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Weaving Indigenous and Western ways of knowing in ecotoxicology and wildlife health: a review of Canadian studies

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Abstract

Western-trained, non-Indigenous researchers in Canada have an ethical responsibility to collaborate with Indigenous Peoples and to re-envision the scientific research process through the lens of reconciliation. The health of the natural environment has long been a concern to both Indigenous and non-Indigenous Peoples, and weaving different ways of knowing could provide a path forward to address critical wildlife health concerns. Here, we conducted a review of the peer-reviewed and grey literature that claims to weave Indigenous and Western ways of knowing in ecotoxicology and wildlife health in Canada, coding for background information, wildlife health stressors, research methods, Indigenous participation, and research outcomes. Seventeen studies met the inclusion criteria, the majority of which were published since 2015 and took place in Canada's North. Research collaborations were often between First Nations or Inuit knowledge holders (most frequently, active harvesters and Elders) and Western-trained, non-Indigenous academics. Most studies were initiated by mutual agreement between community partners and researchers, but no study was "Indigenous-led" at any stage of research. Studies investigated environmental contaminants and health-related topics in a range of wildlife, usually traditional subsistence species. The most commonly studied disease was avian cholera, and the most studied class of toxicants was metals and trace elements. Indigenous knowledge was primarily collected via interviews. Studies often used multiple methodologies to braid or weave knowledge, but the most frequently used methodology was community-based participatory research. To provide a more holistic understanding of the process of weaving knowledge, we conducted an in-depth examination, applying a decolonizing lens, of two exemplar cases of collaborative research with Indigenous communities. This exploration led to the conclusion that research that weaves ways of knowing must not be approached with a "one-size-fits-all" mindset, but instead should emphasize relationship building, continuous engagement, and ethical practices. By adopting such practices, Western-trained, non-Indigenous academics can better address critical wildlife health concerns while contributing meaningfully to advancing healing and reconciliation with Indigenous Peoples.

Key words: Indigenous People, reconciliation, Indigenous knowledge, natural sciences, braiding knowledge systems, collaborative research

Introduction

For many Indigenous Peoples around the world ""research" is one of the dirtiest words" (Smith 2021). Research with Indigenous Peoples and communities in Canada has not always been meaningful and respectful and could often be characterized as "research *on* Indigenous Peoples". Researchers would often arrive in a community, collect data, and "rarely, if ever, return" (Peltier 2018). Despite meaningful change being made to these practices, research can still be "rooted in old colonial practices … historically used as a tool to disadvantage, disempower, and harm Indigenous Peoples" (Reid 2020). Due to these extractive and racist experiences of appropriation between Western-trained, non-Indigenous academics and Indigenous Peoples, it is not surprising there can be skepticism when it comes to current research endeavours.

In response to the history of colonization and legacy of genocidal residential schools in Canada, calls to action have been developed to encourage a new vision for conducting research. In 2015, the Truth and Reconciliation Commission of Canada (TRC) released *94 Calls to Action* to promote reconciliation[1] between Indigenous and non-Indigenous Canadians (Truth and Reconciliation Commission of Canada 2015). The term "Indigenous" will be used to refer specifically to First Nations, Inuit, and Métis Peoples within what is now called Canada (Vowel 2016). The *Calls to Action* call on the federal government in collaboration with Indigenous Peoples, post-secondary institutions, and educators to advance reconciliation through research (Truth and Reconciliation Commission of Canada 2015, Call #65). Wong et al. (2020) responded to the TRC's *Calls to Action Report* urging natural scientists and post-secondary research institutions to develop a new vision for conducting natural sciences, "fundamentally mainstreaming reconciliation in all aspects of the scientific endeavour, from formulation to completion" (Wong et al. 2020, Call #10). To "address past and current inequities that start with shared understandings of the historical and present trauma experienced by Indigenous Peoples", new approaches for conducting research are needed (Raymond-Yakoubian et al. 2022; see also, Bozhkov et al. 2020).

Since time immemorial Indigenous Peoples have been scientists and their knowledge and ways of knowing, in relation to the Earth, have contributed to "our physical and biological understanding" in nearly every scientific discipline throughout history (McGregor 2002; McGregor 2009; Tsosie and Claw 2019). The high-context (Johnson et al. 2016), place-based (Castleden et al. 2017*b*; Jessen et al. 2021) knowledge derived from this enduring relationship "represent[s] more than just "knowledge" (as a noun); [it] represent[s] a way of life, something that has to be lived (as a verb) to be known, understood, and practiced" (McGregor 2021). Tsosie and Claw (2019) argue that we should think of Indigenous knowledge as "knowledge that endures or has been repeatedly tested and remained substantiated" (Tsosie and Claw 2019). In comparison, the origins of Western sciences date back to natural philosophies (see Aikenhead and Ogawa 2007) and were greatly influenced by gaining power over nature and the Chain of Being. Western science is low-context knowledge[2] that has been appropriated from many cultures over time to fit Eurocentric worldviews and value systems, resulting in a powerful and successful way of knowing about nature (Aikenhead and Ogawa 2007). It is important to acknowledge the differences in ways of knowing and the barriers that may exist when weaving them together. Due to the legacy of colonization, Western sciences are often falsely regarded as more "legitimate", "superior", or as needing to "validate" Indigenous ways of knowing (Simpson 2001b; Kutz and Tomaselli 2019; Kadykalo et al. 2021). This can continue the cycle of extractive settler colonial-driven research that attempts to commodify Indigenous ways of knowing if not challenged (Kadykalo et al. 2021).

One way to challenge the status quo and respond to the *Calls to Action* for reconciliation in Canada is to weave Indigenous and Western ways of knowing in research. While a number of different approaches to weaving exist (Table S1), weaving knowledge systems generally aims to bring Indigenous knowledge systems and Western sciences together in a manner that respects the integrity of each knowledge system (Rathwell et al. 2015; Tengö et al. 2017). In this way, weaving knowledge systems challenges the status quo by going beyond "integrating", "combining", or "incorporating" knowledge systems (McGregor 2008; Buell et al. 2020; Reid et al. 2020; Henri et al. 2021), and instead respects what each worldview can contribute to create reciprocal research (Bartlett 2011; Wright et al. 2019). Collaborating with and empowering Indigenous knowledge holders in research can increase the thoroughness of the research process and expands our knowledge of the natural world, which, in turn, has the potential to positively influence policy development and decision making (Alexander et al. 2019*b*; Martin 2012; Johnson et al. 2016; Ban et al. 2018; Hopkins et al. 2019; Popp et al. 2020; Houde et al. 2022). Indigenous ways of knowing often illuminate complex interconnections and synergies, whereas Western sciences can be useful when trying to isolate mechanisms and processes. Thus, weaving knowledge systems can provide a holistic approach and understanding when solving environmental problems related to ecotoxicology and wildlife health.

The health of wildlife in Canada is of social, cultural, and economic importance to Indigenous and non-Indigenous Canadians, but various ecological threats, including pollutants, pathogens, and parasites, can result in unforeseen wildlife health impacts (Pan-Canadian Approach to Wildlife Health [PCAWH], 2018; Stephen 2014; Stephen and Zimmer 2015; Tomaselli et al. 2018). While there is no widely accepted definition for wildlife health, biological, social, and environmental factors all appear to contribute to good wildlife health outcomes (Stephen 2014), and approaching health more holistically—as opposed to "merely what is absent" (e.g., the absence of illness or disease)—is key in defining wildlife health. For many Indigenous communities and Peoples, health is holistic and involves physical, emotional, mental, and spiritual aspects and thus the wellbeing of individuals, families, communities, tribal groups, and nations is directly connected to the wellbeing of the land (Hillier et al. 2021). The inclusion of Indigenous ways of knowing in wildlife health monitoring and management can "improve the detection of emerging trends and the understanding of changes in wildlife health and ecology" (Peacock et al. 2020).

Currently wildlife health issues in Canada are addressed on a "disease-by-disease" basis, which can create challenges for early detection and quick mitigation responses (PCAWH

[1] We define reconciliation as the establishment and maintaining of mutually respectful relationships between Indigenous and non-Indigenous Canadians. This must involve the acknowledgement and reparation of the historical and ongoing harms caused by colonialism, and meaningful action to restore the power imbalances that exist as a result (McGregor 2018; Truth and Reconciliation Commission of Canada 2015; Wong et al. 2020).

