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

Appendix 2 – Extended results and discussion

This appendix contains information on peer-reviewed results that were not included in the main manuscript due to space constraints.

Landscape disturbance

Mammals

Even within the same taxonomic family, responses can be highly species-specific. For example, various *canid* species respond fundamentally differently to disturbance within the OSR, with wolf (*Canis lupus*) seasonally selecting for linear and polygonal features, coyote (*Canis latrans*) generally favouring all types of disturbance, and red fox (*Vulpes vulpes*) generally selecting against linear features (Dickie, Serrouya, McNay, et al. 2017; Toews et al. 2017; Fisher and Burton 2018; Toews et al. 2018).

In *very* general terms, linear disturbances may favour wolf, coyote, deer (*Odocoileus virginianus*), snowshoe hare (*Lepus americanus*), and red squirrel (*Sciurus vulgaris*), at the expense of caribou (*Rangifer tarandus*), moose (*Alces alces*), marten (*Martes americana*), and potentially lynx (*Lynx canadensis*), while polygonal disturbances may favour coyote, deer, and moose, at the expense of wolf, snowshoe hare, red squirrel, and potentially lynx. We found no publications from the OSR in the last decade addressing landscape disturbance effects on mink (*Neovision vision*), otter (*Lontra canadensis*), ermine (*Mustela erminea*) or wolverine (*Gulo gulo*) and several species including fisher (*Pekania pennanti*), marten, red squirrel, and snowshoe received limited consideration (Tigner et al. 2015; but see Fisher and Burton 2018). In some cases, reporting on these species is available from the northern boreal forest outside the OSR (e.g. Scrafford et al. 2017), and the generalisability of wider results to the OSR likely varies between taxa.

Comprehensive reviews of terrestrial biological responses to landscape disturbance, in general, in the larger Alberta boreal region are provided by Toews et al. (2017) for select mammals and

Venier et al. (2014) for all taxa. Mammal responses to various stressors in the OSR have also been summarised in **Appendix 4**Error! Reference source not found..

Local scale

Most Indigenous community-based monitoring (ICBM) programs within the OSR are specifically designed at the local scale as they often address valued components of concern to local communities, but these monitoring programs are seldom reported in peer-reviewed papers (Beausoleil et al. 2021). Local scale monitoring performed by Western Scientists and reported in the literature is typically limited in breadth to very few or a single species and largely confined to larger bodied species such as ungulates, wolf, coyote, lynx, and black bear (*Ursus americanus*).

Wolf is the mostly frequently monitored species at the local scale, largely in the context of caribou predation. Briefly, in local-scale telemetry and snow track studies, this largest canid generally selects for linear disturbance and against polygonal disturbance (e.g. Latham, M. Cecilia Latham, Boyce, et al. 2011; Dickie, Serrouya, McNay, et al. 2017; Dickie et al. 2020), findings consistent with a larger literature review by Toews et al. (2017). Limited literature suggests that coyote responds similarly positively at the local scale to most linear disturbances and human settlements (Latham, M. Cecilia Latham, Boyce, et al. 2011; Toews et al. 2017), with the possible exception of agriculture and younger cutblocks, where snow cover and human activity may favour avoidance of these areas (Toews et al. 2017). Coincidental coyote habitat selection with deer, moose, and hare suggest a strong prey incentive at the local scale (Latham, M. Cecilia Latham, Boyce, et al. 2011; Toews et al. 2017), though these patterns may vary seasonally.

When species respond similarly positively to disturbance for habitat selection, patterns of co-occurrence are also likely to change (e.g. the funnelling of multiple species into desirable features such as linear disturbance will likely increase species co-occurrence) (Tattersall et al. 2020a).

Marten show decreased use of nearly all seismic line disturbances, with the exception of very narrow lines (< 2 m) or wider lines (> 6 m) with partial or full vegetation recovery (Tigner et al. 2015). Conversely, black bear exhibit opposite response patterns in both remote camera and telemetry studies, with bears favouring nearly all linear and (to a lesser extent) polygonal disturbances, with the potential exception of narrow (< 2 m) lines, consistent with those used in *in situ* OS operations (Latham, M. C. Latham, et al. 2011; Tigner et al. 2014; Dickie et al. 2020). Limited local-scale data on lynx show generally neutral or weak negative responses to all human footprint (Toews et al. 2017). Small mammals such as voles and deer mice show altered use and edge effects along pipeline disturbances outside the OSR (Darling et al. 2019). However, there is no evidence for small mammal responses to distance-to-edge of polygonal disturbances (e.g. well pads, compressor stations) with different levels of human activity (Shonfield and Bayne 2019). A single telemetry study from the Alberta boreal forest outside the OSR suggest that wolverine behavioural responses to human footprint, including roads, seismic lines, and active well sites, is variable across seasons and sex, and may change with rates of vegetation regeneration, suggesting a balancing of predation avoidance and foraging opportunities (Scrafford et al. 2017).

Knowledge of caribou behavioural responses to landscape disturbance were established in the literature well prior to the 10-year publication window of our review (e.g. Dyer et al. 2001; Dyer et al. 2002) and papers within our review largely supported and refined this body of knowledge. Caribou generally show reduced use of habitats in proximity to disturbance features, especially roads and industrial facilities (Wasser et al. 2011; Latham et al. 2013; Toews et al. 2017). Caribou avoidance of these features extends beyond the disturbance itself (Dyer et al. 2001), creating a buffering effect that decreases caribou habitat use by more than the disturbance footprints themselves.

Some evidence suggests that deer are more likely to select for most linear and polygonal disturbances, particularly where early seral vegetation may provide forage opportunities (Toews et al. 2017; Fisher et al. 2020), while moose may select for polygonal disturbances and against linear disturbances (Toews et al. 2017). There is less consensus on deer and moose selection for or against landscape disturbance, and patterns may depend on the specific character of the disturbance such as regeneration, snow cover, and surrounding habitat (Dickie et al. 2020; Tattersall et al. 2020b; Tattersall et al. 2020a).

Health responses to landscape disturbance have been investigated for caribou and moose only, reflecting a gap in monitoring of health effects from stressors other than contaminants. A single study inferred physiological stress in both species via scat chemistry, finding stress and nutrition hormone levels in caribou to be negatively related to human activity specifically along roads, although without manifested health responses (Wasser et al. 2011).

In our literature search, we did not find any local-scale information from the OSR on red fox, snowshoe hare, red squirrel, ermine, fisher, mink, or river otter.

