Wetland Mitigation Options for Project Developments in Far Northern Ontario: An Annotated Bibliography

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1. Introduction

This report presents and summarizes an annotated bibliography on the options to mitigate impacts on wetlands for proposed mining project developments in the Ring-of-Fire region in the far north of Ontario. The report and the bibliography were developed for the Priority Species Unit of the Ontario Region of the Canadian Wildlife Service (CWS-ON).

The Ring-of-Fire mineral exploration region is centered around McFaulds Lake (52.8° N, 86.1° W) and covers approximately 3,000 km^2 in the transition zone between the Boreal Shield and Hudson Bay Lowland. Rich mineral deposits have been discovered there of chromite, nickel, copper, platinum group elements, gold and zinc. The region is only connected via winter roads, so any proposed mining development would also include the construction of at least 300 km of all-season roads.

The Hudson Bay Lowland or Hudson Plains is a vast peatland expanse of bog and fen with areas of conifer swamp, as well as coastal marsh along the shores of Hudson Bay and James Bay (OMNRF, 2019; Tarnocai et al., 2011). Wetlands, most of them peatlands, cover almost 100% of the landscape. Uplands are scarce. The adjacent Boreal Shield or Ontario Shield has more upland and less wetland cover, but wetlands, again mostly peatlands, remain extensive and cover at least 50% of the landscape (OMNRF, 2019; Tarnocai et al., 2011).

The objectives of this report are to:

- provide the methods used to assemble the annotated bibliography and present its structure and best strategies for searching it;
- review the probable stressors that will impact wetlands in the Hudson Bay Lowland and the adjacent Boreal Shield and the probable origins of these stressors;
- present mitigation options for these principal stressors, following the mitigation hierarchy;
- review best monitoring methods to evaluate the success of mitigation measures; and
- point out major gaps in our knowledge on how to mitigate or monitor these stressors.

The explicit scope of the report and the annotated bibliography is focused on mitigation options for migratory birds and species-at-risk in wetlands in the Ring-of-Fire region. However, given that few documents cover migratory birds or species at risk in this region, this scope is widened to include mitigation options for wetlands, especially peatlands, without direct consideration of migratory birds or species-at-risk in Hudson Bay Lowland and the adjacent Boreal Shield. Any impacts to wetlands and peatlands will also affect the habitats for migratory birds and faunal and vegetation species-at-risk.

The Cree word for this landscape of peatlands in the Hudson Bay Lowland and adjacent Boreal Shield is ‘muskeg’. It is one of the few Cree words adopted in English. The Cree communities in the Hudson Bay Lowland refer to themselves as the Omushkego Cree, and they form the Mushkegowuk Council. The ‘muskeg’ root in their communities’ and council’s names reflects their ancient closeness to this landscape. We must acknowledge from the start that our effort to compile knowledge on mitigation options for wetlands in this region potentially impacted by resource developments lacks the input from the Omushkego Cree as well from the Cree and Ojibway communities of the Matawa First Nations, the Shibogama First Nations, the Windigo First Nations, Keewaytinook Okimakanak, Fort Severn, Peawanuck, and independent bands in the Far North of Ontario. Our intention is to start this bibliography as a living resource. We hope that we can eventually include the knowledge of First Nations.

2. Approach and Structure of the Annotated Bibliography

The annotated bibliography is found at:

https://www.zotero.org/groups/5814951/peatland_mitigation_bibliography .

The bibliography is large with roughly 1,200 documents to date. The bibliography is currently public, but with restricted access. Access can now be requested from the first author. Full access will open once the bibliography is fully vetted.

In this section, we document (i) the methods used to include documents in the bibliography, (ii) how we structured the bibliography and (iii) how to conduct efficient searches in the bibliography.

2.1 Methodology for document inclusion

We completed the majority of the bibliographic search using the internet and the Web of Science® bibliographic database. Table 1 shows the main search terms.

Since this annotated bibliography was prepared for the Ontario office of the Canadian Wildlife Service, we prioritized any documents on migratory birds and species-at-risk. For species-at-risk, we first identified all federal and provincial species-at-risk in Ontario (COSSARO, 2023; ECCC, 2022), and then, using the species range maps in the federal and provincial status reports, we determined those that have distributions overlapping the Hudson Bay Lowland or the adjacent Boreal Shield (Table 2). We then completed web searches for all COSEWIC (federal) and COSSARO (Ontario) documents and any other documents for these species.

Table 2. Principal search terms used to compile the bibliographic database.

Level	Search Terms
primary	('migratory birds' OR 'species-at-risk' OR individual species-at-risk)
primary	('peatland' OR 'bog' OR 'fen' OR 'string fen' OR 'mire' OR 'aapamire' OR 'sphagnum' OR 'pool'
primary	('wetland' OR 'marsh' OR 'saltmarsh' OR 'swamp') AND ('boreal' OR 'subarctic' OR 'arctic')
secondary	('mitigation' OR 'avoidance' OR 'minimization' OR 'restoration' OR ‘rehabilitation’ OR 'offsetting' OR 'compensation' OR 'treatment wetland' OR 'bioremediation' OR 'phytoremediation')
secondary	('mining' OR 'mineral processing' OR 'mineral exploration' OR 'tailings' OR 'mine wastes' OR ‘road construction’) AND ‘environment’
secondary	(hydrological alteration OR drainage OR flooding OR drought)
secondary	('nutrient enrichment' OR 'contaminant' OR 'pollution' OR 'spill' OR 'fugitive dust' OR 'hydrocarbon' OR 'heavy metal' OR 'metalloid' OR 'antimony' OR 'arsenic' OR 'cadmium' OR 'chromium' OR 'cobalt' OR 'copper' OR 'lead' OR 'nickel' OR 'selenium' OR 'thallium' OR 'zinc')
secondary	('disturbance' OR 'substrate disturbance' OR 'vegetation disturbance' OR 'peat extraction' OR 'compaction' OR 'subsidence' OR 'rutting' OR 'trampling' OR 'erosion' OR 'deposition')
secondary	('ecosystem conversion' OR 'mine footprint' OR 'linear disturbance' OR 'linear feature' OR 'seismic line' OR 'road' OR 'transmission line' OR 'power line' OR 'pipeline')
secondary	('mercury' OR 'methylmercury')
secondary	('herbivory' OR 'overgrazing')
secondary	('invasive species' OR 'individual invasive species')
secondary	'noise pollution'
secondary	'bird collisions'
secondary	('Hudson Bay Lowland' OR 'Boreal Shield' OR 'Ring-of-Fire')
secondary	('federal policy' OR 'provincial policy')
secondary	('climate change OR ‘soil warming’ OR ‘permafrost thaw')
secondary	('remote sensing' OR 'monitoring')

Table 2. Federal or provincial species-at-risk reported from the Hudson Bay Lowland or adjacent Boreal Shield in the Far North of Ontario.

Taxonomic group	Species-at-risk
vascular plants	black ash
arthropods	gypsy cuckoo bumble bee
	yellow-banded bumble bee
	Suckley’s cuckoo bumble bee
fish	lake sturgeon
mammals	eastern red bat
	hoary bat
	silver-haired bat
	little brown myotis
	northern myotis
	tri-colored bat
	caribou boreal population
	caribou, eastern migratory population
	wolverine
	polar bear
birds	Hudsonian godwit
	lesser yellowlegs
	red knot
	red-necked phalarope
	short-eared owl
	common nighthawk
	olive-sided flycatcher
	bank swallow
	barn swallow
	Canada warbler
	evening grosbeak
	rusty blackbird

We included most documents from a draft CWS-ON document on pathways of effects that evaluated ecological stressors on peatlands, monitoring approaches and mitigation measures. Ecological stressors in that document included peatland drainage, flooding, vegetation and peat disturbance, use of industrial equipment, and road or infrastructure placement. However, this list of stressors to the wetlands of the Hudson Bay Lowland and the adjacent Boreal Shield was incomplete (see section 3). We searched for other stressors, including fertility change and contamination, landscape conversion and fragmentation, overgrazing, invasive species and other stressors. Once we established a strong baseline of documents on key stressors, we searched for them again in combination for each level of the mitigation hierarchy, ‘avoidance’, ‘minimization’, ‘restoration’ *or* ‘rehabilitation’, ‘offsetting’ and ‘compensation’ as well as ‘monitoring’.

We reviewed all articles listed by the Peatland Ecology Research Group (PERG), which has published extensively on mitigation to disturbance impacts to peatlands, especially those related to the peat industry in Canada. Students and members of the PERG were also asked to review the bibliography and submit relevant documents from the broader scientific literature.

We were obviously missing documents on the best environmental practices for mining, so we searched for ‘mining’ or ‘mineral exploration’ or ‘mineral processing’ without peatland or wetland search terms. This brought in a large body of literature on environmental mitigation of mining effects, including many mine process or tailings management documents. (Note that we consider open pit or in-situ oil sands extraction as mining in this bibliography.) We only chose a few well-cited review articles or best management practice guides to illustrate them. These will be important to suggest mining practices that avoid impacts to peatlands and other wetlands in the Hudson Bay Lowland.

Finally, because there are relatively few documents on the Hudson Bay Lowland and adjacent Boreal Shield of the Far North of Ontario, we searched for these terms along with ‘peatland’ or ‘other wetland’, without considering stressors or mitigation measures or monitoring. This brought in a series of documents that will be important for establishing baseline conditions to monitor impacts to peatlands in the Hudson Bay Lowland and the adjacent Boreal Shield.

When promising articles were found, we reviewed the list of papers citing them to find other relevant documents. Overall, we followed an inclusive strategy. If documents were deemed to touch the subject of impacts or mitigation measures or monitoring for peatlands or other northern wetlands, they were included in the bibliography. The resultant bibliography is large, but the mechanics of the bibliography should allow to find documents simply.

Despite our best efforts and the resulting large size of the annotated bibliography, we expect that we missed important documents. The annotated bibliography could best be viewed as a living database, to be reviewed and updated periodically.

2.2 Structure of the bibliography

The annotated bibliography is constructed with open source Zotero® bibliographic software. For each document, web links are included, abstracts are given when available, and a short annotation of the document is given under the 'Notes' field. We also created subject categories for the annotated bibliography, which we include in the 'Tags' field of Zotero®. The general subject categories are classified using tags on:

- geographic region,
- ecosystem type,
- principal abiotic or biotic components,
- ecological stressors,
- origins of impacts,
- policies or statutes,
- mitigation hierarchy,
- detail on mitigation, and
- monitoring.

Each general subject category has hierarchical levels of subcategories (Appendix A).

Using this structure of tags, the annotated bibliography could eventually be developed into a web document with hierarchical drop-down menus, similar to the Mitigation Practices Database (MPD) Tool for Offshore Wind (https://briloon.shinyapps.io/MPDTool/).

2.3 Searching the bibliography

The Zotero® bibliography can be searched in two ways. First, the search window in the upper right corner of the screen can be used to search by author, title, tag, or any word. The advanced search option allows for affirmative or negative searches (i.e. title "contains" versus "does not contain" a word).

Second, the tags of subject categories (Appendix A) are listed in the lower left of the Zotero screen. Documents can be searched by selecting one or several tags. Selecting multiple tags allows for intersecting searches. For instance, selecting 'peatland' *and* 'drawdown' *and* 'on-site restoration' will list the documents pertaining to the restoration of peatlands that have suffered a water table drawdown. Consulting the subject categories and subcategories (Appendix A) will help suggest suitable searches.

A search for 'migratory birds' or 'species-at-risk' and each of the mitigation hierarchy categories will bring up all documents in the database related to mitigating impacts on migratory birds or species-at-risk (Table 3). However, this search provides few documents, with only 26 documents covering mitigation options for migratory birds (4.9% of mitigation hierarchy documents in the database) and 37 documents (6.9% of mitigation documents) on mitigation options for species-at-risk.

When the search is expanded to cover peatlands or other wetlands, 401documents cover all levels of the mitigation hierarchy (75.1% of mitigation documents). Most relate to peatlands (72.4.1% of the mitigation documents), with few in other wetland types, mostly marsh or saltmarsh (8.8 % of mitigation documents). This broader search strategy will also be important to determine the mitigation options for habitats for migratory birds or species-at-risk.

Table 3. Searches in the annotated bibliography for the different levels of the mitigation hierarchy with combinations of the tags 'migratory birds', 'species-at-risk', 'peatland' and 'other wetland'.

	additional search terms				
Mitigation Hierarchy	+ 'migratory birds'	+ 'species-at-risk'	+ 'migratory birds' OR 'species-at-risk'	+ 'peatland' OR 'other wetland'	Total
'impact avoidance'	4	3	6	27	55
'impact minimization'	19	20	28	110	194
'on-site restoration'	10	21	28	299	355
'offsetting'	1	1	1	19	39
'compensation'	0	0	0	4	9
Total	26	37	50	401	536

3. Review of Ecological Stressors

The annotated bibliography presents documents on measures to mitigate anthropogenic impacts that are associated with proposed road and mining development in the Ring-of-Fire region. However, road and mining developments, if they proceed, will occur alongside climate change impacts, which will also significantly affect ecosystems in the Far North of Ontario (X. Zhang et al., 2019). It will be difficult to separate impacts originating from mining and roads from those due to climate change.

This section briefly reviews the principal ecological stressors that peatlands and other wetlands will likely face in the Hudson Bay Lowland and the adjacent Boreal Shield from a combination of road and mining developments and climate change.

Seven principal stressors will affect peatlands and wetlands in the Hudson Bay Lowland and the adjacent Boreal Shield (Table 4). They are presented roughly in order of importance for wetlands.

Table 4. The number of documents in the annotated bibliography dealing with each principal category of stressors (total n *= 1,211 documents in database to date).*

Stressor	Number of documents
Hydrological alteration	332
Fertility change and contamination	325
Vegetation or substrate disturbance	382
Landscape conversion and fragmentation	140
Methylmercury	53
Overgrazing	42
Invasive species	27
Other stressors	17

3.1 Hydrological alteration

Keddy (2023a, 2023b) considered that flooding (or drainage) is the principal control on wetland vegetation and habitats. The annual flooding and drainage pattern of the water table is termed the hydropattern (Jackson et al., 2014; Nuttle, 1997). The hydropattern is the primary control on peatland ecosystems, including its vegetation, microflora and fauna. Peatlands, such as fens and bogs, generally have more stable hydropatterns with less water table fluctuations than swamps or marshes.

Hydrological alteration in the Ring of-Fire region, whether it is water table drawdown or flooding, may arise from (i) climate change as temperature warms, which can drop the peatland water table (Breeuwer et al., 2009; Fox & Lehikoinen, 2024; Laine et al., 1995; Macrae et al., 2013; Roulet et al., 1992); (ii) thawing of permafrost peatland, also affected by climate warming, which changes peatland topography, causing permafrost melt scars with increased flooding (Kuhry, 2008; Mack et al., 2023); (iii) increased (or decreased) fire frequency or severity, which shifts the albedo and evapotranspiration (McCarter et al., 2021; J. W. McLaughlin & Packalen, 2021; Thompson et al., 2014; Turetsky et al., 2015; Waddington et al., 2015); (iv) building of aggregate foundation roads, especially across areas of surface or groundwater flow without sufficient culverts or cross-drainage mitigation measures, which increases flooding up-gradient and drawdown down-gradient of the road (Bocking et al., 2017; Miller et al., 2015; Saraswati, Bhusal, et al., 2020; Volik et al., 2020; Willier, 2017); (v) creating seismic line linear disturbances, which can compact and depress the ground surface below the water table and increase flooding (Weiland et al., 2024; Williams et al., 2013); (vi) ditching along roads or for other drainage purposes, which draws down the water table (Koivunen et al., 2023; Prevost et al., 1997) ; (vii) drawdown from pumps for mine working, as well as flooding in areas receiving the mine dewatering (Balliston & Price, 2023; Gautrey et al., 2018; Kohv et al., 2023; Whittington &

Price, 2012, 2013); (viii) damming for hydroelectric power generation (Duchemin et al., 1995; Far North Science Advisory Panel, 2010; Rosenberg et al., 1997); amongst other possible causes.

Alterations to the hydropattern through climate or human-induced flooding or drawdown of the water table can have major impacts on peatland vegetation, microflora and fauna. Waddington *et al.* (2015) reviews the multiple feedbacks of hydrologic controls in peatlands, including on primary production and decomposition of peatland mosses, shrubs and trees. Hydrologic alteration will shift peatland plant communities (Breeuwer et al., 2009; Churchill et al., 2015; Maanavilja et al., 2014; Mälson et al., 2008; Miller et al., 2015; e.g., Weltzin et al., 2003). Drawdown eventually encourages shrubs and trees to dominate (D. R. Campbell et al., 2003; Farrick & Price, 2009; Howson et al., 2021; Laine et al., 1995), with consequent shifts in fauna (Lachance et al., 2005).