[2] Indigenous knowledge is "high-context" because it takes "all relational connections" or "all our relations" into consideration as opposed to 'low-context' Western science (Johnson et al. 2016) that often places scientists as separate from nature and isolates and simplifies study objects (Mazzocchi 2006).

2018). Additionally, because wildlife health is a responsibility shared by many stakeholders, rights-holders, and across many different jurisdictions (i.e., federal, provincial, territorial, municipal, Indigenous, non-governmental, and private sector) it can be challenging to properly allocate funding, resources, and responsibilities when protecting and conserving wildlife (Stephen and Zimmer 2015). Four factors that influence the need for an innovative approach to wildlife health are: (i) the frequency in which disease(s) result in wildlife declines and extinction; (ii) the threat that emerging infectious diseases found in wildlife can pose to public health, agriculture, or conservation; (iii) the public challenging the extent to which monitoring of wildlife health is being done; and (iv) human-induced threats (i.e., climate change, resource extraction) pose a major risk to wildlife (PCAWH 2018). Community-engaged approaches to wildlife health, such as Indigenous community-based monitoring, can help to fill knowledge gaps and provide a better understanding when studying the complex nature of environmental stressor-pathway responses (Beausoleil et al. 2022).

Despite knowledge weaving practices being used in various areas of biodiversity research and monitoring, and a critical need for a more holistic and innovative approaches to wildlife health, there has been little focus on examining how weaving has been carried out in wildlife health research (Alexander et al. 2019*b*, 2021; Henri et al. 2021). Guided by Grand Council Treaty #3 (GCT3) representatives, as part of the "*Spirit of the Lakes*" initiative, our goal was to understand the weaving process in ecotoxicology and wildlife health research to create a pathway forward for engaged and collaborative research between Indigenous communities on Treaty #3 Territory and Western-trained academic and government researchers. To do so, we reviewed the peer-reviewed and grey literature that wove Indigenous ways of knowing and Western science, restricting our study to literature on environmental contaminants and other wildlife health stressors in Canada. First, we assessed trends related to knowledge weaving with regards to various categories (e.g., publication timing and frequency, study location, methods employed, and Indigenous participation). Next, we identified two exemplar case studies and, applying a decolonizing lens, provide an in-depth examination of the process of conducting collaborative research.

Through this critical assessment of the literature that weaves Indigenous ways of knowing and Western science, our study contributes to the growing body of literature that supports and encourages knowledge weaving/bridging/braiding in natural science and biodiversity-related research (e.g., Beausoleil et al. 2022; Buell et al. 2020; Jessen et al. 2021). To the best of our knowledge, we have completed the first review that synthesizes Canadian studies that weave ways of knowing relating to ecotoxicology and wildlife health. This in turn will call attention to and further support existing literature on the benefits of weaving knowledge systems (Abu et al. 2019; Broadhead and Howard 2021; Martin 2012; Johnson et al. 2016; Hopkins et al. 2019), specifically in the context of ecotoxicology and wildlife health but not limited to other natural science disciplines. These benefits not only include enhancing wildlife monitoring, management, and decision making (Mantyka-Pringle et al. 2017; Kutz and Tomaselli 2019; Popp et al. 2020) but benefits to communities as well (Alessa et al. 2016). Findings will also support the promotion and importance of meaningful relationship building and early and continuous engagement among collaborative research partners (Ban et al. 2018; Bozhkov et al. 2020; Wong et al. 2020). Lastly, we hope this review serves to inspire and guide ecotoxicologists, wildlife health experts, and conservation practitioners on approaches to conducting collaborative research that responds meaningfully to the calls for reconciliation in Canada.

Approach

Positionality

Inspired by work from Reid (2020) and Peltier (2018), which encourages both personal and professional self-reflection to recognize privilege when working with Indigenous communities and collaborators, the authors of this manuscript will briefly introduce themselves. We are researchers of Indigenous and non-Indigenous ancestry who study ecotoxicology, wildlife health, and ethnobiology through community-based participatory research (CBPR). We are all constantly growing and learning to challenge our biases brought on by settler colonialism. First author, Lydia Johnson (mixed settler descent and Cree ancestry), was born and raised on Robinson-Superior Treaty territory (Thunder Bay, Ontario) and is a registered member of the Lac La Ronge Indian Band, Saskatchewan (Treaty #6 territory). All co-authors participated in the writing of the manuscript across different unceded, Treaty and Métis territories; however, we would like to acknowledge and give thanks specifically to the traditional Anishinaabe and Haudenosaunee territory in Katarokwi (Kingston, Ontario) on which this manuscript was mainly written. As part of the "*Spirit of the Lakes*" initiative, which seeks to explore how ethical practices around research on environmental contaminants with Indigenous partners brings together Indigenous communities on Treaty #3 Territory with academic and government researchers, the work presented here was guided by C.H. and L.K. who work for Grand Council Treaty #3 (Anishinaabe Nation). We express our profound gratitude for their support and guidance in the development of this research.

Systematic maps

This research builds upon a body of work by Indigenous and non-Indigenous collaborators. The systematic maps that were queried to build the database herein reviewed the weaving of Indigenous knowledge systems and Western sciences in coastal-marine (Alexander et al. 2019*a*; Alexander et al. 2019*b*), freshwater (Alexander et al. 2021), and terrestrial (Henri et al. 2021, Henri et al. unpublished data) ecosystems in biodiversity research, monitoring, or management in Canada. Systematic mapping is a method of evidence synthesis that can maximize transparency and comprehensiveness of specific topics while identifying research gaps or best practices (Haddaway et al. 2016; Haddaway and Westgate 2018). The method of systematic mapping provides a

descriptive overview of all available evidence pertaining to a particular question (Collaboration for Environmental Evidence 2022). Systematic maps are excellent tools for providing answers to broad questions and overviews of evidence bases, and can be used to inform future research, though they are limited to narratively describing evidence as opposed to performing quantitative or qualitative analysis (Haddaway et al. 2016). The authors of these systematic maps used a well-established approach to comprehensively identify research gaps and best practices within the specific topic of interest in both the peer-reviewed and grey literature (Haddaway et al. 2016; Haddaway and Westgate 2018). Specifically, the systematic maps were developed in accordance with the Collaboration for Environmental Evidence Guidelines (Collaboration for Environmental Evidence V.5, 2018) and *Reporting Standards for Systematic Evidence Syntheses in Environmental Research* (ROSES) (Haddaway et al. 2017). Details on the search strategy, screening, and coding of papers for the systematic maps are available in Alexander et al. (2019*b*, 2021) and Henri et al. (2021).

Study selection and inclusion criteria

In this review, we included research and monitoring studies that reported either qualitative or quantitative empirical results on environmental contaminants and/or wildlife health in Canadian coastal-marine, freshwater, and terrestrial ecosystems and discussed or inferred knowledge weaving (Fig. 1). Previously screened studies from the peer-reviewed and grey literature that were included in the original systematic maps were re-screened at title, abstract, and full-text to confirm eligibility for this review. Specifically, studies that included themes related to ecosystem health, wildlife health, monitoring impacts of industrial activity/development, as well as studies that employed specific terms related to ecotoxicology or wildlife health (i.e., contaminant/ion/s, pollut/ion/ant(s), toxin/s, toxicant/s, disease/s, and parasite/s) were flagged and screened for inclusion.

Additional literature searches using the search strings from the original systematic maps were conducted across three bibliographic databases (i.e., ISI Web of Science Core Collections, Scopus, ProQuest Dissertations and Theses Global) to capture all relevant peer-reviewed and grey literature weaving studies relating to ecotoxicology and wildlife health that were published since the original systematic mabl 1). A set of English search terms (see Table S2) relevant to components of each ecosystem were used in conjunction with Boolean operators "AND" and/or "OR" to combine terms and adapted for each ecosystem based on the original protocols. Dates were restricted to the period after searches were performed for the coastal-marine (i.e., January 2018–August 2021) and freshwater (i.e., January 2019–August 2021) systematic maps. Since the terrestrial systematic map was completed at the same time as this review, no additional search of the bibliographic databases was required.

