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REVIEW ARTICLE

Braiding Indigenous knowledge systems and Western-based sciences in the Alberta oil sands region: A systematic review

Alana A. E. Wilcox[a*], Jennifer F. Provencher[a], Dominique A. Henri[b], Steven M. Alexander[cd], Jessica J. Taylor[ef], Steven J. Cooke[ef], Philippe J. Thomas[a], and Lydia R. Johnson[g]

[a]Ecotoxicology and Wildlife Health Division, Science and Technology Branch, Environment and Climate Change, Ottawa, ON K1S 5B6, Canada; [b]Wildlife Research Division, Science and Technology Branch, Environment and Climate Change Canada, Montreal, QC H2Y 2E7, Canada; [c]Environment and Biodiversity Sciences, Fisheries and Oceans Canada, Ottawa, ON K2P 2J8, Canada; [d]Environmental Change and Governance Group, University of Waterloo, Waterloo, ON N2L 3G1, Canada; [e]Canadian Centre for Evidence-Based Conservation, Institute of Environmental Sciences and Interdisciplinary Science, Carleton University, Ottawa, ON K1S 5B6, Canada; [f]Fish Ecology and Conservation Physiology Laboratory, Department of Biology, Carleton University, Ottawa, ON K1S 5B6, Canada; [g]School of Environmental Studies, Queen's University, Kingston, ON K7L 3N6, Canada

*alana.wilcox@ec.gc.ca

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Abstract

The braiding of Indigenous knowledge systems and Western-based sciences offers insights into ecology and has emerged as a way to help address complex environmental issues. We reviewed the publicly available ecological research involving the braiding of Indigenous knowledge systems and Western-based sciences to support collaborative work in the Alberta oil sands region of Canada. We conducted a systematic review, coding for 78 questions in six categories: (1) literature search and bibliographic information; (2) research themes; (3) study setting and design; (4) knowledge systems; (5) power relationships, colonization, and ethical considerations in research; and (6) benefits and challenges of braiding. We identified six articles that braided knowledge, with those articles focusing on environmental management and monitoring for impacts of industrial activity in northern Alberta. Researchers used a broad range of approaches to gather Indigenous knowledge and scientific data and identified multiple challenges (e.g., asymmetries of power, resource availability, and funding) to research. Our findings show that more support is needed to foster, promote, and disseminate interdisciplinary collaborative work involving braiding. Additional support is also required to address Indigenous community research needs related to the assessment of environmental impact and reclamation, as well as the understanding of ecological threats across the region.

Key words: Indigenous knowledge systems, traditional ecological knowledge, environmental research and monitoring, braiding knowledge systems, Alberta oil sands region

Positionality statement

Knowledge is an integral part of our social and cultural constructions of reality and therefore it is important to identify the values, perspectives, and positions in our understanding to undertake

considerate and ethical research (Cornell et al. 2013; Miller and Muñoz-Erikson 2018; Sultana 2015). In this way, a brief description of our roles and standpoints is important to situate ourselves in the review and with respect to the practice of knowledge braiding, particularly as it relates to the Alberta oil sands region. The authors consist of both Indigenous and non-Indigenous scholars from the Government of Canada and academia with backgrounds in natural sciences and environmental social sciences working on Treaty One territory and the homeland of the Red River Métis (Winnipeg, MB), Anishinaabe and Haudenosaunee territory (Ottawa and Kingston, ON), and Kanien'kehá:ka territory (Montréal, QC). As a group of community-engaged researchers dedicated to co-produced research and relational accountability, this review was developed to support future collaborative work with Indigenous communities on species-at-risk in the Alberta oil sands region (Government of Canada 2020b). This work acknowledges that place-based approaches do not lend themselves to universality and "don't necessarily travel" (Liboiron 2021). As such, this work marks an important first step in learning about regionally specific approaches to braiding and to understanding the complex ecological and socio-political landscape in the Alberta oil sands region.

Introduction

Braiding of knowledge systems refers to the process in which multiple types of knowledge are brought together (Alexander et al. 2019a; Johnson et al. 2016; Rathwell et al. 2015; Reid et al. 2021). Knowledge braiding can improve our understanding of socio-ecological systems and help build support and capacity to tackle long-standing and multifaceted environmental challenges (Johnson et al. 2016). There has recently been substantial interest in Canada on how Indigenous ways of knowing can be braided or woven together with Western-based scientific approaches to help improve trust in ecological research and decision-making (Government of Canada 2021; Henri et al. 2020, 2021; Johnson et al. 2016; McGregor 2004a; Popp et al. 2019). Western-trained non-Indigenous researchers and decision-makers are encouraged to prioritize Indigenous knowledge systems and recognize Indigenous history, governance structures, values, cultures, and the role of Indigenous peoples as stewards of the environment (Ban et al. 2018; Wong et al. 2020). By applying knowledge braiding that situates Indigenous ways of knowing and Western-based sciences as equally important and valid, ecological inquiry can be reshaped to foster ethical approaches that tackle environmental concerns to achieve goals for biodiversity conservation and sustainable use of the environment.

Knowledge, perceptions, and values underscore how individuals identify and conceptualize reality (Cornell et al. 2013; Masalo 2002; Miller and Muñoz-Erikson 2018). Knowledge systems describe how we understand and organize information about the world around us, as well as how we transmit and use this knowledge in different ways (Cornell et al. 2013; Miller and Muñoz-Erikson 2018). Indigenous knowledge systems speak of the interconnectedness between all relations (i.e., humans, non-humans, and spirit) and emphasize land-based ethics and values (Berkes 2012; McGregor 2004b; McGregor 2018b; **Supplementary Material Table S1**). Indigenous sciences are embedded in Indigenous knowledge systems and apply an analytical lens to problem solving, such as observation (across long time scales – i.e., human generations) and interpretation, while also emphasizing that all teachings convey spiritual connections (Kimmerer 2013; Michell 2015). A number of academic (Tengö et al. 2014) and regionally specific Indigenous approaches exist to guide the process of mobilizing multiple knowledge systems in ecological research (e.g., Two-Eyed Seeing, Two Row Wampum, Waka-Taurua; Reid et al. 2021). In line with previous scholarly outputs co-authored by Indigenous community members in the Alberta oil sands region (Hopkins et al. 2019), we have chosen the term "braiding" to describe the process of connecting Indigenous knowledge systems and Western-based sciences in a manner that maintains the integrity of each knowledge system and allows for mutual learning (Alexander et al. 2019a; Henri et al. 2021; Rathwell et al. 2015). In this way, the braiding of knowledge systems challenges the simplified dichotomous discourse that leads to an evidentiary

hierarchy and moves past the mechanistic and reductionist tendencies of Western-based sciences to create an opportunity to learn from alternative viewpoints and consider diverse ways of knowing (Castleden et al. 2017).

Within ecological research, Indigenous perspectives and knowledge have strengthened Western-based sciences and the understanding of the mechanisms, interactions, and functions within ecological systems (Ban et al. 2018; Kimmerer 1998; Kutz and Tomaselli 2019; Pierotti and Wildcat 2000). Indigenous peoples have long recognized not only the importance of protecting the land and its inhabitants but also the role of the environment in cultural identity, knowledge transmission, cultural continuity, food sovereignty, and ceremony (Fa et al. 2020; Liboiron 2021; Menzies et al. 2022). Acknowledging the roles that Indigenous stewardship, governance, and management systems have played in environmental protection and empowering Indigenous leadership in research not only helps to address power imbalances in the decision-making process (Nadasdy 1999; Nadasdy 2017; Wheeler et al. 2020) but can also lead to more impactful research that better supports Indigenous communities and governments (Ban et al. 2018; Snook et al. 2018). Further, through the co-production of relevant research priorities and projects (Norström et al. 2020), knowledge braiding can provide new ways forward to care for and protect the environment (Ban et al. 2018), as well as spur progress in addressing environmental challenges (Henri et al. 2021).