Hydrological alterations also change surface water habitats, which are biodiversity hotspots in peatlands for plants and fauna (Beadle et al., 2023; Fox & Lehikoinen, 2024). For instance, hydrologic alteration in northern Europe, apparently caused by climate change as well as by human drainage activities, has reduced the extent of aapamires (Jussila et al., 2024). Aapamires, also called string fens, have expanses of shallow water separated by raised ridges. Reduction in aapamire extent have been linked to lower populations of shorebird and wading birds in Europe (Fox & Lehikoinen, 2024; Fraixedas et al., 2017; R. Heikkinen et al., 2022).

Hydrological alterations, especially flooding, can also lead to the methylation of mercury (Kelly et al., 1997; St Louis et al., 2004), which biomagnifies up the food chain (see section 3.4).

Hydrological alterations will shift decomposition and greenhouse gas production (e.g. Strack et al., 2004, 2008; Strack & Waddington, 2007) and dissolved organic carbon export (DOC; e.g., Strack et al., 2008). These shifts in greenhouse gas production and dissolved organic carbon may not directly affect peatland fauna, but, given the extent of peatlands in the Hudson Bay Lowland, climate-induced water table drawdown may create a positive feedback loop with the release of more greenhouse gases, which will increase the severity of climate change and indirectly affect peatlands through further hydrologic alteration.

3.2 Fertility change and contamination

Keddy (2023a, 2023b) considers that fertility is the second most important control on wetland vegetation and habitats. He defined in terms of the availability of principal growth-limiting macronutrients, namely nitrogen, phosphorus, potassium and sulphur. For peatlands, where these nutrients are scarce, the fertility can also be defined in terms of the minerals calcium and magnesium, which, along with pH, distinguish bogs from fens (Sjörs, 1959, 1963; Wheeler & Proctor, 2000).

Peatlands are nutrient-poor in comparison with swamps and marshes. Nutrient enrichment in peatlands occurs from excess atmospheric deposition of anthropogenic nitrogen in bogs (Bragazza et al., 2006; Ferguson et al., 1984; Press et al., 1986; Vitt et al., 2003), agricultural runoff in fens (Kieckbusch & Schrautzer, 2007), or tertiary treatment of wastewaters in peatlands (Kadlec, 2009; Karjalainen et al., 2016; Kujala et al., 2019; Lavallee & Campbell, 2019).

Nutrient enrichment, even through low but prolonged dosage, can shift peatland productivity and vegetation communities (Aerts et al., 1992; Bubier et al., 2007; Chapin et al., 2003; Ferguson et al., 1984; C. Gignac et al., 2022; Larmola et al., 2013; Lavallee & Campbell, 2019; M. Wang et al., 2016), and consequently impact fauna. Nutrient enrichment can also increase methylation of mercury to form methylmercury (McCarter et al., 2017, 2022; Roth et al., 2021).

Whereas nutrients determine the fertility in peatlands or other wetlands, contaminants, including fugitive dust, hydrocarbons, metals and metalloids, can have the opposite effect and reduce fertility for vegetation and fauna. Note that some contaminants, such as copper and nickel, have beneficial effects on plants at low dosages, but they become toxic at higher dosages (CCME, 1999b, 2015). Methylmercury is a special contaminant that will be considered separately below because it bioaccumulates.

Contaminants can affect primary productivity and can shift vegetation communities and habitat quality (Csavina et al., 2012; L. D. Gignac & Beckett, 1986; Munford et al., 2023; Närhi et al., 2012; Novakovskiy et al., 2021; Racine, 1994). Contaminants may also directly affect peatland or wetland fauna.

Contamination in peatlands or other wetlands may originate from local atmospheric deposition from mining or mineral processing operations (e.g., Bonham-Carter & Kettles, 2001; Cleaver et al., 2021; Shotyk et al., 2017), from distant atmospheric deposition (Meyer et al., 2015; Osborne et al., 2024), from mine waste drainage or mine waters, including from acid rock drainage (Besold et al., 2019; Lazareva et al., 2019; e.g., Sheoran & Sheoran, 2006), or from spills (Jorgenson & Joyce, 1994; Kovaleva et al., 2021). Given that the Ring-of-Fire deposits have massive sulphides (KWG Resources Inc., 2022; Mungall et al., 2010), acid rock drainage will be a major concern.

The large chromite deposits in the Ring-of-Fire are also a large concern because of the possible pollution by hexavalent chromium (Cr(VI)) (Beukes et al., 2017; du Preez et al., 2023; Schindler et al., 2018). Hexavalent chromium is toxic to vegetation and to fauna, as well as to humans (CCME, 1999a, 1999c)

Permafrost thaw in peatlands may also release contaminants (Galloway et al., 2020; Payandi-Rolland et al., 2021; Tarbier et al., 2021). Furthermore, fire in peatlands may resuspend contaminants (Kohlenberg et al., 2018; McCarter et al., 2023; Y. Zhang et al., 2022; Zolkos et al., 2024). Both are tied in with climate warming.

3.3 Vegetation or substrate disturbance

Keddy (2023a, 2023b) considers that disturbance is the third most important control on wetland vegetation and habitats. He defines disturbance as: "*a short-lived event that removes biomass and thereby causes a measurable change in the properties of an ecological community*". While this definition applies to disturbances to vegetation, it could be extended to disturbances to the peat substrate because the peat substrate is so fragile; changes to the substrate will also affect the vegetation.

Fire is an example of a common natural disturbance in peatlands, which temporarily removes the vegetation (Guêné-Nanchen et al., 2022; Shepherd et al., 2021). Fire may be natural or human-caused, but fire frequency is also increasing in the boreal region as a result of climate change (Gibson et al., 2018; J. McLaughlin & Webster, 2013; Nelson et al., 2021; Turetsky et al., 2015). Peat fires are difficult to put out because they smoulder and can reignite, further affecting the peat substrate and the vegetation (Lukenbach et al., 2015; Rein & Huang, 2021).

Humans also disturb vegetation in peatlands and the peat substrate through vegetation clearance, motor vehicle tracks and seismic line construction and peat subsidence (e.g., M. Bérubé & Lavoie, 2000; van Rensen et al., 2015; Williams-Mounsey et al., 2021).

Peat extraction is a well-researched type of severe disturbance for both the vegetation and the peat substrate (e.g., M. Bérubé & Lavoie, 2000; Gagnon et al., 2018; Girard et al., 2002; Poulin et al., 2005). We include peat extraction as a form of disturbance, even though it is a longer-term event and could also be considered as ecosystem conversion.

Overgrazing is also a disturbance under this definition, but it is considered separately below.

3.4 Landscape conversion and fragmentation

Human developments, such as mining, create a footprint of buildings, mine footings, tailings management areas, other mine wastes, ore stockpiles, roads, pipelines and other infrastructure. When they are constructed in peatlands, many require foundations, often achieved by the placement of geotextiles with gravel fill over top of peatlands (De Guzman & Alfaro, 2016, 2018; Mesri & Ajlouni, 2007). Some features, such as mine waste facilities are built directly over peatland. For other features, the underlying peat may be removed to assure stability of built structures or roads.

This mine footprint converts peatland to upland and removes peatland habitat for vegetation, and fauna. Mine camps in the Hudson Bay Lowland, such as Victor Mine or Detour Lake Mine, demonstrate how mining footprints replace peatlands with uplands (CEAA, 2011; De Beers Canada, 2004). Although these mine sites are reclaimed after mine closure, these areas remain as upland habitats and peatlands are lost (e.g., De Beers Canada, 2004).

Besides simply converting habitat, linear disturbances, such as roads, winter roads, pipelines, seismic lines and power transmission lines also fragment the landscape and facilitate the mobility of fauna and flora. In northern Alberta, such linear features through peatlands increase the movement of predators such as wolves and bear, which increases pressure on prey species, including threatened boreal populations of woodland caribou (e.g., DeMars & Boutin, 2018; McKay et al., 2021; St-Pierre et al., 2022). Linear disturbances can also increase the spread of invasive plant species in peatlands (C. Dubé et al., 2011; Jodoin et al., 2008).

As pointed out above, linear disturbances such as roads can also impede water movement and cause hydrologic alterations (Miller et al., 2015; Saraswati, Petrone, et al., 2020; Volik et al., 2020). Furthermore, landscape conversion can lead to increased contact between peat and mineral soil and lead to increased mobilization of methylmercury (Mitchell et al., 2009).

3.5 Mercury and methylmercury

Mercury could just be considered as another contaminant, but it is distinct because (i) it enters peatlands at low concentration through atmospheric deposition as inorganic mercury from distant natural and anthropogenic sources (Osborne et al., 2024); (ii) methylation of inorganic mercury can occur to form toxic methylmercury (e.g., Mitchell et al., 2009); and (iii) methylmercury biomagnifies up the food chain through fauna (CCME, 2000; Driscoll et al., 2013). The impacts of methylmercury will consequently be greater on predatory fauna at higher trophic positions, such as piscivorous fish, polar bear or wolverine. It will also have greater effects on humans who eat this wildlife. Methylmercury is a toxin, and at higher concentrations it remains a key concern for local communities of people dependent on wildlife for food, as well as for regulators (CCME, 2000, 2003).

The methylation of mercury is stimulated by substrate disturbances (Mitchell et al., 2009, 2009), flooding (B. A. Branfireun et al., 2005; Kelly et al., 1997; St Louis et al., 2004), nutrient enrichment (McCarter et al., 2017; Roth et al., 2021), or soil warming/permafrost thaw (Gordon et al., 2016; Kohlenberg et al., 2018; Kolka et al., 2024; Zolkos et al., 2024). Sulphate stimulates methylmercury production (Mitchell et al., 2009), and increased sulphate associated with mining disturbances in the Hudson Bay Lowland also increase methylmercury (Twible, 2017).

3.6 Overgrazing

Keddy (2023a, 2023b) also recognizes herbivory as an important control on wetland vegetation. Herbivory could be simply considered as another natural disturbance because the herbivores are removing biomass. However, some wetland herbivore populations have grown dramatically as a result of human actions, which has led to overgrazing in some wetlands. For instance, the principal agents of overgrazing in wetlands in the Hudson Bay Lowland are lesser snow geese, whose populations have increased multiple fold as a result of food subsidies in agricultural fields in central North America (R. L. Jefferies et al., 2003).

A great deal of research has taken place on the effects of overgrazing by lesser snow geese but also Canada geese on the saltmarsh, marsh and other wetlands in the coastal regions of the Hudson Bay Lowland. Similar research has taken place in peatlands in the high Arctic where greater show geese are the main grazers. Geese overgraze and can effectively convert marsh or saltmarsh to mudflats or low productivity habitats (G. Gauthier et al., 2004; e.g., Handa et al., 2002; R. Jefferies et al., 2006; R. Jefferies & Rockwell, 2002; Kotanen & Abraham, 2013; Nishizawa et al., 2021; Peterson et al., 2013). The overgrazed wetlands in turn affect habitat for other fauna (Flemming et al., 2019; Milakovic et al., 2001; Milakovic & Jefferies, 2003; Park, 2017; Rockwell et al., 2003).

Peatlands are less impacted by goose herbivory (G. Gauthier et al., 2004; Nishizawa et al., 2021; Speed et al., 2010). However, peatlands can also be overgrazed or trampled by ungulate herbivores where their populations are dense (Courchesne et al., 2018; T. Kolari et al., 2019; Mosbacher et al., 2019), with consequent effects on peatland flora and fauna.

Overgrazing can even interact with permafrost and slow down its development (Deschamps et al., 2023).

3.7 Invasive species

Invasive plant species can be an additional stressor to peatlands affecting overall habitat quality. They may accompany the above stressors. For instance, invasive species occur where linear disturbances occur through peatlands or other wetlands (Brisson et al., 2010; C. Dubé et al., 2011; Jodoin et al., 2008). Some invasive weed species even colonize wetlands in the Alberta oil sands region (Allen et al., 2021).

Riley (2003) lists and discusses the non-native species found in the Hudson Bay Lowland. However, there is little indication of the probable invasive species that could spread to the Ring-of-Fire region. *Phragmites* is a main invasive species of concern for wetlands. It is currently rare in the Hudson Bay Lowland (Riley, 2003), but it is found in the adjacent Boreal Shield to the south (Mal & Narine, 2004), so it could spread north with road construction and climate warming.

3.8 Other stressors

Other stressors from mining or road developments in the Ring-of-Fire that may impact migratory birds and species-at-risk in peatlands or wetlands include noise pollution that often, but not always, interfere with bird vocalizations (E. M. Bayne et al., 2008; Douse &

Artz, 2022; Habib et al., 2007; Sánchez et al., 2022, 2023; Shonfield & Bayne, 2017b) or other wildlife (OMECP, 2020), nighttime light pollution that cause bird collisions (Lao et al., 2020; Teck, 2017) and other factors causing bird collision (Baasch et al., 2022; Rioux et al., 2013).

4. Mitigation of Ecological Stressors

The mitigation hierarchy has four to five levels, set in a hierarchy, with lower levels being most desirable to conserve biodiversity (Arlidge et al., 2018; Forest Trends, 2018; Milner-Gulland et al., 2021). The fifth level of mitigation, compensation, is not included in some formulations of the mitigation hierarchy (Milner-Gulland et al., 2021, 2021), but it is considered here given the potential difficulty of even offsetting unavoidable potential impacts from mining and road development to the wetlands in the Hudson Bay Lowland and adjacent Boreal Shield.

4.1 Impact avoidance

Impact avoidance is defined as "*measures taken to avoid creating impacts from the outset (including direct, indirect and cumulative impacts), such as careful spatial or temporal placement of elements of infrastructure, in order to completely avoid impacts on certain components of biodiversity*" (Forest Trends, 2018).

A summary of documents that are related to impact avoidance of principal stressors is presented in Appendix B along with key documents. Given the overwhelming dominance of wetlands, mostly peatlands, in the landscape in the Ring-of-Fire region, it will be very difficult for mining or road developments to completely avoid impacts to these wetlands.

Best practices to avoid disturbances should be implemented at the planning stage of mine and road developments.

4.1.1 Hydrological alteration

Some documents point to the conservation and protection of peatlands in northern Canada, including within the Hudson Bay Lowland, as a means to avoid hydrological alterations, especially linked to climate change (Alexandrov et al., 2020; Drever et al., 2021; Helbig et al., 2020; Humpenöder et al., 2020; Strack et al., 2022). Conserving these peatlands would also avoid fertility change/contamination, vegetation and substrate disturbance, landscape conversion and fragmentation, methylmercury formation, some other stressors as well. It is however difficult to see ways to both conserve peatlands and allow mining development in the immediate Ring of Fire region. Conservation may also be seen as a strategy to offset impacts of mining and road disturbance (see section 4.4).

Other documents present strategies for the construction of roads around peatlands to avoid hydrologic alterations (Gilmour et al., 2022; INAC, 2010; Partington et al., 2016). Again, given the predominance of wetlands in the landscape of the Ring-of-Fire, it will be very difficult to completely avoid hydrological alterations from roads.

4.1.2 Fertility change and contamination

Several documents deal with avoiding contamination. Most relate specifically to the avoidance of mine-related pollution from acid rock drainage (Alam & Shang, 2012; Environment Canada, 2009; INAP, 2018; O'Kane Consultants Inc., 2004a, 2004b, 2004c, 2004d, 2004e, 2007; W. A. Price, 2009; Stratos Inc. & Brodie Consulting Ltd., 2011; Zinck & Griffith, 2013) or the avoidance of hexavalent chromium pollution (Beukes et al., 2017; Deepa et al., 2025; du Preez et al., 2023). Given their important impacts, all efforts should strive to avoid acid rock pollution or pollution by hexavalent chromium. Monitoring for acid rock drainage and hexavalent chromium will play a large role in avoiding their impacts.

Several documents also relate to avoiding air pollution impacts from fugitive dust emissions (Cecala et al., 2019; Environment Canada, 2009; OMECC, 2017). Again, monitoring for fugitive dust will be key.

Given the predominance of peatlands in the Ring-of-Fire landscape and the large deposits of critical metals there, absolute avoidance of the impacts of fertility change and contamination to these wetlands will be difficult and impact minimization may be the more realistic mitigation option.

4.1.3 Vegetation or substrate disturbance

A few documents relate to the avoidance of road construction in peatlands, and consequent vegetation or substrate disturbance (INAC, 2010; Partington et al., 2016). But as already stated, the predominance of wetlands in the landscape makes avoidance of disturbances to vegetation or substrate in the Ring-of-Fire very difficult.

4.1.4 Landscape conversion and fragmentation

Avoiding landscape conversion and fragmentation is considered as a mitigation measure for woodland caribou (OMECP, 2020; OMNR, 2016). Avoiding peatlands for road construction is also recommended to limit landscape fragmentation (INAC, 2010; Partington et al., 2016). However, avoidance of impacts will be difficult to apply given the predominance of peatlands in the landscape of the Ring-of-Fire.