Data coding strategy

We screened 71 coastal/marine studies, 74 freshwater studies, and 180 terrestrial studies from the systematic maps to identify studies that fit our review criteria. The data extraction and coding process was conducted at the case study level (i.e., articles may contain more than one case study) by one coder that went through rigorous consistency checking protocols to ensure decisions made were consistent and repeatable (see Alexander et al. 2019*b*; Alexander et al. 2021; and Henri et al. 2021). We used a standardized questionnaire inspired by that used in the systematic maps to extract key descriptive information from studies across five categories: (i) bibliographic information, (ii) study location, (iii) study purpose and scope, (iv) research methods and mechanisms, and (v) Indigenous knowledge systems. We added additional questions to the questionnaire, that aligned with our research aim, regarding Indigenous participation in research, equity, power sharing. In addition, for the purpose of this review, we added questions on contaminant type (toxin/toxicant vs disease/parasites), specific contaminant(s) studied, and health indicators. In total, 34 questions were coded for each study and included in the review (Table S3).

Data analysis

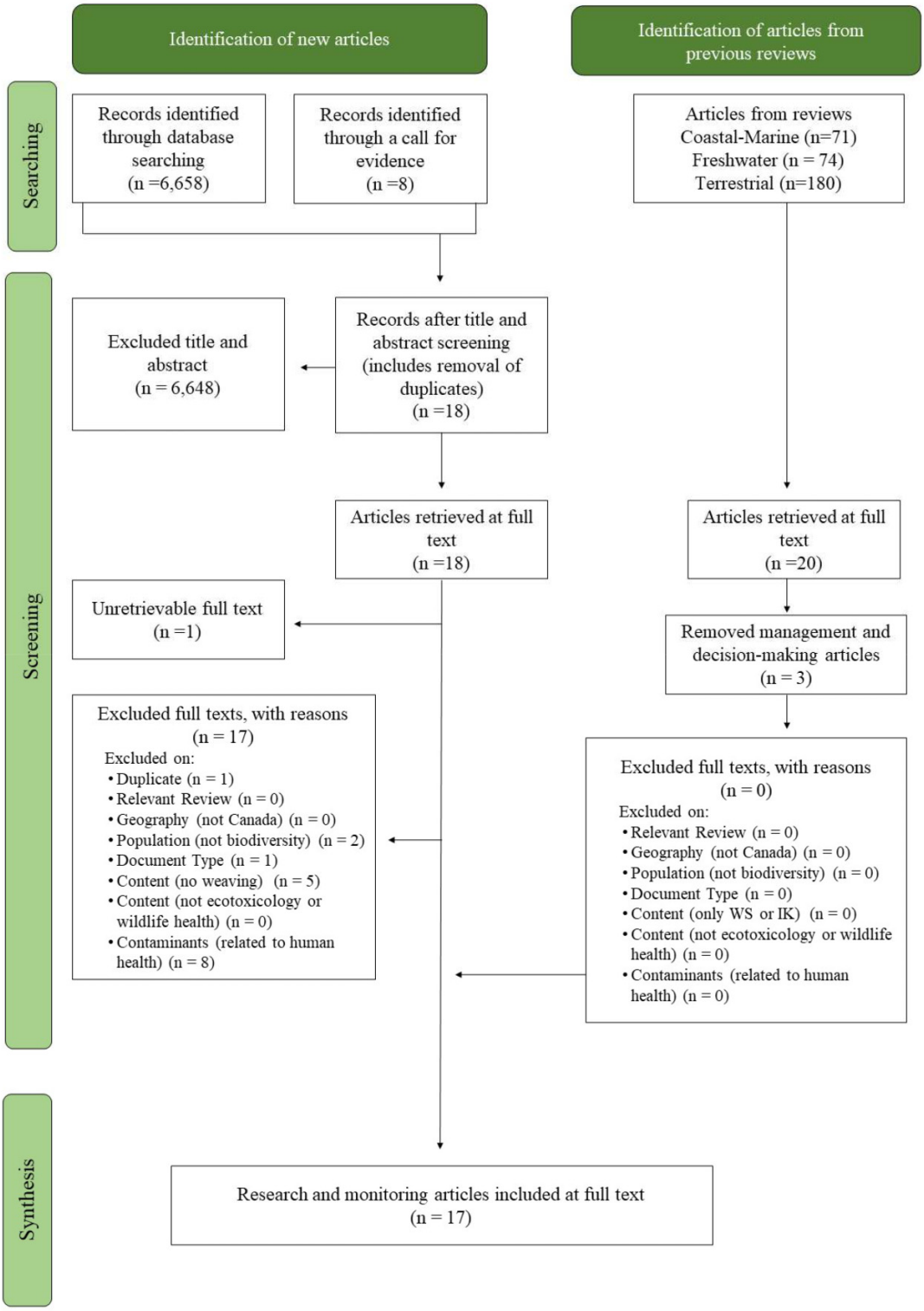
We used a narrative synthesis approach to report results, which is described by Popay et al. (2006) as a form of "story telling" in which statistical analysis can be used but largely text is used to explain findings (Popay et al. 2006). This approach, which groups and clusters studies based on content, was complemented with the use of descriptive statistics that aided in the identification of trends and evidence gaps (Alexander et al. 2021). Additionally, thematic analysis was used to interpret study information from themes that emerged during the data coding process (Liebenberg et al. 2020). Indigenous authority in decision-making was assessed across the various stages of research, adapted from (David-Chavez and Gavin 2018) (Table 1). Statistical graphs for publication dates across time and Indigenous participation across research stages were developed in RStudio (R version 4.0.2) using the package *ggplot2,* and the package *networkD3* was used for the methods versus methodologies Sankey visualization. The study location map was created in QGIS (version 3.20.2). Shapefiles of Canada's provinces/territories and coastal water polygons were downloaded from Statistics Canada 2016 Census—Boundary files (Government of Canada 2019), and the shapefile for Inuit regions (Inuit Nunangat[3] was downloaded from Government of Canada—Open Government portal (Government of Canada 2017). Study locations were taken directly from each article, in cases where communities/hamlets were unspecified the closest community to the Indigenous group involved in the study was chosen for mapping purposes.

Case study selection and analysis

Two exemplar case studies were identified using information coded in this review and through recommendations from Indigenous scholars as having criteria necessary

[3] Inuit Nunangat includes the land, water, and ice that make up the four Inuit regions in Canada: Inuvialuit Settlement Region (Northwest Territories), Nunavut, Nunavik (Quebec), and Nunatsiavut (Labrador) (Inuit Tapiriit Kanatami, 2022).

Fig. 1. ROSES flow diagram, which outlines the source and number of articles obtained at each stage of the review process. ROSES: Reporting Standards for Systematic Evidence Syntheses in Environmental Research.



for meaningful collaboration with Indigenous Peoples/communities in research. This includes authentic relationship building, relevant and reciprocal research that gives back to and benefits the community, early dialogue and involvement of Indigenous community members throughout the research process, utilizing Indigenous methodologies and values, moving beyond "integrating", "combining", or "incorporating" Indigenous ways of knowing, and challenging power imbalances (Kovach 2009; Inuit Tapiriit Kanatami 2018; Peltier 2018; Wilson et al. 2019; Buell et al. 2020;

Table 1. Authority in decision-making across research stages.

Code	Definition
Contractual	No community participation (researchers make all decisions—may employ community to perform tasks; tasks are defined by the academic researcher)
Consultative	Community members consulted by asking for opinions/feedback/recommendations—decisions made by scientists
Collaborative	Community members and researchers work together—researchers have primary authority and make decisions about/facilitate the process for collaboration
Collegial	Researchers and community members work together—local community members have primary authority and make decisions about/facilitate the process for collaboration
Indigenous-led	Community members make all decisions and have authority over all research aspects in every stage of the process

Source: (Henri et al. 2021), adapted from (David-Chavez and Gavin 2018)

Reid et al. 2020; Liboiron et al. 2021). Criteria used to identify these exemplar studies within this set of papers included research: (i) initiated through mutual agreement, (ii) where Indigenous communities had authority in decision-making at each stage in the research process, (iii) where credit was given to the Indigenous community or community members involved in the research, and (iv) where results were shared and made accessible to communities. Information extracted for the case studies includes a more in-depth analysis and critique of data and was assessed with respect to three broad categories: (i) relationship building, (ii) need for continuous engagement, and (iii) ethical practices.

