaminant deposition, and they are monitored within the OSR largely via two projects: (1) the Forest Health Monitoring Program, implemented by the Wood Buffalo Environmental Association (WBEA), and (2) wildlife toxicology monitoring, implemented by Environment and Climate Change Canada (ECCC). Local community collaborations and Traditional Knowledge drive a large portion of the faunal species selection for the latter. While some monitoring has been opportunistic, to a certain extent, as with ICBM of harvested wildlife (Thomas et al., 2021), other monitoring has been initiated in response to specific concerns from traditional land users, such as on unintended impacts of rodenticides (Thomas et al., 2017a). Perceived changes in sentinel or keystone species as early indicators have also triggered monitoring for health hazards to the larger ecological system (Beausoleil et al., 2021; Cruz-Martinez & Smits, 2013).

While uncertainty remains around the pathways that move contaminants into and through the terrestrial biological system in the OSR, some basic vectors are well understood. In very general terms, contaminants transported in the air are deposited on the landscape, either (1) onto bare or snow-covered ground, where they may infiltrate soils and be absorbed by plant roots; (2) into surface water, either via direct deposition or via snowmelt, where they may be detected within aquatic organisms (Arciszewski et al., 2021); or (3) directly onto plants and animals, where they may be absorbed into tissue. The bioaccumulation or simple trophic movement of contaminants through the food chain is also a well-known phenomenon. Although this review does not address aquatic biology directly (covered in Arciszewski et al., 2021), aquatic toxicology issues are relevant to terrestrial organisms that feed on aquatic organisms and may therefore bioaccumulate contaminants in this way (Wallace et al., 2020).

Organisms within the OSR are being exposed to a variety of contaminants—some petrogenic in nature and some pyrogenic, some naturally occurring, and some anthropogenic (Figure 2). Despite the challenge of complex environments, several studies have directly observed the accumulation of petrogenic or other anthropogenic contaminants in plant and animal tissues and linked these accumulations to proximity to OS operations. This has been observed for a variety of chemical constituents in plants (e. g., C. Boutin & Carpenter, 2017; Laxton et al., 2010; Proemse et al., 2016), for polycyclic aromatic hydrocarbons (PACs) in tree swallow (*Tachycineta bicolor*) nestlings (Cruz-

Martinez et al., 2015; Fernie, Marteinson, Chen, et al., 2018; Fernie et al., 2019), and for mercury in colonial waterbird eggs (Dolgova et al., 2018; Hebert, 2019; Hebert et al., 2011, 2013). Similar patterns in larger mammals have been observed (e.g., Lundin et al., 2015) but less frequently. Temporal alignment of contaminant accumulations with extreme weather events such as heavy precipitation and flooding has been observed in colonial waterbird eggs (Hebert, 2019), potentially reflecting a bioaccumulation via aquatic food sources when river sediment is mobilized, and with precipitation and temperature patterns for tree swallow nestlings (Fernie et al., 2019; Godwin et al., 2019). Projected future expansion of OS developments, combined with projected increases in extreme weather events under climate change, may increase contaminant loads.

Chemical changes to soils from contaminants and resulting effects on plant health and communities are the focus of the Forest Health Monitoring Program—a decade-long integrated monitoring effort that simultaneously measures atmospheric deposition and terrestrial effects (soils and vegetation) at acid-sensitive jack pine (*Pinus banksiana*) sites through OSR (C. J. Davidson, Foster, et al., 2020; Foster et al., 2019). Founded on concerns of soil acidification in forest stands, the scope of this monitoring has expanded to include a range of depositional stressors and ecological responses. To date, there is little evidence of acidification of soils or associated effects on understory plant communities in jack pine stands (MacKenzie & Dietrich, 2020; Watmough et al., 2019) and no adverse forest health responses due to acidifying deposition, potentially a result of coincidental and neutralizing base cation deposition. However, data suggest that changes in understory species productivity and communities are occurring, likely driven by fertilization from nitrogen and sulfur deposition (Bartels et al., 2019; C. J. Davidson, Foster, et al., 2020; Watmough et al., 2019).