Western-based sciences long relied on the knowledge and exploitation of Indigenous peoples (Liboiron 2021). As such, Western-trained non-Indigenous researchers have an ethical responsibility to prioritize and meaningfully engage with Indigenous peoples to advance reconciliation and renew relationships (Wong et al. 2020). Distrust of Western-trained non-Indigenous researchers stems from multiple sources, including mistreatment of Indigenous peoples as research subjects (Fitzpatrick et al. 2016), lack of consent (Laycock et al. 2011; Smith 2021), control of Indigenous data by external entities (Battiste and Youngblood Henderson 2000a; Mosby 2013), theft of cultural knowledge and resources (Battiste and Youngblood Henderson 2000c), lack of transparency (Goodman et al. 2018), and lack of access to results relevant to Indigenous communities (Inuit Tapiriit Kanatami 2018; Kovach 2009). On the other hand, calls for more ethically engaged research (Trisos et al. 2021; Riddell et al. 2017) have spurred discussions on culturally safe practices (Ball and Janyst 2008), promoted Indigenous self-determination (Battiste and Youngblood Henderson 2000a, 2000b; Rasmus et al. 2020), and increased Indigenous representation and leadership in research (Alexander et al. 2019a; Government of Canada 2020a). Guidelines developed by Indigenous groups that address cultural research integrity, ethical data collection, intellectual property rights, and relationship building have provided further direction for Western-trained non-Indigenous researchers (e.g., Assembly of First Nations n.d.; Akwesasne Research Advisory Committee and Akwesasne Task Force on the Environment 1996; Inuit Tapiriit Kanatami 2018; McGregor 2018c; Mi'kmaw Ethics Watch 1999; Nuu-Chah-Nulth Tribal Council 2008). Through the cultivation of respectful dialogue and collaboration, the braiding knowledge of systems can support ethical approaches to research that promotes equity, Indigenous self-determination, and begins to address the historical and ongoing injustices in Western-based academic research (Inuit Tapiriit Kanatami 2018; McGregor 2018b; Reid et al. 2021; Wilson et al. 2018).

The importance of braiding practices and Indigenous knowledge systems has been reflected in international and national policies developed by colonial institutions. At the international level, there is recognition of the value of Indigenous knowledge systems in biodiversity conservation policies and sustainable use principles and through the United Nations Declaration on the Rights of Indigenous Peoples (Secretariat of the Convention on Biological Diversity 2020; UN General Assembly 2007). However, despite calls for the incorporation of Indigenous knowledge systems in decision-making, Indigenous knowledge remains underrepresented globally and in national

legislation (McGregor 2016; Secretariat of the Convention on Biological Diversity 2020; Shea and Thornton 2019). In Canada, there is a mandate within many federal government departments to consider and respectively include Indigenous knowledge systems in environmental decision-making (e.g., Beaulieu-Guay 2022; Canadian Environmental Protection Act 1999 c. 33; Impact Assessment Act 2019 c. 28, s. 1; Migratory Birds Convention Act 1994 c. 22; Oceans Act 1996 c.31; Species at Risk Act 2002 c. 29), and several national funding agencies are calling on Western-trained non-Indigenous researchers to braid Indigenous knowledge systems and Western science equitably through the full cycle of research and monitoring (e.g., Natural Sciences and Engineering Research Council, Social Sciences and Humanities Research Council).

In this context, it is therefore essential to identify and understand the current practices and context of braiding of multiple knowledge systems for research and monitoring in Canada. We reviewed the publicly available peer-reviewed and grey literature addressing the braiding of Indigenous knowledge systems and Western-based sciences in environmental research associated with extractive industries in the Alberta oil sands region. Bibliographic information, as well as information related to research themes, study setting and design, knowledge systems, power relationships, colonization, research ethics, and the benefits and challenges of knowledge braiding were coded from the literature and used to assess trends in knowledge braiding in ecological research and monitoring in the oil sands region. Our aim was to provide an overview of the available published evidence on the braiding of Indigenous knowledge systems and Western-based sciences. In doing so, we sought to identify key gaps in the publicly available peer-reviewed and grey literature and provide recommendations to inform future ecological research and monitoring.

Materials and methods

Context

The Alberta oil sands are a globally recognized region situated on Treaty land (i.e., Treaties 6, 8, 10, and 11) and Métis territory and are a prominent site of resource extraction and industrial activity. Studies have demonstrated that oil sands industrial activities have resulted in environmental impacts inside the region, as well as in areas beyond the specific oil sands deposit footprint (Kelly et al. 2009, 2010; Schwalb et al. 2015). The effects of contamination on ecosystem health and biodiversity (Hebblewhite 2017; Timoney and Lee 2009), including wildlife of subsistence, livelihood, and traditional and cultural importance (Schindler 2013; Timoney and Lee 2009), have been an enduring concern among Indigenous groups living within or near the region (Natcher et al. 2020b). However, despite the long-standing public expression of these concerns, and the establishment of government and industry funded multidisciplinary environmental research and monitoring, it is only recently that environmental research programs involving Indigenous peoples have become more common in the oil sands region (Beausoleil et al. 2021).

Databases and original protocols

The present work draws on three datasets from systematic maps that examine the publicly available peer-reviewed and grey literature on knowledge braiding in environmental research, monitoring, and management across Canada (Alexander et al. 2019a, 2021a, 2021b; Henri et al. unpublished data). The original protocols for these systematic maps were published in March 2019 (Alexander et al. 2019b) and February 2021 (Henri et al. 2021). The systematic maps followed guidelines established by the Collaboration for Environmental Evidence (Haddaway et al. 2018) and *RepOrting Standards for Systematic Evidence Syntheses in Environmental Research* (ROSES). In summary, across the three systematic maps, a total of 35,105 articles were screened by up to seven Indigenous and non-Indigenous coders. Prior to the screening stages (i.e., title and abstract, and full-text), a

consistency check was performed using a subset of articles to ensure inter-coder reliability. In every consistency check, the group of coders screened the same subset of articles and only when an acceptable level of agreement was achieved were the coders allowed to screen the remaining articles independently. Screening resulted in the inclusion of 313 articles in total across the three datasets (Alexander et al. 2019a, 2021a, 2021b; Henri et al. unpublished data).

All relevant methodological details supporting this paper are included below, but the following methods deviate from the original systematic protocols: (1) a search was conducted of three existing datasets to identify articles relevant to the present review; (2) a search was conducted of four bibliographic databases with terms specific to the Alberta oil sands region; (3) eligibility criteria were adapted to include articles from any ecosystem within the geographic area of the Alberta oil sands region; (4) data extraction codes were modified to include questions specific to the Alberta oil sands region; and (5) search results for articles in the Alberta oil sands region were compared with articles braiding knowledge across Canada.

Search strategies

Using the three datasets (Alexander et al. 2019a, 2021a, 2021b; Henri et al. unpublished data), we identified articles relevant to the Alberta oil sands region (**Fig. 1**). We then conducted a search of four bibliographic databases (i.e., ISI Web of Science Core Collections, ProQuest Dissertations & Theses Global, Scopus, and the Federal Science Library [Canada]) to capture all relevant articles, reports, and grey literature on the braiding of Indigenous knowledge systems and Western-based sciences in the oil sands region that were not screened in the previous systematic reviews (i.e., published after the original systematic maps). Google and ResearchGate were not used as search engines due to their lack of consistency and ability to return relevant results (Alexander et al. 2019b; Haddaway et al. 2015). General search terms were developed to ensure articles from all different ecosystems were included and included regional qualifiers related to the Alberta oil sands region (e.g., Peace River, Athabasca Oil Sands). Boolean operators "AND" and (or) "OR" were used to combine search parameters. Database-specific search strategies and search strings listing regional qualifiers can be found in the **Supplementary Material**. Lastly, articles listed in bibliographies from all relevant articles published with results from within the oil sands region and papers collected from calls for evidence through professional networks were screened to identify articles, reports, and grey literature within the scope of this review (**Fig. 1**).

Screening articles

Articles braiding Indigenous knowledge systems and Western-based sciences in the oil sands region were screened for relevance and inclusion in the review at two stages: (1) title and abstract and (2) full-text (**Table 1**). Eligibility criteria were adapted to include articles from any ecosystem within the geographic area of the Alberta oil sands region. For the purpose of this review, the oil sands region encompassed not only the geological area of the oil sands deposits (Government of Alberta 2021), including the Athabasca Oil Sands, Peace River Oil Sands, and Cold Lake Oil Sands deposits, but also the surrounding impact area and monitoring region (Government of Canada 2018; **Fig. 2**). We also restricted article inclusion to only research and monitoring studies, excluding articles categorized as management and decision-making (**Fig. 1**), to better understand the context in which braiding occurs in environmental research in the Alberta oil sands region and to focus discussions on how this knowledge can help guide future research activities.