Landscape scale

When scaled up, local-scale mammal responses to disturbance remain consistent for most species, with a few notable exceptions. Species such as coyote and wolf, which locally select for linear disturbances, tend to increase in abundance or occupancy as linear disturbance density on the landscape increases (Toews et al. 2017; Fisher and Burton 2018; Toews et al. 2018). This consistency across scales is also present for species that tend to avoid linear disturbances, such as marten, whose probability of occurrence decreases accordingly in landscapes with higher linear disturbance density (Tigner et al. 2015). A converse example is black bear, which generally selects for linear disturbances at the local scale but, at landscape scales, responds either neutrally (Tigner et al. 2014) or negatively (Fisher and Burton 2018; Tattersall et al. 2020a) to disturbance feature density or proximity.

While such scaled-up inferences are useful, we must also consider them as potential artefacts of monitoring designs. For example, as scale increases, there also becomes a stronger correlation between line density and other disturbances. Ergo, in the black bear example, while it may appear that individuals avoid high linear feature densities, other disturbances (or other landscape stressors) that also begin to occur more frequently may actually drive observed changes in abundance.

Among ungulates, observed local and landscape responses are consistent in their inconsistency, with moose and deer distributions generally increasing on seismic lines, roads, cutblocks and other polygonal features except wellsites, and decreasing on cutlines, pipelines, and trails (Toews et al. 2017; Fisher and Burton 2018; Toews et al. 2018) (**Appendix 4**). Further clarity on the landscape-level pathways by which disturbance affects moose and deer could help reconcile these observed complexities. The ratios for mammal papers followed the general trend in terrestrial literature of focussing on stressors and responses more than pathways, with less than half of mammal-focused studies we considered directly considering pathways, and most of these focusing on predator-prey dynamics, largely between wolves and ungulates.

Equally inconsistent is lynx, with remote camera studies suggesting net increases in lynx with increased human footprint (Fisher and Burton 2018; Tattersall et al. 2020a) and snow tracking studies suggesting the opposite (Toews et al. 2017; Toews et al. 2018). This may be a case of seasonal changes in prey abundance if snowshoe hare (nearly exclusive lynx prey) habitat selection varies seasonally. Further, the decadal lynx-hare predator-prey cycle (O'Donoghue et al. 1997) may also influence detection rates of these species, but how this cycle changes spatially with habitat has not been investigated. Fisher and Burton (2018) utilised summer remote camera data from a 4-year period (2011–14), whereas Toews et al. (2017; 2018) utilised winter snow tracking data from a 12-year period (2001–13), but with few site revisits. It would be logical to expect tight habitat selection alignment between hare and lynx, as well as coyote to a certain extent. Although there is some evidence for this in the single study that considered both species (Fisher and Burton 2018), further consideration of natural predator-prey cycles on species density and habitat selection, as an important pathway, could help identify industry-related changes in the OSR that interrupt predator-prey relationships. Density patterns of red squirrel, another ubiquitous prey species in the OSR, which also favours linear features, are largely consistent with those of snowshoe hare, suggesting a pathway for occupancy and abundance related to predator avoidance.

We found no landscape-scale information on wolverine, mink, river otter, nor any rodents other than red squirrel, although these species are all currently of least conservation concern across their ranges (**Appendix 4**).

Caribou: a complex case study

Consistent with global population trends (Vors and Boyce 2009), caribou populations in Alberta have declined significantly in recent decades and indications for many populations are that this rate of decline is accelerating (Festa-Bianchet et al. 2011; Boutin et al. 2012; Hervieux et al. 2013). While changes in wildfire dynamics have been investigated as a driver of caribou decline (e.g. Stewart et al. 2020), most research indicates that the effect of changes in this natural disturbance regime is secondary to industrial footprint and related wolf predation (Whitman et al. 2017; Stewart et al. 2020). Similar responses are observed for wolf predation on moose, which also increases in both naturally and anthropogenically disturbed habitat (Neilson and Boutin 2017).

Wolf movements favour linear disturbances such as seismic lines (Latham, M. Cecilia Latham, McCutchen, et al. 2011; Mckenzie et al. 2012; Dickie, Serrouya, McNay, et al. 2017), which are ubiquitous throughout the region, particularly during the snow-free season when wolves are divided into more numerous and smaller packs and more often move into lowland caribou ranges (Latham, M. Cecilia Latham, Boyce, et al. 2011; Latham et al. 2013). Wolves move fastest on linear features with minimal vegetation and are more likely to select wider conventional seismic lines than narrower low-impact seismic lines associated with *in situ* OS developments (Dickie, Serrouya, McNay, et al. 2017; Dickie, Serrouya, Demars, et al. 2017). While caribou and other ungulates may avoid predators by avoiding conventional seismic lines and other linear disturbances, this behavioural change may also consequently limit habitat availability (Latham, M. Cecilia Latham, Boyce, et al. 2011; Wasser et al. 2011).

Facilitated movement along linear disturbances increases wolf travel speed and distance, and may consequently increase hunting efficiency via an increased encounter rates between wolves and their prey (Mckenzie et al. 2012; Kansas et al. 2015; Dickie, Serrouya, Demars, et al. 2017). Particularly in summer months, wolf use of linear features may draw them increasingly into caribou habitats, resulting in increased rates of predation (Latham, M. Cecilia Latham, Boyce, et al. 2011; Latham, M. Cecilia Latham, McCutchen, et al. 2011; Latham et al. 2013).

Increases in white-tailed deer populations in the OSR through the 1990s and 2000s also play a role in observed caribou demographic responses. Scat analyses has shown deer replacing moose as primary wolf prey through this period (Latham, M. Cecilia Latham, McCutchen, et al. 2011). The increase in northern white-tailed deer populations is thought to be driven in part decreasing winter severity in recent years, and by human land disturbances, which promote early seral stage communities (Dawe et al. 2014; Dawe and Boutin 2016; Fisher et al. 2020).

Monitoring methods

Mammal occupancy and abundance responses in the OSR have largely been inferred via two field monitoring methods—winter snow tracking and remote cameras—with the latter nearly completely replacing the former in recent years. While both methods have assumptions and biases requiring unique experimental design considerations (E. Bayne et al. 2005; Kolowski and Forrester 2017; Burgar et al. 2018), the logistic ease and much lower cost of remote cameras (to the chagrin of many winter-loving field biologists) has favoured remote cameras as the monitoring tool of choice (Burton et al. 2015). The peer-reviewed literature has not yet addressed problems associated with maintaining statistical consistency in long-term monitoring data when protocols change from snow tracking to remote cameras, although the grey literature may inform such methods. For example, there may be discrepancies between results based on camera and snow track data resulting from seasonal use differences in some species, as camera data are collected year-round, whereas snow tracking data are necessarily limited to winter months. Both remote cameras and snow track surveys measure abundance and occupancy at the landscape scale (e.g. Fisher and Burton 2018; Toews et al. 2018; Tattersall et al. 2020a) or at the local scale. GPS telemetry data, by which movement can be quantified relative to specific locations and disturbance features, is more commonly used in locale-scale response monitoring (e.g. Latham, M. Cecilia Latham, Boyce, et al. 2011; Dickie, Serrouya, McNay, et al. 2017; Scrafford et al. 2017). Small mammals may also be monitored via trapping (e.g. Darling et al. 2019).