Sound mining practices, including innovation, may effectively avoid or at least reduce landscape conversion to the surrounding environment including to wetlands (Environment Canada, 2009; Musetta-Lambert et al., 2019). For instance, the use of paste tailings instead of tailings ponds would reduce the footprint for tailings management (e.g., Franks et al., 2011; C. Wang et al., 2014). Infilling with tailings in underground mine workings will also reduce the surface disposal of tailings (C. Wang et al., 2014). Other mining innovations may exist that would allow to carefully plan and avoid mining-related impacts to wetlands and their fauna. Again however, given the overwhelming extent of wetlands in the landscape of the Ring-of-Fire, it is more realistic that mining innovation mitigation measures will only minimize impacts.

4.1.5 Mercury and methylmercury

Several documents link methylmercury production to peatland disturbances (Braaten & de Wit, 2016; Mitchell et al., 2008, 2009), flooding (Kelly et al., 1997) or to mining-related disturbance (Twible, 2017). Avoiding substrate disturbance, nutrient enrichment and flooding as well limiting the creation of peatland upland interfaces and preventing sulphate pollution will avoid the risk of methylmercury production. However, complete avoidance will be difficult to achieve in the Ring-of-Fire region because of the predominance of wetlands in the landscape. Monitoring of methylmercury will play a large role in avoiding its impacts.

4.1.6 Overgrazing

The overpopulation of lesser snow geese and Canada geese is the main cause of overgrazing in the Hudson Bay Lowland. Increased hunting or population control is the primary means to avoid this stressor (Peterson et al., 2013). However, geese prefer the coastal marshes of Hudson and James Bay instead of peatlands, so overgrazing will most likely be avoided in the Ring-of Fire region because peatlands dominate there. Overgrazing could become a concern during mine reclamation of uplands when early successional vegetation is trying to take hold.

4.1.7 Invasive species

Halloran et al. (2013) present the best management practices to avoid the spread of invasive flora and fauna on equipment before moving them between sites. Careful application of these guidelines and continued monitoring will help avoid the spread of invasive species into the Ring-of-Fire landscape.

4.1.8 Other stressors

OMECP (2020) also presents guidelines to avoid noise disturbances to woodland caribou. Douse and Artz (2022) presents sound protocols on how to avoid disturbances to breeding birds during peatland restoration. Similar measures could be adapted to avoid or at least to minimize disturbance from mining activities during the bird breeding season (June-July).

Lao et al. (2020) presents general protocols to avoid or at least minimize collisions or other impacts on migratory birds. Such measures could be applied by mines or mineral processing facilities in the Ring-of-Fire region to avoid impacts to migratory birds.

4.2 Impact minimization

Impact Minimization is defined as "*measures taken to reduce the duration, intensity and/or extent of impacts (including direct, indirect and cumulative impacts) that cannot be completely avoided, as far as is practically feasible"* (Forest Trends, 2018).

A summary of documents on impact minimization is presented in Appendix B along with key documents. Given the predominance of peatlands in the landscape of the Ring-of-Fire region, road or mining impacts to these wetlands may not be easily avoided, but they may be minimized.

As with impact avoidance, best practices to minimize disturbances should be implemented at the planning stage of mine and road developments.

4.2.1 Hydrological alteration

Osko et al. (2018) and Volik et al. (2020) present the best guidance on how to minimize hydrological impacts to wetlands and how to restore wetlands, which will be applicable to the Ring-of-Fire region. Thom et al. (2019) deal mostly with restoration of peatlands, but they also offers sound advice on minimizing disturbance to the hydrology of peatlands in general. Environment Canada (2009) presents general guidelines to minimize the disturbance to landscape hydrology as a result of mining, but not specifically for wetlands or peatlands.

Several documents point to the best practices for minimizing hydrological alterations in wetlands specifically as a result of the construction of roads (Ducks Unlimited Canada, 2014; INAC, 2010; Partington et al., 2016; Saraswati, Petrone, et al., 2020; Williams et al., 2013). A few from Scotland relate to minimizing impacts from roads or structures on blanket peatlands (Forestry Civil Engineering & Scottish Natural Heritage, 2010; Gilmour et al., 2022; Jorat et al., 2024). Because blanket peatlands do not occur in the Hudson Bay Lowland, these documents may not apply directly, but they still offer sound recommendations to minimize the hydrological impacts of roads on peatlands. Geotechnical studies show that placing roads direct over peat is possible (De Guzman & Alfaro, 2016, 2018; Long et al., 2023), but these studies do not indicate whether they interrupt groundwater flow and thereby cause drawdown or flooding. The careful placement of roads and avoiding wetlands where possible, along with placing multiple culverts or other measures to allow crossflow of groundwater and surface water will help to minimize hydrological alterations from roads in the Ring-of-Fire region.

Mining wastes and mine waters have been shown to capture greenhouse gas emissions (Baena-Moreno et al., 2023; Mervine et al., 2018), which would contribute to reducing global warming and also indirectly reduce hydrological alterations in peatlands. However, any potential gains from greenhouse gas capture from mining wastes would need to be balanced with the greenhouse gas costs of mining activities to determine if mining wastes offer any positive effect against climate warming.

Kinas et al. (2024) present sound guidelines on how to avoid excessive flooding from beaver, especially on road networks.

4.2.2 Fertility change and contamination

Minimizing changes to the fertility of receiving environments, especially contamination, are pervasive themes for mining and mineral processing (Environment Canada, 2009) and will be critical to apply in the Ring-of-Fire region.

Protocols exist to minimize the impacts of explosive residues (BCMECCS, 2018a; Chatterjee et al., 2017), which can lead to nutrient enrichment or contamination in the receiving peatland environments in the Ring-of Fire region.

Many best management practice guides aim to contain and minimize acid rock drainage pollution offsite (INAP, 2018; MEND, 2012; O'Kane Consultants Inc., 2004a, 2004b, 2004c, 2004d, 2004e, 2007; W. A. Price, 2009; Stratos Inc. & Brodie Consulting Ltd., 2011; Zinck & Griffith, 2013). Again, mitigating acid rock drainage impacts to peatlands will be a concern because of the predominance of peatlands in the landscape and the massive sulphides in several Ring-of-Fire deposits (KWG Resources Inc., 2022; Mungall et al., 2010). The desulphurization of tailings, as is done for reactive tailings in the nearby Musselwhite Mine (Alam & Shang, 2012), would also help minimize acid rock drainage.

Because hexavalent chromium (Cr(VI)) is a toxin and a large concern from chromite mining in the Ring-of-Fire , several documents review how Cr(VI)-related pollution could be minimized (Beukes et al., 2017; Deepa et al., 2025; du Preez et al., 2023).

Protocols are also available to minimize the impacts of pollution from fugitive dust (BCMEMLCI & BCMECCS, 2023; Cecala et al., 2019; Golder Associates, 2010; OMECC, 2017). Other guidelines are available to minimize water erosion and sedimentation offsite (BCME, 2015b, 2015a; Environmental Dynamics Inc, 2003; Garneau et al., 2019).

Protocols exist to minimize the effects of spills, usually of hydrocarbons (BCMECCS, 2018b; INAC, 2007). Several papers attempt to understand the movement of hydrocarbons through peatlands to minimize the spreading of contamination from spills (Gharedaghloo & Price, 2018, 2021; P. K. Gupta et al., 2023; Rezanezhad et al., 2012).

Several documents relate to the design and performance of treatment peatlands or northern treatment wetlands to minimize impacts to receiving environments. The receiving environments in the Ring-of-Fire region will generally be fen peatlands and watercourses. Documents exist on peatland tertiary treatment of excess nutrients from municipal wastewaters in (e.g., Kadlec, 2009; Kadlec & Wallace, 2009; Karjalainen et al., 2016; Kujala et al., 2019; McCarter et al., 2017), peatland treatment of excess nutrients from peat extraction sites (K. Heikkinen et al., 2018), or from mine sites (Bishay & Kadlec, 2005; Ronkanen & Kløve, 2009), wetland treatment of hydrocarbon polluted waters (Simair et al., 2021), floating wetland treatment of sulphate (V. Gupta et al., 2020) and peatland treatment of mine waters with metal or metalloid contamination, including arsenic, nickel and antimony (U. A. Khan et al., 2020; Palmer et al., 2015; Sheoran & Sheoran, 2006). Several documents also emphasize cold climate treatment wetland designs for year-round treatment (Eskelinen et al., 2015; Kujala et al., 2019, 2024; M. Wang et al., 2017).

A few documents also demonstrate the capture of metal ions by peat or sphagnum (e.g., Balan et al., 2009; B. Gupta et al., 2009). Several articles also show that it is possible to make biochar from peat and that it effectively removes heavy metals from solution (S.-J. Lee et al., 2015). The abundance of peat and sphagnum in the Ring-of-Fire landscape may allow for their incorporation into filters for mine water treatment systems to minimize impacts of mine waters to the surrounding environments.

4.2.3 Vegetation or substrate disturbance.

Thom (2019) presents general practices on how to minimize disturbances to substrates and vegetation during the management of peatlands.

Best management practices exist to minimize substrate disturbances from heavy equipment in peatlands (APTHQ, 2024; C. Nugent et al., 2003; Sutherland, 2003). Several protocols also exist to identify, minimize and extinguish fires in peatlands, including smouldering peat fires (APTHQ, 2021; Deane et al., 2022; Hokanson et al., 2018).

4.2.4 Landscape conversion and fragmentation

The application of sustainable mining practices could minimize the mining footprint and consequently limit ecosystem conversion (Environment Canada, 2009). For instance, the disposal of thickened or paste tailings (Franks et al., 2011; C. Wang et al., 2014), where excess water is removed from the tailings slurry, would eliminate the need for tailings ponds and dams, thereby minimizing the mine footprint and also eliminating the risk of tailings dam failure. Reusing tailings in underground mine workings as cemented paste tailings (Qi & Fourie, 2019) would further reduce the surface mine footprint and again minimize landscape conversion. A broader review of innovative mining practices would certainly point to other strategies to minimize the mine footprint and minimize ecosystem conversion and landscape fragmentation.

For linear features, Ryder et al. (2005) present best practices to minimize impacts from pipelines. Low impact seismic lines minimize impacts to peatlands and also improve recovery of vegetation (Filicetti et al., 2023; Franklin et al., 2021). These and other best practices (OMECP, 2020; OMNR, 2016) will minimize the impacts on woodland caribou.

4.2.5 Methylmercury

No documents were found that explicitly deal with the minimization of methylmercury formation. However, conditions that enhance the methylation of mercury include peatland flooding (B. Branfireun & Roulet, 2002; Kelly et al., 1997; St Louis et al., 2004), nutrient or sulphate enrichment in peatlands (McCarter et al., 2017; Roth et al., 2021; Twible, 2017), and soil disturbance to peatlands especially at the mineral peat interface (Braaten & de Wit, 2016; Mitchell et al., 2008, 2009), so measures that limit these impacts should also limit methylmercury. Again, careful monitoring will help assess and minimize the production of methylmercury in the Ring-of-Fire region.

4.2.6 Overgrazing

The only documents on minimizing overgrazing relate to the reduction of the populations of the primary herbivores responsible for the overgrazing. For the marshes along the Hudson and James Bay coast, this would involve reducing populations of lesser snow geese (Peterson et al., 2013). Given the preference of lesser snow geese for coastal marshes instead of peatlands, it is likely that overgrazing will need to be mitigated in the Ring-of-Fire region.

4.2.7 Other stressors

OMECP (2020) again presents guidelines to minimize noise disturbances to woodland caribou, and Douse and Artz (2022) presents protocols on how to minimize disturbances to birds during work in peatlands with machinery during the breeding season.

OMNRF (2014), Lao et al. (2020) and Baasch et al. (2022) also present protocols to minimize collisions with migratory birds. Such measures could be applied by mines or mineral processing facilities in the Ring-of-Fire region.

4.3 On-site Restoration

On-site restoration is defined as "*measures taken to rehabilitate degraded ecosystems or restore cleared ecosystems following exposure to impacts that cannot be completely avoided and/or minimised*" (Forest Trends, 2018).

A summary of the documents that cover on-site restoration is presented in Appendix B along with key documents. The Ring-of-Fire region is almost pristine with minimal anthropogenic disturbance except from recent mineral exploration (P. Lee et al., 2010). Efforts should be made to avoid or minimize stressors and thereby limit the need for on-site restoration.

4.3.1 Hydrological alteration

Wetland and peatland restoration is a mature field, and, given the fundamental importance of their hydrology, there are many documents on how to restore hydrology of wetlands and peatlands.

Several documents provide general guidance on rewetting peatland hydrology (Joosten, 2021; NatureScot, 2024c; O'Kelly, 2008; Thom et al., 2019). Biebighauser (2015) also presents practical guidance on restoring water levels during wetland restoration, although with less guidance on peatland restoration.

Several documents also present detailed guidance for rewetting after peat extraction (Landry & Rochefort, 2012; J. Price et al., 1998, 2016; J. S. Price et al., 2003; Quinty et al., 2020b; Taylor et al., 2016). Rewetting also involves tree cutting to reduce evapotranspiration (S. Dubé et al., 1995; Gaffney et al., 2020; Howson et al., 2021; Ketcheson & Price, 2011; J. Price et al., 2016; J. S. Price et al., 2003). Mazerolle et al (2006), Desrochers and Rochefort (2021), Beadle (2023), Soumets et al. (2023) all demonstrate how rewetting improves populations of fauna in peatlands.

Not only are their good guidebooks on rewetting, several recent videos also effectively present best practices to restore the hydrology of peatlands (e.g., Cairngorms National Park Authority, 2022; NatureScot, 2024a, 2024b, 2024d, 2024e; Rochefort & Jutras, 2024, 2025).

Documents also demonstrate best management practices to restore the hydrology of seismic lines for bitumen *in situ* extraction or similar other disturbances where excess flooding now occurs (Alberta Environment and Parks, 2017; Bird & Xu, 2021b; Weiland et al., 2024).

4.3.2 Fertility change and contamination

Nutrient-enriched fens can be restored through harvesting and removal of nutrient-rich biomass (Comber et al., 2023; Hinzke, Li, et al., 2021; Hinzke, Tanneberger, et al., 2021; Jabłońska et al., 2021; Kotowski et al., 2016). In contrast, several documents point to the nutrient-poor conditions of disturbed post-extraction peatlands and provide recommendations on proper phosphorus fertilization during restoration (Liu et al., 2024; Pouliot et al., 2015; Quinty et al., 2020c). These recommendations may be useful for restoring nutrient regimes in other disturbed peatlands.

A series of documents provide sound guidance on how to develop cover systems over acid-generating mining wastes (MEND, 2012; O'Kane Consultants Inc., 2004a, 2004b, 2004c, 2004d, 2004e, 2007). While they are primarily meant to minimize contaminant impacts moving off site, they will also provide guidance to restore ecosystems on-site over mining wastes.

Documents also review best methods to bio- or phytoremediate hydrocarbon spills on site (Jorgenson & Joyce, 1994; Koshlaf & Ball, 2017; Naeem & Qazi, 2020).

4.3.3 Vegetation or substrate disturbance.

Many documents relate to restoration after vegetation or substrate disturbance. Thom (2019) and Nature Scott (2024c) are good general guides that present protocols on the restoration of disturbed peatland substrates or vegetation. Biebighauser (2015) provides also good general guidance for the restoration of wetland vegetation and substrates.

Detailed protocols exist to restore substrates and vegetation in bogs or poor fens following peat extraction using the moss layer transfer technique (MLTT; Allan et al., 2024; Quinty et al., 2019, 2020a, 2020b, 2020c; Rochefort et al., 2003). These will be useful for other peatland disturbances. A protocol manual also exists for tree planting in peatland with thin peat (Hugron et al., 2013). Protocols are also available to restore peat-extracted fens, but these are still in the developmental stage (GRET, 2016; A. Khan et al., 2025; Rochefort et al., 2016). Several documents present specific protocols for donor sites for sphagnum moss transfer material (Bird & Xu, 2021a; Guêné-Nanchen et al., 2019; Quinty et al., 2019). Peatlands restored using MLTT return to net carbon sequestering ecosystems (K. A. Nugent et al., 2018), lower methane emissions (K. Nugent et al., 2021) and have only very short impacts to carbon sequestration as a result of donor material collection (K. Murray et al., 2017).

The restoration of peatland pool environments is more challenging, but several documents aim specifically at pool restoration (Bourgeois et al., 2019; Laberge et al., 2015; Mazerolle et al., 2006; Poulin et al., 2011).

Multiple documents aim to restore vegetation and substrate disturbances along seismic lines (Alberta Environment and Parks, 2017; Filicetti et al., 2019; Finnegan et al., 2019; Kleinke et al., 2022; Pinzon et al., 2023; van Rensen et al., 2015; Yemshanov et al., 2023). Murray et al. (2021) describes the greenhouse gas emissions of these seismic line restorations.