Synthesis and data extraction

Eligible research and monitoring articles relevant to the braiding of Indigenous knowledge systems and Western-based sciences in the oil sands region were coded using a standard questionnaire that

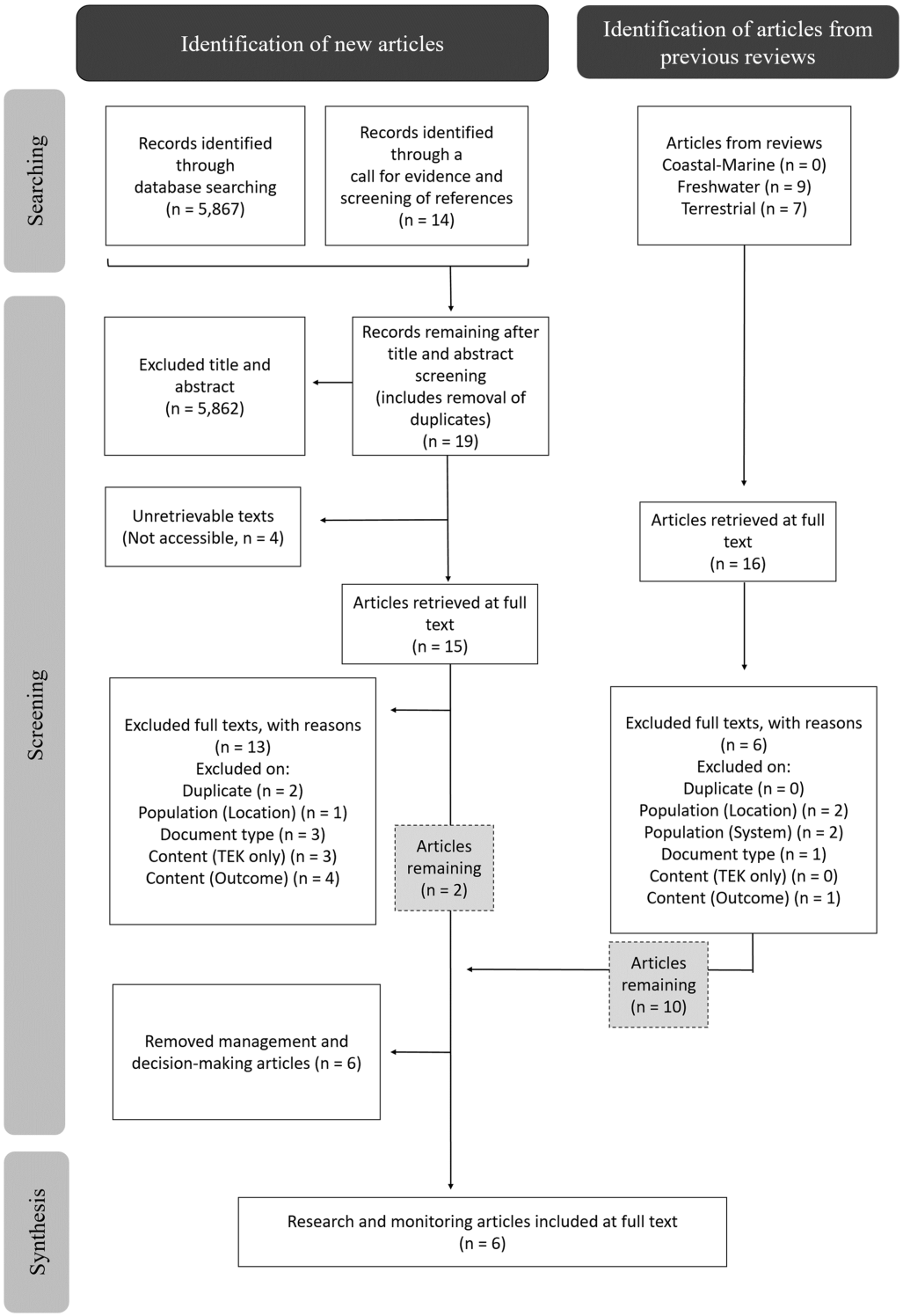

Fig. 1. ROSES flow diagram outlining the source and number of articles obtained at each stage of the review process (i.e., searching, screening, and synthesis).

Table 1. Description of eligibility criteria for article screening.

Topic	Description
Geographical location	Articles that take place in the geological area of the oil sands deposits, including the Athabasca Oil Sands, Peace River Oil Sands, and Cold Lake Oil Sands, but also the surrounding impact area and monitoring region. Articles include case studies within Canada's jurisdictional boundaries, as well as from traditional territories that transcend the nation-state boundaries (i.e., Canada-US border)
Population	Articles that concern all coastal, marine, freshwater, and terrestrial ecosystems, habitat, or species. Articles must be directly related to biodiversity, wildlife or ecosystem health, and (or) climate change. Studies related to silviculture/timber production, agriculture, harvest optimization or techniques, or human adaptation to climate change are excluded
Study design	Articles reporting empirical results (either qualitatively or quantitatively) where braiding practices and (or) methods are discussed or inferred. Studies will fall into three broad categories: (1) environmental/ecological research and monitoring; (2) processes and practices of bridging knowledge systems in environmental decision-making; or (3) studies concerned with perceptions of ecological or environmental phenomenon that braid IKS and Western sciences. Articles focusing solely on traditional ecological knowledge or local environmental knowledge are excluded
Language	English

included 78 categorical, binary, and open-ended questions in six general categories: (1) literature search and bibliographic information; (2) research themes; (3) study setting and design; (4) knowledge systems; (5) power relationships, colonization and ethical considerations in research; and (6) benefits and challenges of knowledge braiding. In the context of this review, "power relationships" refer to inequities in control, authority, and (or) influence between Indigenous community members and the researchers (Paksi and Kivinen 2021; Singleton et al. 2021) and "colonization" refers to the process by which one group assumes control of another society's territories and imposes its own economies, cultures, laws, and governance (McGregor et al. 2020; Whyte 2017). Articles were also classified as either: (a) research and monitoring (i.e., involving direct or indirect ecological observations from both Western-based sciences and Indigenous knowledge holders) or (b) management and decision-making (i.e., where knowledge braiding occurred in the context of decision-making; Alexander et al. 2019a). Data extracted from new articles screened for inclusion were recorded by two coders using Microsoft Excel (v 16.0.5134.1000) to collate responses and any discrepancies in coding were discussed among coders. Prior to analysis, a single reviewer (AAEW) confirmed that data were extracted consistently between different coders. Data are presented as a case-based matrix with the coded responses to questions presented for each case study (see Data Availability Statement).

Comparison of search results

We developed a second set of search terms to select for articles relating to biodiversity research and management in the Alberta oil sands region regardless of braiding (**Supplemental Material**). Once again, we searched four bibliographic databases (i.e., ISI Web of Science Core Collections, ProQuest Dissertations & Theses Global, Scopus, and the Federal Science Library [Canada]); results were screened using a modified version of the screening criteria (**Table 1**, but without the qualifiers for study design). Any articles screened in that involved braiding of Indigenous knowledge systems and Western science in the oil sands region (n = 2) were removed to obtain mutually exclusive search results. The number of articles related to biodiversity was compared to the total number of research/monitoring and management articles published in the oil sands region that involved braiding.