Birds

Community-level responses

Alberta’s boreal forest contains a large and diverse community of landbirds, often necessitating multi-species, functional group, or guild approaches to environmental monitoring and assessment. While larger bodies of knowledge exist on a few select species such as Canada warbler (*Cardellina canadensis*), ovenbird (*Seiurus aurocapilla*), and yellow rail, for most landbird species within the OSR, environmental responses are considered within multi-species studies of larger scope (e.g. Bayne et al. 2016; Foster et al. 2017).

There are many ways to describe a bird community. Shifts in community metrics in the OSR have been observed with evidence for change in richness and composition (Mahon et al. 2019; Wilson and Bayne 2019; ABMI 2020). As with mammals, there are winners and losers in the bird community. Species richness measurements in areas surrounding existing OS developments are often higher, as species associated with human disturbance colonise these areas and forest specialist species, although reduced in abundance by the loss of local habitat, are still present in adjacent intact forest.

For example, species richness on well pads is typically quite low per unit area, dominated by species that select early seral habitat such as agricultural fields or forest harvest blocks (Wilson and Bayne 2019). However, when birds from the forest edge adjacent to a well pad are considered "present" at the site, richness in the well pad area can be higher than in the forest interior, as species that use the forest, forest edge, and early seral habitat can be found in the same local area (Bayne et al. 2016). Similarly, house sparrows (*Passer domesticus*) are commonly observed at OS facilities and camps but are virtually absent in the forest (Bayne, pers. obs.). Conversely, the threatened Canada warbler has never been reported to use energy sector footprints like well pads or pipelines (Wilson and Bayne 2019) but is able to use the forest immediately adjacent to energy sector disturbances and will defend territories across seismic lines. Thus, the scale of analysis has implications for the magnitude of reported change in bird communities.

Relatively few energy sector disturbances (i.e. well pads and wide pipelines) provide foraging or nesting habitat for species considered forest specialists, but bird species with a more generalized diet do use disturbances that have some vegetation regrowth (Carpenter 2020). Seismic lines are the most widespread OS-related landscape disturbance and many (but not all) species use seismic lines as territorial boundaries (i.e. the species do not include the line as part of their home range). Despite this, there is little evidence in the bird literature for an edge effect caused by seismic lines. Further, when narrower low-impact seismic exploration techniques are used or once lines regenerate with woody vegetation, there is strong evidence from the OSR and beyond that birds begin to include seismic lines in their home ranges (e.g. Lankau et al. 2013).

Species-level knowledge

Conversion of boreal forest or boreal parkland in the southern oil sands region, predominantly for agriculture, has predictably benefitted open habitat dwelling birds at the expense of those preferring intact forest cover. This trend is seen in both upland and wetland habitat specialists, although the preservation of wetlands within agricultural landscapes outside the OSR, even when trees are removed, tends to limit declines in open wetland specialist species (Morissette et al. 2019). Indicator bird species with larger associated bodies of knowledge tend to be those species selective for habitats in decline in the OSR, such as old growth forests, wetlands, and particularly graminoid fens, which are a particularly rare habitat primarily found in proximity to OS surface mines.

Ovenbirds are migratory old-growth and intact forest dwelling songbirds that tend to avoid human-disturbed landscapes, largely due to edge effects associated with territorial boundaries (i.e. avoidance of conspecifics) and a lack of food resources in locations of low crown closure (Lankau et al. 2013; Wilson and Bayne 2018). Despite these observed behavioural changes, the birds remain common throughout the OSR, although cumulative effects represent additional long-term risks in multi-stressor landscapes such as the OSR (Sólymos et al. 2019). By combining all available research and monitoring data on ovenbirds, Solymos et al. (2019) estimated that the current ovenbird population in the OSR is ~9.4 million birds (males and females). However, based on the known relationships between ovenbird abundance and different energy sector disturbances, the number of ovenbirds expected to inhabit the region, if OS development had not occurred, is ~11.2 million individuals. This discrepancy is explained via cumulative anthropogenic footprint, primarily the loss of suitable ovenbird habitat to roads and road edges, but also to pipelines, mine sites, well sites, and other industrial facilities (Sólymos et al. 2019).

Yellow rails are reclusive wetland-nesting migratory songbirds whose breeding grounds are threatened by industrial developments that remove wetlands (e.g. urban development, surface mines) or change hydrologic regimes such that fen water levels are impacted or inconsistent. Although knowledge of this species is still limited, recent bioacoustic surveys have both increased yellow rail population estimates and confirmed wetland complexes in the OSR as important breeding areas for the species (Hedley et al. 2020). The current yellow rail population estimate is between 1,650 and 2,747 males. Recent analyses indicate the species population fluctuates considerably over time but, in recent years, species abundances have declined in the area near the OS surface mines. Whether this decline is due to specific activities at the mines, or to more general changes in the hydrology in the area around the mines, remains an area of scientific investigation. Roughly 17% of the current population is considered at risk of losing habitat due to continued OS development, specifically surface mine expansion (Hedley et al. 2020).

Relatively little information exists about raptors in the OSR. Recent development of new processing techniques for audio recordings has increased the availability of owl data in the region (Shonfield et al. 2018). Landscape scale owl occupancy and abundance varies across species with different patterns of disturbance and largely align with species' habitat preferences, especially the presence of and proximity to agricultural cropland, although a strong and consistent effect of climate is also observed (Domahidi et al. 2019). Barred owl (*Strix varia*) occurrence is negatively associated with roads and total human footprint while great horned owls (*Bubo virginianus*) show a positive relationship with linear features (e.g. seismic lines and pipelines), although they avoided energy facilities, and boreal owls (*Aegolius funereus*) show no response to energy sector activities (Shonfield 2018). None of the these three species (barred, great horned, or boreal owls) appear to avoid areas with industrial noise (Shonfield and Bayne 2017a), suggesting rather that human presence and/or light from industrial sites may be the mechanism that leads to great-horned owl avoidance of energy sector sites.

Spatial scale

As with mammals, bird responses at the local and landscape scale are not always consistent. For example, Canada warbler abundance across its North American range declines with increasing human disturbance on the landscape. While this is most evident in the eastern breeding region, the trend occurs in the western breeding region also, much of which coincides with areas of oil and gas exploration, including OS operations (Wilson et al. 2018). However, although warbler abundance at the landscape scale responds negatively to the removal of larger tracts of older forest stands (e.g. agriculture, forestry cutblocks), local scale fragmentation (e.g. seismic lines, wellsites) has not been found to greatly affect abundance provided there remains ample preferred habitat in the area (Ball et al. 2016).