Other documents aim to restore infrastructure pads in peatlands such as drill pads or other linear disturbances including winter roads, wood chip-base roads and aggregate-based roads (Alberta Ministry of Environment and Parks, 2017, 2020; Bird et al., 2016, 2017; Bird & Xu, 2021c; D. Campbell & Corson, 2014; Caners & Lieffers, 2014; Corson & Campbell, 2013; M. Gauthier et al., 2018; Lemmer et al., 2020, 2023; MacKenzie & Renkema, 2013; Shunina et al., 2016; Sobze et al., 2013; St-Pierre et al., 2021; Xu et al., 2022).

Granath et al. (2016) presents peatland restoration using MLTT as means to restore peatlands after severe fire that has burned deep into peatlands.

4.3.4 *Landscape conversion and fragmentation*

A series of documents presents the design and performance results of experimental fen creation in Alberta, including the hydrology, geochemistry, carbon dynamics and vegetation (Biagi et al., 2019, 2021; Borkenhagen & Cooper, 2019; Clark et al., 2019; Coulas et al., 2021; Davidson et al., 2021; Irvine et al., 2021; Khadka et al., 2016; K. R. Murray et al., 2017; Nwaishi, Petrone, Macrae, Price, Strack, & Andersen, 2016; Nwaishi, Petrone, Macrae, Price, Strack, Slawson, et al., 2016; Oswald & Carey, 2016; J. S. Price et al., 2010; Prystupa et al., 2023; Spennato et al., 2018). This approach may be useful for creating peatlands on-site following severe disturbance and ecosystem conversion in the Ring-of-Fire region. However, given the relative difficulty, high cost and high maintenance to create these peatlands, minimizing landscape conversion of peatlands should be favoured.

Other documents may also be useful to minimize landscape fragmentation as a result of ecosystem conversion (Alberta Ministry of Environment and Parks, 2017; OMECP, 2020). Several of the documents under substrate or vegetation disturbance of seismic lines or other linear disturbances will also act to restore peatlands and reduce landscape fragmentation and conversion (e.g., Alberta Environment and Parks, 2017; Alberta Ministry of Environment and Parks, 2020; Filicetti et al., 2019; Kleinke et al., 2022). Several documents deal more specifically with rehabilitating habitat fragmentation (Alberta Ministry of Environment and Parks, 2020; Golder Associates, 2015; Hornseth et al., 2018; OMECP, 2020; St-Pierre et al., 2021; Yemshanov et al., 2023).

4.3.5 *Methylmercury*

We could find no explicit protocols restore peatlands or other northern ecosystems affected by elevated methylmercury production. Again, monitoring will be an important strategy to identify problematic areas.

4.3.6 *Overgrazing*

We found only one document that relates to the restoration of overgrazed wetland habitats by lesser snow geese (Handa & Jefferies, 2000). However, the authors point out the futility of restoring these habitats unless populations of geese can first be reduced.

4.3.7 *Invasive species*

Sound protocols exist to restore peatlands or other wetlands invaded by *Phragmites* (Nichols, 2024), if it appears in the region as a result of mining and road disturbances. Lavoie (2019) presents good summaries of control methods for many other invasive species found in wetlands.

4.3.8 Other stressors

No protocols provide precise guidance related to on-site restoration following noise pollution or bird collisions.

4.4 Offsetting

Offsetting is defined as "*measures taken to compensate for any significant residual, adverse impacts that cannot be avoided, minimised and/or rehabilitated or restored, in order to achieve no net loss or preferably a net gain of biodiversity. Offsets can take the form of positive management interventions such as restoration of degraded habitat, arrested degradation or averted risk, protecting areas where there is imminent or projected loss of biodiversity"* (Forest Trends, 2018). A summary of documents on offsetting is presented in Appendix B along with key documents. Offsetting is considered here across all stressors, without distinction of stressor type.

Several useful documents discuss biodiversity offsetting in general globally (BBOP, 2009; Gardner et al., 2013; ICMM & IUCN, 2012; Pope et al., 2021) or from the United States where offsetting is much more prevalent (Ecosystem Planning and Restoration, 2022; National Academies of Sciences, Engineering, and Medicine, 2001). Although wetland mitigation is often the specific biodiversity component that is offset, peatlands such as fens and bogs are rarely considered because they are difficult to successfully create (National Academies of Sciences, Engineering, and Medicine, 2001). However, the experimental peatland creation in Alberta demonstrates that offsetting by creating or restoring peatlands elsewhere is possible (see section 4.3.4 above).

In Canada, at the federal level, a draft policy for biodiversity compensation is available (ECCC, 2020), but Poulton and Ray (2023) point out that few examples of actual offsetting exist and monitoring is usually deficient, limiting any assessment of success. A review of federal fisheries habitat offsetting points to the low offsetting ratio in many projects and problems with compliance and monitoring of success (Harper & Quigley, 2005).

Ontario has considered implementing wetland offsetting (Bell & Hedges, 2016; Ontario Nature, 2022; D. Poulton, 2015; D. Poulton & Bell, 2017; Wetland Conservation Strategy Advisory Panel, 2018) and local governments in Ontario have actually applied wetland offsets (Hasenack et al., 2023). However, these have all been in highly developed southern Ontario, where many degraded wetland ecosystems occur.

The Hudson Bay Lowland and the adjacent Boreal Shield in the Far North of Ontario are part of one of the largest intact forest landscapes in Canada and globally (P. Lee et al., 2010). (They include all wetlands in the Hudson Bay Lowland within their 'intact forests'.) Few if any degraded wetlands occur in this region, except in the coastal environments as a result of goose overgrazing. Consequently, it will be difficult to offset by restoring degraded wetlands within the Hudson Bay Lowland or the adjacent Boreal Shield.

Offsetting by restoring degraded wetlands or creating wetlands outside the Far North of Ontario would be possible, as for instance in the highly degraded environment of southern Ontario where an estimated 68% of wetlands have been lost (Penfound & Vaz, 2022). This remains a viable option, even though offsetting is generally meant to be applied within the same ecoregion that was impacted (Arlidge et al., 2018; Milner-Gulland et al., 2021). Out-of-region offsetting projects could focus on birds that breed in the Hudson Bay Lowland but migrate through southern Ontario, if suitable stopover habitat there is degraded and available for restoration.

From the definition of offsetting above, protecting areas is a form of offsetting if those areas are in imminent or projected danger of being lost. Many documents highlight the role of peatlands in the global carbon cycle and point to the value of conserving these peatland to minimize climate change (Alexandrov et al., 2020; Drever et al., 2021; L. I. Harris et al., 2022; Helbig et al., 2020; Humpenöder et al., 2020; Strack et al., 2022). It may be possible to protect wetlands in the broader Hudson Bay Lowland or Boreal Shield outside of the Ring-of-Fire region. However, these wetlands are not yet in imminent or projected danger of being lost, so it is difficult to use this concept of offsetting for this region. Conservation of the vast peatlands in the Hudson Bay Lowland and adjacent Boreal Shield should be better considered as a measure to avoid impacts.

Indigenous perspectives inform biodiversity offsetting in Ontario and Canada (Bois-Charlebois, 2018; McDermott & Bell, 2017). The importance of the land and the duty to consult is stressed. Habitat improvements for wildlife important to indigenous communities may be considered as offsetting. However, offsetting through wildlife improvements would need to exceed the scale and value of wetlands or peatlands lost.

4.5 Compensation

Compensation is defined as "*measures to recompense, make good or pay damages for loss of biodiversity caused by a project that can fall short of achieving no net loss or a net gain. For instance, this may occur if: conservation actions have been planned to achieve no net loss; losses and gains of biodiversity have been quantified; no mechanism is in place for long term implementation; it may be impossible to offset the impacts; or compensation payments are used for training, capacity building, research or other outcomes that will not result in measurable conservation outcomes on the ground*" (Forest Trends, 2018).

As pointed out above, compensation is often not considered as part of the mitigation hierarchy, because it will result in a net loss of biodiversity. However, given the difficulties in even offsetting some effects of proposed mining and road developments in the Ring-of-Fire region, consideration may have to be given to it. Again, the key documents on compensation are given in Appendix B.

Impact benefit agreements (IBA) follow under the compensation definition in the mitigation hierarchy (Baird et al., 2023; e.g., Gunton et al., 2020). Funding for research on best mitigation solutions could be another form of compensation.

5. Monitoring

Monitoring is key because it allows proponents, regulators and local communities to gauge whether the mitigation hierarchy is being successfully implemented.

We include documents that describe useful approaches or techniques to monitor changes in the Ring-of-Fire region. We also include documents that provide baseline environmental conditions of the Hudson Bay Lowland and the adjacent Boreal Shield, for instance studies of recent ecological conditions and vegetation (Riley, 2003, 2011; Sjörs, 1959, 1963), past conditions as determined from paleoecological analyses (Davies et al., 2021; Hargan et al., 2020; Jeziorski et al., 2015; Packalen et al., 2016), and pre-development trace element concentrations in peatlands (Glooschenko & Capoblanco, 1982; McDonough et al., 2022; Su et al., 2021).

Several tools from the Alberta oil sands will be useful to monitor overall changes in the Ring-of-Fire region. The Before-After Dose Response (BADR) program is a strong model that uses multiple biomonitoring organisms (E. Bayne et al., 2022). More specific wetland biomonitoring tools from the Alberta oil sands could also be useful to monitor changes in wetlands in the Ring-of-Fire region (Ficken et al., 2022; Mahoney et al., 2023; Rooney & Bayley, 2011, 2012). These biomonitoring approaches could be modified to consider the predominance of wetlands and peatlands in the Ring-of-Fire landscape and the peculiarities of these mining and road disturbances. Although these biomonitoring techniques allow an assessment of anthropogenic change, they do not always allow for a diagnosis of the cause of these shifts. Other monitoring approaches will be required.

5.1 Hydrological alteration

Wetland hydrology monitoring programs in the Alberta oil sands region may be useful for the Ring-of-Fire region (Eaton & Charette, 2016; Mahoney et al., 2023). These are based on ground-based measurements. For instance, wells and piezometer nests provide point samples, but they will provide detail of hydrological alterations (e.g., McCarter & Price, 2013; Whittington & Price, 2013). Gutierrez-Pacheco et al. (2021) provides a protocol to estimate daily water levels from longer term well measurements.

Given the large area of the Ring-of-Fire and the predominance of wetlands and peatlands, remote sensing approaches will be important to assess shifts in the hydrology of these peatlands and act quickly to minimize them, restore them or offset or compensate for them. Satellite, LiDAR or drone remote sensing methods are used to monitor surface hydrology, but also subsurface moisture conditions (Banskota et al., 2017; Bradley et al., 2022; Jussila et al., 2024; Lees et al., 2021; Meingast et al., 2014; Neta et al., 2011; Olthof & Fraser, 2024; Rahman et al., 2017). They are also useful to monitor post-restoration conditions of northern peatlands (Haghighi et al., 2018; Isoaho et al., 2024) or blanket bogs (Ball et al., 2023). Remote sensing with drones allow for broadscale monitoring of the hydrology of seismic lines (Lovitt et al., 2018). Satellite remote sensing allows for an assessment of wildfire risk (Millard et al., 2022). On the ground, Evans et al. (2021) proposes a camera trap method to remotely sense water table dynamics and hydrological condition. Ground truthing of hydrological remote sensing will be required.

Several documents use paleoecological approaches using peat cores to present a history of hydrologic alterations in the Hudson Bay Lowlands (Davies et al., 2021; Hargan et al., 2015, 2016, 2020; Holmquist et al., 2016; Jeziorski et al., 2015). These will be important to assess any current hydrological alterations in the Ring-of-Fire region.

Tanneberger et al. (2024) presents a method to monitor hydrological alteration using hydrological services, which may also be useful.

5.2 Fertility change and contamination

Monitoring for contamination is primary concern in mining and is intensely regulated. Many government documents dictate best management practices for mine monitoring (ECCC, 2015; e.g., Environment Canada, 2009, 2012; OMECP, 2018). Where acid mine drainage is a concern, monitoring is especially important and best management protocols are well laid out (INAP, 2018; e.g., O'Kane Consultants Inc., 2004d, 2007).

Fugitive dust is a common source of contamination from mining sites as well as from roads and documents compare and present best monitoring techniques (Cleaver et al., 2022; Opekunova et al., 2020). Shotyk et al. (2023) presents a protocol to monitor dusts dissolved in peatland pore waters, and Chen et al (2024) examine the bioaccessibility of trace metals deposited in this dust.

Multiple documents use biomonitoring methods, often with sphagnum moss, other bryophytes or lichens, to monitor trace metals nearby or farther away from contaminant sources (Anicic et al., 2009; Ares et al., 2015; Boquete et al., 2020; Gacnik et al., 2024; Kempter et al., 2017; Landis et al., 2019; Mullan-Boudreau et al., 2017; Salo et al., 2016; Stefanut et al., 2019; Szczepaniak et al., 2007). Given their prevalence in the Ring-of-Fire region, this biomonitoring approach should be useful.

The paleoecological documents mentioned above under hydrological alteration will also inform the fertility conditions in the Hudson Bay Lowland and the Ring-of-Fire region. Peat cores can also be used to monitor changes in longer term contamination (Mullan-Boudreau et al., 2017; Shotyk et al., 2017; Shotyk & Noernberg, 2020).

Forward-thinking researchers also determined the background levels of contamination by trace metals in the Hudson Bay Lowland (Glooschenko & Capoblanco, 1982; Su et al., 2021). These will be useful baselines against which future changes in contamination can be evaluated.

5.3 Vegetation or substrate disturbance

Multiple documents present remote sensing protocols to characterize peatland vegetation that could be used to follow changes in peatland vegetation (Beyer et al., 2019; Bourgeau-Chavez et al., 2017; Carless et al., 2019; Chasmer et al., 2021; Ghazaryan et al., 2024; Haghighi et al., 2018; A. Harris et al., 2015; Isoaho et al., 2024; T. H. M. Kolari et al., 2022; Middleton et al., 2012; Minasny et al., 2024; Mohammad Mirmazloumi et al., 2021; Pang et al., 2023; Räsänen et al., 2019, 2020; Salko et al., 2023; Steenvoorden et al., 2024; Stuart et al., 2022). Specialized examples include remote sensing to characterize permafrost thaw (Pironkova, 2017), wildfire vulnerability in peatlands (Millard et al., 2022) or vegetation change following linear disturbances (Finnegan et al., 2019; Jones et al., 2022).

Remote sensing always needs ground-truthing, and Rochefort et al. (2013) compare protocols for sampling vegetation. Assessing vegetation change also relies on comparisons with reference conditions and indicators of success (V. Bérubé et al., 2017; Gonzalez & Rochefort, 2014).

5.4 Landscape conversion and fragmentation

Any remote sensing techniques will allow to monitor landscape conversion and fragmentation. Even simple analyses with Google Earth can help follow wetland conversion (e.g., Saint-Marc et al., 2024).

Best management practices also exist for monitoring ecosystem conversion or landscape fragmentation following the restoration of drill pads and power lines (Alberta Ministry of Environment and Parks, 2017, 2020). Similar approaches could be applied to the Ring-of-Fire.

Camera trap techniques will also allow an assessment of the use of linear features by wildlife (Feldman et al., 2024; Sun et al., 2021).

5.5 Methylmercury

Monitoring will be key to avoid or minimize methylmercury production in wetlands in the Ring-of-Fire. Passive monitoring and biomonitoring approaches are used to monitor for total mercury (Bargagli, 2016; Gacnik et al., 2024; Shotyk & Cuss, 2019). Brazeau (2012) presents background data of total mercury for the Hudson Bay Lowland.

Best practices are available to biomonitor methylmercury concentrations in fauna in industrial regions (e.g., E. Bayne et al., 2022; De Beers Canada Victor Mine, 2024).

5.6 Overgrazing

Remote sensing was even used to monitor vegetation changes as a result of goose overgrazing along the coast of Hudson Bay (Gadallah, 2002; Jano et al., 1998). Barnas et al. (2019) compares field plots with drone flights to assess overgrazing.

5.7 Invasive species

Monitoring will again be important to avoid or minimize (control) their introductions in the Ring-of-Fire region. Best practice protocols are available to monitor invasive species (E. Bayne et al., 2022; Small et al., 2018).

5.8 Other stressors

Shonfield and Bayne (2017a) present best practices for using autonomous recording units to remotely monitor bird songs.

6. Gaps in Mitigation and Monitoring Knowledge

Despite the large size of the annotated bibliography, knowledge gaps are present. Here, we only provide a cursory review of major gaps we observed while preparing this annotated bibliography.

6.1 Wetlands, migratory birds and species-at-risk

The links between these wetlands in Hudson Bay Lowland or the adjacent Boreal Sheld and migratory birds or species at risk are tenuous. For many species, the distribution in this region and their habitat uses are poorly known. For instance, several species, such as at-risk bats or bumblebees have few sightings and mostly from human settlements in the region, so we have little idea of the importance of bogs, fens, string fens or other wetland types for these species in this region. Even the distribution of migratory birds is very patchy across this region, and few detailed data are available on their habitat use (Cadman et al., 2007; Robert et al., 2019). Data on species distribution and the use of different wetland and peatland habitats are required to understand how to best mitigate impacts from proposed development activities in the Ring-of-Fire region.