Contaminants: gaps and opportunities. Multiple gaps and opportunities were identified during this review. Among the gaps was inconsistency of linking observed tissue or body contaminant accumulations in monitored fauna. Changes in functional or health responses of organisms, while observed under certain environmental conditions, are inconsistent and seldom directly linked to chemical stressors (see the review by Wallace et al., 2020). Additionally, despite evidence of exposures, very few effects on populations or the health of organisms such as mammals have been confirmed (Appendix S2). A recent exception to this was an observed change in baculum bone strength in PAC-exposed otters within the OSR, suggesting a change in organism condition with increased PAC burdens (Thomas et al., 2021). However, evidence of reproductive declines in otters was lacking and spatial relationships with OS operations were unclear. Similarly, a large body of contaminant-related literature has been produced for tree swallow nestlings (Appendix S2), and while contaminant burdens in tissues and corresponding functional changes (e.g., thyroid function) have

been observed, how these factors may manifest in survival and reproduction responses are not obvious. Evidence suggests that health responses depend not only on tissue burdens but also on a variety of other environmental variables, making effects measurable only in years of extreme weather when cold and/or wet conditions prevail (Fernie, Marteinson, Soos, et al., 2018; Godwin et al., 2019).

Many studies rely on spatial gradients or site orientations to attribute cause. Experimental designs that use spatial proximity with OS operations as a causal proxy, as is the case in the aforementioned otter and tree-swallow monitoring, may be limited in their ability to pinpoint sources of petrogenic PACs and other contaminants. Naturally exposed bituminous geology is common in the area around OS development, and patterns of atmospheric deposition of contaminants may not be as straightforward as assumed in many monitoring designs (Horb et al., 2021). Additionally, large mammals such as wolf, caribou, and moose (*Alces alces*) have large home ranges, making source apportionment conclusions difficult to draw. Direct tissue sampling of smaller mammals may be better suited to clarify these patterns, as smaller home ranges can more appropriately pinpoint exposure. Even for stationary organisms such as plants, the underlying spatial structure of environmental covariates can introduce confounding patterns in results. For example, jack pine growth rates in response to nitrogen and sulfur deposition appear to be correlated with proximity to OS operations as point sources but may equally or more likely be driven by existing patterns of forest stand ages or natural gradients of growing conditions, which favor sites closer to the Athabasca River, where OS operations are also concentrated (Bartels et al., 2019; C. J. Davidson, Foster, et al., 2020). Increased integration of wildlife toxicology research with larger aerial contaminant and deposition monitoring programs would be advantageous, as would leveraging geospatial data sets that catalog development over time or real-time industrial activity.

Despite these challenges, there may be times when the strategy of ascribing anthropogenic source apportionment in terrestrial receptors based on spatial proximity to development can provide some level of inference. However, this would be limited to when sources and pathways are well understood and when the spatial arrangement of sites is relevant in the context of known and confirmed stressor or deposition patterns around industrial activity (Horb et al., 2021). However, for focused monitoring efforts intended to investigate cause where knowledge—particularly of pathways—is limited, carefully designed studies with experimental controls should be preferred (to the extent possible in a natural environment). To support these efforts, scientists also require reliable and timely data on the location and activity levels of different industrial facilities or even different areas within individual facilities, such as OS surface mines (e.g., Landis et al., 2019). For example, in studies that measure local air contaminants directly, exposure and uptake may not correlate linearly with geographic proximity to

OS facilities or lease centroids but rather may be linked to proximity to active mining locations, amount of road traffic, etc. (e.g., Fernie, Marteinson, Chen, et al., 2018).

