Drivers, pressures, and state responses to inform long-term oil sands wetland monitoring program objectives

Cari D. Ficken · Stephanie J. Connor · Rebecca Rooney ·
Danielle Cobbaert

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Abstract Boreal peatlands provide numerous ecosystem services ranging from carbon sequestration to the provisioning of habitat for species integral to Indigenous communities. In the Oil Sands Region of Alberta, Canada, human development related to oil and gas extraction occurs in a wetland-dominated landscape. Wetland monitoring programs can determine the extent to which development impacts wetlands, but existing monitoring programs focus on characterizing biodiversity across the region and on compliance and regulatory monitoring that assumes impacts from oil sands development do not extend past lease boundaries. This is unlikely to be true since some impacts, such as particulate deposition, can extend over large areas contingent on local weather and topography. To inform the development of a new

regional wetland monitoring program to assess the cumulative effects of oil sands development on wetlands, we synthesized information on the scope of wetland research across the Oil Sands Region, including the anthropogenic stressors that impact wetlands and the wetland characteristics sensitive to different disturbances. We developed a conceptual model linking human development with wetland ecology in the region to make explicit the relationships among oil sands development stressors and different components of wetland ecosystems. By highlighting testable relationships, this conceptual model can be used as a collection of hypotheses to identify knowledge gaps and to guide future research priorities. We found that the majority of studies are short-term (77% were ≤ 5 years) and are conducted over a limited spatial extent (82% were sub-regional). Studies of reclaimed wetlands were relatively common (18% of all tests); disproportionate to the occurrence of this wetland type. Results from these studies likely cannot be extrapolated to other wetlands in the region. Nevertheless, the impacts of tailings contaminants, wetland reclamation activities, and surface water chemistry are well-represented in the literature. Research on other types of land disturbance is lacking. A coordinated, regional monitoring program is needed to gain a complete understanding of the direct and indirect impacts of human development in the region and to address remaining knowledge gaps.

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C. D. Ficken (✉)
Department of Geology, University at Buffalo, Buffalo,
NY, USA
e-mail: cficken@buffalo.edu; cari.ficken@gmail.com

C. D. Ficken · R. Rooney
Department of Biology, University of Waterloo,
Waterloo, ON, Canada

S. J. Connor · D. Cobbaert
Alberta Environment and Parks, Edmonton,
AB, Canada

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Introduction

Boreal wetlands represent less than 3% of the Earth's surface area yet store 20–30% of the total terrestrial carbon (Yu 2012; Xu et al. 2018). These wetlands, which in Alberta are predominantly peatlands (Vitt and Chee 1990; Vitt 1996; Ficken et al. 2019), provide globally important climate regulation services due to their ability to reduce air temperatures (Helbig et al. 2020), sequester carbon, and mediate greenhouse gas fluxes (Millennium Ecosystem Assessment 2005). They also provide important water regulating services by diluting downstream pollution, filtering atmospheric pollutants, and retaining and sequestering nutrients; they further mediate water flows by attenuating runoff and discharge rates, and mitigate downstream floods (IPBES 2019). Boreal wetlands also provide important socio-cultural connections for local Indigenous communities who have long histories and relationships with the landscape and biodiversity supported by these ecosystems (Berkas and Davidson-Hunt 2006; Dyck and Garibaldi 2018; IPBES 2019; Kassi 2019). For example, boreal peatlands are the primary habitat for woodland caribou (*Rangifer tarandus caribou* (Banfield)) (McLoughlin et al. 2005), which are a culturally important species for Indigenous communities. Despite the importance of boreal peatlands, they continue to be degraded and lost (Leifeld and Menichetti 2018; Humpenöder et al. 2020).

Peatland area across the globe is generally declining (Joosten 2010) due to draining for forestry, agricultural, and/or peat extraction. Between 2002 and 2005, Canada experienced the second largest gross forest cover loss in the world (Hansen et al. 2010), with substantial forest loss occurring from development in Canada's Oil Sands Region (OSR; Rosa et al. 2017). Local Indigenous communities are concerned that development in the OSR will have significant effects on wetland biodiversity, such as by impacting habitat for culturally-important plant species and other wetland-reliant at-risk species (Gilmour and Twin 2015).

The development of boreal wetlands in the OSR is largely driven by the oil sands and natural gas sectors, which contributed \$105 billion to the Canadian economy and represented 6% of Canada's GDP in 2020 (CAPP 2021). In Alberta, Canada, the OSR covers 142,200 km² of boreal ecosystems (Fig. S1) and is underlain by >160 billion barrels of oil, making it the world's third largest oil reserve (Alberta Energy Regulator 2018). Oil sand mining and other development activities may impact OSR wetlands through numerous means. Oil sands mine development alters surface water flow and quality due to land clearing, construction and early operational activities (Alexander and Chambers 2016; Rosa et al. 2017), which may affect the ecological condition of nearby wetlands, especially those downstream of development. Additionally, mines typically withdraw large volumes of shallow and basal groundwater during operations (Rosa et al. 2017; Ali and Kumar 2017), which can cause drying of wetlands in areas adjacent to the mines (Volik et al. 2020). Oil sands development activities have led to increased emissions of oxidized nitrogen and sulfur (notably NO_x, SO₂, and NH_x) to the atmosphere (Makar et al. 2018; Zhang et al. 2018), potentially increasing nitrogen and sulfur inputs to surrounding ecosystems through atmospheric deposition (Simpson et al. 2010; McLinden et al. 2012).

To address knowledge gaps, a regional monitoring program was established in 2012 by the governments of Canada and Alberta. The Oil Sands Monitoring Program was developed as a 'world class monitoring program' within the OSR to provide assurance of environmentally responsible development of the resources therein. To evaluate the effects of human activities on OSR ecosystems, long-term environmental monitoring programs have been developed to assess water quality and quantity, air quality, and biodiversity (Oil Sands Monitoring Program 2019). However, to date no program is implemented to assess the effects of oil sands development on wetland ecosystems regionally nor to evaluate the impacts of multiple concurrent stressors.