6.2 Mitigation options for the Hudson Bay Lowland and Boreal Shield

We could only find 45 documents out of 536 documents on ‘mitigation hierarchy’ to date (8.4% of mitigation documents) that dealt with mitigation options specifically in the Hudson Bay Lowland or the adjacent Boreal Shield. Most of these documents were federal or provincial recovery strategies for species-at-risk; they are only linked with the Hudson Bay Lowland via their species range maps, which can be tenuous as mentioned above.

If we eliminated the 'migratory birds' and 'species-at-risk' from our search, we could only find 16 documents that discuss mitigation measures in peatlands or other wetlands in the Hudson Bay Lowland or the adjacent Boreal Shield. Given the overwhelming predominance of wetlands, especially peatlands, in the Ring-of-Fire region, this is clearly insufficient. It will be important to adapt and test mitigation techniques or develop new mitigation options specifically for the Ring-of-Fire region.

Best management practices could be developed based on studies elsewhere until region-specific mitigation protocols are tested and established. Efforts would then be needed to ensure that mine and road planners and engineers are aware of, understand and apply these best practices.

6.3 Mining innovations and wetland mitigation

Mitigation mining or road construction impacts to wetlands and peatlands in the Ring-of-Fire region relies on two broad areas of knowledge: (i) wetland and peatland sciences, and (ii) mining or road engineering design. The cross-pollination of these fields of knowledge will lead to the best mitigation measures and the best approaches to monitor their success (Mitsch, 1993, 2014).

The annotated bibliography and this report provide great detail on mitigation measures in peatland and wetland science. However, they only slightly touch the mine or road engineering solutions that could help mitigate impacts to the wetlands in the Ring-of-Fire region. A separate review is needed on the sound road construction or mining mitigation options, and gaps in our knowledge, on how to avoid hydrological alteration to peatlands, minimize fertility changes or contamination in this landscape, minimize vegetation or substrate disturbance, avoid methylmercury production, and minimize noise and wildlife collisions.

For instance, we did include techniques such as paste tailings or cemented tailings for mine infill, which could reduce the mining footprint and thereby limit the ecosystem conversion of peatlands and other wetlands. But other innovations must exist or could be developed in the fields of low footprint mine design, sound road design to minimize hydrological alteration across roads, cold weather treatment wetland design, or advanced filtration techniques to treat mine drainage waters, to name but a few.

Mitsch (2014) pointed out the need for engineers and ecologists to work together and learn from one another to find appropriate solutions to large environmental problems in wetland science. Perhaps one way forward is to ensure that this annotated bibliography is shared with engineers working on the design of the Ring-of-Fire mines and roads. Another good step would be to organize workshops between wetland scientists and engineers to develop best practices on mine and road design applicable to the Ring-of-Fire region.

7. Interim Best Mitigation Guidelines

We have brought together over 1,200 documents, of which 536 (to date) discuss mitigation practices or mitigation research applicable to wetlands in the Ring-of-Fire region. They originate from disparate sources: environmental management of the Alberta oil sands; the Canadian peat extraction industry; blanket bog restoration in the UK; peatland restoration after agriculture or forest harvest across Europe; and mine water management in Scandinavia, to name a few. The next steps are to digest this material, synthesize it, propose best practices and identify detailed knowledge gaps on the mitigation of wetlands in the Ring-of-Fire region.

We do not attempt to provide this detailed synthesis here. More time and a broader suite of expertise are required. However, broad themes emerge that allow us to identify interim best mitigation guidelines to apply while considering developments in the Ring-of-Fire region. We present these interim mitigation guidelines below, giving general guidelines first, followed by guidelines for each stressor in the order presented above.

7.1 General

1. Strictly apply the mitigation hierarchy: The Hudson Bay Lowland and the adjacent Boreal Shield are sensitive environments of global importance. Where avoidance of impacts is possible, do so. If impacts cannot be avoided, minimizing them. Plan to restore on the same site only if minimization is not realistic. Consider offsetting elsewhere only if you cannot restore. As a last resort, compensate.

2. Collaborate among disciplines: The Hudson Bay Lowland and the adjacent Boreal Shield are novel environments in which to design roads and mines. Many standard engineering design practices will not be applicable, and innovation will be required. Understanding how to proceed will require collaboration between design engineers and environmental scientists and hydrologists, especially those with peatland expertise. Working together, interdisciplinary design teams will have greater ability to avoid or minimize impacts to these wetlands and to restore them if they are damaged.

3. Minimize footprints: Mine development footprints will remove wetlands in the Ring-of-Fire region, mostly peatland. Some wetlands may be restored following mine closure, but some will not. Minimizing the footprint of mine developments and associated infrastructure and roads will minimize the overall impacts on wetlands. For instance, favouring underground mines instead of open pits should reduce the mine footprint because open pits have larger surface footprints and also require surface disposal of

non-ore waste rock. The use of paste tailings and tailings infill in underground mines could also limit the surface area of tailings facilities.

4. Biomonitoring program: Devise and apply a strong biomonitoring program using most informative bioindicators prior to mining developments for early detection of environmental change (e.g., E. Bayne et al., 2022). Early detection will allow best adaptive mitigation.

7.2 Hydrological alteration

5. Place mine or road footprints on uplands: Placing mine or road footprints on uplands will avoid or minimize hydrological alterations to wetlands. However, given the scarcity of uplands in the Hudson Bay Lowland and their consequent value for biodiversity, weigh the ecological importance of these uplands and evaluate these impacts as well.

6. Understand peatland flow paths: Surface water and groundwater movement through peatland systems is complex, but water generally flows from bog systems to fen systems, including string fens, before they enter streams and larger water courses. Understand the flow paths and water volumes in these fens and water courses to determine the potential for any hydrologic alterations and find the best sites for mine footprints and linear disturbances.

7. Minimize disturbance to flow paths: Avoid placing mine footprints over water courses or in fens. Where roads are required to cross peatlands, preferentially rout them parallel to fen flow paths or watercourses and not across them (Volik et al., 2020).

8. Ensure adequate crossflow: Where roads are constructed in peatlands, install engineered products (e.g., corduroy, geogrid, geocell, culverts) to retain natural crossflow (MacKenzie & Renkema, 2013; Osko et al., 2018), thereby avoiding flooding on one side and water table drawdown on the other. Monitor wells to ensure that hydrological alterations do not occur.

9. Mine dewatering: Evaluate the susceptibility of surrounding peatlands to mine dewatering. Innovate techniques to minimize mine dewatering impacts to surface peatlands.

10. Monitor hydrology: Given the importance of hydrology and its alteration to wetlands and peatlands, it will be critical to set up a hydrological monitoring network to follow changes in wetland hydrology. This can be done through a network of hydrological and climatological stations (Eaton & Charette, 2016; Volik et al., 2020) to set a strong baseline and then continuous follow any shifts. Remote sensing of the hydrology will be important as well (e.g., Neta et al., 2011; Olthof & Fraser, 2024). Given expected change in peatland hydrology from climate change, ensure that any monitoring system

can adequately separate anthropogenic changes from climate-induced changes in hydrology.

7.3 Fertility change and contamination

11. <u>Avoid and monitor for acid rock drainage:</u> Test all mine rock and wastes for acid generating potential. If acid-generating, apply best practices to avoid acid generation (INAP, 2018; e.g., Zinck & Griffith, 2013). Consider desulphurizing tailings to reduce the risk of acid rock generation (e.g., Alam & Shang, 2012). Closely monitor drainage waters for acid rock generation and total metal release.

12. <u>Avoid and monitor for hexavalent chromium:</u> Evaluate current best practices to avoid all release of hexavalent chromium (Cr(VI)) (du Preez et al., 2023), and, if they are adequate to this region, apply them. If not, innovate to avoid Cr(VI) release. Monitor for Cr(VI).

13. <u>Minimize and monitor fugitive dust:</u> Apply best management guidelines (BCMEMLCI & BCMECCS, 2023; OMECC, 2017) to avoid or minimize fugitive dust emissions from mining operations, including from tailings facilities. Monitor fugitive dust emissions.

14. <u>Monitor and filter mine water discharges:</u> Monitor mine water discharge quality. If needed, incorporate treatment systems to remove sulphate and trace metals from mine water discharges, including treatment wetlands or filtration systems. Cold climate treatment peatlands in Scandinavia have a long track record (e.g., Kujala et al., 2019). Innovations using peat or peat-derived biochar may be designed to filter trace metals from mine waters (Balan et al., 2009; S.-J. Lee et al., 2015).

7.4 Vegetation or substrate disturbance

15. <u>Encourage winter construction work:</u> Working on frozen ground will minimize disturbances to the substrate. Ensure that the ground is well frozen before using heavy machinery. Passing with snowmobiles beforehand will compact the snow cover and force frost deeper in the soil (D. Campbell & Bergeron, 2012). Winter work will also reduce the impacts to fauna, especially migratory birds.

16. <u>Restore peatland disturbances:</u> Where disturbances to peatlands unavailable, apply best restoration practices, such as adapting the moss layer transfer technique because in moss dominated ecosystems, it is paramount to reintroduce moss material (Quinty et al., 2019, 2020a, 2020b, 2020c).

7.5 Landscape conversion and fragmentation

17. <u>Minimize then restore linear disturbances:</u> Where mine exploration creates seismic-line-like disturbances, apply low impact practices for these features (Filicetti et al.,

2023). Where linear disturbances such as seismic lines, roads or buried pipelines occur, use best practices to restore these sites back to peatland ecosystems with suitable microtopography (e.g., Alberta Environment and Parks, 2017).

18. Minimize fragmentation and monitor wildlife use: The mine footprints and the roads, pipelines, seismic lines and other linear disturbances will fragment the wetland and peatland landscape of the Ring-of-Fire region. In the Alberta oil sands, this fragmentation impacts boreal populations of caribou by allowing preferential corridors for predators. Minimize this fragmentation and monitor the preferential use of linear features by wildlife.

7.6 Melthylmercury

19. Monitor for mercury and sulphate: Monitor for mercury and methylmercury. Also monitor for sulphate since it is associated with methylmercury production. This should be especially the case where there are larger areas with substrate disturbances, flooding, or nutrient enrichment. Early detection will aid in mitigation.

7.7 Invasive species

20. Avoid and monitor for invasive species: Use Riley (2003) to determine native and non-native species to the region. Apply available guidelines (Halloran et al., 2013) to avoid the spread of invasive species. Monitor the spread continuously and apply remedies promptly.

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APPENDIX A: Subject Categories in the Annotated Bibliography

Appendix A. Hierarchical list of subject categories used in the annotated bibliography.

HEADING	**2º FILTER**	**3º FILTER**	**4º FILTER**
Geographic Region	Canada	Ontario	
		Hudson Bay Lowland	
		Boreal Shield	
Ecosystem Type	peatland	bog fen string fen swamp	
	other wetland	marsh saltmarsh pools/ponds	
	coastal ecosystem		
	upland		
	ecotone		
	watercourse		
	water body		

Appendix A (cont.)

HEADING	2º FILTER	3º FILTER	4º FILTER
Abiotic/Biotic Component	ecoregions		
	physiography	landform	
		microtopography	
	climate	precipitation	
		microclimate	
		soil temperature	
		cold climate	
		energy balance	
	hydrology	evapotranspiration	
		soil moisture	
		groundwater	
		spring thaw	
		snowpack	
		surface water/runoff	
		water table	
	substrate	peat	
		sediment	
		permafrost	
	biogeochemistry	nutrients	
		water quality	
		pH	
		electrical conductivity	
		salinity	
		sulphur compounds	
	carbon cycle	greenhouse gases	
		biochar	
		decomposition	
		dissolved organic carbon	
		primary productivity	
		carbon sequestration	
		carbon storage	
	food web		
	microbial activity		
	vegetation	functional group	
		vascular plants	woody plants
			graminoids
			black ash
		bryophytes	sphagnum
	lichens		
	fauna	arthropods	gypsy cuckoo bumble bee
			yellow-banded bumble bee
			Suckley’s cuckoo bumble bee
		fish	lake sturgeon
		amphibians	
		reptiles	
		birds	migratory birds
			shorebird
			snow geese
			Hudsonian godwit

Appendix A (cont.)

HEADING	2º FILTER	3º FILTER	4º FILTER
Abiotic/Biotic Component	Fauna (cont.)	birds (cont.)	lesser yellowlegs red knot red-necked phalarope short-eared owl common nighthawk olive-sided flycatcher bank swallow barn swallow Canada warbler evening grosbeak rusty blackbird
		mammals	bats beaver moose coyote timber wolf eastern red bat hoary bat silver-haired bat little brown myotis northern myotis tri-colored bat caribou caribou boreal population caribou, eastern migratory population wolverine polar bear
	human society	social license	
		indigenous perspective	traditional use
			wild foods

Appendix A (cont.)

HEADING	2º FILTER	3º FILTER	4º FILTER
Origin of Impacts	climate change		
	aggregate extraction		
	agriculture		
	cities/towns/villages		
	cumulative effects		
	peat/moss extraction		
	ditching		
	fire		
	forest harvest		
	cities/towns/villages		
	industrial equipment		
	infrastructure		
	linear disturbance	roads winter roads seismic lines pipelines transmission lines	
	mine exploration		
	mining	mine footprint aggregate pads drill pads tailings mine wastes	
	mineral processing		
	motor vehicles		
	pollution	air pollution acid rock drainage explosives landfill spills wastewater water pollution	
	power generation		

Appendix A (cont.)

HEADING	2º FILTER	3º FILTER	4º FILTER
Stressor	hydrological alteration	drawdown	
		drought	
		flooding	
	landscape conversion and fragmentation	ecosystem conversion	
		linear feature	
	fertility change / contamination	fugitive dust	
		herbicide	
		hydrocarbons	
		metal/metalloid	antimony
			arsenic
			chromium
			cobalt
			copper
			lead
			mercury
			nickel
			selenium
			thallium
			zinc
		nutrient enrichment	
		suspended solids	
	substrate disturbance	subsidence	
		compaction	
		geotechnical properties	
		soil warming	
		permafrost thaw	
		smouldering	
		erosion	water erosion
			wind erosion
	vegetation disturbance		
	herbivory		
	predation		
	invasive species		
	other stressors	noise	
		wildlife collisions	

Appendix A (cont.)

HEADING	2º FILTER	3º FILTER	4º FILTER
Policy/Statute	federal policy/statute	migratory birds policy	
		species-at-risk	status report recovery strategy management plan conservation agreement
		wetland policy	
	provincial policy/statute	migratory birds policy	
		species-at-risk	status report recovery strategy conservation agreement
		wetland policy	
		mapping	
	policy discussion paper		
Mitigation Hierarchy	impact avoidance impact minimization on-site restoration offsetting compensation		
Mitigation Detail	mine planning	tailings management sedimentation pond mine reclamation	
	remediation	bio/phytoremediation nutrient removal treatment wetland	
	hydrologic management	peat dams rewetting culverts	
	substrate rehabilitation		
	revegetation	passive restoration active restoration donor site	
	best management practice		
Monitoring	remote sensing	unmanned aerial vehicle LiDAR satellite imagery camera traps automated acoustic survey	
	peat/sediment cores		
	vegetation sampling		
	reference conditions		
	biomonitoring		
	dendrochronology		

APPENDIX B: Breakdown of Mitigation Options by Ecosystem Stressor

Appendix A. Breakdown of mitigation options by ecosystem stressor, with the number of documents in the database and key references (total n = 1,211 documents).