ICBM programs represent ongoing local-scale contaminant monitoring opportunities, with Indigenous hunters and trappers in the OSR providing samples of semi-aquatic mammals for toxicological analysis for mammal health monitoring (e.g., Thomas et al., 2021) and ongoing methodological developments in mammal toxicology (Eccles, Littlewood, et al., 2019; Eccles et al., 2020). Monitoring plant contaminants, specifically the deposition of contaminants onto food, medicinal, and culturally important plants, is also conducted within ICBM programs and there is extensive Traditional Knowledge on the topic, covered in the ICBM review in this special series (Beausoleil et al., 2021). Plant contaminant knowledge is less extensive within the Western science peer-reviewed literature, and Indigenous communities have assisted in identifying priority focal species or groups. Logistical sampling limitations, such as the inability to access remote regions or the efficiency of using roads and trails for site access (Kolowski & Forrester, 2017; Sólymos et al., 2020), can also spatially bias monitoring data. Integration of ICBM programs and collaboration between Western scientists and holders of local and Indigenous Knowledge represents an opportunity to address this limitation (Beausoleil et al., 2021), as is demonstrated by recent ICBM collaborations with local hunters and trappers (e.g., Thomas et al., 2021).

Established thresholds for evaluating toxicological endpoints, such as tissue burdens, are neither widely available nor widely used in the OS literature. The near complete absence of well-established thresholds or limits-of-change for contaminant burdens in terrestrial organisms, other than those based on bioaccumulation in aquatic prey (Canadian Council of Ministers of the Environment [CCME], 1999), may hinder adaptive monitoring programs that rely on specific triggers to guide monitoring effort (Lindenmayer & Likens, 2009) and encourage the development and/or application of inconsistent criteria, potentially limiting the straightforward consolidation of conclusions, further stalling the development of robust and rigorous integrated monitoring programs (Arciszewski et al., 2021, 2022).

Infrastructure. Physical infrastructure related to industrial development in the OSR, such as worker camps and large facilities, received limited attention in the reviewed literature relative to both landscape disturbance and contaminants. This may be a result of a lack of specific data for these features, as they are often grouped in with other anthropogenic features in the oft-used human footprint index. The notable exception to this is above-ground pipelines (35–50 cm diameter pipes mounted on support racks within a cleared right-of-way), noise from industrial facilities, and aquatic tailings ponds in the context of whooping crane stopovers. Light pollution and its potential effects on wildlife received no attention in the published literature from the OSR in the last decade.

Noise from industrial operations and facilities has been studied and was not found to influence occupancy or detection of three different owl species (Shonfield & Bayne, 2017b) or the abundance, movement, or body mass of mice and voles (Shonfield & Bayne, 2019). However, some pre-2009 studies on songbirds in the boreal forest documented declines in species abundance as a result of industrial noise exposure (see the review by Venier et al., 2014).

Stopover location monitoring within the OSR for the endangered whooping crane (*Grus americana*) is undertaken by the Canadian Wildlife Service. The whooping crane migration corridor passes through the OSR on the way to or from northern breeding grounds in the Wood Buffalo National Park and overwintering areas in the southern United States. Stopover patterns in the OSR are important as the selection of landing sites by birds on industrial water features such as tailings ponds, while low risk as direct mortality events (Pearse et al., 2018), has the potential to expose birds to OS-related contaminants. While publications specific to whooping crane in the OSR are limited, there is extensive reporting on range-wide migration patterns (e.g., Pearse et al., 2019).

Some limited research indicates that above-ground pipes do not restrict the movement of deer and wolves due to the animals' willingness to cross underneath pipes, even when clearance is very low (Dunne & Quinn, 2009). For larger ungulates such as moose and caribou, however, they can represent a movement barrier, though moose are largely unimpeded when pipes have high clearances underneath (>140 cm) or where equipped with purpose-built crossing structures (Dunne & Quinn, 2009). Models based on remote camera data suggest that caribou remain impeded even where above-ground pipe crossing structures exist—caribou movement patterns change and home range sizes decrease nonlinearly as landscapes contain more infrastructure and become less permeable (Muhly et al., 2015). Although studies did not investigate the effects of altered movement or range sizes on species survival or reproduction, given the ubiquity of above-ground pipes due to in situ developments and the likelihood that they will increase in density and coverage in the future, they should be considered an important stressor of in situ development, particularly for larger mammals such as moose and caribou. Careful management of construction standards (e.g., including areas of higher clearance and crossing structures) can mitigate these responses for some species. For caribou, potential nonlinear relationships suggest that even small increases in habitat permeability may result in facilitated movement and increased home range sizes (Muhly et al., 2015), though the demographic implications of these benefits are not clear.