Monitoring at a regional level is required for a complete understanding of the impacts of oil sands development to ecosystems both on and off leased land. A regional environmental monitoring program should (a) reduce uncertainty in cause-effect relationships by assessing indicators of wetland ecosystem condition that are sensitive to specific types of

disturbance (Colodey and Wells 1992; Roach and Walker 2017), (b) include indicators of wetland health and condition that are valued by local Indigenous communities, and (c) consider multiple stressors impacting wetlands for a holistic assessment of ecosystem condition (i.e. consider the cumulative effects of multiple stressors, sensu Gosselin et al. 2010; Squires et al. 2010).

We developed a conceptual model within the Drivers-Pressures-State-Impact-Response framework (DPSIR; Lammers and Gilbert 1999; Smeets and Weterings 1999) framework to synthesize information on the relationships among human activities and wetland ecological characteristics for wetlands in the OSR (Fig. 1). The DPSIR framework is used to organize, clarify, and formalize cause-effect relationships between human systems and the environment. It is used by diverse agencies, including the European Union Environmental agency, Organisation of Economic Co-operation and Development, the United Nations Environment Program, and the United States Environmental Protection Agency (reviewed in Patrićio et al. 2016). We adopted the definitions proposed by Oosterwind et al. (2016) to differentiate between Drivers and Pressures in our framework. Under these definitions, *Drivers* are natural or anthropogenic “superior complex phenomena” that govern the nature

of ecosystem change. They are beyond our direct management, such as the human demand for oil. *Pressures* alter the environmental state of the wetland as a result of a Driver-initiated mechanism. They may or may not be manageable, depending on the Driver(s) responsible. Pressures can be conceptualized as the mechanisms by which the Drivers alter the state of the wetlands. *States* represent the condition of the wetland and its components and may be defined by measurable abiotic and biological variables. Examples could include the diversity of wetland flora or the quality of surface water. If supported by the literature, such measurements of wetland state could serve as scientifically defensible indicators in a long-term regional wetland monitoring program.

Our goal was to inform the development of a wetland component of the Oil Sands Monitoring Program by characterizing the state of knowledge on wetland sensitivity to environmental conditions within the OSR. Specifically, we aimed to: (1) examine the spatial, temporal, and ecological scope of wetland ecosystem studies in the OSR, (2) examine the overall state of knowledge on the natural and anthropogenic Drivers and Pressures affecting OSR wetlands, and (3) evaluate the weight of scientific evidence supporting candidate wetland state indicators that are sensitive to

Fig. 1 Conceptual model illustrating the relevant Drivers, Pressures, States (Abiotic and Biotic), and Impacts. Definitions of Drivers, Pressures, and States were adapted from Oosterwind

et al. (2016). The color coding of Drivers (green), Pressures (orange), States (purple), and Impacts (pink) is maintained throughout

oil sands development and valued by local communities.

Methods

Conceptual model development

We focused our conceptual model (Fig. 1) and synthesis on one main *Driver*: human development associated with oil sands mining (hereafter oil sands development). However, this is not the only *Driver* within the region and disentangling the impacts of different drivers is an important area of ongoing research (e.g. Hewitt et al. 2020; Chowdhury et al. 2021). The landscape is affected by multiple land use types (e.g. forestry, agriculture, transportation), as well as underlying natural variability in geology and topography. Finally, the habitats within this region exist on a backdrop of natural weather patterns (Pacific Decadal Oscillations; 20–30 year cycle; Mantua and Hare 2002) and potential effects from climate change. We focus on three broad *Pressures* regarding oil sands development: land disturbance, hydrologic alteration, and contamination. Wetland reclamation was added after the original literature search due to the volume of studies that cover this topic. We separated wetland state into *Biotic State* and *Abiotic State* variables to allow for the identification of any mechanisms underlying wetland State responses to a Pressure or Driver. We stress that these components of the model, in particular, interact bidirectionally. *Impact* generally considers how the value of wetlands (e.g., the services provided) is affected by changes in State. The *Response* part of the DPSIR framework is largely beyond scope of a monitoring program, such as the concerns of local stakeholders and Indigenous communities (e.g., Sect. 35 Treaty Rights), and falls within the responsibility of policymakers and land/resource managers so it is not discussed here further.

Literature search

We conducted a systematic literature review to examine the research being conducted on stressors to wetlands in the OSR (Fig. S1). On January 9, 2020 we searched for papers published in the Web of Science Core Collection between 1900 and 2019 with the following search terms: [“oil sands” or “tar sands” or

“athabasca” or “boreal plains” or “peace river” or “cold lake”] and [“wetland” or “peatland” or “fen” or “bog” or “marsh” or “wet meadow” or “shallow open water wetland” or “shallow lake” or “pond”]. We read the abstracts of all 410 returned papers (Table S3) and kept the 160 studies which met the following inclusion criteria: (1) published in a peer-reviewed scientific journal, (2) conducted in wetland habitat within our geographic focal area (i.e. OSR, Peace-Athabasca Delta, or Boreal Plains), and (3) reported quantitative results of at least one test of a relationship between Driver(s), Pressure(s), and/or State(s) (i.e., Driver-Driver, Driver-Pressure, Driver-State, Pressure-Pressure, Pressure-State, or State-State).

Study and test coding

We next read through each relevant paper to extract information on its study design and variables associated with each test it examined (Table S1). For each paper, we recorded its focal wetland class, type, or zone (bog, fen, marsh, peatland, shallow open water wetland, swamp, wet meadow, other/multiple/unspecified), the spatial scale of the study (microcosm, mesocosm, single site, multiple sites, regional), and the temporal scale of the study (<1 year, 1–5 years, 5–10 years, >10 years).