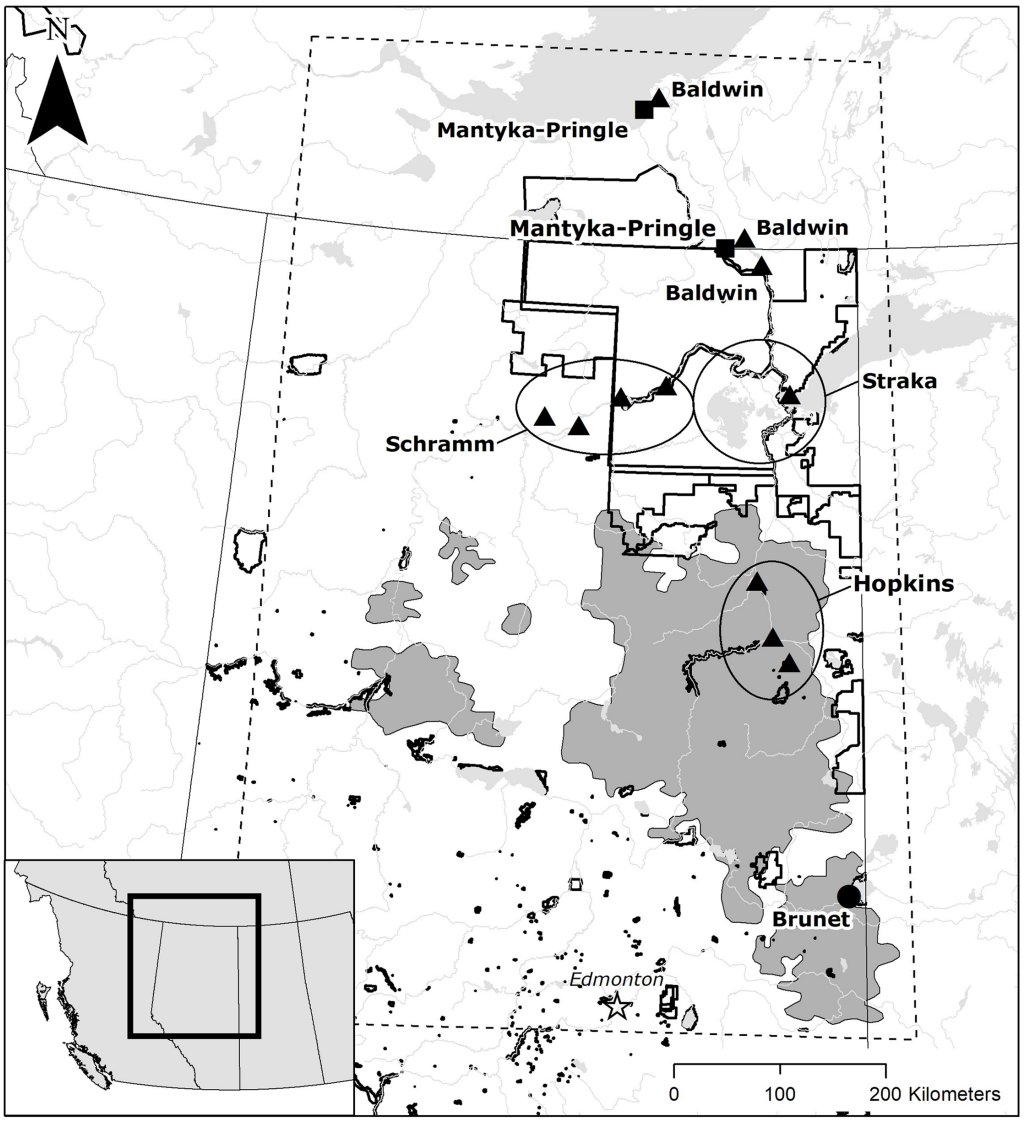

Fig. 2. Location of research and monitoring studies (n = 6) identified in publications braiding Indigenous knowledge systems and Western sciences in the Alberta oil sands region (dotted black line). Research themes (■, ecosystems; ▲, community; ●, species) and the outlines of the Alberta oil sands deposits (dark grey); Canadian national parks and protected areas (solid black line) are indicated (UTM NAD83; base layers: Alberta Parks 2017; GeoBC Branch 2005a, 2005b, 2005c; 2014a, 2014b).

We also obtained the number of relevant articles that included braiding knowledge in Canada using data from Alexander et al. (2021, n = 74) and Henri et al. (unpublished data; n = 179) and calculated the concentration of articles published per 1,000 km^2 (total area of Canada: 9,984,670 km^2). The value was then compared to the total number of research and monitoring and management and decision-making articles (**Fig. 1**) that included braiding knowledge in the oil sands region per 1,000 km^2 (total area of the oil sands region: 462,974 km^2).

Narrative synthesis

A narrative synthesis approach that summarizes and explains the findings was used to identify variability in study design, methodology and methods, setting, and study populations, as well as to explore relationships in the data (**Table S1**; Lisy and Porritt 2016; Popay et al. 2006). Similarities and differences between articles were identified to provide an understanding of how the research contributes to the body of literature braiding Indigenous knowledge systems and Western-based sciences in the oil sands region (Henri et al. 2021). Unless otherwise stated, the results presented in this review were generated using only data extracted from research and monitoring articles (**Fig. 1**). Qualitative evidence is supported by descriptive statistics, tables, and figures developed in Excel or the package *base* in R (R Core Team 2013), and the number of articles is listed in text or in brackets for each result. Technical terminology is defined in **Supplementary Table S1**.

The scale of community involvement was developed from David-Chavez and Gavin (2018). Briefly, "contractual involvement" does not require community participation, whereas "consultation" refers to situations where community members provide feedback. "Collaborative engagement" is when community members and researchers collectively make decisions about the process of collaboration and, when the engagement is "collegial," community members have primary authority in determining the process of collaboration.

To analyze how authors described Indigenous knowledge systems, we used the categorical definitions developed by Houde (2007). Descriptions of Indigenous and (or) traditional knowledge were categorized into one of six groups: (first face) factual observations, classifications, and system dynamics (i.e., empirical observations and information); (second face) management systems; (third face) factual knowledge regarding past and current uses of the environment; (fourth face) ethics and values; (fifth face) traditional ecological knowledge as a vector for cultural identity; and (sixth face) cosmology (i.e., assumptions and beliefs about how things work; Houde 2007). If descriptions used by authors fell into multiple categories, both categories were coded.

Mapping

Composite maps showing the study location in the oil sands were developed using ArcMap (v 10.6.1; ESRI Inc. 2019). Study locations were identified for each article or, when the location was not indicated, the nearest town or community of the Indigenous groups participating in the research was used to map the study. A shape file of the Alberta oil sands deposits was created using open source imagery (Einstein 2006), and overlaid on a map of Alberta, along with the location of Canadian national parks and protected areas in the region.

Limitations

Our results are based on the available published literature, but limitations in search strategies may exist and may have unintentionally affected our systematic review. Though we conducted an extensive search of the literature using multiple databases and tested for the sensitivity of our search strings and terms to yield the desired search results, changes in keywords or parameters could have yielded different search results. Publication bias could have also affected our search strategies. For example, the identity of the first author (e.g., nationality and gender) can affect publication and citation rate (Einav and Yariv 2006; Kothiaho 1999a, Kothiaho et al. 1999b; Møller and Jennions 2001; Tregenza and Wedell 1997; Tregenza 2002). Although we are unaware of any research that explicitly studies the role of Indigeneity on publication and citation rate, it is well known that Indigenous contributions have long been excluded from peer-reviewed authorship lists (Cooke et al. 2021) and, given the extent of gender- and nationality-oriented citation bias, it is expected that similar patterns may be observed for Indigenous-authored papers. Further, some unpublished literature, particularly grey literature,

may not have been accessible and, thus, was not included in our review (Møller and Jennions 2001). Notably, Indigenous community-led reports are often held by Indigenous organizations and not widely shared (Alexander et al. 2021b). Therefore, future work must directly engage with Indigenous community members, with the aim to co-develop research and, where permitted, braid knowledge held by communities with Western-based sciences. However, it is important to note that there are many reasons for Indigenous knowledge to be held by communities and not in the public record, including, but not limited to, cultural appropriateness, concerns over fragmentation of knowledge, and lack of need or desire to participate in colonial systems. Lastly, search strategies would have been unable to identify literature where Indigenous knowledge holders were not acknowledged or where the Indigenous knowledge component was published as a separate study (Alexander et al. 2021b).

We also used a narrow definition of knowledge braiding (i.e., focused on articles that reported empirical results from both Indigenous knowledge systems and Western-based natural sciences) and recognize that there is a continuum of braiding strategies available. Articles from Baker (2020) and Natcher et al. (2020a, 2020b), for example, demonstrated highly collaborative research that involved interviews and surveys of Indigenous communities in the oil sands region (i.e., TEK only); however, by the definitions determined in our protocols they were missing braiding with Western-based scientific data related to ecosystems, habitat, and biodiversity and were excluded from analysis. Similarly, articles that did not detail the ways in which researchers engaged with or involved Indigenous communities could not be recognized or coded for braiding. For example, there are a number of reports on environmental co-monitoring programs (e.g., Beausoleil et al. 2021) and research (e.g., Kelly et al. 2010; Thomas et al. 2017) in the Alberta oil sands region that discuss the importance of biodiversity and potential contamination in relation to Indigenous communities, but because knowledge braiding is not part of the published record they were not captured using a systematic literature search as we have undertaken here. Finally, we acknowledge that many methodologies and methods used in the social sciences also constitute a form of Western-based knowledge and evaluation of the braiding approaches used in this field should be investigated.

Results

Literature search and bibliographic information

A total of 5,881 articles were identified through four bibliographic databases, calls for evidence, and screening of bibliographies. Screening at the title and abstract stage excluded 5,862 articles (**Fig. 1**). Four articles were unretrievable (**Supplementary Material Table S2**), even via institutional subscriptions or interlibrary loans, and were, therefore, not screened for relevance to the review (**Fig. 1**). This left 15 articles to review at full-text, with an additional 16 articles retrieved from the datasets from the previous systematic maps (**Fig. 1**). Full-text screening of the 31 articles available resulted in a further 19 articles being excluded, with removals occurring because of duplication (n = 2), location (n = 3; i.e., study not located in the Alberta oil sands and greater impact region), system (n = 2; i.e., study not related to biodiversity or climate change), document type (n = 4; i.e., study not including qualitative or quantitative data), traditional ecological knowledge (TEK) only (n = 3; i.e., study did not include Western sciences), or outcome (n = 5; i.e., study did not include Indigenous or Western science component or braiding; **Fig. 1**). A total of six "management and decision-making" articles were excluded to focus discussion on the remaining six "research and monitoring" articles deemed relevant to the braiding of knowledge in the oil sands region (**Fig. 1**; **Supplementary Material Table S3**). However, in comparison to the total "management and decision-making" and "research and monitoring" articles (n = 12), a search of four databases yielded 224 articles related to ecological studies in the Alberta oil sands that used just Western sciences.

Moreover, there were 0.025 articles/1,000 km^2 published in the oil sands region that braided Indigenous knowledge systems and Western sciences compared to 0.020 articles/1,000 km^2 across Canada.