Climate change. Global climate change has well-established causal links to anthropogenic greenhouse gas production in general, and carbon-intensive industries in particular, including OS production (Environment and Climate Change Canada, 2018; Horb et al., 2021). However, while there are some limited examples of climate

change-related investigations from the last decade specific to the OSR (e.g., Campos-Ruiz et al., 2018), none consider change in the context of OS industrial activity or cumulative effects. For the most part, climate change is considered in the context of larger habitat change studies, such as changes in mammal distributions (Barber et al., 2018; Dawe et al., 2014; Dawe & Boutin, 2016; Fisher et al., 2020) and boreal bird communities (Cadieux et al., 2020). In contrast to climate change as a pressure, studies also linked microtopographic simplification and altered soil water depth from landscape disturbance pressures to greenhouse gas emissions via methane and carbon release (Lovitt et al., 2018; Strack et al., 2018), presenting an important opportunity for cross-theme integration with atmospheric emissions monitoring.

Further opportunities for leveraging long-term observations to inform environmental change in response to climate change exist via ICBM programs or collaborations between Indigenous Knowledge holders and Western scientists. Local community histories and Indigenous Knowledge often include long periods of record of local environmental conditions, such as water levels and floods or phenology and distribution of culturally important plants (Beausoleil et al., 2021).

Novel geospatial methods and newly available remotely sensed data sets represent an emerging opportunity—both within and beyond climate change applications—to investigate long-temporal-scale landscape changes. In one such example, researchers used Google Earth Engine and the historical archive of Landsat satellite imagery to develop time-series data of wetland inundation in the Peace-Athabasca Delta, linking hydrologic alteration to a corresponding decrease in the abundance of muskrat—a semi-aquatic rodent that relies on ephemeral water bodies as habitat (Ward & Gorelick, 2018).

Issues of scale

Ecological systems operate on a continuum of spatial and temporal scales (Wiens, 1989), and thus scales of measurement and analysis are influential methodological variables in monitoring. Small-scale processes may or may not translate into large-scale patterns and vice versa (Allen & Holling, 2002; Fisher et al., 2011; Levin, 1992; O'Neill et al., 1996), necessitating the monitoring of indicators at multiple spatial scales. This is recognized, for example, in measured changes in populations, where effects may appear magnified or minimized as the spatial scale of monitoring or analysis is decreased or increased, respectively. For this reason, we must exercise caution when generalizing to larger or smaller time and space scales from smaller- or larger-scale monitoring.

Space. Terrestrial biological stressors and responses in the OSR manifest at nearly every spatial scale, from the local (e.g., anticoagulant rodenticides around facilities; Thomas et al., 2017b), to regional (e.g., mammal responses to seismic line density; Tigner et al., 2015), to global (e.g., boreal bird responses to climate change; Stralberg et al., 2015). A basic ecological premise is that the extent to which disturbance affects taxa or alters communities is dependent on the spatial and temporal scales of measurement as well as the spatial and temporal scales (and duration and/or intensity) of the disturbance.

There are examples of the same stressor producing different terrestrial biological responses when considered at different spatial and/or temporal scales. For example, the magnitude and direction of large mammal abundance response to human landscape disturbance vary both by species and by scale (Toews et al., 2018). Conversely, similar terrestrial biological responses may result from different stressors operating simultaneously at different spatial and temporal scales. For example, species occupancy may change simultaneously at the local scale due to edge effects from disturbances, at the landscape scale by overall density of disturbances, and at the global scale due to climate change. Unravelling these patterns represents a key challenge within terrestrial monitoring.