Spatial structure of monitoring data is highlighted in Yellow Rail abundance observations, which show surface mining leases harbouring a disproportionately high number of yellow rails relative to their area, likely attributable to the proximity of mines to the high-quality rail habitats of the McLelland Fen more so than to any particular character of the mine areas themselves (Hedley et al. 2020). Natural habitat structures and other landscape covariates have to be included in spatial analyses alongside oil sands related stressors if the effects of the former are to be separated from those of the latter.

Pathways

Specific pathways of bird responses to landscape disturbance are seldom directly investigated and responses are most often interpreted via species habitat preferences, within the wider context of natural disturbance regimes (e.g. forest age, seral stage, etc.) and edge effects. An exception to this includes the physical destruction of nests when forests are removed for development, which may represent an important pathway affecting interannual bird recruitment. While estimates of nest loss are high across the province (~1,600 lost nests annually), narrower seismic lines will have a lesser impact than wider seismic lines, pipelines, wellsites, or other polygonal disturbances, so the overall contribution of OS operations is difficult to estimate (Van Wilgenburg et al. 2013). Previous literature has shown that, while nesting success of birds near pipelines is similar to those in the forest interior (Ball et al. 2008), there is evidence of decreased reproductive success when an energy sector disturbance creates noise, relative to quiet nesting areas (Habib et al. 2007).

Bird monitoring methods

Birds in the OSR are monitored either directly by humans in the field (looking, listening, and identifying) or increasingly by autonomous recording units (ARUs), which are placed at pre-determined sites to record sound for a given length of time to monitor vocalising species and anthropogenic noise (Shonfield and Bayne 2017b). Comparisons of ARU and human observer data suggest that the two are relatively comparable for most species (Van Wilgenburg et al. 2017) and ARU-based data reliability is constantly improving (Wilson and Bayne 2018; Knight et al. 2020). While detectability distances differ between human observers and ARUs, corrections have been developed to standardise these data (Yip et al. 2017) and recent ARU methods are proving more accurate than human observers for distance estimation (Yip et al. 2020). However, comparisons of forests and disturbed (open) areas identify differences in sound attenuation affecting species counts (biasing counts along disturbances upwards), and such biases should be considered and corrected if possible in both ARU and human observer surveys (Yip et al. 2017). This ability to combine different types of data in the same analysis has allowed very accurate bird models to be created for the OSR for hundreds of species (ABMI 2020).

As with mammals, geospatial approaches are common tools to investigate bird responses to resource development in the boreal forest in general (see reviews by Schieck and Song 2006;

Venier et al. 2014). While direct effects from OS operations (e.g. surface mines, *in situ* facilities, 3D seismic) were not specifically investigated in any of the landscape disturbance papers we reviewed from the last decade, much work on this topic was done prior to this period (E.M. Bayne et al. 2005). Again, increased attribute resolution in geospatial layers such as the Human Footprint Inventory (ABMI 2017) could facilitate causal attribution to specific industries. Of course, generalisable results, such as those identifying pathways common across all disturbances types (e.g. edge effects) would include OS-specific operations such as 3D seismic or *in situ* well pads.

Given that an individual species' response to a particular disturbance type is likely to be consistent across space and time, it is tempting to view predictive models of habitat use or species abundance change under different development projections to be reliable. However, such models must also consider cumulative effects from other environmental stressors, including climate change.

Vegetation & soils

Soils

Physical soil properties are changed within and around landscape disturbance features. Increased soil moisture may result from vegetation removal or from soil compaction by heavy equipment, limiting infiltration (Dabros et al. 2017; Dabros et al. 2018; S.J. Davidson et al. 2020). Further, reductions in soil organic content and increased decomposition have been observed on seismic lines relative to adjacent forests, with resulting changes in soil chemistry (S.J. Davidson et al. 2020). Vegetation removal on disturbance features outside the oil sands region, including narrow seismic lines, also alters light penetration, driving changes in soil temperature and soil moisture, which may interactively affect vegetation on and adjacent to lines (Finnegan et al. 2019).

In forested peatlands, the construction of both conventional and 3D seismic lines can lead to persistent microtopographic simplification and flattening (Lovitt et al. 2018; Stevenson et al. 2019). In addition to changes in vegetation community, altered water depths and soil hydrology has been linked to increased emissions of greenhouse gasses driving climate change (Lovitt et al. 2018; Strack et al. 2018).

On linear disturbances used as winter roads through peatlands, where surfaces are not covered in hard material for summer travel but still subjected to snow compaction from vehicles and heavy machinery, changes in soil character and resulting plant communities have been observed. Disturbances used as winter roads tend to have higher bulk soil density, shallower water tables, and an earlier thawing date, with associated changes in vegetation including higher graminoid cover (Strack et al. 2018).

Summer roads, which represent “hard” linear features in the OSR, can alter the hydrology of forested peatlands by impounding water on one side of the road, leading to changes in understory plant and bryophyte communities, water table depth, hydraulic gradient, and tree biomass. However, the spatial extent and severity of these effects may be interactively affected by underlying substrate type, road orientation relative to water flow, and culvert placement (Miller et al. 2015; Saraswati et al. 2020). Such mechanisms, by which linear and polygonal disturbances may alter local hydrology and plant communities, are persistent and far-reaching in the OSR. These edge effects, potentially in concurrence with other natural drivers, may be responsible for changes in vegetation condition within undisturbed forests near OS developments in the OSR, as observed via remote sensing (Latifovic and Pouliot 2014).

Edge effects

Decades post-construction, edge effects from 3D seismic lines (< 3 m wide) persist, maintaining environmental conditions that differ from adjacent undisturbed forests (based on data from outside the OSR; Finnegan et al. 2019). The longevity of these effects is potentially driving observed differences in vascular plant diversity and cover in coniferous sub-boreal forests, both on 3D lines as well as up to 15 m into adjacent forest (Dabros et al. 2017; Finnegan et al. 2018). While 15 m may seem a localised effect, *in situ* OS developments can cover large areas with tight grids of 3D seismic lines with densities often > 5 km/km^2. In a scenario with seismic line spacing of 30–50 m, edge effects may comprise the majority area, potentially resulting in terrestrial biological responses across larger contiguous landscapes (Dabros et al. 2018; Riva and Nielsen 2021).