Research and monitoring articles that braided knowledge were published between 2002 and 2020, which included a report (n = 1) published in 2002 and peer-reviewed literature (n = 5) published between 2017 and 2020. Peer-reviewed literature was published in journals with a focus on environmental sciences (n = 3) or resource development and management (n = 2), and the majority (n = 4) of the articles were published in journals with a focus on research that crosses disciplines. For all articles included in the review, first authors were principally affiliated with academic institutions (n = 4) or government (n = 2; provincial: Government of Alberta; federal: Parks Canada). Articles that included Indigenous authorship (n = 3) were represented by individuals (n = 2), committees (n = 1), or communities (n = 1). However, no first authors were identified as Indigenous within the context of the papers.

Research themes

Informing scientific research and monitoring regarding the impacts of industry in the oil sands region were the main focus of the articles in our review. Authors published using a variety of keywords (**Supplementary Material Fig. S1**), but many included terms for environment and wildlife (n = 4; e.g., "environment," "ecological," "wildlife," species names), monitoring and management (n = 4; e.g., "monitoring," "(co-)management," "assessment," "indicator/indicator species"), Indigenous knowledge (n = 3; "Indigenous knowledge," "traditional knowledge"), and (or) regional-specific information (n = 2; e.g., "Alberta," "Lower Athabasca Region"). Articles in our review centered on fundamental (n = 5) and applied (n = 1) research but focused principally on monitoring industrial activity (n = 5) and informing scientific research (n = 5; **Fig. 3**). In these articles, researchers were addressing resource and wildlife management (n = 3), documenting Indigenous knowledge (n = 3), bridging Indigenous and Western-based scientific knowledge (n = 3), tracking environmental change (n = 3) and wildlife health (n = 2), documenting access to culturally important species (n = 2), and protection of species habitat (n = 1; **Fig. 3**). All studies (n = 6) in our review looked at enhancing the use of Indigenous knowledge in environmental management (**Fig. 3**). Specific wildlife species were the main research subject across articles (n = 4) and centered on aquatic (n = 2; i.e., mussels and fish) and terrestrial species (n = 2; i.e., moose, woodland caribou), while community interactions and ecosystem interactions were the focus of a single article each (**Table 2**).

Articles mentioned different industries and activities within the oil sands region, including resource extraction (n = 6), agriculture (n = 4), mining (n = 2), forestry and logging (n = 2), hydroelectric development (n = 2), pulp and paper mills (n = 2), and water withdrawals (for the oil sands, agriculture, or municipalities; n = 1). Two articles focused specifically on environmental contamination and investigated metals (n = 2) and polycyclic aromatic hydrocarbons (n = 2) in aquatic wildlife. Monitoring industries and activities in the oil sands region led to investigations of various environmental impacts and concerns, such as environmental health concerns (n = 6), species loss (n = 6), contamination (n = 5), quality and quantity of water (n = 2), cumulative effects (n = 2), climate change (n = 2), habitat loss and (or) fragmentation (n = 2), and wildlife disease (n = 2), in addition to sociocultural impacts and concerns related to hunting and harvesting (n = 5), human health (n = 4), food safety and (or) quality (n = 3), economic or financial concerns (n = 3), spiritual (n = 3), social (e.g., cultural practices, n = 2), tourism and travel (n = 2), and emotional/psychological distress (n = 1).

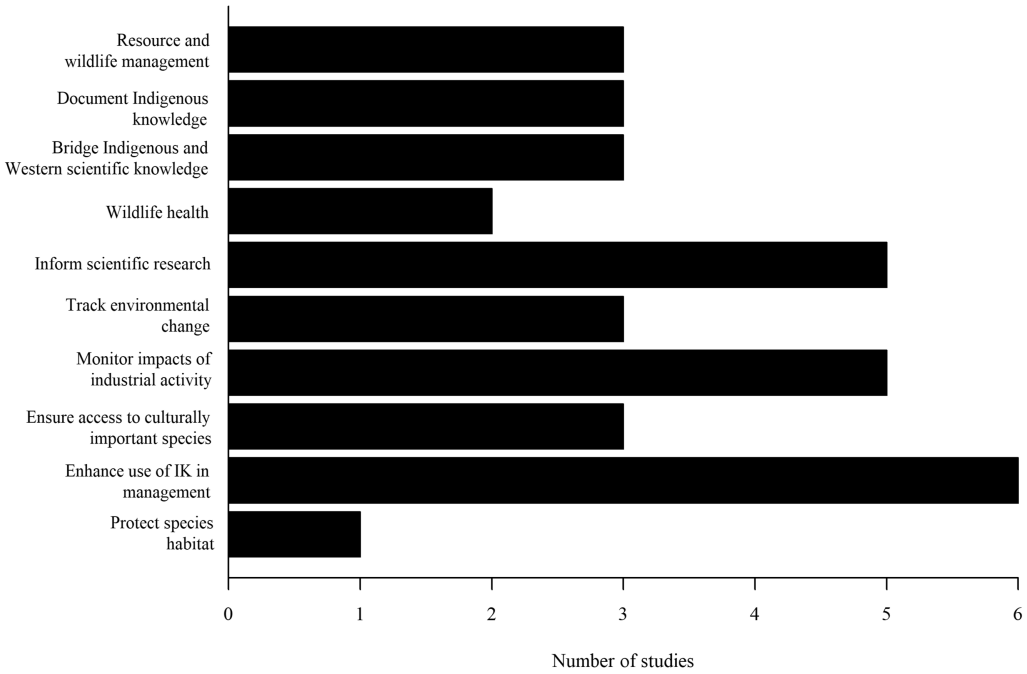

Fig. 3. Research themes discussed in research and monitoring articles (n = 6) that are included in the review of publications braiding Indigenous knowledge systems and Western sciences in the Alberta oil sands region.

Study setting and design

The composite map of the oil sands region, including both the geological area of the oil sands deposits and the surrounding impact area, is shown with the study locations and the research themes (**Fig. 2**). There were 12 study locations identified in the articles in our review, with 10 situated north of the Athabasca and Peace River Oil Sands deposits. Two locations were in Canadian national parks and protected areas, with an additional four situated adjacent to Wood Buffalo National Park.

Articles employed a broad range of methodological approaches and methods to collect and braid Indigenous and Western scientific knowledge (**Table S1**). Community-based participatory research was the main methodology employed in research (n = 3), followed by cultural consensus analysis (n = 1), Two-Eyed Seeing (n = 1), participatory modeling (n = 1), and experimental approaches (n = 1). All methodologies were Western-based, with the exception of the one article which applied a Two-Eyed Seeing approach. Two articles did not report on the methodology used for the research. All six articles distinguished between Indigenous and Western-based methodological approaches or methods.

Methods used to collect and interpret Indigenous knowledge included interviews (n = 4), surveys (n = 2), workshops (n = 2), GIS (n = 1), Bayesian network modeling (n = 1), participant observation (n = 1), participatory mapping (n = 1), and ground truthing (n = 1; i.e., land-based interviews, **Supplementary Material Table S1**; Hopkins et al. 2019). While abiotic sampling (n = 3), counts (n = 2, including census data and stock assessments), field observations (n = 2), and secondary data (n = 2) were the main methods used to obtain Western scientific data, articles also employed document review (n = 1), chemical analysis (n = 1), GIS (n = 1), dissections and tissue sampling (n = 1), and computer simulations (n = 1). Data that derived from secondary sources included counts, abiotic

Table 2. Ecological scale and research subjects for research and monitoring articles (n = 6) included in the review of publications braiding Indigenous knowledge systems and Western sciences in the Alberta oil sands region.

Ecological scale	Type of animal	Research subject
Species (n = 4)	Mussels (n = 1)	Giant floater Western floater Creek/brook heelsplitter White heelsplitter Fat mucket
	Fish (n = 1)	Inconnu Burbot Walleye Northern pike Goldeye Longnose sucker White sucker Flathead chub Lake whitefish Lake trout
	Mammal (n = 2)	Moose Woodland caribou Barren ground caribou Wood bison Muskrat
Community (n = 1)		Lake whitefish Lake trout
Ecosystem (n = 1)		Rivers

samples, and biological samples, and in one instance these data were collected with involvement from Indigenous communities.

Indigenous involvement in research was critical to the articles that we reviewed. Two studies involved First Nations communities (n = 2), while the remaining studies (n = 4) sought involvement from both First Nations and Métis communities. Knowledge holders were often described by the authors of the articles in our review as Elders (n = 6), but researchers also obtained Indigenous knowledge from community members <29 years old (n = 2), 30–59 years old (n = 3), and 60+ years old (n = 3). The age of the participants was not reported in three studies. Indigenous knowledge was provided by knowledge keepers (n = 6) or active harvesters (n = 4), and gender was reported in four of the articles, all of which had both male and female participation. Community involvement occurred at almost all stages in the research process (**Fig. 4**; David-Chavez and Gavin 2018) but was generally collaborative (i.e., community members and researchers worked together) at the design, implementation, and analysis stages of the research. All studies derived from multi-year research collaborations (n = 6), with studies being initiated through mutual agreement between the community and researchers (n = 3) or community-initiated (n = 1). A single study was initiated by academic researchers, and one study did not report who initiated the research.