Increasingly vexing for terrestrial biological researchers, the spatial grain or extent of field measurement or data analysis of stressors and responses can influence conclusions. For example, for bird abundance responses to landscape disturbance, both the magnitude and the associated uncertainty of measured responses tend to decrease with larger sampling areas (Bayne et al., 2016). Similarly, the importance of predictors in bird habitat models also varies with the spatial grain of data layers (J. Zhang et al., 2013). When modeling large mammal abundance, Toews et al. (2018) found variations in model selection and support across different spatial grains for different species but consistency among the relative magnitude and direction of responses. Likewise, Fisher and Burton (2018) observed that the spatial scale at which OS features best explained mammal distribution changed among species. Spatial scale is thus a key part of understanding OS impacts and should continue to be a focus.

Another consideration for landscape- and regional-scale analyses is the size of the OSR itself, nearly 500 km latitudinally, and therefore containing many ecologically relevant spatial environmental gradients. While these include some commonly considered gradients, such as climate, photoperiod, and geology, other gradients may be more clandestinely important to distributions of terrestrial biota, and thus potentially mischaracterized in explanatory models or other analyses. For example, the distance to agricultural development (in the south), where species abundances are markedly different, may yield different community compositions concordantly across latitude. Also potentially confounded by other north–south gradients are the impacts of the OS surface mines, which are concentrated in the northern latitudes of the OSR.

Such spatial complexities have implications not just for scientific inference or even management recommendations but also for the usefulness of monitoring data and knowledge to people in local communities. Indigenous

communities in the OSR may utilize resources in areas much smaller (e.g., a single berry patch) than what Western science might consider a local monitoring program, consequently limiting the utility of monitoring knowledge for local communities practicing traditional lifestyles. Such "super-local" monitoring may occur through ICBM or other Indigenous-led programs and may be reported in ICBM reports or gray literature (Beausoleil et al., 2021; Fisher et al., 2021). In this respect, this may represent a gap in the Western science literature more so than a gap in the monitoring knowledge itself. Though opportunities for integrated analysis or integrated interpretation of monitoring data may be currently limited, improvements in data cataloguing and publicly accessible data systems could provide additional analytical opportunities.

Spatial structure within the environment. Environmental data of all kinds are typically fraught with underlying spatial autocorrelation (Legendre, 1993) and monitoring data from the OSR are no exception, as this is a landscape where both natural and anthropogenic stressors are structured in space (Figures 1 and 3). For example, along the south-to-north gradient of the Athabasca River, environmental covariates such as natural geology can affect water chemistry, elevation can affect climate and thus community composition, and even latitude itself can affect day length and thus productivity (Rose & Lyon, 2013). This is exemplified in jack pine growth in the OSR, where differences in growth are correlated with proximity to OS operations but are also likely due to environmental site differences—also structured in space but unrelated to industrial development and associated deposition patterns from OS facilities (Bartels et al., 2019; C. J. Davidson, Foster, et al., 2020).

Nonindependent data collection—for example, collection of multiple samples from the same site, same colony, or even simply too close together in a structured landscape—results in statistical pseudoreplication when samples are treated as independent observations, increasing the potential for Type 1 errors (false positives). Thoughtful analytical approaches and careful statistical analysis can address such sampling issues, even while simultaneously integrating data sets, via range standardization, spatial averaging, and aggregation of observations (Eccles, Pauli, et al., 2019). Logistic and economic challenges of fieldwork in the OSR notwithstanding, comprehensive monitoring along known gradients (stressors and otherwise) is critical if strong causal inferences are to be made.

Time. Spatial topics were more prevalent in the peer-reviewed publications than temporal topics, despite both being necessary to guide sampling and monitoring methodologies and to inform our understanding of ecological processes. Terrestrial biological monitoring has unique temporal considerations such as multiyear population cycles (O'Donoghue et al., 1997) that must be considered when investigating change or trends over longer periods if reliable inferences are to be made (Barraquand et al., 2017).