Studies often included results from multiple tests such that there were more tests ($n = 898$) than there were relevant studies ($n = 160$; Table S2). For each test, we recorded which components were examined (i.e. Drivers, Pressures, Abiotic States, Biotic States) and categorized the test variables into classes within the component (Table S1). We categorized the Drivers into the following classes: Oil Sands Production, Weather and Climate, Wildfires, Landscape Factors (e.g. surficial geology, topography), and Other Human Development (e.g. forestry, transportation, agriculture). We categorized the Pressures into the following classes: Landscape Ablation (i.e. disturbance to soil layers below the rooting zone), Surficial Soil/Peat Disturbance, Vegetation Removal, Wetland Reclamation, Surface Water Diversions, Groundwater and Surface Water Withdrawals and Releases, Tailings Contamination (including liquid and solid tailings), and Aerial Emissions (stack emissions and fugitive dust). Pressures are not damaging by definition, and so Wetland Reclamation was included as a Pressure

variable since it is a management action with a direct influence on the wetland's Abiotic and Biotic States (i.e. Substrate Physical Properties, Surface Water Chemistry; Alberta Environment 2008). We categorized the wetland states into Abiotic (Wetland Extent, Substrate Physical Properties, Substrate Chemistry, Hydrology, Micrometeorological Conditions, Surface Water Chemistry, Groundwater Chemistry) and Biotic (Abundance, Diversity, Richness, Tissue Stoichiometry, Biomass, Growth Rate, Nutrient Cycling, Other) classes. For Biotic States we also recorded the taxa measured (algae, amphibians, birds, fish, fungi, invertebrates, mammals, microbes, plants—general, plants—nonvascular, plants—vascular). Finally, for each bivariate test we recorded the nature of the reported relationship: statistically significant and positive, statistically significant and inverse, nonsignificant, or nonlinear/nondirectional. Nondirectional refers to tests of relationships between a continuous response variable and an ordinal predictor where differences among predictor levels were either not consistent in statistical significance or in the directionality of the relationship with the response.

Assessments of research scope

To evaluate the scope of research being conducted on wetlands in the OSR, we examined the number of studies conducted at different spatial and temporal scales. We also quantified the number of studies performed on each wetland class, type or zone, largely following the Canadian Wetland Classification System (National Wetlands Working Group 1997).

Weight of effort assessments

To evaluate the weight of research effort allocated to understanding the impacts of different disturbances on wetlands in the OSR, we first assessed which Drivers, Pressures, Abiotic State, and Biotic State variables were most commonly studied. We next examined which relationships with Biotic States were most commonly studied (i.e. Pressure vs. Biotic State, Abiotic State vs. Biotic State). To identify candidate bioindicators of regional wetland health, we focused on four commonly-studied wetland taxa (i.e. plants, invertebrates, birds, and amphibians). For each of these taxa, we identified which Drivers, Pressures, Abiotic States, and Biotic States were the most

commonly studied. We consider the most well-studied taxon-specific Biotic State variable to be candidate bioindicators, since we should have the best understanding of their ecology.

Weight of evidence assessments

To evaluate the extent to which oil sands disturbances have consistent, directional impacts on wetlands, we focus on the most commonly tested Abiotic State variables and the candidate bioindicators identified in our weight of effort assessments (see above). For the Abiotic State variable and each taxon-specific candidate bioindicator, we tallied the total number of tests for each Pressure and Abiotic State variable tested against it. Finally, we tallied the number of tests that reported positive, inverse, nonlinear, or nonsignificant relationships.

Result and discussion

Scope of studies

Out of 410 papers returned through our Web of Science search, 160 were identified as relevant based on the inclusion criteria. Of the 160 studies, most occurred over limited spatial and temporal extents (Fig. 2). Most studies (83%; $n = 132$) occurred in microcosms, mesocosms, one or a few spatially localized sites, whereas only 17% of studies ($n = 27$) were conducted at the regional level (Fig. 2a). Since the results of small-scale and highly controlled studies may not extrapolate to wetlands with different environmental conditions, regional studies are needed to validate their results. Similarly, 44% of studies lasted < 1 year ($n = 71$) while only 14% of studies reported long-term results (i.e. >10 years; $n = 22$; Fig. 2b). Hydrology in the OSR is strongly controlled in part by seasonal climatic conditions (Rooney et al. 2015; Biagi and Carey 2020; Volik et al. 2020), so short-term studies provide important information on wetland responses to typical intra-annual changes. However, short-term studies may not capture the impacts of stochastic climate events (Smith 2011) or gradual changes in human development extent (Alexander et al. 2020).

Most of our focal studies were conducted in the Oil Sands Region ($n = 117$; Fig. S1). There were 33

Fig. 2 A breakdown of the number of studies which were conducted at different **a** spatial and **b** temporal scales. In **a**, “Micro.” and “Meso.” refer to microcosm and mesocosm studies, respectively. Note that in **a**, the spatial scale of one

modeling study was not classified so $n = 159$. In **b**, the temporal extent of one modeling study and one study which did not report the temporal scale were not classified so $n = 158$

studies from the Boreal Plains and 8 studies from the Peace Athabasca Delta. These studies captured a wide range of wetland classes, including bogs ($n = 14$), fens ($n = 32$), marshes ($n = 10$), shallow open water (SOW) wetlands ($n = 14$), and undifferentiated peatlands ($n = 24$; Fig. 3). Peatlands make up the majority of wetlands in the Oil Sands Region, followed by swamps, SOW wetlands, and marshes (Vitt 1996, Alberta Environment and Parks, Government of Alberta 2018, Ficken et al. 2019). Swamps were not specifically targeted in our original search terms, as mineral swamps are rare in our area and organic swamps are likely categorized as peatlands (Locky et al. 2005).