Findings

Publication timing and frequency

Of the 6991 articles that were screened for inclusion (including previous databases, and the updated literature search; Fig. 1), less than 1% ($n = 17$) were included in this review (Table S4). This number also represents 5% of the total case studies included in the final systematic maps ($n = 325$) upon which the present work was built upon (i.e., Alexander et al. 2019*b*; Alexander et al. 2021; Henri et al. 2021, Henri et al. unpublished data). Articles were published across 22 years, from 1998 (Pellerin and Grondin 1998) to 2020 (Brunet et al. 2020), and there was an exponential increase in studies published after the year 2015. The frequency of studies from 1998–2014 (i.e., 16 years) was six studies (<1/year) compared to 11 studies from 2015 to 2021 (i.e., 6 years) (~2/year) with five studies published in 2018 alone (Gérin-Lajoie et al. 2018; Henri et al. 2018; Nesbitt et al. 2018; Ostertag et al. 2018; Tomaselli et al. 2018) (Fig. 2).

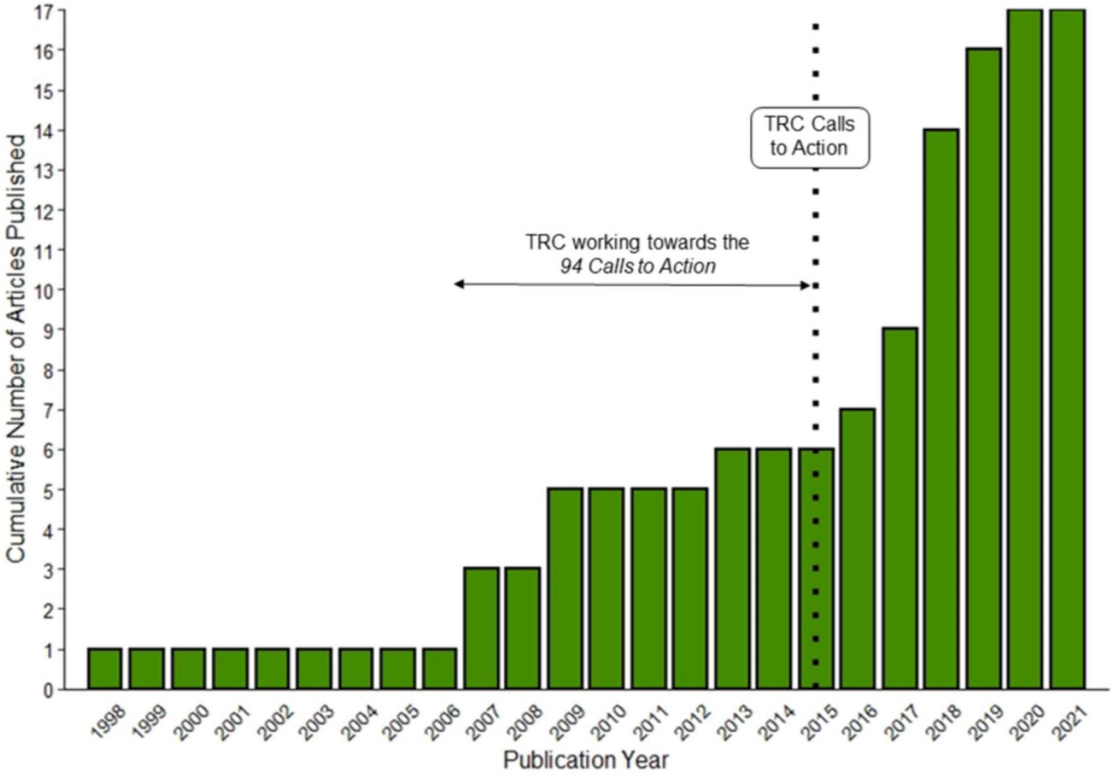
These findings indicate that studies that weave knowledge systems in ecotoxicology and wildlife health are sparse, but on the rise. The increase in studies after 2015 may imply an increased awareness and movement by academics toward collaborative and decolonial research, which could be driven by the push from Indigenous scholars and communities (Wilson 2008; Simonds and Christopher 2013; Battiste 2017; McGregor 2018). Additionally, the Canadian adoption (without qualification) of United Nations Declaration on the Rights of Indigenous Peoples in 2016 (Mitchell 2019), the TRC (2015), and most recently Wong et al. (2020) and Bozhkov et al. (2020)have called upon non-Indigenous Canadians, and specifically natural scientists, to respect the inherent rights of Indigenous Peoples to continue to protect and sustain their knowledge, traditions, lands, waters, plants, and animals and to reconcile the historical and exploitative relationship of research between Indigenous Peoples, communities, and academics (Bozhkov et al. 2020; United Nations General Assembly 2007; Truth and Reconciliation Commission of Canada 2015; Wong et al. 2020). Lastly, Indigenous resistance movements, like *Idle No More* (2012), have received significant mainstream and social media coverage, which can create a ripple effect that positively influences public perceptions of historical, social, and environmental issues facing Indigenous communities and Peoples in Canada, thus creating a greater societal interest and awareness in these topics (Moscato 2016; Wilson and Zheng 2021). In turn, awareness of critical issues related to Indigenous Peoples has been suggested to drive social change by impacting the political narrative at a federal level in Canada (Richez et al. 2020) and is likely to play a role in informing "what funders, researchers, NGOs and settler activists support, sharpening the focus on where time, labour and money is invested" (Gobby et al. 2022).

Study location

Of the 17 studies, most (~70%) took place in the northernmost regions of Canada (Figure 3); specifically, Yukon (and Alaska) ($n = 1$), Northwest Territories ($n = 2$), Inuvialuit Settlement Region (ISR) ($n = 2$), Nunavut ($n = 3$), and Nunavik ($n = 4$). The remainder (~30%) spanned several provinces; Alberta ($n = 2$), Saskatchewan ($n = 2$), southern Quebec ($n = 2$), and Newfoundland and Labrador ($n = 1$). Most studies were conducted in partnership with Inuit ($n = 8$) and First Nation ($n = 6$) communities, whereas three studies ($n = 3$) were conducted with both First Nation and Métis communities. The communities Oujé-Bougoumou (Quebec), and Kinngait (formerly known as Cape Dorset) (Nunavut) were each involved in two studies (Figure 3).

The concentration of studies in the North may be attributed to the push for more ethically engaged and culturally respectful research in northern Canada. Additionally, the effects of climate change are being faced by Canadian Arctic communities at a much faster rate than the remainder

Fig. 2. Publication dates of studies across time versus cumulative number of articles that met inclusion criteria relating to weaving ways of knowing in ecotoxicology and wildlife health. Arrow indicates the years the TRC worked towards the *94 Calls to Action* (2007–2015). Dotted line indicates the year of publication of the *TRC*'s *94 Calls to Action*. TRC: Truth and Reconciliation Commission of Canada.