However, temporal-scale issues have received less direct attention in the OS terrestrial literature, with very few papers directly addressing the influence of temporal sampling variability or breadth, such as considerations of site revisit frequency or analytical period of record (but see Fisher et al., 2020; J. Zhang et al., 2014). Temporal considerations and periods of record represent an opportunity to integrate Traditional Knowledge from local Indigenous communities, as many have extended time scales of environmental observations. For example, populations of bison in the Wood Buffalo region have long been monitored by local communities in the region (Beausoleil et al., 2021).

With a number of long-term and consistent-protocol terrestrial biological sampling projects currently operating in the OSR, the data resources to perform such investigations exist but thus far remain underutilized for this task. This could reflect simply the extended period required for long-term data to identify meaningful change in the context of high degrees of natural variation, or could reflect something academically more (but environmentally less) problematic, such as a publication bias against negative results (i.e., most monitored changes are non-significant). Ergo, such investigations may more often appear in the gray literature (e.g., ABMI, 2018; Bayne et al., 2017) and so would fall beyond the scope of this review.

Geospatial methods

Geospatial methods—encapsulating geographic information systems (GIS) and remote sensing—are quickly emerging as important methodological tools to assess stressors and associated ecological responses in the OSR. In the past decade, a variety of monitoring and analytical opportunities have been identified and applied in the OSR, largely either for data generation (i.e., production of geospatial data, such as complete coverages of stressor surfaces, potentially for use as covariates in empirical models) or analysis and modeling (e.g., response modeling to geospatial surfaces such as human footprint). See Appendix S2 for a more comprehensive coverage of the recent geospatial literature.

Increases in the past decade in computing power, open-source GIS, image processing, and statistics software, and availability of remotely sensed data have dramatically increased the quantity and utility of geospatial data products. Many of these products have been used to inform environmental monitoring in the OS, including large-scale landcover data (e.g., Castilla et al., 2014; Latifovic & Pouliot, 2014; Pouliot & Latifovic, 2016) and disturbance mapping and the development of human footprint inventories (ABMI, 2017). While these data layers are becoming essential environmental science tools, they can be expensive and labor-intensive to create and may lack required feature resolution for many analyses. They also require comprehensive validation and ground truthing if they are to be trustworthy reporters on landscape condition.

Human footprint and other landcover data, including habitat classifications, are used extensively to support the development of species models for the OSR. Nearly every

wildlife modeling study within the OSR, including spatially explicit analyses of field-collected data, relies on geospatial data sets, geospatial analytical tools, or both. Typically, geospatial data are incorporated into empirical or statistical models as habitat or resource selection predictor variables, with a GIS often used to determine landcover or human footprint classes (i.e., anthropogenic landscape disturbance) at or around species observation locations or monitoring sites. Such studies use models to explain species occurrence (e.g., Fisher & Burton, 2018; Latham, Latham, Boyce, 2011; Shonfield & Bayne, 2017b), abundance (e.g., Ball et al., 2016; Mahon et al., 2016; Toews et al., 2018), movement (e.g., Latham, Latham, Latham, Boyce, & Boutin, 2011; Whitman et al., 2017), predation (e.g., Neilson & Boutin, 2017), reproduction (e.g., Fisher & Burton, 2021), or contaminant burdens (e.g., Thomas et al., 2017b).