Weight of effort

To understand which Drivers, Pressures, Abiotic States, and Biotic States are most studied, we tallied the number of tests performed on each component as well as the number of pairwise relationships studied. The 898 bivariate tests included 1796 variables: 242 Drivers, 478 Pressures, 349 Abiotic States, and 727 Biotic States (Fig. 4). Oil Sands (OS) Production was the most commonly tested Driver variable ($n = 73$ or 4% of all tested variables; Figs. 4 and 5) and included, for example, tests of the distance to the industrial

Fig. 3 The number of studies which were conducted in each natural wetland class. Some studies reported results for more than one wetland class so $n = 166$. Wetlands classified as “Other” ($n = 72$) are primarily those conducted in reclaimed wetlands ($n = 45$) and also include studies which group multiple wetland classes in analyses and studies of unclassified wetlands. Note that the majority of reclaimed wetlands are marshes or SOWs; only 2 peatlands have thus far been reclaimed. Wetlands classified as “Peatland” include studies of undifferentiated peatlands or bog-fen complexes

Fig. 4 The number of tests of each a Driver, b Pressure, c Abiotic State, and d Biotic State variable. There were 898 bivariate tests and 1790 individual variables reported. These numbers include all tests, including those with nonsignificant results. See Fig. 1 for all conceptualized variables within each category. Drivers include Other Human Development (“Other Human Dev”), Fire, Weather and Climate (“Weather & Clim.”), Landscape Factors, and Oil Sands Production (“OS Production”). Pressures include Surface Water Diversion (“Water Div.”), Vegetation Removal (“Veg. Removal”), Aerial

Emissions (“Aerial Emiss.”), Other, Wetland Reclamation (“Wetland Reclam.”) and Tailings Contaminants (“Tailings Contam”). Abiotic States include Micrometeorological Conditions (“Micromet. Conditions”), Substrate Chemistry (“Subst. Chem.”), Substrate Physical Properties (“Subst. Phys. Properties”), Hydrology, and Surface Water Chemistry (“Surface Water Chem.”). Biotic States include Richness (“Rich.”), Diversity (“Div.”), Tissue Stoichiometry (“Stoch.”), Nutrient Cycling (“Nut. Cycling”), Growth Rate (“GR”), Biomass (“Biom.”), Abundance (“Abund.”), and Other

center (Plach et al. 2016; Strack et al. 2018). Tailings Contamination was the most commonly tested Pressure variable ($n = 282$ or 16% of all tested variables;

Figs. 4 and 5). Surface Water Chemistry was the most commonly tested Abiotic State variable ($n = 216$ or 12% of all tested variables Figs. 4 and 5). Of the tests

Fig. 5 Sankey Flow diagram illustrating the number of tests of each bivariate relationship between variables classified as Drivers (green boxes), Pressures (orange boxes), Abiotic States (purple boxes) and Biotic States (pink boxes). The height of each colored variable box is proportional to the number of tests of that variable and the thickness of each grey ribbon connecting two variable boxes is proportional to the number of tests of that

relationship. or visual clarity, we depict only relationships with 10 or more tests. The Key inset converts ribbon thickness to the number of tests associated with each box. The inset depicts the variables which had < 10 tests; boxes are colored as Pressures and State types according to the main figure. Note that the 15 Abundance-Abundance tests are not depicted, as this would require a circular ribbon

of Biotic State variables, 400 were tests of the structure of wetland biota (e.g. Abundance, Biomass, Diversity) while 173 were tests of the functioning of the wetland (i.e. Nutrient Cycling or Growth Rate; Fig. 1). Biotic variables classified as “Other” were the most commonly tested Biotic State variable ($n = 154$ or 9% of all tested variables; Fig. 4d); these included various metrics of organism health and endocrine function (e.g. survival, antibody production, testosterone, clutch size). Measures of organism Abundance were the second most commonly tested Biotic State variable ($n = 141$ or 8% of all tested variables; Fig. 4d).

Of the 478 tests of Pressure variables, 293 were tests of contaminants and 165 were tests of land disturbance; surprisingly, we found only 3 tests of hydrologic alteration (Fig. 1). We note that research on

the impacts of hydrologic alteration in the region are ongoing, but were either classified differently or excluded from our set of relevant studies. For example, tests of the impacts of the hydrology of reclaimed wetlands were classified as Wetland Reclamation (e.g. Ketcheson and Price 2016; Scarlett and Price 2019); tests that examined the impacts of road construction (e.g. Plach et al. 2016; Strack et al. 2018) or seismic lines (e.g. van Rensen et al. 2015; Riva et al. 2018; Abib et al. 2019), which both would likely impact hydrology, were classified as examining Other Human Development and OS Production Drivers, respectively. In addition, studies that examined hydrologic variables (e.g. depth to water table; Rezanezhad et al. 2012; Spennato et al. 2018; Scarlett and Price 2019) without actually quantifying the degree of alteration from a baseline were classified as examining the

Hydrology Abiotic State variable. Studies that were determined to be out of scope included, for example, observational studies that characterized wetland hydrology but did not include tests of independent and dependent variables (e.g. Ketcheson et al. 2017; Goodbrand et al. 2019; Elmes and Price 2019). Overall, however, this finding suggests the need for explicit metrics of, and research on, surface water diversions and groundwater and surface water withdrawals and releases. Pressure variables classified as “Other” included, for example, composite metrics of generalized stress (Raab and Bayley 2013) and scores in multivariate ordination space (Rooney and Bayley 2010; Wilson et al. 2013).

The relative research effort linking different Drivers, Pressures and States is depicted in Fig. 5. Highlighted are the most commonly tested bivariate relationships, including the Oil Sands Production Driver, Tailings Contamination and Wetland Reclamation Pressures, and Surface Water Chemistry and Organism Growth Rate States. Specifically, the most commonly tested Driver-Pressure relationship was between Oil Sands Production and Tailings Contamination ($n = 15$; 94% of all Driver-Pressure tests). The most commonly tested Pressure-Pressure relationship was between Tailings Contamination and Wetland Reclamation ($n = 15$; 60% of all Pressure-Pressure tests). The most commonly tested Pressure-Abiotic State relationship was Wetland Reclamation and Surface Water Chemistry ($n = 29$; 38% of all Pressure-Abiotic State tests) and the most commonly tested Abiotic-Biotic State relationship related Surface Water Chemistry to an Organism's Growth Rate ($n = 31$; 18% of all Abiotic-Biotic State tests). Additional bivariate relationships that were well tested in the published literature include the Pressure of Tailings Contamination being related to the Biotic States of Biodiversity ($n = 34$; 10% of all Pressure-Biotic State tests), Tissue Stoichiometry ($n = 27$; 8%), and Organism Biomass ($n = 25$; 5%). The Abiotic State of Surface Water Chemistry was also commonly tested in its relationship to the Biological States of Organism Abundance ($n = 26$; 15% of all Abiotic State-Biotic State tests), Biomass ($n = 17$; 10%), Tissue Stoichiometry ($n = 15$; 9%), and Nutrient Cycling ($n = 15$; 8%).