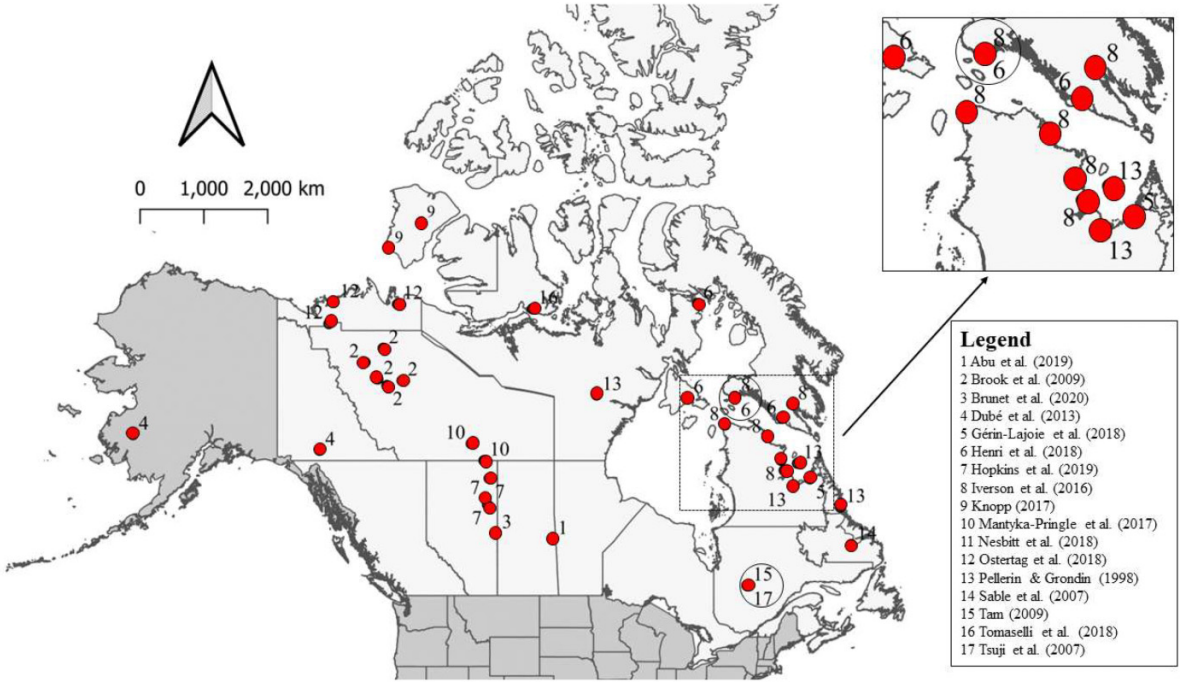
of the planet, placing strain on the environment, subsistence species, and food systems (Wenzel 2009; Bergmann et al. 2022). Research that "include[s] local Indigenous Peoples, their priorities, and knowledge throughout the research process" (Loseto et al. 2020) is occurring more frequently in the Arctic, with, for instance, the National Inuit Strategy on Research advocating for Inuit self-determination, quality of life, and rights through Inuit-specific research (Inuit Tapiriit Kanatami 2016). For instance, Inuit Tapiriit Kanatami (2018) forwards that research should advance Indigenous governance, enhance ethical conduct, fund Inuit research priorities, ownership, access, and control over data, and improve capacity building (Inuit Tapiriit Kanatami 2018). This example is one of many research guides that exist for conducting research in an ethical way that supports Indigenous sovereignty and rights (ArcticNet 2022; Assembly of First Nations 2009; Hayward et al. 2021; Manitoulin Anishinaabek Research Committee 2003).

Research partners and Indigenous knowledge holders

Most first authors were academics ($n = 11$). Other professions represented by first authors included government ($n = 2$), multiple (i.e., both academic and government) ($n = 2$), business/industry ($n = 1$), or were not reported ($n = 1$). Over half of the studies ($n = 10$) had some form of Indigenous authorship, most being individual authorship ($n = 9$) and one being collective authorship (Mantyka-Pringle 2017). For the sake of our review, Indigenous authorship was only coded if explicitly mentioned within each study. We did not conduct further searches for details into authors identities or make any assumptions regarding Indigenous identity. This highlights the importance of positionality statements from all authors, regardless of nationhood or ethnicity. The dominant representation by academics as first authors may be attributed to the heavily peer-reviewed focused search strategy used. Westman and Joly (2019) argue that there is a disconnect between grey and scholarly literature, "particularly research driven by proponents", and thus there is a large body of unpublished work being conducted by or on behalf of Indigenous communities, relating to environmental impacts (Westman and Joly 2019). Most studies ($n = 10$) were initiated as a mutual agreement between community partners and researchers. Community members/groups were responsible for initiating three studies, whereas academic researchers initiated two studies. In two studies, details on project initiation were not reported. More than half of the studies were built upon mutual agreements between Indigenous and Western trained, non-Indigenous partners, a step in the right direction in terms of creating a shared vision for research, challenging power inequities, and decolonizing research (Held 2019; Wong et al. 2020).

Indigenous knowledge holders that participated in the weaving ecotoxicology and wildlife health studies varied in

Fig. 3. Map of Canada indicating study locations (red symbols). Numbers correspond to studies listed in the legend (Abu et al. 2019; Brook et al. 2009; Brunet et al. 2020; Dube et al. 2013; Gérin-Lajoie et al. 2018; Henri et al. 2018; Hopkins et al. 2019; Iverson et al. 2016; Knopp 2017; Mantyka-Pringle et al. 2017; Nesbitt et al. 2018; Ostertag et al. 2018; Pellerin & Grondin 1998; Sable et al. 2007; Tam 2009; Tomaselli et al. 2018; Tsuji et al. 2007). Circled locations highlight locations in which more than one study was conducted. Inset box highlights an area where studies are concentrated (Nunavut and Nunavik). Inuit Nunangat is the distinct geographic, political, and cultural region that includes the Inuvialuit Settlement Region (Northwest Territories), Nunavut, Nunavik (Northern Quebec), and Nunatsiavut (Northern Labrador) (Inuit Tapiriit Kanatami 2018). Shapefiles of Canada's provinces/territories and coastal water polygons were downloaded from Statistics Canada 2016 Census—Boundary files (Government of Canada, 2019), and the shapefile for Inuit regions (Inuit Nunangat) was downloaded from Government of Canada—Open Government portal (Government of Canada, 2017). Coordinate reference system used was WGS 84 (Authority ID: EPSG:4326).



age and sex. Most commonly, knowledge holders' sex and age range were not reported ($n = 10$). Male and female knowledge holders in the middle (35–59 years) and late (60+ years) age ranges were reported in six and five studies, respectively. Whereas the early/youth (<29 years) age range was least represented/reported, in three studies. The occupation of knowledge holders was diverse, and studies often included knowledge holders across multiple occupations. The most prominent occupation was active harvester (11 studies), followed by Elder (nine studies), knowledge keeper (six studies), and local guide (three studies). Retired harvester, heads of households, and "not reported" were each present in one study. Despite most studies failing to report on sex and age range of Indigenous knowledge holders, the dominant voices represented were middle-aged active harvesters. In a review conducted by Hitomi and Loring (2018), research that involves lay, local, and traditional knowledge related to environmental change places more emphasis on older male (often "hunter" or "Elder") participants as opposed to women and youth. Similarly, Sadowsky et al. (2022) speak to the fact that experienced harvesters, hunters, trappers, are more often included in community-based research, at that [Inuit] youth are far less likely to be given opportunities to participate in environmental research (Sadowsky et al. 2022). Thus, reporting on and representing a variety of demographics is important "to advance the equal engagement of local people and local ways of knowing in environmental decision-making' (Hitomi and Loring 2018).

Research subject and ecological scale

The ecological scale of each study was conducted equally at the ecosystem-level and species-level ($n = 7$), and the remaining studies ($n = 3$) at the community-level. Seventeen species were studied as the main research subject including lake trout, lake whitefish, Arctic char, caribou, muskoxen, and common eider on two occasions each. Approximately 65% of studied species were aquatic. At an ecosystem level, the main research subjects were delta, lake, and river ($n = 2$).

The focus of many studies was on traditional subsistence species like caribou, muskoxen, common eider, and many aquatic species (Knopp 2017; Henri et al. 2018; Tomaselli et al. 2018). Many Indigenous communities in Canada, specifically in the Arctic, rely on traditional food sources and thus can be at a greater risk of exposure to contaminants and parasites found within wildlife (e.g., Pellerin and Grondin 1998). Despite the ability of Indigenous Peoples to identify

indicators of health and contamination in wildlife and water through sensorial information (e.g., taste, odour, visual evidence of disease, colour, and turbidity), coupling this knowledge with Western scientific tools like laboratory analysis can provide a more holistic understanding of these issues (Ostertag et al. 2018; Houde et al. 2022). For example, in a study conducted by Hopkins et al. (2019) prioritizing the needs of Indigenous knowledge holders allowed for questions to be answered that Western science may not have considered alone, ultimately "creating new learnings together" (Hopkins et al. 2019). Active and respectful communication between resource users, wildlife managers, and Western-trained, non-Indigenous academics is crucial when monitoring the health of wildlife in Canada (Provencher et al. 2013; Henri et al. 2018).

Research themes and wildlife health stressors

Across the 17 studies "wildlife health" ($n = 12$) was the most recurrent research theme. Thereafter, the most common themes were "answer scientific questions/inform scientific research" ($n = 10$), "ecosystem health" ($n = 9$), "document Indigenous knowledge" ($n = 8$), and "track and adapt to environmental/climate change" ($n = 8$) (Table S5).