Species richness

At the regional scale in the boreal forest, vascular plant species richness has been suggested to peak at intermediate disturbance levels, both natural and anthropogenic (Mayor et al. 2012; J. Zhang et al. 2014), and community evenness is largely unaffected by disturbance, possibly due to the ubiquity of habitat generalists in the boreal forest (Mayor et al. 2015; Crisfield et al. 2020). Local scale plant species richness tends to be higher in sites closer to OS operations (Boutin and Carpenter 2017; Mao et al. 2018) or near urban and industrial sites (J. Zhang et al. 2014), or at larger scales, within OS lease boundaries (Mao et al. 2018). The former is driven by higher proportions of non-native species (Boutin and Carpenter 2017) while the latter may potentially relate to non-random placement of lease areas relative to regional diversity hotspots (Mao et al. 2018). The spatial pattern of increased non-native species presence near developed areas is not unique to the OS region, and fits a well-established global trend linking human activity to the prevalence of non-native species. Even long after their construction, seismic lines are observed to harbour different plant communities than nearby interior forests, often with a greater abundance of disturbance tolerant taxa (Dabros et al. 2017; Finnegan et al. 2018). Conversely, phylogenetic diversity among boreal angiosperms at the regional scale is generally unrelated to anthropogenic disturbance (J. Zhang et al. 2014).

Pathways associated with increased species richness or increased proportions of invasive species receive some consideration in the literature, particularly with respect to microclimates created by linear disturbances and new forest edges. Patterns of increased light and wind intensity on seismic lines and other linear disturbances are well established and tend to depend on line width, canopy height, and the direction of line orientation (Roberts et al. 2018; Stern et al. 2018). For example, seed dispersal along seismic lines (especially narrow lines associated with *in situ* OS operations) may be up to four times farther than through undisturbed forest, largely due to higher wind speeds (Roberts et al. 2018). Light and wind intensities in larger clearings such as well pads can be even higher, although they tend to receive less attention (Stern et al. 2018).

Invertebrates

A body of knowledge from the larger boreal region (see reviews by Venier et al. 2014; Dabros et al. 2018) considers effects of forest harvesting more than those of conventional oil and gas or OS effects on invertebrates, although many of the disturbance-related conclusions may be relevant within the OSR also. Exceptions to this include monitoring responses to energy-related disturbances of a few native butterfly and non-native earthworm species, though most knowledge on the latter comes from pre-2010 publications.

For boreal butterflies, conclusions are inconsistent. When narrow, as with 3D seismic lines for *in situ* development, linear disturbances either had no effect on butterfly species abundance (Riva et al. 2018a) or were associated with increases in abundance (Riva et al. 2018b) or increased selection for movement (Riva et al. 2018c) for different species. Similarly, wider seismic lines and polygonal disturbances such as well pads are associated with both higher (Riva et al. 2018a) and lower (Riva et al. 2018b) abundances of different butterfly species. Post-fire butterfly communities remain more diverse along burned linear disturbances than adjacent forests, though the combination of fire and disturbance interacts differently for different taxa, likely driven more by differences in the recovering legacy plant communities in those locations (Riva et al. 2020). Larger scale assessments, including wider landscape patterns of abundance, for butterflies and other invertebrates have not been undertaken.

Extensive surveys across the OSR have found that several species of non-native earthworms are far more likely to occur in proximity to recreational areas and adjacent to roads but have similar abundance near seismic lines relative to the forest interior (Cameron et al. 2007). Based on these surveys, earthworms were estimated to exist in about 9% of north-eastern Alberta in 2009 and with their rate of spread are estimated to expand to about 49% of suitable forest habitat by 2060 (Cameron and Bayne 2009). Depending on the earthworm species modelled, carbon stocks on the forest floor are predicted decline by 49.7–94.3% through the next century. Most of this reduction occurs 35–40 years after initiation of invasion. As earthworms reduce the amount of carbon available for burning by consuming leaf litter, carbon emissions from wildfire are concordantly expected to be lower when earthworms are present (Cameron et al. 2015). Road development by the energy sector is partially responsible for these introductions and spread.

Contaminants

The source, transport, and deposition of airborne contaminants is covered in the air and deposition review in this special issue (Horb et al., forthcoming).

Vegetation and soils

Spatial gradients of contaminant concentrations, with higher levels closer to OS operations, are observed for polycyclic aromatic compounds (PACs, a.k.a. polycyclic aromatic hydrocarbons or PAHs) and trace metals in vascular plants (Boutin and Carpenter 2017), for PACs and trace metals in lichen species (Graney et al. 2017), for elements such as nitrogen (N), sulphur (S), calcium (Ca), boron (B), zinc (Zn), and iron (Fe) in jack pine (*Pinus banksiana*) (Proemse et al. 2016a), and for N in jack pine and lichen species (Laxton et al. 2010). In some studies, accumulation is at levels of concern to plant health (e.g. Boutin and Carpenter 2017), while in others it is not (e.g. Laxton et al. 2010; Proemse et al. 2016b). Specific source attribution of these contaminants is not always clear (C.J. Davidson et al. 2020), although some observed patterns are fingerprinted via correlation with other source-attributed contaminants from OS operations (e.g. Laxton et al. 2010), while others are attributed to fugitive dust from roads or wind-blown particles from industrial operations (e.g. Proemse et al. 2016b; Graney et al. 2017). Some source attribution techniques (e.g., Positive Matric Factorization) have been applied to air and deposition data sets to determine major source categories of various contaminants, although these efforts are discussed in more detail in Horb et al. (forthcoming).

Jack pine forest stands in the OSR have been the focus of comprehensive monitoring in the last decade, including atmospheric deposition in these ecosystems and the environmental effects thereof (Foster et al. 2019; C.J. Davidson et al. 2020). While concerns were originally related specifically to acidification in forest stands, the scope of monitoring has expanded to include a range of depositional stressors and ecological responses. To date, there is little evidence of acidification of soils or understory plant communities in jack pine stands (Watmough et al. 2019; MacKenzie and Dietrich 2020) and no adverse forest health responses due to acidifying deposition (C.J. Davidson et al. 2020). This is potentially a result of coincidental and neutralising base cation deposition. However, data suggests fertilisation responses in understory species and tree growth exists (Watmough et al. 2019; C.J. Davidson et al. 2020). While foliar sulphate (SO_4^{2-}) and N concentrations correlate spatially with observed S and N deposition patterns respectively, topsoil SO_4 and soil N do not (MacKenzie and Dietrich 2020), suggesting potential uptake of these chemicals by plants (Bartels et al. 2019). Acidifying deposition in the northern OSR is not driving decreases in soil pH, potentially due the already-acidic quality of soils in the area (Cho et al. 2019; MacKenzie and Dietrich 2020), although there is evidence of a slowly decreasing pH trend (pH change of < -0.1 per decade) in the less acidic soils of the Cold Lake region (Cho et al. 2019).

Increases in tree growth rates have also been observed in white and black spruce (*Picea glauca* & *P. mariana*) via tree ring records. Since 1880 and until widespread OS industrial development, tree growth was tightly coupled to climate variables, after which there was consistent divergence (Savard et al. 2014). Contrary to the jack pine system, this change in spruce was attributed not to chemical fertilisation but rather a dendrochronological response to isotopic carbon (13C) that indicates historic changes in air quality.