Most reclaimed wetlands are exposed to oil sands contaminants (e.g. Rooney and Bayley 2010), either through the intentional incorporation of oil sands

process water, tailings sand, and petroleum coke in their construction (Alberta Environment 2008), or through unintended exposure to seepage (Fennell and Arciszewski 2019; Hewitt et al. 2020) and aerial deposition (Cho et al. 2014) of these materials from the surrounding mine site. Tests of Wetland Reclamation were almost universally performed by comparing reclaimed wetlands on company leaseholds to either remnant natural wetlands also on company leaseholds or to off-lease natural wetlands. The Wetland Reclamation Pressure therefore encompasses multiple stressors (e.g. contaminant inputs, soil disturbance, landscape fragmentation, loss of the seed-bank), the impacts of which cannot be easily disentangled. Tests that actually measured an aspect of contaminant concentration or land disturbance in reclaimed wetlands were categorized as such, whereas tests that simply compared reclaimed wetlands to naturally occurring wetlands on or off company leaseholds, without measuring contaminants or land disturbance directly, were attributed to the Wetland Reclamation Pressure.

To evaluate the research effort on important wetland indicator taxa, we compared the number of tests of each Biotic State variable measured in amphibians, birds, macroinvertebrates, and plants (Fig. 6). For each taxon, we consider the Biotic State variable with the most tests (excluding “Other” Biotic States) a candidate indicator metric for that taxon (blue bars in Fig. 6). We note that this approach cannot distinguish between strong and weak empirical tests (e.g. those with high versus low sample size), but was chosen because the heterogeneity of examined variables precluded a meta-analytical approach. For amphibians and plants, the most commonly measured Biotic State was Abundance ($n = 13$ or 52% of all amphibian tests, $n = 97$ or 29% of all plant tests; Fig. 6). For birds and macroinvertebrates, variables classified as “Other” were the most commonly tested Biotic State variables ($n = 10$ or 43% of all bird tests, $n = 10$ or 32% of all macroinvertebrate tests; Fig. 6). In birds, variables classified as “Other” were metrics of endocrine and immune system functioning ($n = 4$ tests; e.g. corticosterone, T cell proliferation; Smits et al. 2000; Harms et al. 2010), fecundity ($n = 3$ tests; i.e. clutch size, hatchling success, nestling survival; Smits et al. 2000), and direct biomarkers of exposure to organic pollution ($n = 3$ tests; i.e. EROD activity; Mundy et al. 2019). In macroinvertebrates, Biotic

Fig. 6 The number of tests of each Biotic State variable measured in the four most commonly studied taxa: a amphibians, b birds, c invertebrates, and d plants. For each taxon, we consider the defined Biotic State variable with the most tests (i.e. excluding the “other” category) a strong candidate indicator in biomonitoring. These bars are highlighted in blue. The Plant

taxon includes tests of both vascular and nonvascular plants. The Biotic State variables are Abundance (Abun.), Diversity (Div.), Richness (Rich.), Tissue Stoichiometry (Stoich.), Biomass (Biom.), Growth Rate (GR), Nutrient Cycling (Nut. Cycling), and Other. See Fig. 1 for the full list of Biotic State variables

State variables classified as “Other” were measures of morphological deformities ($n = 1$ test; Bendell-Young et al. 2000), oxidative stress ($n = 2$ tests; Wiseman et al. 2013), endocrine disruption ($n = 2$; Wiseman et al. 2013), and measures of growth ($n = 5$ tests; Anderson et al. 2012; Wiseman et al. 2013). Excluding

the variables classified as “Other,” the most commonly tested Biotic State variables were Biomass in birds ($n = 6$; 26%) and Tissue Stoichiometry in invertebrates ($n = 7$; 23%).

Weight of evidence

To evaluate the consistency with which Pressures and Abiotic States affect the most commonly studied Biotic State variables for each of the four biological taxa (Fig. 6) and the most commonly studied Abiotic State variable (Surface Water Chemistry), we compare the number of tests reporting positive, inverse, non-linear, and nonsignificant relationships.

There were 59 tests relating Pressure variables to the Abiotic State variable Surface Water Chemistry (27% of all tests of Surface Water Chemistry; Fig. 4). The most commonly measured Pressure variables related to Surface Water Chemistry were Wetland Reclamation ($n = 29$ or 49% of all Pressure—Surface Water Chemistry tests) and Tailings Contamination ($n = 19$ or 32% of all Pressure—Surface Water Chemistry tests); whereas Aerial Emissions are much less studied as a source of contaminants to surface water ($n = 11$ or 19%; Fig. 7). Of the 13 tests of amphibian Abundance, four included Abiotic State variables; this accounted for 31% of all tests of amphibian Abundance or 16% of all tests involving amphibians). Three of these compared amphibian Abundance to the Abiotic State of Surface Water Chemistry (Fig. 7). Of the 97 tests of plant Abundance, 35% included Pressure or Abiotic State variables (10% of all tests involving plants), again with Surface Water Chemistry being the most common ($n = 14$ or 14% of tests of plant Abundance; Fig. 7). All six tests of bird Biomass and all seven tests of invertebrate Tissue Stoichiometry involved either the Pressure variable Wetland Reclamation or Tailings Contamination. Based on the strong research connection between these Pressure variables and the Abiotic State variable of Surface Water Chemistry, this result indicates that the effects of Surface Water Chemistry on bird Biomass and invertebrate Tissue Stoichiometry is being studied implicitly. In contrast, the effects of Surface Water Chemistry on amphibian Abundance and plant Abundance are being addressed directly.