Studies were categorized based on the type of health stressor studied, these included toxin/toxicant, disease/parasite, or both. Twenty-four different contaminants were studied across papers. The toxin/toxicant class ($n = 9$) and disease/parasite studies ($n = 5$) were most common, whereas few studies simultaneously investigated effects of toxin/toxicants and disease/parasites ($n = 3$). Studies often investigated more than one contaminant at a time, and five studies mentioned contaminants, disease, and/or parasites but did not specify what was being tested. The most studied disease was avian cholera ($n = 2$) which is a naturally occurring bacterial disease that poses a major risk to waterfowl (Henri et al. 2018). The most studied toxin/toxicant was metals or trace elements ($n = 8$), followed by polycyclic aromatic hydrocarbons, nutrients, major ions, and general water quality parameters ($n = 3$). Metals can be released into the environment (e.g., water, soil, air) through both natural and anthropogenic sources, and can cause adverse effects to the health of plants, animals, and humans (Ali and Khan 2019). Metal pollution has been exacerbated by anthropogenic activities and industries including (but not limited to) mining, landfills, agriculture, and urbanisation (Briffa et al. 2020). These environmental changes brought about by "settler colonial jurisdictional arrangements and regulatory systems" can be described as "contamination through occupation" in which settler colonialism and the occupation of settlers itself is considered a form of "contamination" (Wilson et al. 2021). This "contamination through occupation" can further contribute to the inability of Indigenous Peoples to practice, develop, and conserve their culture and traditions (Kwiatkowski 2011) that are "inextricably bound to the surrounding landscape" (Huseman and Short 2012). Overall, papers placed an emphasis on wildlife and ecosystem health stressors commonly resulting from human-related activities, which can cause harm to Indigenous communities' way of life, especially activities that are dependent on healthy ecosystems (e.g., hunting, fishing, trapping, and gathering) (Kwiatkowski 2011).

Methods and methodologies

When collecting Western scientific data, eight studies used tissue sampling for physiological metrics and/or genetic analysis (i.e., taking blood samples from live birds; hair samples; blubber samples; and swabs for disease monitoring), and seven studies used document/literature review and abiotic field data collection. Indigenous knowledge was most often collected via interviews (structured/semi-structured/unstructured; $n = 14$), and workshops (including community meetings; $n = 8$). Studies often used multiple methods and methodologies to braid or weave knowledge, but the most recurrent methodology was case study ($n = 4$) and CBPR ($n = 7$) (Fig. 4).

Buell et al. (2020) state that good Indigenous-led research does not necessarily use one weaving methodology, but instead embeds Indigenous ways of knowing throughout the entire research process. Despite the many methodologies that exist to conduct collaborative research, CBPR may be the most popular due to its "potential to contribute to efforts to decolonize the university researcher-Indigenous community relationship" (Castleden et al. 2012). CBPR allows for the inclusion and privileging of Indigenous epistemologies, shared decision-making power (or Indigenous-led decision-making) and ownership, ultimately building trust, and producing mutually beneficial results (Castleden et al. 2012, 2017*a*; Hopkins et al. 2019). Deliberate actions and behaviour changes are required to fundamentally shift the colonial aspects of research, and "research methodologies are one such route for such change" (Liboiron et al. 2021). No two projects or Indigenous communities are the same, thus each project must be undertaken on a case-by-case basis always respecting Indigenous ways of knowing are "connected to the specific cultural values and practices that have evolved from particular environments and geographic contexts" (Wilson et al. 2020).

Indigenous participation across research stages

Previous partnerships, relationships, or collaborations with Indigenous communities were split evenly: nine studies reported a previous collaboration, and eight studies did not report any prior collaboration. The level of authority given to Indigenous community members/partners varied across the five stages of research (i.e., objective setting, research design, implementation, analysis, and dissemination). The most common level of authority for decision-making given to Indigenous community members was "collaborative". No study was "Indigenous-led" at any stage of research (Fig. 5). Authors gave credit to Indigenous community members for their knowledge contributions for project initiation and objective setting ($n = 11$), designing data collection methods ($n = 12$), collecting data ($n = 14$), analyzing and interpreting data ($n = 11$), and dissemination ($n = 9$). Colonization and/or power was acknowledged or discussed in less than half of the studies ($n = 6$), and not mentioned in the remaining eleven studies.

Fig. 4. Relationship among Indigenous knowledge collection methods, weaving knowledge methodologies, and scientific data collection methods for studies that met inclusion criteria relating to weaving ways of knowing in ecotoxicology and wildlife health. The Sankey diagram shows the path between source (Indigenous knowledge or scientific data collection methods) and target (weaving methodologies) node(s), with the width of each arc representing the magnitude of flow between nodes (i.e., total combination of variables from source node to end node). (Otto et al. 2022)

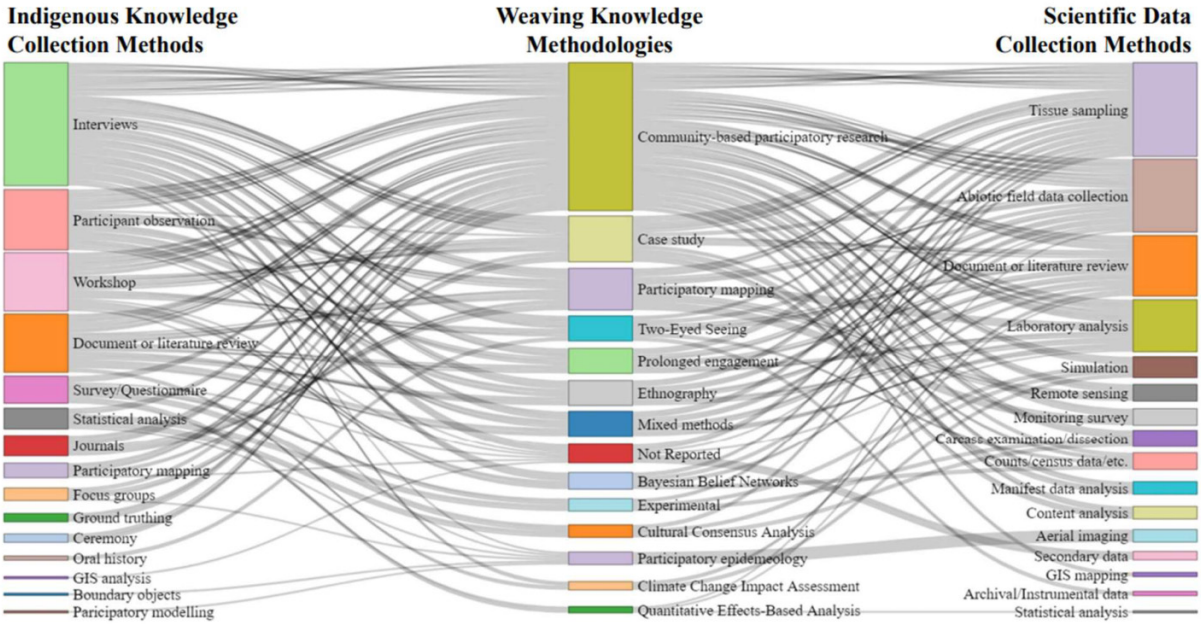
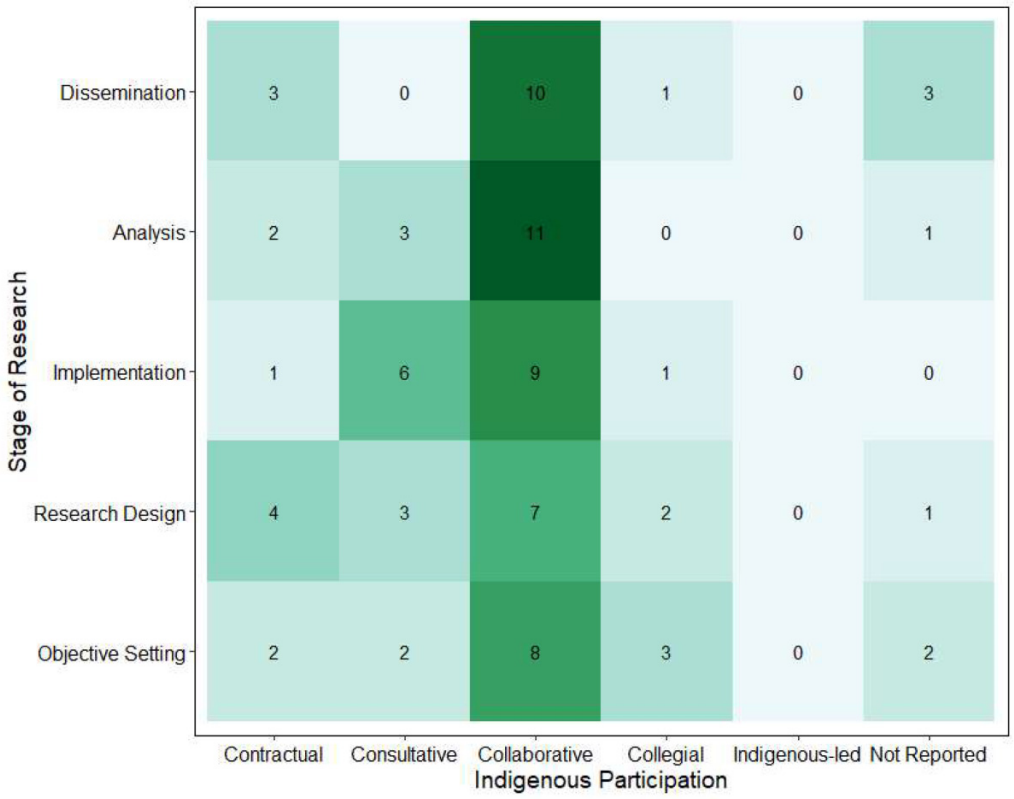