Dust accumulation on harvested berry species have revealed trace elements accumulated on and/or in locally harvested berries from closer to industrial operations, specifically surface mines and upgraders (Stachiw et al. 2019). Local ICBM of traditional plant and animal food species, including vascular and non-vascular plants, waterfowl, and some land mammals, showed high variability in total mercury (THg), methylated mercury (MeHg), and Se concentrations across species, but none exceeding Health Canada consumption guidelines (Golzadeh et al. 2020). The study design did not enable source attribution of contaminants.

On mercury sources, recent publications have shown that deposition from global background is the largest contributor to THg deposition in the OSR (Emmerton et al. 2018; Dastoor et al. 2021). Though, within close proximity (10 km) to OS sources, THg deposition from global sources contributed a slightly smaller proportion (~70-94%) of annual THg deposition (Dastoor et al. 2021). Because the atmosphere is an oxidizing environment, the atmospheric concentrations and subsequent deposition of MeHg—which can trophically bioaccumulate—are generally negligible.

Mammals

Despite a large body of work on contaminant accumulation in lichens (e.g. Percy 2013; Landis et al. 2019), and despite their being key food for caribou and other ungulates (Dunford et al. 2006), there has been little published in the last decade on contaminant accumulations in ungulates or other large mammal tissue within the OSR (Wallace et al. 2020). The single paper within our review that looked at large mammal toxicology, solely via scat surveys, found evidence of both pyrogenic (from wildfire) and petrogenic (from petroleum) PACs, the balance of which depends on both geographic distribution and food sources (Lundin et al. 2015). Caribou PAC exposure, particularly in the area of the 2002 House River Fire (> 238,000 ha in the OSR), is largely pyrogenic, and speculated to be due to lichen food-source accumulation. Moose scat surveys suggest strong geographic patterns of PAC exposure, with petrogenic PAC accumulations closer to the intensive *in situ* OS areas south of Fort McMurray and pyrogenic PAC signatures in areas farther removed from OS operations where wildfires were larger and more recent. Wolves demonstrate PAC exposure patterns consistent with predation on both moose and caribou, with wolf scat samples showing the highest levels of overall PACs among the large mammals considered and showing a mix of pyrogenic and (to a lesser extent) petrogenic fingerprints, as well as remnant scat contents consistent with predation on moose, deer, and (to a lesser extent) caribou (Lundin et al. 2015).

While many relevant mammal toxicology projects in the OSR have collected and publicly provided data (ECCC 2018), associated publications have yet to appear in the literature. Further, PAC ratios may not be reliable discriminators (Galarneau 2008), particularly in biota that metabolise these compounds at different rates. Isotopic ratios may be a more reliable tool (Jautzy et al. 2013), although the applicability of the latter to scat analysis is uncertain.

By contrast, contaminant accumulation in small mammals is more frequently investigated, though largely to answer focused OS-related questions. For example, observed bioaccumulation in marten and fishers of anticoagulant rodenticides commonly used around human infrastructure (Thomas et al. 2017) led to one of the most straightforward management actions in the OSR, with operators immediately removing these products from their pest control inventories. Similarly, in response to two accidental *in situ* bitumen spills, voles were monitored as a sentinel species for adverse health responses following site remediation. While no body morphology changes (e.g. size, weight, liver weight) nor body burdens of associated metals were noted in individuals from exposed areas, some differences in liver function were observed, although these changes were not associated with population-level biological outcomes (Berger et al. 2016).

Early analyses of semi-aquatic mammals have linked bioavailability of THg to levels in trapped otter and mink fur and stomachs to environmental factors such as soil pH and organic carbon, as well as habitat structure within home range areas, including forest type, burned area, and wetland prevalence, and not to proximity of industrial features (Eccles et al. 2020). Further, ICBM analyses of otter tissue burdens and baculum bone mineral density showed the existence of both trace metals and PACs in otters, and relationships between these chemical burdens and bone mineral density. While these data showed some relationships between some bone health metrics and spatial proximity to OS mining or *in situ* operations, results were inconsistent, but could be clarified via continued data collection within this ICBM program (Thomas et al. 2021).

Birds

Literature on bird toxicology in the OSR from the last decade is dominated by two major monitoring programs: (1) THg accumulation in colonial waterbird eggs in the Peace-Athabasca Delta (PAD), and (2) contaminant accumulation in tree swallow (*Tachycineta bicolor*) nestlings. While these topics are well developed in the literature, it is largely to the exclusion of other bird toxicology research, which represents a knowledge gap, particularly for local Indigenous communities who may have concerns about the impact on various waterfowl given their importance as harvested resource. Specifically, the OSR is an important flyway for birds overwintering in more southern locations but breeding in habitats to the north of OS operations (e.g. the PAD, Wood Buffalo National Park).

Colonial waterbird eggs

The PAD is an important region for contaminant monitoring because it receives water from the Athabasca River. It lies downstream of the core OS operations but also downstream of bitumen-rich geologic formations, burned areas, and the city of Fort McMurray, all of which represent potential confounding contaminant sources. Toxicological sources must be isolated if causal links to OS operations of accumulation are to be clarified. Toxicology work in this region has focused on THg levels in eggs of colonial waterbirds—specifically a selection of upper trophic level gull and tern species—but also arsenic (As) and PACs (Hebert et al. 2011; Hebert et al. 2013; Dolgova et al. 2018; Hebert 2019). Comparisons of accumulations in different species across sampling sites is critically facilitated via a trophic position adjustment using an amino acid compound-specific stable nitrogen isotope analysis (Dolgova et al. 2018).

Early research compared eggs from two or three sites in the PAD, in the receiving waters of the Athabasca River, at sites identified in collaboration with local Indigenous communities (Beausoleil et al. 2021) against reference sites either from a more remote but nearby location in

Lake Athabasca (Hebert et al. 2011), or much farther afield near the city of Calgary in southern Alberta (Hebert et al. 2013). These comparative studies suggested relatively low levels of As and PACs in the Athabasca River site eggs, but generally increased levels THg beyond expected trophic accumulation patterns (Hebert et al. 2011). However, with the exception of measurements from 2012, THg concentrations in waterbird eggs did not reach levels that would be associated with negative health responses for birds (Hebert et al. 2013). These results are largely confirmed via egg sampling across Alberta and into the southern Northwest Territories, incorporating the nitrogen stable isotope adjustment for trophic position. Normalised THg concentrations were highest in the Lake Athabasca region, north (downstream) of the main OS developments (Dolgova et al. 2018).