Ecological indicators are used as proxies of the overall condition of an ecosystem (Cairns et al. 1993; Lindenmayer and Likens 2011). Because they are sensitive and show predictable responses to known environmental stressors and disturbances, ecological indicators are used to evaluate the extent to which that ecosystem is being impacted by a stressor. Effective indicators must balance a trade-off between

characterizing the condition of the whole ecosystem (including both the Abiotic and Biotic States) and being simple enough to monitor efficiently (Dale and Beyeler 2001). The use of biological indicators can be a cost-effective way to monitor the condition of the environment where they are found, because their status reflects the cumulative effects of multiple environmental variables (Siddig et al. 2016). Since a single indicator rarely captures the full complexity of environmental conditions in an ecosystem, multiple indicators can provide a complementary evaluation of environmental condition.

Plants, invertebrates, and amphibians are common indicators of ecosystem condition, especially in wetlands (Siddig et al. 2016), because taxa within these groups differ predictably in their sensitivity to environmental pollution and stress (Rosenberg and Resh 1993; Hodkinson and Jackson 2005; Clayton and Edwards 2006; Craft et al. 2007; Dupler et al. 2020). Bird habitat is an economically and culturally important function provided by wetland ecosystems, so wetland monitoring protocols often include assessments of bird populations. We recognize that individual species within these taxonomic groups are likely to respond differently to different stressors and, as such, additional research is likely needed to identify the best indicator species within each taxon. Nonetheless, synthesizing the available information on the most well-studied Biotic States for wetland taxa enables us to identify knowledge gaps and connections that can facilitate monitoring in the oil sands region. We also provide a synthesis of an Abiotic State variable—Surface Water Chemistry—although it does not meet the traditional criteria for a bioindicator, because a number of Biotic State variables were sensitive to it.

Synthesizing research on candidate indicators

Surface water chemistry

There were 29 tests linking Wetland Reclamation to Surface Water Chemistry (3% of all tests), 19 linking Tailings Contaminations to Surface Water Chemistry (2% of all tests), and 11 linking Aerial Emissions to Surface Water Chemistry (1% of all tests; Fig. 7). This includes only studies that intentionally tested the relationship between Wetland Reclamation and Surface Water Chemistry, not those that measured Surface Water Chemistry as a covariate when

Fig. 7 The number of tests between candidate indicators (Surface Water Chemistry and taxon-specific Biotic States) and Pressures and Abiotic States. Bars are filled by the reported

direction of the relationship: positive (purple), inverse (rose pink), or non-linear (yellow). Grey indicates relationships found not to be statistically significant

examining Biotic State responses to Reclamation (e.g. Smits et al. 2000; Wayland et al. 2008). Wetland Reclamation increased water salinity (van den Heuvel et al. 2012; Roy et al. 2016), conductivity (Roy et al. 2016), dissolved oxygen (Roy et al. 2016), pH (van den Heuvel et al. 2012), trace metal concentrations

(Murray et al. 2019), and nutrient concentrations (Murray et al. 2019). Wetland Reclamation reduced methane production (Murray et al. 2017, 2019), sediment nitrogen and organic content (Roy et al. 2016), and water nutrients (Rooney and Bayley 2011).

Clearly, Wetland Reclamation is associated with vastly different water chemistry conditions relative to natural wetlands and these differences are likely due in part to the construction materials employed. Indeed surface water of wetlands exposed to Tailings Contamination had higher naphthenic acid concentrations (Armstrong et al. 2010), salinity (Rooney and Bayley 2011; Mollard et al. 2013), conductivity (Mollard et al. 2013), pH (Mollard et al. 2013), and chloride concentrations (Mollard et al. 2013). If off-lease wetlands are exposed to oil sands tailings accidentally (CEC 2020; Ahad et al. 2020) or through controlled releases (Alberta Environment and Parks 2015), Surface Water Chemistry and wetland Biotic States are likely to be impacted. Additional research can help to identify thresholds in Biotic State and wetland health impairment in response to tailings exposure.

Compared to the impacts of Wetland Reclamation and Tailings Contamination, Aerial Emissions appear to have more moderate impacts on Water Chemistry (Fig. 7). Modeled acid deposition had little impact on catchment-scale acid neutralizing capacity and water chemistry (Whitfield et al. 2010) and neither elevated nitrogen nor elevated sulfur deposition were detected across 10 bogs (measured using ion exchange resin collectors; Wieder et al. 2010). However, aerial deposition of nitrogen and sulfur were observed to increase exponentially as distance from source decreases (Wieder et al. 2016), so are likely to be heterogeneous across the landscape. The effects of acid and nutrient deposition on surface water chemistry will therefore depend on the proximity to the emission source, as well as the underlying hydrogeologic conditions. Future research should aim to identify at-risk wetlands based on these characteristics.

Amphibian abundance

Abundance was the most commonly measured Biotic State variable for amphibians (13 tests or 52% of all amphibian tests; Fig. 7), though it was tested only four times in relation to Abiotic State variables. (It was also tested six times in relation to Driver variables, primarily Landscape Factors.) These tests indicated that, across 24 Boreal Plains wetlands, wood frog abundance increased with increasing dissolved oxygen concentrations and decreased with increasing conductivity, water depth, and total dissolved solids

concentration (Browne et al. 2009). Although this indicates that wood frog abundance may be a useful proxy for perturbations to hydrology and associated changes to surface water chemistry, additional research is needed to confirm these relationships and to evaluate their extension to the Oil Sands Region. In addition, wood frog abundance was inversely correlated with aquatic plant density (a Biotic State—Biotic State relationship), suggesting that wood frog abundance may be a proxy for wetland plant biomass. In contrast, the abundances of other amphibians measured in this study were relatively insensitive to the same Abiotic State variables; research is therefore also needed to identify which other biota are correlated with wood frog abundance.