Fig. 5. Level of authority in decision-making given to Indigenous community members/partners across each stage of research. Numbers within matrix boxes indicate the number of studies. Indigenous participation codes (*x*-axis) are defined in Table 1.



Our findings relating to Indigenous participation across research stages are similar to those by Turreira-García et al. (2018) and Thompson et al. (2020) in which Indigenous participation is most reported during data collection, and less clear during initiation, objective setting, designing methods, analysis, and dissemination of findings. These findings highlight the opportunity for researchers embarking in research involving the weaving of ways of knowing to improve collaboration from project initiation to completion (Wong et al. 2020), specifically at the front and back ends of any given project. While David-Chavez and Gavin (2018) highlight the importance of crediting knowledge contributions, collaborative research that uses Indigenous research methods must also include the values of the Indigenous group(s) involved across all stages and components of the process (Drawson et al. 2017). Our findings suggest that, despite collaboration with Indigenous Peoples, wildlife health research found within the peer-reviewed and grey literature is likely to be initiated by academia or government and seldom led by Indigenous Peoples (Sanderson et al. 2015). The studies included in our review highlight the need for improvements in terms of decision-making power and authority for Indigenous partners to fully reconceptualize and decolonize the research process. By doing so we can move toward Indigenous-led collaborative research that promotes self-governance and sovereignty (Wilson et al. 2018).

Research outcomes and results sharing

Nearly 75% of studies ($n = 13$) proposed or intended to have a direct impact on management of wildlife health. "Adding to scientific knowledge/research" was an outcome in 10 studies and "increased interest in Indigenous knowledge from scientists" was reported in six studies (Table S6). In over half of studies ($n = 9$) no information on whether project findings were reported to community members was given. When findings were shared the most common method of sharing was in-person communication (meetings/workshops/community visits; $n = 8$), followed by written communication (report/local publication/policy brief/infographic/living document; $n = 3$), digital communication/products (video/audio/photographs; $n = 2$), and via social media (Twitter/Facebook/Instagram/etc.; $n = 1$). Dissemination of findings back to communities and community members is a crucial final step in the research process that is often overlooked and/or underreported in the peer-reviewed literature. In fact, only one study mentioned the dissemination of results to the local community in an Indigenous language. Findings should be made accessible to wide audiences but may require additional funding and the use of creative mediums to translate results and decisions (David-Chavez and Gavin 2018; Wong et al. 2020). Hopkins et al. (2019) provides an example of community involvement in dissemination of results, where sharing of results only occurred after validation by the participating community members and done so in "a way that is mutually beneficial" (Hopkins et al. 2019). To share findings and include youth in the research process, the team in the Hopkins et al.'s (2019) study opted for the use of a "living" community-based booklet that supplements findings with photos in addition to attending secondary schools to discuss the project. Making space and time for the sharing of findings is critical to truly decolonize the research process.

Case studies

To provide a deeper understanding of the diversity and process of weaving knowledge systems, two exemplar case studies were chosen (as described in *Case study selection and analysis)* for critical analysis: Ostertag et al. (2018) and Hopkins et al. (2019). In the first case study by Ostertag et al. (2018), through partnership with communities in Inuvik, Paulatuk, and Tuktoyaktuk (ISR), the authors co-produced knowledge with local leaders and committees (Fisheries Joint Management Committee, Hunters and Trappers Committee, and Inuvialuit Game Council), and federal government researchers, to support monitoring and co-management of beluga whales (*Delphinapterus leucas*), a traditionally significant subsistence species in the region. In the second case study from Hopkins et al. (2019), McMurray Métis community members, working with provincial government researchers and consultants share the journey and partnership that came from addressing questions related to freshwater mussel health and population declines in the lower Athabasca Region in Alberta, Canada (Tables S7–S9). These studies were analyzed through a decolonizing lens—we understand "decolonization" as inspired by Held (2019) as a mutual process that involves both the "colonizer and the colonized". This mutual process should then be undertaken to challenge the status quo, counteract the "processes, structures, and institutions imposed on Indigenous peoples" (Raymond-Yakoubian et al. 2022) and to encourage collaboration that uplifts Indigenous voices, perspectives, and worldviews. In the case studies section, we aim to decolonize our approach by highlighting themes commonly left out of the Western scientific peer-review process across three broad categories: relationship building, need for continuous engagement, and ethical practices.

Relationship building

Seeking meaningful relationships and collaboration between scientists and Indigenous Peoples can result in positive outcomes for all involved, and thus relationship building must be placed at the forefront of any collaborative or knowledge weaving research (Thompson et al. 2020; Wong et al. 2020). Authentic and respectful research relationships with Indigenous communities requires Western-trained, non-Indigenous academics to recognize and consciously weave unique ways of knowing and work together collaboratively, ensuring mutual research interests are being enacted throughout the entire research process. (Ermine et al. 2004; Bull 2010; Castleden et al. 2012; Sanderson et al. 2015; Kutz and Tomaselli 2019). Strong pre-existing relationships between community harvesters, their families, and the Western-trained academics conducting community-based monitoring efforts in the ISR region, were discussed in the Ostertag et al. (2018) study as vital to the research and emphasized as equally important in the Hopkins et al. (2019)

study. Early dialogue and engagement undertaken mutually between Indigenous and Western-trained, non-Indigenous academics prior to the initial start of a project and that goes beyond what is required of researchers, promotes reconciliation and meaningful relationship building and is essential in decolonizing research (Held 2019; Wong et al. 2020). Reid (2020) states that researchers have a responsibility to conduct "anti-oppressive" research, which includes involving the community as early as possible to help build-relationships and gain mutual understanding of community needs prior to the formulation of research questions or design (Reid 2020). Mutual agreement refers to the shared decision between community partners and researchers to initiate a study; this occurred in both studies. Specifically, Hopkins et al. (2019) approached McMurray Métis Elder Harvey Sykes who had over a decade of previous experience advocating for freshwater mussel health and thus an already apparent interest in the proposed work. Despite mutual agreement on study initiation, the McMurray Métis led the research with invited support from government scientists and research consultants. In comparison, the study by Ostertag et al. (2018) was mutually designed and agreed upon with government scientists and local committees with the hopes of co-producing knowledge to support beluga population monitoring. Regardless of the mutual agreement to initiate this study, as seen similarly in Hopkins et al. (2019), the Western-trained, non-Indigenous researchers from the Ostertag et al. (2018) led the research. Raymond-Yakoubian et al. (2022) emphasize the importance of relationship development being continuously revisited throughout the research process to ensure mutual trust and respect. In both cases, mutual agreements were reached by placing needs of Indigenous community members at the forefront instead of solely perpetuating the needs and desires of Western-trained, non-Indigenous academics. Prioritizing the needs of community members must take precedence over the needs of Western-trained, non-Indigenous researchers for true equitable and decolonial collaborative research to occur (Castleden et al. 2017*a*). Responding to community needs and desires may include place-based approaches, supporting local governance structures and legal systems, practices that reflect the worldviews of the Indigenous communities involved, and acknowledging the interconnections and holism between all beings living and non-living (Baker 2017; Peacock et al. 2020; Redvers et al. 2020; Artelle et al. 2022). Ultimately, the difference in research goals between the two case studies highlights that each case is unique, and that good relationship building can lead to projects that meaningfully meet the needs of the community in diverse ways (Castleden et al. 2012).