Indigenous community members were credited for their knowledge contributions and efforts either through co-authorship (n = 3) or in the acknowledgments (n = 6). Credit was given for project initiation (n = 4), objective setting (n = 3), research design (n =5), data collection (n = 6), analysis

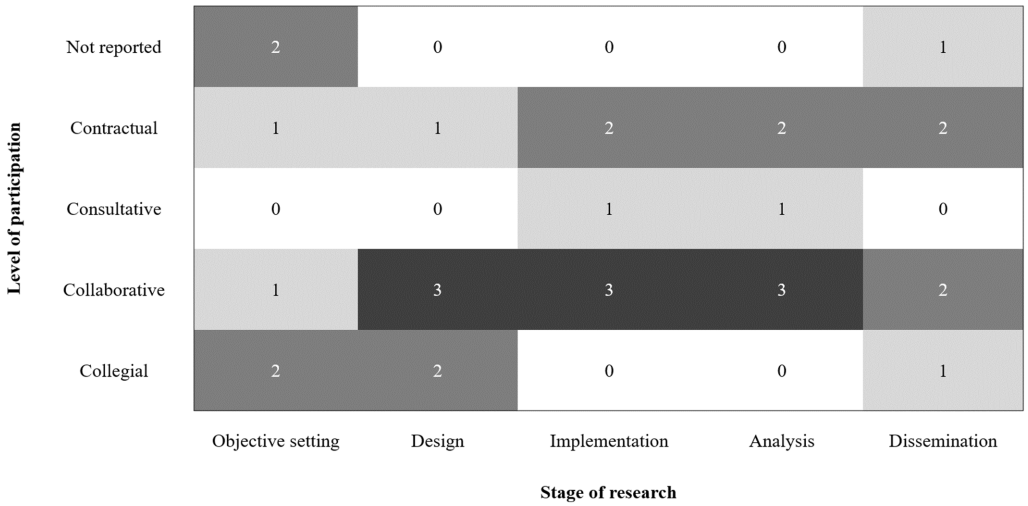

Fig. 4. Matrix showing the number of articles at each stage of research (i.e., objective setting, design, implementation, analysis, dissemination) for a given level of participation by Indigenous community members in research and monitoring articles (n = 6) that include the braiding of Indigenous knowledge systems and Western sciences in the Alberta oil sands region. The level of participation is coded into four categories at each stage of the research for: (1) contractual, no community participation; (2) consultative, community members consulted and asked to provide feedback; (3) collaborative, community members and researchers collectively make decisions about the process of collaboration; and (4) collegial, community members and researchers work together and community members have primary authority in determining the process of collaboration (developed from David-Chavez and Gavin 2018).

and interpretation (n = 3), and dissemination (n = 3; **Fig. 5**). However, only one article that acknowledged Indigenous community involvement in dissemination provided details on whether results were accessible to the community and indicated that research dissemination occurred through in-person meetings or presentations, written communications (i.e., reports, living documents), and social media.

Knowledge systems

Definitions of Indigenous knowledge from Houde (2007) were used to classify how authors described the knowledge systems. Indigenous knowledge was described in some studies as factual observations, classifications, or system dynamics (first face; n = 4) but also as resource management systems adapted to local environments (second face, n = 1) and as factual knowledge regarding past and current uses of the environment (third face, n = 2). Two studies identified Indigenous knowledge as grounded in specific ethics and values (fourth face, n = 0), while none indicated Indigenous knowledge as a vector for cultural identity (fifth face, n = 0). Two studies also mentioned an underlying culturally based cosmology (sixth face; n = 2). Western sciences were defined in three articles, all of which emphasized how Indigenous knowledge compared to the reductionist and analytical approaches of Western-based sciences. Lastly, researchers sought Indigenous knowledge to provide both contemporary (n = 3) and historical context (n = 3) or to aid in the collection and analysis of data (n = 3).

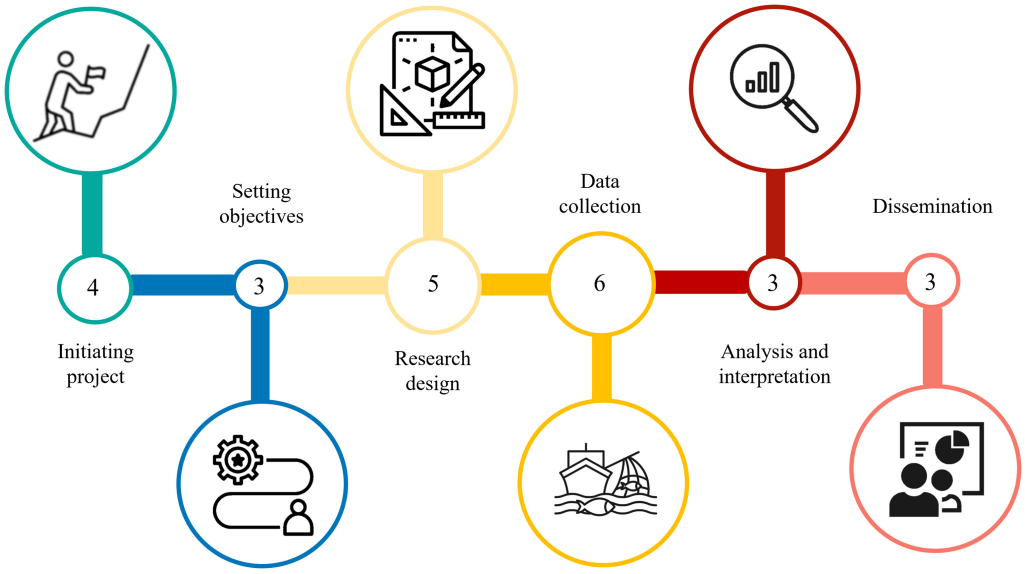

Fig. 5. Number of articles where credit is given to Indigenous participants at each stage of the research process (i.e., initiating project, setting objectives, research design, data collection, analysis and interpretation, and dissemination) in research and monitoring articles (n = 6) that include the braiding of Indigenous knowledge systems and Western sciences in the Alberta oil sands region. Relative size of central circles corresponds to the total number of articles where credit is given.

Power relationships, colonization, and ethical considerations in research

Articles discussed aspects of colonization (n = 4) more frequently than power relationships (n = 2) in research. Moreover, though findings were generally considered relevant to the community (n = 5), the majority of articles did not provide details on the ethical considerations or procedures guiding the research (Table 3). Half of the studies acknowledged following some form of ethical guidelines (n = 3), underwent institutional review for research ethics (n = 1), or followed community protocols (n = 3), while the other half of the articles discussed participant (n = 3) or community consent (n = 1; Table 3). Where consent was indicated, free consent (n = 2; i.e., respondents participated voluntarily) was given or researchers provided information prior to consent being given (n = 1). Data sovereignty was mentioned in a single article, while no authors acknowledged intellectual property rights or acknowledged that participants were offered anonymity (Table 3).

Benefits and challenges of knowledge braiding

Authors often discussed a variety of challenges to the braiding of Indigenous knowledge systems and Western-based sciences (n = 5). Power asymmetries (n = 2) and bias (n = 2) were considered to be the main hurdles to overcome to effectively braid different perspectives on the environment, while inadequate/inconsistent funding (n = 1), local capacity (n = 1), epistemological differences (n = 1), pace of research (n = 1), training requirements (n = 1), and the situation-specific nature of Indigenous knowledge (n = 1) were also mentioned. Many benefits and outcomes were also seen to come from collaborative research and knowledge braiding. Half of the articles reported proposed (n = 4) and realized (n = 3) outcomes from the studies, and benefits and outcomes of the studies included: the potential to inform management (n = 6); increased interest in Indigenous knowledge by scientists (n = 5); contributions to scientific research and knowledge (n = 4); increased environmental awareness (n = 3); ensuring not only Western-based sciences are used in decision-making

Table 3. Ethical considerations described in research and monitoring articles (n = 6) included in the review of publications braiding Indigenous knowledge systems and Western sciences in the Alberta oil sands region.

	Yes	No
Followed ethical guidelines	3	3
Formal ethical review	1	5
Followed community protocols	3	3
Participant consent sought	3	3
Community consent sought	1	5
Assurance of anonymity or confidentiality	0	6
Addresses intellectual property rights	0	6
Addresses data sovereignty or information governance	1	5

(n = 2); local communities feeling that their perspectives are being considered (n = 1); and an increased opportunities for inter-generational knowledge transmission (n = 1).