Bird biomass

Of the 23 tests involving birds, six tests (26% of all bird tests) related mallard and tree swallow Biomass metrics to Pressure variables (Fig. 7). As noted above, Wetland Reclamation is strongly connected to the introduction of contaminants through oil sands process water, tailings sand, and petroleum coke, so these Pressures may be expected to elicit similar responses in Biotic State variables. Mallard body mass and skeletal size were lower for birds raised on two so-called opportunistic wetlands that formed on land leased for oil sands mining from liquid tailings seepage, as compared to one off-lease wetland (Gurney et al. 2005). In another study of three on-lease wetlands, tree swallow nestling weight and wing length varied inconsistently across sites varying in tailings exposure (Harms et al. 2010). Finally, a study of wild tree swallows showed inconsistent differences in clutch mass across six reclaimed wetlands varying in tailings exposure (Smits et al. 2000). Overall, research on bird populations is likely to have important ecological implications, since the region is under a major continental waterfowl flyway (Beck et al. 2015). Nevertheless, from these studies there is insufficient documentation linking bird Biomass to Tailings Contamination for it to serve as a rigorous indicator of oil sands activity or a proxy for overall wetland integrity. Additional research on wild individuals nesting across quantified tailings contamination gradients can help confirm the relationship between tailings exposure and bird biomass metrics.

Invertebrate tissue stoichiometry

Of the 31 tests involving invertebrates, seven tests (23% of all invertebrate tests) related invertebrate Tissue Stoichiometry—carbon and nitrogen isotopes (Farwell et al. 2009), polycyclic aromatic hydrocarbon (PAH) concentrations, trace metal concentrations—to Tailings Contamination and Wetland Reclamation (Fig. 7). Tests of the impact of Wetland Reclamation on invertebrate Tissue Stoichiometry suffered from a lack of replication. In one study, concentrations of vanadium, nickel, lanthanum, and yttrium were measured in benthic snails, dragonflies, and larval chironomids inhabiting microcosms built with different soil substrates and located in a reclaimed wetland, but a lack of replication and of reference samples prevented statistical comparisons of the metal concentrations (Baker et al. 2012). In another study, tissue PAH concentrations were higher in insect larvae inhabiting experimental wetlands exposed to fine tailings than on-lease opportunistic wetlands, but did not differ between experimental and off-lease constructed wetlands (Wayland et al. 2008); tissue PAH concentrations in adult insects did not differ across wetland construction history or vary consistently with sediment PAH concentrations. We observed that studies frequently compared Abiotic State or Pressure variables across wetland types (e.g. constructed, on-lease, off-lease, tailings-exposed, runoff-exposed) and also frequently compared Biotic State variables across wetland types, but studies more rarely compared Abiotic State and Pressure variables directly to Biotic State variables. This methodological choice is likely made to simplify analyses of wetland types where numerous environmental variables co-vary and are confounded. Nevertheless, it makes it difficult to clearly demonstrate evidence of a generalizable relationship between wetland biota and the environmental characteristics of wetlands impacted by oil sands activity (e.g. on-lease wetlands). Although aquatic invertebrates are considered responsive to habitat condition and water quality (Gresens et al. 2009), additional research is needed to identify which invertebrate Biotic States are sensitive to specific Pressure and Abiotic State variables, to disentangle the covarying properties of reclaimed wetlands, and to elucidate mechanisms underlying invertebrate responses.

Plant abundance

Of the 342 tests involving plants, 13 tests (4% of all plant tests) related Pressure variables to plant Abundance and 21 tests (6% of all plant tests) related Abiotic State variables to plant Abundance (Fig. 7). Unsurprisingly, the direction of plant Abundance response differed depending on which focal plant and which environmental conditions were studied. Despite the number of tests of plant abundance, the diversity of plant species in the area—and the number of environmental variables potentially impacted by oil sands activity—meant limited replication of results and hence constrained conclusions about Plant Abundance—Abiotic State variables. One nitrogen addition experiment in a bog revealed that *Rhododendron groenlandicum* (Labrador tea), *Andromeda polifolia* (Bog rosemary), *Sphagnum magellanicum*, and vascular plants in general increased in abundance with nitrogen addition, while *Sphagnum fuscum* decreased in abundance and *Sphagnum angustifolium* did not respond to nitrogen additions (Wieder et al. 2019). In another study of 63 shallow open water wetlands, *Ceratophyllum demersum* was associated with high levels of water nutrients and total suspended solids, *Myriophyllum* spp. and *Hippuris vulgaris* were associated with low water nutrient levels, and *Ruppia cirrhosa* was associated with high sodium concentrations and total dissolved solids (Rooney and Bayley 2011).

Like Water Chemistry, the impacts of Hydrology on plant Abundance differed by plant taxon. High water levels in a constructed fen were associated with increased *Typha latifolia* cover, decreased bryophyte cover, and reduced vascular plant cover (Borkenhagen and Cooper 2019). Longer inundation periods in shallow open water wetlands were associated with increased graminoid (Töyrä and Pietroniro 2005) and aquatic plant abundances (Timoney 2008), and reduced shrub abundance (Töyrä and Pietroniro 2005; Timoney 2008). These results suggest that plant indicators based on the abundance of individual taxa, species, or growth forms—or on community composition itself—will be most sensitive to specific disturbances and that species within a community will respond differently.