Mitigation hierarchy	**Stressor**	**Number of documents**	**Component**	**Key references**
Impact Avoidance	Hydrological Alteration	12	Conservation	Alexandrov, et al. (2020) The capacity of northern peatlands for long-term carbon sequestration. Drever, et al. (2021) Natural climate solutions for Canada. Helbig, et al. (2020) The biophysical climate mitigation potential of boreal peatlands during the growing season. Humpenöder, et al. (2020) Peatland protection and restoration are key for climate change mitigation. Strack, et al. (2022) The potential of peatlands as nature-based climate solutions.
			Roads	Gilmour, et al. (2022) Effectiveness of Construction Mitigation Measures to Avoid or Minimise Impact to Groundwater Dependent Wetlands and to Peat Hydrology. INAC (2010) Northern Land Use Guidelines, Access: Roads and Trails. Partington, et al. (2016) Resource Roads and Wetlands: A Guide for Planning, Construction and Maintenance.
Impact avoidance	Fertility Change and Contamination	24	Acid rock drainage	Alam & Shang (2012) Effect of operating parameters on desulphurization of mine tailings by froth flotation. Environment Canada (2009) Environmental Code of Practice for Metal Mines. INAP (2018) Global Acid Rock Drainage Guide. O'Kane Consultants Inc. (2004a) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 1 – Summary. O'Kane Consultants Inc. (2004b) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 2 – Theory and Background. O'Kane Consultants Inc. (2004c) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 3 – Site Characterization and Numerical Analyses of Cover Performance. O'Kane Consultants Inc. (2004d) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 4 – Field Performance Monitoring and Sustainable Performance of Cover Systems. O'Kane Consultants Inc. (2004e) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 5 – Case Studies. O'Kane Consultants Inc. (2007) Macro-Scale Cover Design and Performance Monitoring Manual. CANMET- Mining and Mineral Sciences Laboratories, Pouw, et al. (2014) Study to Identify BATEA for the Management and Control of Effluent Quality from Mines. Price WA (2009) CANMET Mining and Mineral Sciences Laboratories Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials. Stratos Inc. & Brodie Consulting Ltd. (2011) Climate Change and Acid Rock Drainage – Risks for the Canadian Mining Sector. Zinck & Griffith (2013) Review of Mine Drainage Treatment and Sludge Management Operations.
			Chromium	Deepa, et al. (2025) Bioremediation approaches for chromium detoxification and transformation: advanced strategies and future perspectives. Beukes, et al. (2017) Review of Cr(VI) environmental practices in the chromite mining and smelting industry – Relevance to development of the Ring of Fire, Canada. du Preez, et al. (2023) An overview of currently applied ferrochrome production processes and their waste management practices.
			Fugitive dust	Cecala, et al. (2019) Dust Control Handbook for Industrial Minerals Mining and Processing. OMOECC (2017) Management Approaches for Industrial Fugitive Dust Sources.
Impact avoidance	Substrate and vegetation disturbance	8	Roads	INAC (2010) Northern Land Use Guidelines, Access: Roads and Trails. Partington, et al. (2016) Resource Roads and Wetlands: A Guide for Planning, Construction and Maintenance.
Impact avoidance	Landscape conversion and fragmentation	14	Woodland caribou	INAC (2010) Northern Land Use Guidelines, Access: Roads and Trails. OMECP (2020) Best Management Practices for Mineral Exploration and Development Activities and Woodland Caribou in Ontario. OMNR (2016) Best Management Practices for Aggregate Activities and Forest-dwelling Woodland Caribou. Partington, et al. (2016) Resource Roads and Wetlands: A Guide for Planning, Construction and Maintenance.

Appendix B (cont.)

Mitigation hierarchy	Stressor	Number of documents	Component	Key references
Impact avoidance	Landscape conversion and fragmentation (continued)		Mining innovation	Environment Canada (2009) Environmental Code of Practice for Metal Mines. Franks, et al.(2011) Sustainable development principles for the disposal of mining and mineral processing wastes. Musetta-Lambert, et al. (2019) Industrial innovation and infrastructure as drivers of change in the Canadian boreal zone. Qi & Fourie (2019) Cemented paste backfill for mineral tailings management: review and future perspectives. Wang et al. (2014) Current state of fine mineral tailings treatment: a critical review on theory and practice.
Impact avoidance	Mercury/ methylmercury	5	Substrate disturbance	Braaten, et al. (2016) Effects of disturbance and vegetation type on total and methylmercury in boreal peatland and forest soils. Mitchell, et al. (2008) Spatial characteristics of net methylmercury production hot spots in peatlands. Mitchell, et al. (2009) Methylmercury dynamics at the upland-peatland interface: topographic and hydrogeochemical controls.
			Flooding	Kelly, et al. (1997) Increases in fluxes of greenhouse gases and methyl mercury following flooding of an experimental reservoir.
			Nutrient/ sulphate enrichment	Twible LE (2017) Linking Mining Wastewater Discharge to Methylmercury Production in a Sub-Arctic Peatland.
Impact avoidance	Overgrazing	1		Peterson et al. (2013) The legacy of destructive snow goose foraging on supratidal marsh habitat in the Hudson Bay Lowlands.
Impact avoidance	Invasive species	1		Halloran, et al. (2013) Clean Equipment Protocol for Industry: Inspecting and Cleaning Equipment for the Purposes of Invasive Species Prevention.
Impact avoidance	Other stressors	3	Noise	Douse & Artz (2022) Peatland Restoration and Breeding Birds: Undertaking Work in the Bird Breeding Season. OMECP (2020) Best Management Practices for Mineral Exploration and Development Activities and Woodland Caribou in Ontario.
			Collisions	ECCC (2023) Guidelines to Avoid Harm to Migratory Birds.

Appendix B (cont.)

Mitigation hierarchy	Stressor	Number of documents	Component	Key references
Impact minimization	Hydrological alteration	27	General	Thom et al. (2019) Conserving Bogs: The Management Handbook.
				Environment Canada (2009) Environmental Code of Practice for Metal Mines.
				Osko, et al. (2018) COSIA In-Situ Oil Sands Shared Practices for Working in and Around Wetlands.
				Volik, et al. (2020) Wetlands in the Athabasca oil sands region: the nexus between wetland hydrological function and resource extraction.
			Roads	Ducks Unlimited Canada (2014) Forest Road Wetland Crossings: Learning from Field Trials in the Boreal Plains Ecozone of Manitoba and Saskatchewan, Canada.
				De Guzman, et al. (2016) Performance of road embankments on seasonally-frozen peat foundations with and without corduroy bases.
				De Guzman, et al. (2018) Geotechnical properties of fibrous and amorphous peats for the construction of road embankments.
				Forestry Civil Engineering & Scottish Natural Heritage (2010) Floating Roads on Peat: A Report into Good Practice in Design, Construction and Use of Floating Roads on Peat with Particular Reference to Wind Farm Developments in Scotland.
				Gilmour et al. (2022) Effectiveness of Construction Mitigation Measures to Avoid or Minimise Impact to Groundwater Dependent Wetlands and to Peat Hydrology.
				INAC (2010) Northern Land Use Guidelines, Access: Roads and Trails.
				Jorat, et al (2024) Future carbon-neutral societies: minimising construction impact on groundwater-dependent wetlands and peatlands.
				Long et al. (2023) Behaviour of 60-year-old trial embankments on peat.
				Partington et al. (2016) Resource Roads and Wetlands: A Guide for Planning, Construction and Maintenance.
				Saraswati et al. (2020) Hydrological effects of resource-access road crossings on boreal forested peatlands.
				Williams et al. (2013) Linear disturbances on discontinuous permafrost: implications for thaw-induced changes to land cover and drainage patterns.
			Climate change mitigation	Baena-Moreno, et al. (2023) Effluents and residues from industrial sites for carbon dioxide capture: a review.
				Mervine, et al. (2018) Potential for offsetting diamond mine carbon emissions through mineral carbonation of processed kimberlite: an assessment of De Beers mine sites in South Africa and Canada.
			Beaver	Kinas, et al. (2024) Alberta Beaver Beneficial Management Practices.
Impact minimization	Fertility change/ contamination	105	General	Environment Canada (2009) Environmental Code of Practice for Metal Mines.
			Explosive residues	BCMECC (2018) Guidance on Preparing Nitrogen Management Plans for Mines using Ammonium Nitrate Fuel Oil Products for Blasting.
				Chatterjee, et al. (2017) Common explosives (TNT, RDX, HMX) and their fate in the environment: emphasizing bioremediation.
			Acid rock drainage	Alam & Shang (2012) Effect of operating parameters on desulphurization of mine tailings by froth flotation.
				INAP (2018) Global Acid Rock Drainage Guide.
				MEND (2012) Cold Regions Cover System Design Technical Guidance Document.
				O’Kane Consultants Inc. (2004a) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Vol. 1 – Summary.
				O’Kane Consultants Inc. (2004b) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Vol. 2 – Theory and Background.
				O’Kane Consultants Inc. (2004c) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Vol. 3 – Site Characterization and Numerical Analyses of Cover Performance.
				O’Kane Consultants Inc. (2004d) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Vol. 4 – Field Performance Monitoring and Sustainable Performance of Cover Systems
				O’Kane Consultants Inc. (2004e) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Vol. 5 – Case Studies.
				O’Kane Consultants Inc. (2007) Macro-Scale Cover Design and Performance Monitoring Manual.
				Pouw, et al. (2014) Study to Identify BATEA for the Management and Control of Effluent Quality from Mines.

Appendix B (cont.)

Mitigation hierarchy	**Stressor**	**Number of documents**	**Component**	**Key references**
Impact minimization	Fertility change/ contamination (continued)		Acid rock drainage (continued)	Price WA (2009) CANMET Mining and Mineral Sciences Laboratories Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials. Stratos Inc. & Brodie Consulting Ltd. (2011) Climate Change and Acid Rock Drainage – Risks for the Canadian Mining Sector. Zinck & Griffith (2013) Review of Mine Drainage Treatment and Sludge Management Operations.
			Chromium	Beukes, et al. (2017) Review of Cr(VI) environmental practices in the chromite mining and smelting industry – Relevance to development of the Ring of Fire, Canada. Deepa, et al. (2025) Bioremediation approaches for chromium detoxification and transformation: advanced strategies and future perspectives. du Preez, et al. (2023) An overview of currently applied ferrochrome production processes and their waste management practices.
			Fugitive dust	BCMEMLCI & BCMECCS (2023) Developing a Fugitive Dust Management Plan for Mines in BC: Technical Guidance. Cecala, et al. (2019) Dust Control Handbook for Industrial Minerals Mining and Processing, Second Edition. Golder Associates (2010) Literature Review of Current Fugitive Dust Control Practices within the Mining Industry. OMECC (2017) Management Approaches for Industrial Fugitive Dust Sources.
			Erosion/ sedimentation	BCME (2015a) Assessing the Design, Size, and Operation of Sediment Ponds Used in Mining, Version 1.0 BCME (2015b) Developing a Mining Erosion and Sediment Control Plan. Environmental Dynamics Inc (2003) Runoff, erosion and sediment control best management practices for Yukon placer mining operations.
			Hydrocarbons	BCMECCS (2018) Preparing Spill Contingency Plans. British Colombia Ministry of Environment and Climate Change Strategy Gharedaghloo & Price (2018) Fate and transport of free-phase and dissolved-phase hydrocarbons in peat and peatlands: Developing a conceptual model. Gharedaghloo & Price (2021) Assessing benzene and toluene adsorption with peat depth: Implications on their fate and transport. Gupta, et al. (2023) Multiphase flow behavior of diesel in bog, fen, and swamp peats. INAC (2007) Guidelines for Spill Contingency Planning. Rezanezhad, et al. (2012) How fen vegetation structure affects the transport of oil sands process-affected waters.
			Treatment wetlands	Bishay & Kadlec (2005) Wetland treatment at Musselwhite Mine, Ontario, Canada. Eskelinen, et al. (2015) Purification efficiency of a peatland-based treatment wetland during snowmelt and runoff events. Gupta, et al. (2020) Shallow floating treatment wetland capable of sulfate reduction in acid mine drainage impacted waters in a northern climate. Heikkinen, et al. (2018) Long-term purification efficiency and factors affecting performance in peatland-based treatment wetlands: an analysis of 28 peat extraction sites in Finland. Kadlec RH (2009) Wastewater treatment at the Houghton Lake wetland: hydrology and water quality. Kadlec & Wallace (2009) Treatment wetlands, second edition. Karjalainen, et al. (2016) Long-term accumulation and retention of Al, Fe and P in peat soils of northern treatment wetlands. Khan, et al. (2020) Long-term data reveals the importance of hydraulic load and inflow water quality for Sb removal in boreal treatment peatlands. Kujala, et al. (2019) Design parameters for nitrogen removal by constructed wetlands treating mine waters and municipal wastewater under Nordic conditions. Kujala, et al. (2024) Year-round activity of microbial communities in cold-climate peatlands treating mining-affected waters. McCarter, et al. (2017) Nutrient and mercury transport in a sub-arctic ladder fen peatland subjected to simulated wastewater discharges. Palmer, et al. (2015) Efficient removal of arsenic, antimony and nickel from mine wastewaters in northern treatment peatlands and potential risks in their long-term use. Ronkanen & Kløve (2009) Long-term phosphorus and nitrogen removal processes and preferential flow paths in northern constructed peatlands. Sheoran & Sheoran (2006) Heavy metal removal mechanism of acid mine drainage in wetlands: a critical review. Simair, et al. (2021) Treatment of oil sands process affected waters by constructed wetlands: evaluation of designs and plant types. Wang, et al. (2017) Constructed wetlands for wastewater treatment in cold climate: a review.

Appendix B (cont.)

Mitigation hierarchy	Stressor	Number of documents	Component	Key references
Impact minimization	Fertility change/ contamination (continued)		Peat-based filtration systems	Balan, et al. (2009) Sphagnum moss peat as a potential sorbent and reductant for chromium (VI) removal from aqueous solutions. Gupta, et al. (2009) Adsorption characteristics of Cu and Ni on Irish peat moss. Lee, et al. (2015) Comparison of heavy metal adsorption by peat moss and peat moss-derived biochar produced under different carbonization conditions.
Impact minimization	Vegetation or substrate disturbance	33	General	Thom, et al. (2019) Conserving Bogs: The Management Handbook.
			Heavy equipment	APTHQ (2024) Best Practices Guide for Extracting Mired Equipment in Peat Fields. Nugent, et al. (2003) Characteristic site disturbance due to harvesting and extraction machinery traffic on sensitive forest sites with peat soils. Sutherland (2003) Preventing Soil Compaction and Rutting in the Boreal Forest of Western Canada: A Practical Guide to Operating Timber-Harvesting Equipment.
			Fire suppression	APTHQ (2021) Fire Emergency Response Guide for Peatlands (Fields). Deane, et al. (2022) Peat surface compression reduces smouldering fire potential as a novel fuel treatment for boreal peatlands. Hokanson, et al. (2018) A hydrogeological landscape framework to identify peatland wildfire smouldering hot spots.
Impact minimization	Landscape conversion and fragmentation	31	Mining innovation	Environment Canada (2009) Environmental Code of Practice for Metal Mines. Franks, et al.(2011) Sustainable development principles for the disposal of mining and mineral processing wastes. Qi & Fourie (2019) Cemented paste backfill for mineral tailings management: review and future perspectives. Wang et al. (2014) Current state of fine mineral tailings treatment: a critical review on theory and practice.
			Linear disturbances	Filicetti, et al. (2023) Low-impact line construction retains and speeds recovery of trees on seismic lines in forested peatlands. Franklin et al. (2021) Seismic line width and orientation influence microclimatic forest edge gradients and tree regeneration. Ryder, et al. (2005) Pipelines and Peat: A Review of Peat Formation, Pipeline Construction Techniques and Reinstatement Options.
			Woodland caribou	OMECP (2020) Best Management Practices for Mineral Exploration and Development Activities and Woodland Caribou in Ontario. OMNR (2016) Best Management Practices for Aggregate Activities and Forest-dwelling Woodland Caribou.
Impact minimization	Mercury/ methylmercury	8	Flooding	Branfireun & Roulet (2002) Controls on the fate and transport of methylmercury in a boreal headwater catchment, northwestern Ontario, Canada. Kelly, et al. (1997) Increases in fluxes of greenhouse gases and methyl mercury following flooding of an experimental reservoir. St Louis, et al. (2004) The rise and fall of mercury methylation in an experimental reservoir.
			Substrate disturbance	Braaten, et al. (2016) Effects of disturbance and vegetation type on total and methylmercury in boreal peatland and forest soils. Mitchell, et al. (2008) Spatial characteristics of net methylmercury production hot spots in peatlands. Mitchell, et al. (2009) Methylmercury dynamics at the upland-peatland interface: topographic and hydrogeochemical controls.
			Nutrient/ sulphate enrichment	McCarter, et al. (2017) Nutrient and mercury transport in a sub-arctic ladder fen peatland subjected to simulated wastewater discharges. Twible LE (2017) Linking Mining Wastewater Discharge to Methylmercury Production in a Sub-Arctic Peatland.
Impact minimization	Overgrazing	2		Peterson, et al. (2013) The legacy of destructive snow goose foraging on supratidal marsh habitat in the Hudson Bay Lowlands.
Impact minimization	Invasive species	3		Halloran, et al. (2013) Clean Equipment Protocol for Industry: Inspecting and Cleaning Equipment for the Purposes of Invasive Species Prevention. Nichols G (2024) Invasive Phragmites (*Phragmites australis*) Best Management Practices in Ontario: Improving Species at Risk Habitat through the Management of Invasive Phragmites.

Appendix B (cont.)

Mitigation hierarchy	Stressor	Number of documents	Component	Key references
Impact minimization	Other stressors	8	Noise	Douse & Artz (2022) Peatland Restoration and Breeding Birds: Undertaking Work in the Bird Breeding Season. OMECP (2020) Best Management Practices for Mineral Exploration and Development Activities and Woodland Caribou in Ontario.
			Bird collisions	Baasch, et al. (2022) Mitigating avian collisions with power lines through illumination with ultraviolet light. Lao, et al. (2020) The influence of artificial light at night and polarized light on bird-building collisions. OMNRF (2014) Significant Wildlife Habitat Mitigation Support

Appendix B (cont.)