The source attribution of this THg accumulation remains uncertain, though several potential explanations have been put forward. Normalised northern THg concentrations away from the receiving waters of the Athabasca are significantly higher than southern concentrations (Dolgova et al. 2018), fitting a previously identified THg bioaccumulation pattern that increases with latitude, potentially driven by lower temperatures and productivity (Lavoie et al. 2013). While this relationship may address background THg concentrations in the northern OSR, it is an insufficient explanation for the patterns observed in the downstream Athabasca region. Temporal patterns may be more complex than originally anticipated, however, with recent work linking egg THg levels to flow rates of the Athabasca River (Hebert 2019). Higher THg levels in eggs are observed in years following high flow conditions, suggesting that, while local THg inputs (e.g. via atmospheric deposition onto the snowpack, surficial geology, etc.) may end up in surface waters, they may not be transported downstream except under high-flow conditions that readily mobilise river sediment (Hebert 2019). Wildfire is considered an unlikely driver of THg accumulations in the OSR, given that coincidental timelines of major wildfires and THg accumulations do not align (Hebert et al. 2013).

Along the Athabasca river itself, THg concentrations in tissue of forage fish follow a nonlinear gradient, with concentrations lowest in locations upstream and farthest downstream of the OS mines, consistent with trophic sources of THg found in waterbird eggs (Dolgova et al. 2018). The contribution of the urban development of Fort McMurray is implicated in this pattern also, as prey fish THg levels begin to increase significantly in the stretch of the Athabasca River immediately downstream of Fort McMurray but upstream of the southernmost OS surface mines, an area also coincidental with the entry of the river into bitumen-rich geologic formations (Dolgova et al. 2018). Monitoring data along the reach of the Athabasca River upstream of Fort McMurray, as could be informed with data from established surface water and fish mentoring programs in the OSR (Arciszewski et al. forthcoming), could help clarify patterns of THg accumulations in a wider breadth of fish species across larger spatial extents.

Knowledge of these complex interactions may assist in causal attribution of THg accumulation going forward; such assessments should integrate the most recent approaches to quantifying landscape deposition patterns on the OSR landscape (e.g. Landis et al. 2019; C.J. Davidson et al. 2020).

Tree swallow nestlings

Establishment and monitoring of tree swallow nest boxes and passive air samplers at lake sites both near OS surface mines and in remote southern locations (> 60–100 km from OS surface mining operations) have yielded data on airborne contaminant exposure and health responses of tree swallow hatchlings and nestlings in the OSR. Tree swallow nestlings have been monitored for accumulation in tissues of metals (Godwin et al. 2016) and of a wide breadth of PACs (Cruz-Martinez, Fernie, et al. 2015; Fernie, Sarah C. Marteinson, et al. 2018), a suite of toxicants, commonly linked to oil and gas facilities and operations (Kelly et al. 2009). PACs are associated with adverse health responses such as reproductive and developmental complications and immunosuppression (Albers 2006), many of which are also directly measured in tree swallow nestlings in the OSR (Cruz-Martinez, Fernie, et al. 2015; Fernie, S. C. Marteinson, et al. 2018; Fernie et al. 2019). While the interpretation of the suite of data from the tree swallow monitoring is specifically challenging due to the small number of monitoring sites in an inherently multi-stressor landscape, important inferences are reported in the OS literature from the past decade.

The stories for PAC and metal accumulation are somewhat different. With the exception of cobalt (Co) and lead (Pb), for which tree swallow nestling accumulation is actually higher in sites farther removed from OS mining operations, these birds do not accumulate metals and metalloids, as measured in liver and kidney tissues, consistently showing elemental concentrations well below levels of toxicological concern (Godwin et al. 2016). Conversely, tree swallow nestlings throughout the OSR, but especially those resident at sites close to OS operations, are exposed to and uptake a mixture of PACs, likely via a combination of direct air and water exposure, as well as dietary selection for terrestrial and aquatic invertebrates that also accumulate these contaminants (Cruz-Martinez, Fernie, et al. 2015; Fernie, Sarah C. Marteinson, et al. 2018; Fernie et al. 2019). While contaminant deposition was specifically monitored on site in some studies (e.g. Cruz-Martinez, Smits, et al. 2015; Fernie, Sarah C. Marteinson, et al. 2018), others infer exposure based on spatial proximity to OS facilities (e.g. Godwin et al. 2019).

Tree swallow nestlings exhibit thyroid (i.e. metabolism and growth) and reproductive responses to PAC accumulations (Fernie, S. C. Marteinson, et al. 2018; Fernie et al. 2019), but there are confounding environmental interactions also, such as weather (Fernie et al. 2019; Godwin et al. 2019). Compromised thyroid function in nestlings is observed at sites with higher PAC exposure and uptake (Fernie, Sarah C. Marteinson, et al. 2018; Fernie et al. 2019), mirroring results from reclamation studies looking at hatchling exposure to oil sands process-affected water (e.g. Gentes et al. 2007). Fernie et al. (2019) found PAC accumulation, air temperature, and diet to be significant drivers of thyroid activity in nestlings (using a non-parametric multiple regression approach). VOCs receive comparatively limited consideration in the tree swallow nestling research, despite links between VOC accumulation and altered thyroid function (Fernie et al. 2019).

Altered thyroid function can signal negative health responses, and thus direct measurements of reproductive and developmental success in tree swallow nestlings have also been undertaken. And while health responses have been observed, they are inconsistent (Fernie, S. C. Marteinson, et al. 2018; Godwin et al. 2019). Hatchling weight, condition, and survival were significantly lower at one site in proximity to OS operations but not at a second OS site, the latter of which resembled reference sites in terms of health and survival despite measuring the highest PAC exposures and uptakes of all sites (Fernie, S. C. Marteinson, et al. 2018). This may be explained by dietary differences between the sites as well as significantly warmer temperatures at the more successful OS site, both of which may have contributed to earlier clutch initiation at the less successful site, a factor associated with decreased survival and health (Fernie, S. C. Marteinson, et al. 2018; Godwin et al. 2019). This corresponds with a parallel study (Godwin et al. 2019), which found precipitation during the incubation period to be the key driver of reproductive metrics such as hatchling and fledgling success, and found little support for reproductive responses linked to proximity to OS operations (a proxy for contaminant exposure), though sites proximal to OS operations did have a much wider range of success rates, especially in extreme weather years. This lack of observed OS-driven effects on reproduction may be due to different diets, as Godwin et al. (2019) reports a much higher proportion of terrestrial invertebrates (vs. aquatic), which may shelter these nestlings from contaminant accumulations.

As a sentinel species, tree swallows are representative of a larger community of birds that nest and forage near wetlands, and whose diets are composed largely of aquatic and terrestrial invertebrates (Smits and Fernie 2013). For such species, however, manifestations of survival and reproduction responses may be complex and dependent on a variety of variables and may only be significant or measurable in years of extreme weather when cold and wet conditions prevail.