Hydrologic alteration can occur, for example, when aquifers are drained in the process of bitumen extraction, or more generally if oil sands activity

drains or dams wetlands or alters surface or ground water connectivity (Jordaan 2012). The water demand in and hydrologic impact to the region may be compounded under future climatic scenarios (Schindler and Donahue 2006; Mannix et al. 2010; Kompanizare et al. 2018). There is a notable knowledge gap relating Hydrology as an Abiotic State to Hydrologic Alteration a Pressure (i.e. surface water diversions, ground or surface water withdrawals or releases). This knowledge gap is in contrast to other well-studied relationships linking Pressures (Wetland Reclamation, Tailings Contaminants, Aerial Emissions) to Abiotic States (Surface Water Chemistry, Hydrology).

Concluding remarks

Wetlands in the Alberta OSR have received extensive study, yet the distribution of effort has been uneven and has failed to test the range of assumed relationships between Drivers, Pressures, and States that comprise our conceptual framework for the system (Fig. 1). Key knowledge gaps include research areas that are understudied, as well as those that are well-studied but where a lack of methodological consensus prevents synthesis and prediction. We identify four key research gaps which should be addressed to support and inform a regional wetland monitoring program. We also provide recommendations for which variables show promise as monitoring tools.

Knowledge gaps

First, there is a strong bias in the published literature towards studying reclaimed wetlands—the majority of which are marshes—short-term studies, and studies of limited spatial extent. In contrast, substantially less research is conducted on off-lease wetlands, long-term studies, and studies of regional spatial extent. Thus, it is difficult to reliably extrapolate findings to a big-picture understanding of regional wetlands. For example, because much of the work on wetlands in the OSR has focused on in situ comparisons of reclaimed wetlands to reference or less impacted sites, it is not possible to identify which of the numerous artificial abiotic characteristics of reclaimed wetlands are key in driving differences in biotic communities. Additionally, even studies testing similar relationships were often conducted using different variables and/or

procedures, making their findings essentially unrepliated among studies. This diversity of research approaches has identified numerous environmental variables that are impacted by oil sands activities and which in turn affect numerous wetland characteristics. However, a predictive model linking oil sands activity to environmental change to wetland biotic response cannot yet be developed. A coordinated research effort is needed that encompasses a variety of wetlands, tests clearly defined hypotheses, and links Pressures, Abiotic States, and Biotic States.

Second, while there has been substantial effort to understand the effects of tailings contamination and wetland reclamation activities, research is lacking on other types of land disturbance (e.g. surficial peat/soil disturbance, landscape ablation, vegetation removal), aerial emissions, and hydrologic alteration. These knowledge gaps limit our ability to predict how regional wetlands—the majority of which are off-lease—might respond to other natural and anthropogenic stressors. We find the paucity of studies on hydrologic alteration (but see Wilkinson et al. 2018) particularly concerning, since hydrology is a key landscape variable that determines wetland functioning and since we expect it to be impacted by a number of oil sands activities.

Third, we lack tests linking wetland Abiotic States (other than those classified as Hydrology and Surface Water Chemistry) to Biotic States. These Abiotic State—Biotic State relationships have the potential to provide crucial mechanistic understanding of the responses observed in wetland ecosystems. A mechanistic understanding of why changes to Biotic States are observed is also necessary to anticipate changes to wetland functioning under future climate scenarios. To identify thresholds and tipping points, studies must use known gradients in Abiotic State variable levels and control for other confounding factors. In addition, Abiotic State—Biotic State relationships are bidirectional, meaning that not only can a change to an Abiotic State variable cause a response in a Biotic State variable, a change in a Biotic State variable can also cause a response in an Abiotic State variable. Research on these relationships can therefore help to identify key relationships which might amplify or moderate other changes in the system.

Fourth, amphibians, birds, and invertebrates are understudied relative to wetland plants. To understand fully the impacts of oil sands activity on wetland

condition, additional research is needed to identify indicator metrics for other taxa, such as invertebrates, that can complement plant monitoring. Additional research can also aim to link plant responses to measures of overall wetland condition (e.g. to identify if other biotic and abiotic variables covary with plant responses). Interestingly, while studies link invertebrate and bird responses to Pressure variables, less is known about the actual mechanisms underlying the response (i.e. the Abiotic State variable mediating the Pressure—Biotic State relationship).

What to monitor

Plants appear to be particularly sensitive to the stressors associated with oil sands activity and show promise as an indicator. Unsurprisingly, different plant taxa respond differently to different stressors and plant communities are generally exposed to numerous stressors at once. To manage this nuance, there are two potential approaches. Land managers can (1) monitor the responses of individual species (or groups of species) whose responses to specific stressors are known and predictable. Importantly, since oil sands activity causes changes to numerous environmental variables at once, simple bivariate relationships may be obscured or may not be an appropriate model. Thus, land managers can alternatively (2) monitor whole plant communities and relate changes in composition, especially of functional groups (i.e. forbs, graminoids, woody shrubs) to cumulative stressors. Given the high plant diversity and variety of wetland classes in the region, as well as the number of Pressure and Abiotic State variables that may be impacted by oil sands activity, it may however be difficult to identify consistent responses across all wetland types. It is also important to note, as discussed above, that while our synthesis identified plants as being good candidate indicators due to their sensitivity to Pressures and Abiotic States, we did not evaluate the extent to which they can be also be linked to changes in the abundance of other important wetland taxa. As such, additional research on the relationship among Biotic States of different taxa is needed to robustly use plant indicators as proxies for whole wetland functioning.

Water chemistry and hydrology were relatively well-studied Abiotic State variables and show promise for their connection to Pressures and Biotic States. Future work should clarify which water chemistry

parameters are most important in driving Biotic State responses (e.g. pH versus nitrogen versus salinity). While the importance of hydrology for maintaining wetland condition is well-accepted, specific metrics of hydrologic *alteration* have not yet been developed, so far as we are aware. These metrics are crucial for monitoring hydrology and wetland health at the regional scale in a cost- and time-efficient manner.

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Data availability The data used in this synthesis are available in Table S2 and Table S3 and published through figshare at DOIs 10.6084/m9.figshare.14439704 and 10.6084/m9.figshare.15183351, respectively.

Code availability The code used to analyze and visualize these data are available from the first author upon request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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