There has been substantial progress on landscape disturbance mapping and the development of inventories of human footprint, including several wall-to-wall (i.e., gapless spatial coverages) human footprint inventories created by the ABMI (Figure 3) for the entire province of Alberta at regular time intervals since 2010 (ABMI, 2017). These data have high accuracy and have been created for multiple years, allowing for critical temporal matching of environmental monitoring and anthropogenic landscape features. However, these data are assembled in a cumulative-only framework and, as such, do not track regeneration or recovery of human footprint features postdisturbance (i.e., features are constantly added but never removed). While some features may be considered permanent vegetation alteration (e.g., roads, agriculture), many others are likely to regenerate, at least partially, after the initial disturbance has ceased (e.g., forestry cut blocks, some seismic lines). The current cumulative footprint inventory approach may result in an overestimation of landscape disturbance (failing to account for regeneration and succession), potentially biasing model conclusions. There exist geospatial tools capable of assessing vegetation regeneration and recovery on some disturbance features (e.g., Abib et al., 2019; Chasmer et al., 2018; Van Rensen et al., 2015), and widening the application of these techniques to assess regeneration and recovery on all human footprint would help address this shortcoming. This, in combination with increased attribute resolution of human footprint layers (e.g., specific industry attribution of features), could permit more confident causal attribution within the OSR.

In addition to mapping and monitoring human footprint development, geospatial science can assess vegetation disturbance more broadly through the development of disturbance indices, which are sensitive to vegetation disturbance due to fire, insect infestation, and changes in moisture conditions (Coops et al., 2009). Such approaches typically assess regional-scale changes using coarse resolution satellite imagery, and as such are unable to resolve fine-scale human footprint features (Coops et al., 2009). However, regional-scale vegetation disturbance monitoring (e.g., Guo et al., 2017) could complement smaller-scale

human footprint and land use change monitoring and provide regional context and information on natural variability and regional-scale stressors.

Some limitations of geospatial approaches for wildlife data analysis and modeling are similar to other environmental monitoring challenges. Geospatial data are not immune to spatial biases, including inconsistencies in effects across scales of measurement, so spatial and temporal resolutions and breadths must be carefully considered. Direct comparison between model outputs is also difficult, as the source of geospatial data used to create the same predictor variables is inconsistent between studies and the quality of input data is rarely assessed. More problematic for ecological understanding, the choice of geospatial data used to parameterize models may affect subsequent interpretations of species' habitat characterizations when landcover classifications differ systematically between layers. For example, Hedley et al. (2020) compared habitat predictions for yellow rail (*Coturnicops noveboracensis*) based on four different geospatial landcover layers, finding that the characterization of preferred habitat varied between several different wetland classes and wet coniferous forest.

Further, limited availability of landcover or other geospatial data within the OSR can result in temporal differences between the data used as predictor variables and the observed biological monitoring response data, undermining the recognition of causal linkages. To fill data gaps, there may be opportunities to work in collaboration with local Indigenous communities, who have a long history of monitoring local environmental conditions, including landcover and land change, especially vegetation change (Beausoleil et al., 2021).

CONCLUSIONS

We structured this review based on major anthropogenic terrestrial biological stressors in the OSR, but it is important to recognize that no stressor, natural or anthropogenic, acts in isolation. The OSR is a multistressor landscape, with terrestrial biota simultaneously subject to habitat alteration, human activity and infrastructure, chemical contaminants from both natural and anthropogenic sources, natural disturbance regimes, and climate change. The interconnectedness of model components, specifically the convergence of multiple pathways into single responses, within the terrestrial conceptual model (Figure 2) exemplifies this challenge and helps visualize the accumulated environmental state as it is captured in the peer-reviewed literature.

Despite widespread recognition of this complexity, very few research papers from the past decade have incorporated multiple stressors (multivariate modeling papers being the notable exception) and even fewer directly addressed cumulative effects (excluding analyses of human footprint impacts across sectors). The pathway—or mechanistic processes—through which species respond to many stressors, especially landscape disturbance, remain largely unaddressed. The exception to this is the pathway of contaminant loading of wildlife tissue, where many transport

and uptake vectors are known and the general process of trophic bioaccumulation is understood. With respect to cumulative effects, knowledge is limited and it has been suggested that species-level data are largely insufficient to attempt cumulative effects assessments in the boreal forest in general (Venier et al., 2014). The situation may not be quite so bleak if innovative approaches are implemented that (1) integrate multiple data and knowledge sources and (2) address cumulative effects questions with geospatial or other computational/statistical tools that make the most of limited or disparate data.