Mitigation hierarchy	Stressor	Number of documents	Component	Key references
On-site restoration	Hydrological alteration	162	Peatland drainage	Biebighauser (2015) Wetland Restoration and Construction: A Technical Guide.
				Joosten (2021) Practical Peatland Restoration.
				Large, et al.(2007) Using long-term monitoring of fen hydrology and vegetation to underpin wetland restoration strategies.
				Maanavilja, et al. (2015) Rewetting of drained boreal spruce swamp forests results in rapid recovery of *Sphagnum* production.
				NatureScot (2024c) Peatland ACTION - Technical Compendium.
				O'Kelly, (2008) On the geotechnical design and use of peat bunds in the conservation of bogs.
				Schwieger, et al.(2021) Wetter is better: rewetting of minerotrophic peatlands increases plant production and moves them towards carbon sinks in a dry year.
				Thom, et al. (2019) Conserving Bogs: The Management Handbook.
				Van Dijk, et al (2007) The contribution of rewetting to vegetation restoration of degraded peat meadows.
			Post peat extraction	Landry & Rochefort (2012) The drainage of peatlands: impacts and rewetting techniques.
				Ketcheson & Price (2011) The impact of peatland restoration on the site hydrology of an abandoned block-cut bog.
				Price, et al. (1998) Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration.
				Price, et al. (2003) Hydrological processes in abandoned and restored peatlands: An overview of management approaches.
				Price, et al. (2016) Peatland restoration and hydrology. Taylor, et al. (2016) Hydrological controls on productivity of regenerating Sphagnum in a cutover peatland.
				Quinty, et al. (2020) Peatland Restoration Guide: Site Preparation and Rewetting.
				Taylor, et al. (2016) Hydrological controls on productivity of regenerating *Sphagnum* in a cutover peatland.
			Tree cutting	Dubé, et al. (1995) Watering up after clear-cutting on forested wetlands of the St. Lawrence Lowland.
				Gaffney, et al. (2020) Ecohydrological change following rewetting of a deep-drained northern raised bog.
				Howson, et al. (2021) The effect of forest-to-bog restoration on the hydrological functioning of raised and blanket bogs.
				Price, et al. (2016) Peatland restoration and hydrology.
			Pools	Beadle, et al. (2023) Landscape-scale peatland rewetting benefits aquatic invertebrate communities.
				Desrochers & Rochefort (2021) Avian recolonization of unrestored and restored bogs in Eastern Canada.
				Mazerolle, et al. (2006) Animal and vegetation patterns in natural and man-made bog pools: implications for restoration.
				Soomets, et al. (2023) Restoring functional forested peatlands by combining ditch-blocking and partial cutting: an amphibian perspective.
			Videos	Cairngorms National Park Authority (2022) Wave Damming & Zippering Method - Technique Guide.
				NatureScot (2024a) Bunding.
				NatureScot (2024c) Ditch Blocking.
				NatureScot (2024d) Reprofiling.
				NatureScot (2024e) Scrub Clearance.
				Rochefort & Jutras (2025) Construction de barrages en tourbière.
				Rochefort & Jutras (2024) Où bloquer les canaux de drainage en tourbière.
			Seismic lines	Alberta Environment and Parks (2017) Visual Guide for Implementing the Restoration and Establishment Framework in Woodland Caribou Habitat.
				Biagi, et al. (2021) Hydrological functioning of a constructed peatland watershed in the Athabasca oil sands region: potential trajectories and lessons learned.
				Bird & Xu (2021) Hydrology and Microtopography Importance for Wetland Reclamation.
				Weiland, et al. (2024) The influence of seismic lines on local hydrology and snow accumulation in the boreal region of northern Alberta.
On-site restoration	Fertility change/ contamination	45	Nutrient enrichment	Comber, et al. (2023) Restoration management of phosphorus pollution on lowland fen peatlands: A data evidence review from the Somerset Levels and Moors.
				Hinzke, et al. (2021) Potentially peat-forming biomass of fen sedges increases with increasing nutrient levels.
				Hinzke, et al. (2021) Can nutrient uptake by *Carex* counteract eutrophication in fen peatlands?
				Jabłońska, et al. (2021) Impact of vegetation harvesting on nutrient removal and plant biomass quality in wetland buffer zones.
				Kotowski, et al. (2016) Restoration of temperate fens: matching strategies with site potential.

Appendix B (cont.)

Mitigation hierarchy	**Stressor**	**Number of documents**	**Component**	**Key references**
On-site restoration	Fertility change/ contamination (continued)		Post peat extraction fertilization	Liu, et al. (2024) Improving restoration outcomes of boreal *Sphagnum*-dominated peatlands after peat-extraction: the key role of phosphorus fertilization. Pouliot, et al. (2015) Manure derived biochar can successfully replace phosphate rock amendment in peatland restoration. Quinty et al. (2020d) Peatland Restoration Guide: Spreading of Plant Material, Mulch and Fertilizer. PERG, CSPMA and APTHQ, Québec
			Mine waste cover systems	MEND (2012) Cold Regions Cover System Design Technical Guidance Document. O'Kane Consultants Inc. (2004a) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 1 – Summary. O'Kane Consultants Inc. (2004b) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 2 – Theory and Background. O'Kane Consultants Inc. (2004c) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 3 – Site Characterization and Numerical Analyses of Cover Performance. O'Kane Consultants Inc. (2004d) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 4 – Field Performance Monitoring and Sustainable Performance of Cover Systems. O'Kane Consultants Inc. (2004e) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 5 – Case Studies. O'Kane Consultants Inc. (2007) Macro-Scale Cover Design and Performance Monitoring Manual.
			Hydrocarbon bioremediation	Koshlaf & Ball (2017) Soil bioremediation approaches for petroleum hydrocarbon polluted environments. Naeem & Qazi (2020) Leading edges in bioremediation technologies for removal of petroleum hydrocarbons.
On-site restoration	Vegetation or substrate disturbance	182	General	Biebighauser (2015) Wetland Restoration and Construction: A Technical Guide. Thom, et al. (2019) Conserving Bogs: The Management Handbook. NatureScot (2024b) Peatland ACTION - Technical Compendium.
			Post peat extraction	Allan, et al. (2024) Meta-analysis reveals that enhanced practices accelerate vegetation recovery during peatland restoration. GRET (2016) Restauration des tourbières minérotrophes: état des connaissances 2015. Hugron, et al. (2013) Tree plantations within the context of ecological restoration of peatlands: a practical guide. Khan et al. (2025) Unfolding a peatland's story: assessing the restoration outcomes and driving factors from a disturbed minerotrophic peatland in Eastern Canada. Nugent, et al. (2018) Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink. Nugent, et al. (2021) Cutover peat limits methane production causing low emission at a restored peatland. Quinty, et al. (2019) Peatland Restoration Guide: Plant Material Collecting and Donor Site Management. Quinty, et al. (2020) Peatland Restoration Guide: Planning Restoration Projects. Quinty, et al. (2020) Peatland Restoration Guide: Site Preparation and Rewetting. Quinty, et al. (2020) Peatland Restoration Guide Spreading: Plant Material, Mulch and Fertilizer. Rochefort, et al. (2003) North American approach to the restoration of *Sphagnum* dominated peatlands. Rochefort, et al. (2016) Reintroduction of fen plant communities on a degraded minerotrophic peatland.
			Donor material	Bird & Xu (2021) Donor Moss Transfer: How and When to Use in Peatland Restoration. Guêné-Nanchen, et al. (2019) Harvesting surface vegetation does not impede self-recovery of Sphagnum peatlands. Murray, et al. (2017) Growing season carbon gas exchange from peatlands used as a source of vegetation donor material for restoration. Quinty, et al. (2019) Peatland Restoration Guide: Plant Material Collecting and Donor Site Management.
			Pool vegetation	Bourgeois, et al. (2019) Seed storage behaviour of eight peatland pool specialists: Implications for restoration. Laberge, et al. (2015) Influence of different bryophyte carpets on vascular plant establishment around pools in restored peatlands. Mazerolle, et al. (2006) Animal and vegetation patterns in natural and man-made bog pools: implications for restoration. Poulin, et al. (2011) Restoration of pool margin communities in cutover peatlands.
			Seismic lines	Alberta Environment and Parks (2017) Visual Guide for Implementing the Restoration and Establishment Framework in Woodland Caribou Habitat. Filicetti, et al. (2019) Caribou conservation: restoring trees on seismic lines in Alberta, Canada.

Appendix B (cont.)

Mitigation hierarchy	**Stressor**	**Number of documents**	**Component**	**Key references**
On-site restoration	Vegetation or substrate disturbance (continued)		Seismic lines (continued)	Finnegan, et al. (2019) Predicting patterns of vegetation recovery on seismic lines: Informing restoration based on understory species composition and growth. Kleinke, et al. (2022) How mounds are made matters: seismic line restoration techniques affect peat physical and chemical properties throughout the peat profile. Pinzon, et al. (2023) Soil mounding as a restoration approach of seismic lines in boreal peatlands: implications on microtopography. van Rensen, et al. (2015) Natural regeneration of forest vegetation on legacy seismic lines in boreal habitats in Alberta's oil sands region.
			Roads/ drill pads	Alberta Ministry of Environment and Parks (2017) Reclamation Criteria for Wellsites and Associated Facilities for Peatlands. Alberta Ministry of Environment and Parks (2020) Reclamation Practices and Criteria for Powerlines. Bird, et al. (2016) Wood Chip Overburden Reclamation in Peatland. Bird & Xu (2021) Natural Ingression and Supplemental Planting for Revegetation of Reclaimed Wetlands. Campbell & Corson (2014) Can mulch and fertilizer alone rehabilitate surface-disturbed subarctic peatlands? Caners & Lieffers (2014) Divergent pathways of successional recovery for *in situ* oil sands exploration drilling pads on wooded moderate-rich fens in Alberta, Canada. Corson & Campbell (2013) Testing protocols to restore disturbed *Sphagnum*-dominated peatlands in the Hudson Bay Lowland, Canada. Gauthier, et al. (2018) Testing the moss layer transfer technique on mineral well pads constructed in peatlands. Lemmer, et al. (2020) Greenhouse gas emissions dynamics in restored fens after *in-situ* oil sands well pad disturbances of Canadian boreal peatlands. Lemmer, et al. (2023) Reestablishment of peatland vegetation following surface leveling of decommissioned in situ oil mining infrastructures. Lieffers, et al. (2017) Re-establishment of hummock topography promotes tree regeneration on highly disturbed moderate-rich fens. MacKenzie & Renkema (2013) In-Situ Oil Sands Extraction Reclamation and Restoration Practices and Opportunities Compilation. Murray, et al. (2021) Restoration approach influences carbon exchange at in-situ oil sands exploration sites in east-central Alberta. Shunina, et al. (2016) Comparison of site preparation and revegetation strategies within a *Sphagnum*-dominated peatland following removal of an oil well pad. Sobze, et al. (2013) Peatland Restoration – Site Re-Vegetation. St-Pierre, et al. (2021) Drivers of vegetation regrowth on logging roads in the boreal forest: Implications for restoration of woodland caribou habitat. Xu, et al. M (2022) Restoration of boreal peatland impacted by an in-situ oil sands well-pad 1: Vegetation response.
			Fire	Granath, et al. (2016) Mitigating wildfire carbon loss in managed northern peatlands through restoration.
On-site restoration	Landscape conversion and fragmentation	62	Constructed peatlands for mine reclamation	Biagi, et al. (2021) Hydrological functioning of a constructed peatland watershed in the Athabasca oil sands region: potential trajectories and lessons learned. Biagi, et al. (2019) Increases in salinity following a shift in hydrologic regime in a constructed wetland watershed in a post-mining oil sands landscape. Borkenhagen & Cooper (2019) Establishing vegetation on a constructed fen in a post-mined landscape in Alberta's oil sands region: A four-year evaluation after species introduction. Clark, et al. (2019) The initial three years of carbon dioxide exchange between the atmosphere and a reclaimed oil sand wetland. Coulas, et al. (2021) Organic matter decomposition at a constructed fen in the Athabasca Oil Sands region: effect of substrate type and environmental conditions. Davidson, et l. (2021) High sulfate concentrations maintain low methane emissions at a constructed fen over the first seven years of ecosystem development. Irvine, et al. (2021) Dissolved organic carbon production and transport within a constructed fen watershed in the Athabasca Oil Sands Region, Alberta, Canada. Ketcheson, et al. (2017) The hydrological functioning of a constructed fen wetland watershed. Khadka, et al. (2016) Dissolved organic carbon in a constructed and natural fens in the Athabasca oil sands region, Alberta, Canada. Murray, et al. (2017) Methane emissions dynamics from a constructed fen and reference sites in the Athabasca Oil Sands Region, Alberta. Nwaishi, et al. (2016) Preliminary assessment of greenhouse gas emissions from a constructed fen on post-mining landscape in the Athabasca oil sands region, Alberta, Canada. Nwaishi, et al. (2016) Above and below-ground nutrient cycling: a criteria for assessing the biogeochemical functioning of a constructed fen. Oswald & Carey (2016) Total and methyl mercury concentrations in sediment and water of a constructed wetland in the Athabasca Oil Sands region. Pouliot, et al. (2013) Fen mosses can tolerate some saline conditions found in oil sands process water. Price, et al. (2010) Landscape restoration after oil sands mining: conceptual design and hydrological modelling for fen reconstruction.

Appendix B (cont.)

Mitigation hierarchy	**Stressor**	**Number of documents**	**Component**	**Key references**
On-site restoration	Landscape conversion and fragmentation (continued)		Constructed peatlands for mine reclamation (continued)	Prystupa, et al. (2023) Response of dissolved organic carbon dynamics to salinity in a constructed fen peatland in the Athabasca oil sands region. Spennato HM, Ketcheson SJ, Mendoza CA, Carey SK (2018) Water table dynamics in a constructed wetland, Fort McMurray, Alberta. Water table dynamics in a constructed wetland, Fort McMurray, Alberta. Hydrological Processes 32:3824–3836
			Ecosystem conversion	Alberta Ministry of Environment and Parks (2017) Reclamation Criteria for Wellsites and Associated Facilities for Peatlands. OMECP (2020) Best Management Practices for Mineral Exploration and Development Activities and Woodland Caribou in Ontario. OMNR (2016) Best Management Practices for Aggregate Activities and Forest-dwelling Woodland Caribou.
			Linear features	Alberta Environment and Parks (2017) Visual Guide for Implementing the Restoration and Establishment Framework in Woodland Caribou Habitat Alberta Ministry of Environment and Parks (2020) Reclamation Practices and Criteria for Powerlines. Golder Associates (2015) Boreal Caribou Habitat Restoration Operational Toolkit for British Columbia. Hornseth, et al. (2018) Motorized activity on legacy seismic lines: a predictive modeling approach to prioritize restoration efforts. OMECP (2020) Best Management Practices for Mineral Exploration and Development Activities and Woodland Caribou in Ontario. St-Pierre, et al. (2021) Drivers of vegetation regrowth on logging roads in the boreal forest: Implications for restoration of woodland caribou habitat. Yemshanov, et al. (2023) Restoration of linear disturbances from oil-and-gas exploration in boreal landscapes: how can network models help?
On-site restoration	Mercury/ Methylmercury	0		No explicit options for on-site restoration.
On-site restoration	Overgrazing	4		Handa & Jefferies (2000) Assisted revegetation trials in degraded salt-marshes.
On-site restoration	Invasive species	10		Lavoie (2019) 50 plantes envahissantes: Protéger la nature et l'agriculture. Nichols (2024) Invasive *Phragmites* (*Phragmites australis*) Best Management Practices in Ontario: Improving Species at Risk Habitat Through the Management of Invasive *Phragmites*.
On-site restoration	Other stressors	3		No options for on-site restoration.

Appendix B (cont.)