Climate Change

Projections and recent observations of climate change in the OSR are larger in magnitude than the typically cited global averages of 2–3°C over the next century (Schneider et al. 2009). A large breadth of research, not specifically considered here, provides projections of change to vegetation and wildlife communities in the boreal forest at larger provincial or continental scales (e.g. Shank and Nixon 2014; Stralberg et al. 2015).

Climate change, and specifically winter temperature increase, is a key driver of past and future northward expansion of white tailed deer in the OSR. Decreases in winter severity, particularly when combined with human land disturbance, will continue to expand northern habitat for white tailed deer in the future (Dawe et al. 2014; Dawe and Boutin 2016; Fisher et al. 2020). Changing wildfire regimes result in habitat changes by affecting the relative occurrence of forest seral stages. This can benefit moose and deer—and thereby wolves—potentially further exacerbating caribou declines (Barber et al. 2018).

Geospatial methods

To date, detailed land use and landcover data has been created for the OSR via remote sensing and earth observation (Castilla et al. 2014; Latifovic and Pouliot 2014; Pouliot and Latifovic 2016), manual interpretation of stereo imagery (e.g. Alberta Vegetation Inventory, Alberta Environment and Parks 1991), or classification of satellite imagery (Castilla et al. 2014; Jiao et al. 2015; Powers et al. 2015; Pouliot and Latifovic 2016; Chowdhury et al. 2017). However, few datasets covered the entire OSR region and the development of consistent and regularly updated wall-to-wall landcover data within the OSR represents a critical gap. Infrequently updated or static data layers do not allow for change detection and monitoring at appropriate temporal scales. The potential to utilise satellite remote sensing in the OSR to generate a time series of landcover data, and to undertake change detection and monitoring at local scales (Y. Zhang et al. 2014; Pouliot and Latifovic 2016; Chowdhury et al. 2017), represents a significant opportunity.

The Alberta Biological Monitoring Institute (ABMI) has generated a wall-to-wall human footprint layer for the entire province of Alberta at regular time intervals since 2010. These datasets date from between 2010 and 2018, and are created in a GIS by combining available disturbance data from multiple agencies with digitised anthropogenic disturbance features from high resolution SPOT 6 satellite data (ABMI 2017). However, although such landcover data provide a fairly accurate and comprehensive representation of human footprint within the OSR and beyond, their reliance on existing GIS data layers and manual interpretation and digitisation makes the production of these datasets both highly labour intensive and potentially prone to human errors (though the alternative, unsupervised classification of remote sensing data, is also prone to errors, just different errors).

A more efficient alternative may be to develop remote sensing approaches to map inventories of industrial features, as has been implemented to some extent within the OSR, often using freely available or low-cost satellite imagery (e.g. Chen et al. 2014; Salehi et al. 2014; Jiao et al. 2015; Powers et al. 2015; Chowdhury et al. 2017; Wasson and Franklin 2018). Unfortunately, publicly available and free satellite imagery is typically of moderate resolution and largely insufficient to resolve fine scale industrial features (Chen et al. 2014; Chowdhury et al. 2017), leading to relatively low accuracy via both omission and commission errors (Wasson and Franklin 2018). However, new methodologies including spectral unmixing (Chowdhury et al. 2017) and analysis of time series data (Chen et al. 2014) are being developed to overcome this limitation. Further, integrated methodologies, such as combining annual remote sensing imagery with ancillary GIS data, can overcome some limitations of manual interpretation and remote sensing approaches alone, as well as generate annual disturbance inventories with increased attribution of human footprint type (Pouliot and Latifovic 2016; Chowdhury et al. 2017).

In assessing and monitoring vegetation health in the OSR, studies have incorporated numerous remote sensing applications, including several common spectral indices derived from optical satellite imagery, to estimate above-ground biomass, including the Normalised Difference Vegetation Index (NDVI), which uses a measure of chlorophyll concentration as a proxy for vegetation vigour (Rouse et al. 1973), or Leaf Area Index (Zheng and Moskal 2009). More recently, Light Detection and Ranging (LiDAR), an active remote sensor typically flown on fixed wing aircraft, has been used to characterise vegetation density and structure in the OSR (Lefsky et al. 2001; Lefsky et al. 2002; Dietmaier et al. 2019), quantifying ecologically relevant measures of vegetation health including vegetation height, structural complexity, and canopy cover. While expensive to collect, LiDAR data are now becoming ubiquitous, with regional-scale characterisation of vegetation structure now conducted for the entire boreal region of Alberta, including the OSR (Coops et al. 2016; Guo et al. 2017). However, LiDAR data remain expensive to obtain and repeated acquisition over the same location, as required for continued time-series monitoring, is cost intensive. For smaller geographic extents, unmanned aerial vehicles may be useful and inexpensive tools for LiDAR or other remote sensing data collection (e.g. Chen et al. 2017). Existing LiDAR data for the OSR were obtained between 2003 and 2014 (Guo et al. 2017), representing multiple years and a variety of seasonal conditions. While these data may remain underutilised for monitoring, they have been used more readily for methodological development (Chen et al. 2017; Dietmaier et al. 2019).

Applications of geospatial science to abiotic monitoring include mapping and monitoring uplift and subsidence of land, arising from steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CCS) OS operations. Several studies have developed remote sensing approaches to map and monitor vertical displacement from satellite Synthetic Aperture Radar (SAR) imagery (Samsonov and Czarnogorska 2014; Singhroy et al. 2014; Samsonov et al. 2015), although these studies are largely focused on on-lease locations and have not monitored regional deformation.

Trend detection in a time-series of vegetation indices has been calculated from the Landsat archive to monitor OSR vegetation health over time (Latifovic and Pouliot 2014) and measures of leaf area index have been derived from satellite imagery and assessed against field measures within the OSR with good results (Hassan and Bourque 2010). While these studies demonstrate the applicability of using remote sensing to map and monitor vegetation health over large areas at relatively low cost, wall-to-wall monitoring of vegetation health for the OSR has not yet been conducted using optical satellite imagery (such as the freely available Landsat, Sentinel, or MODIS data). At smaller scales, LiDAR has been used to explore the controls on vegetation recovery for seismic lines, and to build predictive models of seismic line longevity in the OSR (e.g. Van Rensen et al. 2015; Abib et al. 2019). Derived LiDAR data have proven effective for the development of, for example, avian species richness models (Coops et al. 2016). Further, when combined with measures of terrain and climate, LiDAR data have successfully predicted vascular species richness, including assessments of vascular plant species diversity between on-lease and off-lease sites in the OSR (Mao et al. 2018) and rare species at the regional scale (Nielsen et al. 2020).

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