Discussion

Our systematic review reveals key insights into research and monitoring involving the braiding of Indigenous knowledge systems and Western-based sciences in the Alberta oil sands region. Six articles were identified that braided knowledge, though most articles focused research on monitoring for impacts from industrial activities and expanding the scope of understanding on this research topic. Researchers used a broad range of approaches to gather Indigenous knowledge and scientific data, working alongside Indigenous community members aged ~29–60+ years old from areas principally in the subarctic and boreal regions of Northern Alberta. Indigenous knowledge was often described as factual observations, without mention of underlying worldviews, values, and beliefs. Lastly, researchers identified challenges in asymmetries of power, resource availability, and funding and noted that more support is needed to conduct research that involves braiding of knowledge systems.

Literature search and bibliographic information

Our review consisted of relatively few articles compared to previous systematic maps (Alexander et al. 2019a, 2021b). However, after accounting for the total area examined in each review, we found that the number of articles per 1,000 km^2 was somewhat higher in the oil sands region as compared to a similar number for the national level. The slightly higher concentration of braiding articles taking place in the oil sands region relative to Canada may be due to the importance of environmental and community-based monitoring for impacts caused by extractive industries in the region (Government of Alberta 2019). On the other hand, there were ~18 times more articles published on ecological research and monitoring in the oil sands region based on Western sciences alone compared to those that use braiding methodologies and methods, suggesting a lack of engagement with Indigenous communities from the outset of research or potential limitations to conducting and publishing research involving braiding. Nonetheless, the value imparted through knowledge braiding can help to tackle complex socio-ecological issues in the oils sands and we encourage further work in this area.

Peer-reviewed literature in our review was published between 2017 and 2020 and principally by journals, including *Arctic*, *Environment International*, *Extractive Industries and Society*, and the *Journal of Ethnobiology*, that have mandates to publish interdisciplinary environmental research by multidisciplinary collaborative teams. Interdisciplinary research has gained popularity through an effort to tackle multifactorial problems and challenges that bridge disciplines and knowledge systems (Hazra et al. 2019; Hejazi 2019; Okamura 2019). In the context of the natural sciences, interdisciplinary approaches are particularly useful for work on social–ecological systems (Dick et al. 2016) but can be impeded by obstacles including funding allocation, publishing constraints, and the devaluation of interdisciplinary work by the academic system (McLeod 2018; Cooke et al. 2020). Thus, it may be more difficult to publish collaborative research, particularly if the availability of interdisciplinary journals is limited. Therefore, as the field of interdisciplinary environmental research grows, we call on academic institutions, publishers, and funders to provide platforms and support for interdisciplinary work, particularly in the context of biodiversity conservation and the braiding of knowledge systems (Wong et al. 2020).

Research themes

Themes related to environmental management and monitoring for the effects of industry activity on the environment featured prominently in the articles in our review. Researchers principally addressed topics and used keywords associated with wildlife management and monitoring for environmental change (**Fig. 3**; **Supplementary Material Fig. S1**), while two articles investigated issues related to wildlife health (**Fig. 3**), a concern mentioned in all articles due to environmental impacts of industry activity in the oil sands region. Aquatic ecosystems and species were featured most often in the articles in our review and, while numerous studies and monitoring projects have focused on avian species (Government of Canada 2018), only one article focused on the conservation of terrestrial species (Schramm et al. 2002). The lack of diversity in research subjects may be attributed to the sample size of this review, local monitoring priorities, or the type of research being conducted in the oil sands region.

An important component of research in the Alberta oil sands region is contamination studies. Western-based data-driven studies in the oil sands region commonly screen for suspected chemicals in the environment and the effect on species-at-risk or bioindicator species (Government of Canada 2018). While this provides information on the environmental impacts of extractive industries, the approach limits the opportunity for knowledge braiding when examining the impact of environmental contamination. Moreover, though culturally relevant species have been identified in the oil sands region (Garibaldi 2009), limited work has been done collaboratively with Indigenous communities to understand Indigenous-identified indicators of environmental contamination (Baker 2020) and the effect of contaminants on culturally important species (e.g., Schramm et al. 2002; **Table 2**). We, therefore, encourage the identification of community research needs related to culturally important species and environmental indicators of health; we also emphasize the importance of braiding knowledge systems in a manner and context guided and deemed appropriate by local Indigenous communities.

Industrial developments and resource extraction in the oil sands region are known to release environmental contaminants (Jordaan 2012; Kelly et al. 2010), which can impact land and water resources (Jordaan 2012), wildlife (Brunet et al. 2020; Idowu et al. 2019), and human health (Jones 2009). While many articles in our review discussed the impacts of resource extraction, only two articles assessed levels of contamination in the oil sands region. Prompted by community concerns related to "oil sands impacts to fish" (i.e., lake trout and lake whitefish; Brunet et al. 2020) and observed declines in subsistence food sources (Hopkins et al. 2019), researchers assessed water quality (Hopkins et al. 2019) and quantified levels of heavy metals (e.g., lead, mercury, arsenic) and polycyclic

aromatic hydrocarbons in aquatic organisms (i.e., fish and mussels) using stable isotopes and tissue sampling (Brunet et al. 2020; Hopkins et al. 2019). The contaminants quantified in the articles in our review are known to have toxic effects on aquatic life, vertebrates, and humans (Jones 2009; Idowu et al. 2019). In fact, a distinguishing feature of studies involving braiding, and exemplified by Brunet et al. (2020) and Hopkins et al. (2019), is the emphasis on the relationship between environmental health and the physical, emotional, and spiritual health of Indigenous communities and individuals' ability to feel "connected to [their] culture" (Brunet et al. 2020). While the human–animal–nature connection is foundational to Indigenous worldviews (McGregor 2009; Todd 2016), Western-based sciences, particularly wildlife biology and ecological sciences, are only beginning to apply holistic approaches to understanding social–ecological systems. Only one study in our review included cumulative effects. Given the emerging importance of cumulative effects and studies of multiple interacting stressors (e.g., contaminants, climate change, habitat degradation), this is an area that should be explored more in the region as there is a growing body of literature undertaking cumulative effects work via braiding knowledge systems (e.g., Mantyka-Pringle et al. 2017).

Study setting and design

In the study region, Indigenous knowledge and communities are often treated as homogeneous despite the expansive range of the oil sands region and numerous First Nations and Métis communities located there (Natcher et al. 2020a). The majority of study locations indicated in articles in our review were in the subarctic and boreal regions of Northern Alberta (i.e., n = 10 of 12; **Fig. 2**) and in or near national parks and protected areas (**Fig. 2**), potentially as a result of recent academic interest in this region (Westman et al. 2020). Indigenous knowledge holders identified in the articles in our review ranged from <29 years old to 60+ years old and researchers only considered knowledge from knowledge keepers and active harvesters. Further, while few articles provided details related to gender, gender identification in the articles in our review was limited to two categories (i.e., women and men). Though it is possible that participants did not identify elsewhere on the spectrum of gender (American Psychological Association 2015; Egan and Perry 2001), the binary identification of gender points to the importance of establishing ethical and inclusive research environments that represent individuals across the gender spectrum, including from Indigenous gender identities (Halverson 2013; Natural Sciences and Engineering Research Council 2022; Robinson 2019). Overall, our results show that more work needs to be done in regions outside of Northern Alberta (i.e., south of Wood Buffalo National Park), with a broader range of knowledge holders (e.g., youth, women's groups), and that steps are to be taken to conduct research in an ethical manner that respects the diversity and integrity of individuals.

Similar to Alexander et al. (2019a) and Alexander et al. (2021b), the articles examined demonstrated a variety of methodological approaches and methods used for the braiding of Indigenous knowledge systems and Western-based sciences. Despite the diversity of approaches, community-based participatory research was most commonly used and was typically coupled with abiotic sampling/counts and interviews/surveys of First Nations and Métis community members. Community-based participatory research is a research approach that empowers local communities to become involved in research and collaborate with Western-trained non-Indigenous researchers as equal partners (Israel et al. 1998; Tremblay et al. 2018). In this way, the majority of articles in our review indicated that projects were mutually initiated or, in one case, initiated by the community. Studies were also highly collaborative, notably at the design, implementation, and analysis stages of research (**Fig. 4**) and, in one case, researchers also considered Indigenous involvement when selecting secondary sources of data (Straka et al. 2018). It is possible that the long-term nature of studies in our review necessitated engaged research practices like community-based approaches and that researchers selected methods similar to harvest studies (i.e., counts and surveys;

Usher and Wenzel 1987), which may be familiar to Indigenous research participants. Nevertheless, only one article applied an Indigenous research methodology, suggesting undisclosed factors that may drive hesitation for Western-trained non-Indigenous researchers collaborating with Indigenous peoples to apply Indigenous research frameworks. However, post-colonial and Indigenous scholars also highlight the importance of researchers understanding Indigenous ontology, epistemology, axiology, and methodology, thereby underscoring the need to center and prioritize Indigenous-led research and scholarship (Smith 2021; Wilson 2008), particularly in the oil sands region.