Mitigation hierarchy	Stressor	Number of documents	Component	Key references
Offsetting	Any stressor(s)	39	General	BBOP (2009) Biodiversity Offset Design Handbook. Ecosystem Planning and Restoration (2022) Mitigation Bank Instrument Review Workbook. Gardner et al. (2013) Biodiversity offsets and the challenge of achieving no net loss. ICMM, IUCN (2012) Independent Report on Biodiversity Offsets. National Academies of Sciences, Engineering, and Medicine (2001) Compensating for Wetland Losses Under the Clean Water Act. Pope, et al. (2021) When is an offset not an offset? A framework of necessary conditions for biodiversity offsets.
			Canada	ECCC (2020) Offsetting Policy for Biodiversity - Draft. Poulton & Ray (2023) Knowledge, Perception and Application of the Mitigation Hierarchy Among Officials in Canadian Federal Regulatory and Resource Management Agencies. Harper & Quigley (2005) No net loss of fish habitat: a review and analysis of habitat compensation in Canada.
			Ontario	Bell & Hedges (2016) Biodiversity Offsetting in Ontario: Issues, Accomplishments and Future Directions. Hasenack, et al. (2023) Wetland Offsetting Policies for Local Planning Authorities: A Review of Wise Practices in Ontario. Ontario Nature (2022) A Primer on Wetland Offsetting in Ontario: Practices, Policies and Resources. Penfound & Vaz (2022) Analysis of 200 years of change in Ontario wetland systems. Poulton D (2015) Key Issues in Biodiversity Offset Law and Policy: A Comparison of Six Jurisdictions. Ontario Nature Poulton D, Bell A (2017) Navigating the Swamp: Lessons on Wetland Offsetting for Ontario.
			Conservation	Alexandrov, et al. (2020) The capacity of northern peatlands for long-term carbon sequestration. Drever, et al. (2021) Natural climate solutions for Canada. Helbig, et al. (2020) The biophysical climate mitigation potential of boreal peatlands during the growing season. Humpenöder, et al. (2020) Peatland protection and restoration are key for climate change mitigation. Lee, et al. (2010) Atlas of Canada's Intact Forest Landscapes. Strack, et al. (2022) The potential of peatlands as nature-based climate solutions.
			Indigenous perspectives	Bois-Charlebois M (2018) Les défis de la compensation écologique des impacts sur les milieux humides dans le nord du Québec : étude de cas en territoire Cri. McDermott & Bell (2017) Indigenous Perspectives on Conservation Offsetting: Five Case Studies from Ontario, Canada.
Compensation	Any stressor(s)	9	General	Baird, et al. (2023) Impact Benefit Agreements: Key Insights from First Nations', Government and Industry Leaders. Gunton, et al. (2020) Impact Benefit Agreement Guidebook.

APPENDIX C: Best Monitoring Approaches by Ecosystem Stressor

***APPENDIX C: Best monitoring approaches by ecosystem stressor (Total* n = 1006 documents).**

Stressor	Number of documents	Component	Key documents
All stressors	193	Baseline conditions	Davies, et al. (2021) Ecohydrological controls on apparent rates of peat carbon accumulation in a boreal bog record from the Hudson Bay Lowlands, northern Ontario, Canada. Glooschenko & Capoblanco (1982) Trace element content of northern Ontario peat. Hargan, et al. (2020) Post-glacial lake development and paleoclimate in the central Hudson Bay Lowlands inferred from sediment records. Jeziorski, et al. (2015) Differences among modern-day and historical cladoceran communities from the 'Ring of Fire' lake region of northern Ontario: Identifying responses to climate warming. McDonough, et al. (2022) Establishing trace element concentrations for lichens and bryophytes in the Ring of Fire region of the Hudson Bay Lowlands, Ontario, Canada. Packalen, et al. (2016) Climate and peat type in relation to spatial variation of the peatland carbon mass in the Hudson Bay Lowlands, Canada. Riley, et al. (2003) Flora of the Hudson Bay Lowland and its Postglacial Origins. Riley JL (2011) Wetlands of the Hudson Bay Lowland: an Ontario Overview. Su, et al. (2021) Baseline air monitoring of fine particulate matter and trace elements in Ontario's Far North, Canada.
		Biomonitoring	Bayne, et al. (2022) A Before-After Dose-Response (BADR) Terrestrial Biological Monitoring Framework for the Oil Sands. Ficken, et al. (2022) Drivers, pressures, and state responses to inform long-term oil sands wetland monitoring program objectives. Mahoney, et al. (2023) Oil sands wetland ecosystem monitoring program indicators in Alberta, Canada: transitioning from pilot to long-term monitoring. Rooney & Bayley (2011) Setting reclamation targets and evaluating progress: submersed aquatic vegetation in natural and post-oil sands mining wetlands in Alberta, Canada. Rooney, et al. (2012) Development and testing of an index of biotic integrity based on submersed and floating vegetation and its application to assess reclamation wetlands in Alberta's oil sands area, Canada.
Hydrological alteration	47	General	Eaton & Charette (2016) Drivers, stressors, and indicators of wetland change in Alberta's Oil Sands Region – potential for use in wetland monitoring. Mahoney, et al. (2023) Oil sands wetland ecosystem monitoring program indicators in Alberta, Canada: transitioning from pilot to long-term monitoring.
		Remote sensing	Ball, et al. (2023) Assessing the potential of using Sentinel-1 and 2 or high-resolution aerial imagery data with machine learning and data science techniques to model peatland restoration progress - a northern Scotland case study. Banskota, et al. (2017) Continuous wavelet analysis for spectroscopic determination of subsurface moisture and water-table height in northern peatland ecosystems. Bradley, et al. (2022) Identification of typical ecohydrological behaviours using InSAR allows landscape-scale mapping of peatland condition. Evans, et al. (2021) A novel low-cost, high-resolution camera system for measuring peat subsidence and water table dynamics. Haghighi, et al. (2018) Use of remote sensing to analyse peatland changes after drainage for peat extraction. Isoaho, et al. (2024) Monitoring changes in boreal peatland vegetation after restoration with optical satellite imagery. Jussila, et al. (2024) Quantifying wetness variability in aapa mires with Sentinel-2: towards improved monitoring of an EU priority habitat. Lees, et al. (2021) Using remote sensing to assess peatland resilience by estimating soil surface moisture and drought recovery. Lovitt, et al. (2018) UAV remote sensing can reveal the effects of low-impact seismic lines on surface morphology, hydrology, and methane (CH4) release in a boreal treed bog. Meingast, et al. (2014) Spectral detection of near-surface moisture content and water-table position in northern peatland ecosystems. Millard, et al. (2022) Seasonally-decomposed Sentinel-1 backscatter time-series are useful indicators of peatland wildfire vulnerability. Neta, et al. (2011) Development of new spectral reflectance indices for the detection of lichens and mosses moisture content in the Hudson Bay Lowlands, Canada. Olthof & Fraser (2024) Mapping surface water dynamics (1985-2021) in the Hudson Bay Lowlands, Canada using sub-pixel Landsat analysis. Rahman, et al. (2017) A new method to map groundwater table in peatlands using unmanned aerial vehicles.
		Well monitoring	Gutierrez-Pacheco, et al. (2021) Estimation of daily water table level with bimonthly measurements in restored ombrotrophic peatland. McCarter & Price (2013) The hydrology of the Bois-des-Bel bog peatland restoration: 10 years post-restoration. Whittington & Price (2013) Effect of mine dewatering on the peatlands of the James Bay Lowland; the role of marine sediments on mitigating peatland drainage.
		Peat cores	Davies, et al. (2021) Ecohydrological controls on apparent rates of peat carbon accumulation in a boreal bog record from the Hudson Bay Lowlands, northern Ontario, Canada. Hargan, et al. (2020) Post-glacial lake development and paleoclimate in the central Hudson Bay Lowlands inferred from sediment records. Holmquist, et al. (2016) Boreal peatland water table depth and carbon accumulation during the Holocene thermal maximum, Roman Warm Period, and Medieval Climate Anomaly. Jeziorski, et al. (2015) Differences among modern-day and historical cladoceran communities from the 'Ring of Fire' lake region of northern Ontario: Identifying responses to climate warming.
		Other	Tanneberger, et al. (2024) Quantifying ecosystem services of rewetted peatlands – the MoorFutures methodologies.

Appendix C
(*cont.*)

Stressor	**Number of documents**	**Component**	**Key documents**
Fertility change /contamination	57	General	Environment Canada (2009) Environmental Code of Practice for Metal Mines.
			Environment Canada (2012) Metal Mining Technical Guidance for Environmental Effects Monitoring.
			ECCC (2015) Third National Assessment of Environmental Effects Monitoring Information from Metal Mines Subject to the Metal Mining Effluent Regulations.
			OMECP (2018) Mining Sites - Industry Standard.
		Acid mine drainage	INAP (2018) Global Acid Rock Drainage Guide.
			O'Kane Consultants Inc. (2007) Macro-Scale Cover Design and Performance Monitoring Manual.
			O'Kane Consultants Inc. (2004) Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings Volume 4 – Field Performance Monitoring and Sustainable Performance of Cover Systems.
		Fugitive dust	Cleaver, et al. (2022) Field comparison of fugitive tailings dust sampling and monitoring methods.
			Opekunova, et al. (2020) Comparative analysis of methods for air pollution assessing in the Arctic mining area.
			Shotyk, et al. (2023) Trace elements in peat bog porewaters: indicators of dissolution of atmospheric dusts and aerosols from anthropogenic and natural sources.
			Chen, et al. (2024) Estimating the bioaccessibility of atmospheric trace elements within the Athabasca bituminous sands region using the acid soluble ash fraction of Sphagnum moss.
		Biomonitoring trace metal with mosses lichens	Anicic, et al. (2009) Monitoring of trace element atmospheric deposition using dry and wet moss bags: accumulation capacity versus exposure time.
			Ares, et al. (2015) Do moss bags containing devitalized *Sphagnum denticulatum* reflect heavy metal concentrations in bulk deposition?
			Boquete, et al. (2020) Matching times: trying to improve the correlation between heavy metal levels in mosses and bulk deposition.
			Gacnik, et al. (2024) Comparison of active measurements, lichen biomonitoring, and passive sampling for atmospheric mercury monitoring.
			Kempter, et al. (2017) Validating modelled data on major and trace element deposition in southern Germany using *Sphagnum* moss.
			Landis, et al. (2019) Use of an epiphytic lichen and a novel geostatistical approach to evaluate spatial and temporal changes in atmospheric deposition in the Athabasca Oil Sands Region, Alberta, Canada.
			McDonough, et al. (2022) Establishing trace element concentrations for lichens and bryophytes in the Ring of Fire region of the Hudson Bay Lowlands, Ontario, Canada.
			Mullan-Boudreau, et al. (2017) *Sphagnum* moss as an indicator of contemporary rates of atmospheric dust deposition in the Athabasca Bituminous Sands Region.
			Salo, et al. (2016) Seasonal comparison of moss bag technique against vertical snow samples for monitoring atmospheric pollution.
			Stefanut, et al. (2019) National environmental quality assessment and monitoring of atmospheric heavy metal pollution - A moss bag approach.
			Szczepaniak, et al. (2007) Comparison of dry and living *Sphagnum palustre* moss samples in determining their biocumulative capability as biomonitoring tools.
		Peat cores	Mullan-Boudreau, et al. (2017) Reconstructing past rates of atmospheric dust deposition in the Athabasca Bituminous Sands Region using peat cores from bogs.
			Shotyk, et al. (2017) Peat bogs document decades of declining atmospheric contamination by trace metals in the Athabasca bituminous sands region.
			Shotyk & Noernberg (2020) Sampling, handling, and preparation of peat cores from bogs: review of recent progress and perspectives for trace element research.
		Trace metal reference conditions	Glooschenko & Capoblanco (1982) Trace element content of northern Ontario peat.
			Su, et al. (2021) Baseline air monitoring of fine particulate matter and trace elements in Ontario's Far North, Canada.
Vegetation and substrate disturbance	64	Remote sensing	Beyer, et al. (2019) Multisensor data to derive peatland vegetation communities using a fixed-wing unmanned aerial vehicle.
			Bourgeau-Chavez, et al. (2017) Mapping boreal peatland ecosystem types from multitemporal radar and optical satellite imagery.
			Carless, et al. (2019) Mapping landscape-scale peatland degradation using airborne lidar and multispectral data.
			Chasmer, et al. (2021) Shrub changes with proximity to anthropogenic disturbance in boreal wetlands determined using bi-temporal airborne lidar in the Oil Sands Region, Alberta Canada.
			Finnegan, et al. (2019) Predicting patterns of vegetation recovery on seismic lines: Informing restoration based on understory species composition and growth.
			Ghazaryan, et al. (2024) Enhancing peatland monitoring through multisource remote sensing: optical and radar data applications.
			Haghighi, et al. (2018) Use of remote sensing to analyse peatland changes after drainage for peat extraction.
			Harris, et al. (2015) Hyperspectral remote sensing of peatland floristic gradients.
			Isoaho, et al. (2024) Monitoring changes in boreal peatland vegetation after restoration with optical satellite imagery.
			Jones, et al. (2022) Use of mobile laser scanning (MLS) to monitor vegetation recovery on linear disturbances.

Appendix C
(*cont.*)

Stressor	Number of documents	Component	Key documents
Vegetation and substrate disturbance (continued)		Remote sensing (continued)	Kolari , et al. (2022) Ongoing fen–bog transition in a boreal aapa mire inferred from repeated field sampling, aerial images, and Landsat data.
			Middleton, et al. (2012) Ordination and hyperspectral remote sensing approach to classify peatland biotopes along soil moisture and fertility gradients.
			Millard, et al. (2022) Seasonally-decomposed Sentinel-1 backscatter time-series are useful indicators of peatland wildfire vulnerability.
			Minasny, et al. (2024) Mapping and monitoring peatland conditions from global to field scale.
			Mohammad Mirmazloumi, et al. (2021) Status and trends of wetland studies in Canada using remote sensing technology with a focus on wetland classification: a bibliographic analysis.
			Pang, et al. (2023) Upscaling field-measured seasonal ground vegetation patterns with Sentinel-2 images in boreal ecosystems.
			Pironkova (2017) Mapping palsa and peat plateau changes in the Hudson Bay Lowlands, Canada, using historical aerial photography and high-resolution satellite imagery.
			Räsänen, (2019) Comparing ultra-high spatial resolution remote-sensing methods in mapping peatland vegetation.
			Räsänen, et al. (2020) Detecting northern peatland vegetation patterns at ultra-high spatial resolution.
			Salko, et al. 2023) Intra- and interspecific variation in spectral properties of dominant *Sphagnum* moss species in boreal peatlands.
			Steenvoorden, et al. (2024) Towards standardised large-scale monitoring of peatland habitats through fine-scale drone-derived vegetation mapping.
			Stuart, et al. (2022) Peatland plant spectral response as a proxy for peat health, analysis using low-cost hyperspectral imaging techniques.
		Vegetation sampling	Rochefort, et al. M (2013) Comparing survey methods for monitoring vegetation change through time in a restored peatland.
		Reference conditions	Bérubé, et al. (2017) Fen restoration: defining a reference ecosystem using paleoecological stratigraphy and present-day inventories.
			González & Rochefort (2019) Declaring success in Sphagnum peatland restoration: identifying outcomes from readily measurable vegetation descriptors.
Landscape conversion & fragmentation	21	General	Alberta Ministry of Environment and Parks (2017) Reclamation Criteria for Wellsites and Associated Facilities for Peatlands.
			Alberta Ministry of Environment and Parks (2020) Reclamation Practices and Criteria for Powerlines.
		Camera traps	Feldman, et al. (2024) Using camera traps to estimate habitat preferences and occupancy patterns of vertebrates in boreal wetlands.
			Sun, et al. (2021) Simultaneous monitoring of vegetation dynamics and wildlife activity with camera traps to assess habitat change.
Mercury/ Methylmercury	12	Total mercury	Bargagli (2016) Moss and lichen biomonitoring of atmospheric mercury: a review.
			Brazeau M (2012) Historical deposition and microbial redox cycling of mercury in lake sediments from the Hudson Bay Lowlands, Ontario, Canada.
			Gacnik, et al. (2024) Comparison of active measurements, lichen biomonitoring, and passive sampling for atmospheric mercury monitoring.
			Shotyk & Cuss (2019) Atmospheric Hg accumulation rates determined using *Sphagnum* moss from ombrotrophic (rain-fed) bogs in the Athabasca Bituminous Sands region of northern Alberta, Canada.
		Methylmercury	CPAWS Wildlands League (2015) Nothing to See Here - Failures of Self-monitoring and Reporting at De Beers Victor Diamond Mine in Canada.
			De Beers Canada Inc. Victor Mine (2024) Mercury Performance Monitoring 2023 Annual Report Per Environmental Compliance Approval #3960-7Q4K2G Conditions 7(5) And 7(6).
Overgrazing	4		Barnas, et al. (2019) A comparison of drone imagery and ground-based methods for estimating the extent of habitat destruction by lesser snow geese (*Anser caerulescens caerulescens*) in La Perouse Bay.
			Gadallah (2002) Historical vegetation reconstruction of a degraded sub-arctic coastal marsh using Landsat imagery and ancillary data.
			Jano, et al. (1998) The detection of vegetational change by multitemporal analysis of LANDSAT data: the effects of goose foraging.
Invasive species	3		Small, et al. (2018) Optimizing Weed Control for Progressive Reclamation: Literature Review.
			Bayne, et al. (2022) A Before-After Dose-Response (BADR) Terrestrial Biological Monitoring Framework for the Oil Sands.
Other stressors	4		Shonfield & Bayne (2017) Autonomous recording units in avian ecological research: current use and future applications.