The complexity of the ecological system, and correlations of the multiple natural and anthropogenic stressors in the OSR also make direct linking of terrestrial biological responses to specific OS operations extremely difficult. For stressors such as contaminant exposure or tissue toxicology, a key challenge lies in differentiating responses to natural versus anthropogenic exposures as well as between OS-related and other anthropogenic sources (e.g., nearby upstream urban development, background global industrialization). For stressors such as habitat alteration and landscape disturbance, the challenge is not in quantifying the impact or source attribution of development, which is more straightforward, but rather in building cohesive conceptual understanding from a complicated mix of interacting species and stressors.

Simple data limitations, such as the lack of attribution of landscape disturbances to specific industries, also hinder causal investigation. Geospatial approaches are powerful tools that can address these and other analytical or data shortcomings, but they are not a magic solution for every monitoring or knowledge gap. Truly integrated monitoring involves temporally concurrent and spatially coincidental monitoring of multiple indicators (stressors and responses), preferably at multiple spatial scales. An integrated monitoring program must be more than integrated interpretation of results from disparate and independently designed projects. The Forest Health Monitoring Program for jack pine acidification is a good example of integrated monitoring across theme areas, as it measures contaminant deposition coincidentally with biotic responses in an ecologically sensitive indicator. Similarly, the tree swallow contaminant work sought to connect deposition and contaminant burdens with population effects. Monitoring on multiple scales (e.g., measuring local reproductive effects in combination with regional population effects) would also facilitate stronger causal inferences for larger-scale indicator metrics such as populations.

Although geospatial science has been widely used as a tool for terrestrial monitoring within the OSR, both opportunities and challenges remain. Critically, geospatial science can produce several of the foundational data sets that are required for subsequent analyses including the development of statistical models and quantifying stressor–response relationships (e.g., Ball et al., 2016; Fisher & Burton, 2018; Latham, Latham, Boyce, & Boutin, 2011). Several studies have demonstrated the applicability of remote sensing to map and monitor land cover, land use, and vegetation health over regional scales (e.g., Castilla et al., 2014; Guo et al., 2017; Pouliot & Latifovic, 2016), and the development of annual, consistent, wall-to-wall (i.e., complete spatial coverage) data products would allow for change detection monitoring and serve as foundational data in species response models. Producing such foundational data would allow for species response models to be constructed at appropriate spatial extents (Toews et al., 2017), allow for the temporal alignment of predictor and response variables, and facilitate comparison between model outputs.

Over the past decade, the scientific community has generated a great deal of knowledge about the responses of terrestrial biota to various stressors in the OSR. While there remain critical knowledge gaps, terrestrial ecologists and monitoring professionals have a heavy toolbox, and continued development of both field and desktop methodologies will present numerous opportunities going forward. A key lesson from well-understood terrestrial biological responses, encapsulated by the complicated caribou story, is that the development of knowledge within complex ecological systems takes not only time and resources but also productive collaboration among scientists and other knowledge holders, local communities, industry, and regulators. Integration between monitoring theme areas (e.g., air, water, land, and biodiversity) is challenging but essential for comprehensive reporting on the state of the environment in the Alberta OS.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

AUTHOR CONTRIBUTION

Monique G. Dubé conceived the work. David R. Roberts, Danielle Beausoleil, Roderick O. Hazewinkel, Diogo Sayanda, and Faye Wyatt developed the methods and assisted with the review. David R. Roberts performed the main review and led manuscript writing, with Erin M. Bayne, Jacqueline Dennett, and Jason T. Fisher contributing content according to their subject matter expertise. All authors reviewed the final manuscript.

DATA AVAILABILITY STATEMENT

No new data were generated by this literature review.

SUPPORTING INFORMATION

Appendix 1: Compiled tables of all reviewed literature.
Appendix 2: Extended results and discussion.

Appendix 3: Numbered bibliography of reviewed literature, sorted by conceptual model column and box.

Appendix 4: Summary table of mammal responses to landscape disturbance in the OSR.

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