Knowledge systems

Indigenous knowledge varies between cultures and with age, gender, livelihood, and individual and collective histories (Boster 1986; Ellen 1979; Natcher et al. 2020a, 2020b) and it can offer unique insights into environmental processes (Latulippe 2015). The majority of articles in our review described Indigenous knowledge as factual observations or knowledge about past and current uses of the environment and management systems (i.e., first, second, and third faces of traditional ecological knowledge; see Houde 2007), and, thereby, referring to the knowledge and practices of "[I]ndigenous and local communities that are developed, sustained and passed on from generation to generation" (Mantyka-Pringle et al. 2017). Indigenous knowledge was initially used by researchers and colonial governments to inform environmental management (Latulippe 2015; McGregor 2004a), so it is not surprising that empirical descriptions of Indigenous knowledge dominate the scientific literature (see Ford et al. 2016). In this way, Indigenous knowledge can be "reduced to a series of facts, observations, and practices, ripe for extraction" (Latulippe 2015). In contrast, two of the articles in our review indicated that Indigenous knowledge provides guidance rooted in cultural values and cosmology (i.e., fourth and sixth faces of traditional ecological knowledge, Houde 2007). In this case, Indigenous knowledge is embedded in a system (Hopkins et al. 2019) where the "[values] and cosmological contexts" are understood by the community (Baldwin et al. 2018). Given that few articles describe the underlying worldview associated with Indigenous knowledge, more is needed to be done to recognize the complexity of knowledge systems, and how place-based observations are understood and embedded within complex relationships of accountability, daily practices, values, and beliefs.

Notwithstanding the trends in articles in our review, the categorization of Indigenous knowledge and Indigenous knowledge systems is rooted in Western paradigms, which have been criticized for "hollow and potentially damaging" (McGregor 2021) representations of Indigenous knowledge and overemphasis on ecological observations in environmental research and governance (Nadasdy 2003). Stemming from this compartmentalization, a wide range of literature exists that seeks to extract Indigenous knowledge as "factual observations" to incorporate into policy and management, whereas in reality, Indigenous knowledge is inseparable from Indigenous knowledge systems and the people who hold and live this knowledge (McGregor 2021). Without a more holistic approach to engage and better represent the systems of beliefs, values, and spirituality at the foundation of Indigenous knowledge and Indigenous knowledge systems, efforts at meaningful collaboration will be fraught with challenges and Indigenous perspectives will be misinterpreted or neglected (Reo 2011).

Power relationships, colonization, and ethical considerations in research

Publications have the tendency to minimize historical and contemporary power relationships (Singleton et al. 2021), neglecting that relationships formed for research and environmental monitoring support the goals of lead, often non-Indigenous, researchers (Davies et al. 2020; Hastings et al. 2020; Peacock et al. 2020). While few articles in our review discussed power relationships, those that did took steps to empower local communities throughout the research process aimed at increasing

levels of Indigenous leadership and control (also see Indigenous-led research as a practice in Indigenous governance, Wilson et al. 2018). Hopkins et al. (2019) developed a community-based research project that ensured that Indigenous community members could "meaningfully participate in all phases of this work… [including] mutual ownership of the research process and products, as well as shared decision making" (pp. 321–322). The rapport developed with community members also allowed Hopkins et al. (2019) to address issues of power and ensure that their "project was not… an exercise in non-participation and tokenism" (p. 322). Further, the impacts of colonialism are often situated in the past, excluding discussion on the intergenerational impacts of colonialism and the potential for contemporary colonialism (Singleton et al. 2021; Wheeler et al. 2020). Though rarely discussed in Western-based scientific literature, four articles in our review examined aspects of colonialism and ensuing challenges. Schramm et al. (2002), for instance, reviewed how the relocation of the Little Red River community, with whom they collaborated, affected community livelihood:

> "In the 1950s and 1960s the federal government strongly encouraged [Little Red River] members to move to settlements on newly established reserves in Fox Lake and John D'Or Prairie. This change in location brought about a major change in lifestyle where people had to adapt from an independent family unit lifestyle where they lived in a remote place and made decisions quite freely, to a more restrictive community lifestyle where decisions were often mediated by a modern administration" (Schramm et al. 2002, p. 6).

Ethical considerations should also be clearly articulated in publications and Indigenous communities should have the opportunity to negotiate their level of involvement, confidentiality, data ownership, and access (McGregor 2018c; First Nations Information Governance Centre 2021). However, few articles in our review discussed ethical guidelines and protocols, consent, and information governance (**Table 3**), which, in part, may be due to publishing guidelines (e.g., word counts, prescribed sections, and lack of multidisciplinary approach). More recently, publishers have begun to shift reporting practices, with some, including Canadian Science Publishing (2022), establishing reporting guidelines for community-engaged research and encouraging discussion on research relevance for communities, community-engaged research design, and equity. While this shift in the publication process can encourage inclusive research practices and supports ethical ecology (Trisos et al. 2021), further efforts are needed to ensure that community-based research is relevant, action-oriented, equitable, and, ultimately, accessible to communities after publication.

Benefits and challenges of knowledge braiding

The complex nature of knowledge braiding makes it important to note the benefits and challenges associated with collaborative research involving braiding of knowledge systems. Though articles reported a variety of outcomes, more than half of the articles in our review reported that the inclusion of Indigenous knowledge systems can help inform Western-based scientific research and impact environmental management. This is not surprising given that inclusion of Indigenous knowledge has often been premised on the potential for Indigenous ways of knowing to improve Western-based management practices (Latulippe 2015) but also suggests that dominance hierarchies in natural sciences research still exist. In fact, power asymmetries and bias were mentioned in the articles in our review as key challenges to address in research involving knowledge braiding. To begin breaking down the colonial structures, changes must be made in the ways in which Western-based academic research is conducted, including through the adoption of stronger community-based participatory approaches and decolonizing and anti-colonial methodologies (Liboiron 2021; Simonds and Christopher 2013). Specifically, it will be critical for academic institutions to enhance support for Indigenous community-led scientific research and collaborations between Indigenous communities and Western-trained non-Indigenous researchers. Previous research has shown that time constraints, resource availability, lack of funding, lack of capacity, and need for cultural awareness training are

barriers to engagement (Bozhkov et al. 2020) and articles in our review spoke to differences in the pace of research between Western-based academic systems and Indigenous communities, as well as the need to learn how to work effectively with Indigenous peoples. Nevertheless, it is important to emphasize that research involving the braiding of knowledge systems should only take place with the approval and collaboration from local Indigenous groups throughout the research process. Further, the relevance of academic research to Indigenous communities needs to be addressed. Promoting Indigenous community-led scientific research and improved funding that supports long-term relationship-building and research are important ways to develop and support relevant academic research for Indigenous communities. In addition, the appointment of Indigenous science advisors and programs could help to set research direction and play key roles building relationships between Indigenous communities and Western-trained non-Indigenous researchers. We conclude that it is critical that academic institutions, funders, and Western-trained non-Indigenous researchers be attentive to and take intentional action to address the challenges of research involving braiding and to work toward achieving beneficial and impactful research.

Conclusion

In this review, we summarize six publicly available peer-reviewed articles in the ecological sciences from studies in northern Alberta to examine how the braiding of Indigenous knowledge systems and Western-based sciences has occurred in the Alberta oil sands region. The results of this review highlight the diverse and collaborative research happening in the oil sands region and potential limitations to conducting and disseminating interdisciplinary work involving braiding of knowledge systems. Additionally, we emphasize the need for researchers, alongside with Indigenous communities, to identify and study topics that support community interests and the right to self-governance, and that expand our understanding of the ecological threats and threats to species at risk and other valued ecosystem components throughout the oil sands region. By doing so, the braiding of Indigenous knowledge systems and Western-based sciences has the potential to address complex environmental challenges and enhance decision-making abilities that could, ultimately, improve conservation and environmental management efforts in the oil sands region and beyond.

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Author contributions

AAEW, JFP, DAH, PJT, and SMA conceived and designed the regional review based on systematic reviews developed by SMA, DAH, JFP, JJT, and SJC. AAEW collected the data and conducted the data analysis. AAEW wrote the original manuscript and LRJ provided the data and drafted the section on environmental contaminants. All authors contributed to writing and revising the manuscript and gave final approval for publication.

Data availability statement

Data presented in the main text are available from the *figshare* digital repository: 10.6084/m9.figshare.16580579.

Competing interests statement

The authors declare there are no competing interests.

Supplementary material

The following Supplementary Material is available with the article through the journal website at doi:10.1139/facets-2022-0052.

Supplementary Material 1

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