Need for continuous engagement

Collaborative and knowledge weaving science must consider the needs of community members for the entire duration of the research process (Wong et al. 2020). Ban et al. (2018) argue that early dialogue and engagement between Indigenous communities and researchers can result in a stronger framework of questions to ask, which both case studies examined here exemplify. While both teams scheduled multiple meetings with community members to collaboratively refine the research direction and methods, Hopkins et al. (2019) took additional steps to explicitly ensure that equal weight was given to both Indigenous and Western scientific ways of knowing in the design and implementation of the research. For example, the McMurray Métis led the entire research project and received support from government researchers and research consultants to co-produce and answer mutually agreed upon questions regarding freshwater mussels (Hopkins et al. 2019). In both cases, Indigenous values and worldviews were critical components that helped guide the research process as opposed to "add-ons or afterthoughts" typical of Western scientific research and monitoring (McGregor 2018).

Call #5 from Wong et al. (2020) advises natural scientists to provide meaningful opportunities for Indigenous community members to experience and participate in science. Both studies involved Indigenous community members in different ways during the implementation of research. For example, Ostertag et al. (2018) hired community-based research assistants to assist with public meetings, interviews, questionnaires, and co-presenting of results during community and conference presentations. In addition to the involvement of the entire research team (Indigenous and non-Indigenous members) for the duration of field work, ground truthing (Table S1) was used when on the land or water with McMurray Métis Elders and land users. McGregor (2018) argues that Indigenous research must not be based on colonial methods and should bring forward "Indigenous worldviews, epistemologies, ontologies, ethics, values, and intellectual traditions" (McGregor 2018). Hopkins et al. (2019) took steps to acknowledge that their research methodology, "community-based participatory research", was rooted with "Eurocentric bias" and thus the Seven Sacred Teachings (Hopkins et al. 2019 ["from a poster hanging in McMurray Métis Local 1935"]) (love, humility, courage, wisdom, honesty, respect, and truth) were woven into the research framework. By including ceremonial protocols and McMurray Métis cultural history the research was then guided by relationships to self and others (including non-human beings) and honoured tradition and spirit (Hopkins et al. 2019).

When discussing data analysis and dissemination of study findings, Reid (2020) argues that Indigenous knowledge holders "must be given the opportunity to review the knowledge that was collected" in addition to returning all data to communities as sole owners. Study findings were explicitly mentioned to be validated and reviewed by harvesters and beluga whale monitors in the Ostertag et al. (2018) study. In the Hopkins et al. (2019) study, "research is grounded in shared decision making and data ownership, dissemination occurs once information is validated by the Clam Team [research team] and in such a way that is mutually beneficial". This demonstrates that research teams' commitment to ensuring engagement in many aspects of the research, although it should be recognized that the power balance was not equal across the different phases of research. Despite the collaboration with Indigenous community members in the data analysis stage, both studies give more power to

Western-trained, non-Indigenous academics. Thus, to ensure continuous engagement across every stage of research improvements could be made in the reporting of data analysis procedures in both cases.

Ethical practices

Despite the large body of literature calling for ethically engaged collaborative research with Indigenous communities and Peoples that supports Indigenous values, culture, self-determination, and sovereignty (Bull 2010; Alessa et al. 2016; Raymond-Yakoubian et al. 2022), fulsome reporting of these practices in the peer-reviewed literature is still sparse. David-Chavez and Gavin (2018) state that Western-trained, non-Indigenous academics hold ethical responsibilities to Indigenous communities to promote benefits and reduce harm (David-Chavez and Gavin 2018). Ostertag et al. (2018) argue that the inclusion of Inuvialuit values regarding beluga health in their study will benefit the communities by helping to shape monitoring and management decisions in the region. This also includes the encouragement for the Fisheries Joint Management Committee to support knowledge transmission between older and younger generations, and the recommendation for community engagement during the design and implementation of future beluga studies. Hopkins et al. (2019) state their research is embedded with shared decision making, data ownership, and results dissemination that is mutually beneficial. By challenging the status quo of natural science research and placing less focus on quantitative results, the research team gained a better understanding of freshwater mussel health through "physical, mental, emotional, and spiritual connections to life around us" (Hopkins et al. 2019). Despite both studies providing evidence that their research supports community needs, there is some divergence between studies when reporting on ethical standards. One way to challenge and resist the power imbalances that exist within Western science research is to receive the free, prior, and informed consent of Indigenous Peoples and communities involved (Castleden et al. 2017b). The authors Ostertag et al. (2018) do not make explicit mention of following community or cultural protocols, but do mention free, prior, and informed consent being granted prior to interviews with Indigenous community partners. On the contrary, Hopkins et al. (2019) acknowledge the inclusion of ceremonial protocols, cultural stories, cultural protocols, and relational ethics, but do not explicitly mention free, prior, and informed consent. The nature of the Ostertag et al.'s (2018) study being conducted across three unique communities and with a focus on qualitative data to support monitoring and management may explain why following community protocols and cultural practices was more challenging to undertake and report in a paper in the peer-review manuscript. That the Hopkins et al. (2019) was led by Indigenous community members and placed focus on the relationship building process as opposed to sharing of quantitative results may explain why so much emphasis was placed on community protocols and cultural practices. Ultimately, ethical practices must be "at the center of relationships between Indigenous Peoples and the research community", and by collaboratively determining the values and practices used to guide research build trust, respect, and strong relationships (Raymond-Yakoubian et al. 2022). Future works should consider the use of appendices and online supplemental material options to include additional material that communicates these components of knowledge weaving studies that most journals based in Western scientific practices do not specifically call for in their submissions.

Discussion

Benefits and drivers

Increased public awareness, calls to action, and shifts towards Indigenous self-determination are driving collaborative and weaving research in Canada. Indigenous communities and ways of life are being negatively impacted by environmental contamination, and often these effects cannot be solely determined using scientific knowledge alone (Tsuji et al. 2007; Tomaselli et al. 2018). Clearly, given the values of Indigenous knowledge systems, inclusion of Indigenous ways of knowing in research not only advances Western science but also provides benefits to communities (Alessa et al. 2016).

Substantial evidence supports the power of bringing together Indigenous and Western ways of knowing. Weaving multiple ways of knowing can provide many mutual benefits to research including improving problem solving (Hopkins et al. 2019; Brunet et al. 2020), helping to answer questions neither knowledge system could answer on its own (Johnson et al. 2016), encouraging co-capacity and authentic relationship building (Sable et al. 2007; Brook et al. 2009; Mantyka-Pringle et al. 2017), enhancing co-management of wildlife (Mantyka-Pringle et al. 2017; Ostertag et al. 2018), promoting intergenerational knowledge transfer (Gérin-Lajoie et al. 2018; Henri et al. 2022), and building trust and respect between research partners (Pellerin and Grondin 1998; Adams et al. 2014; Tomaselli et al. 2018). Specifically relating to wildlife health and conservation, Kutz and Tomaselli (2019) argue weaving Indigenous and Western ways of knowing achieves "better-informed and more timely and effective decision-making". In their study on avian cholera and common eiders, Iverson et al. (2016) concluded that using "a community-based, participatory approach to disease surveillance and control stands the greatest chance of minimizing the population impact on eiders and other affected species". Similarly, Knopp (2017) argues that utilizing multiple knowledge systems aided in thoroughness of the research process in addition to providing an ecological and environmental understanding that could not have been found with one methodology or knowledge system. Weaving knowledge systems can act as a stepping-stone to healing and reconciling relationships between settler-Canadians and Indigenous Peoples (Castleden et al. 2017b).

Perhaps in part due to the *Calls for Action* from the TRC (2015), and in part because of the demonstrated power of weaving knowledge systems, funding bodies like the Northern Contaminants Program (Government of Canada 2021),

the Northwest Territories Cumulative Impact Monitoring Program (Government of the Northwest Territories, n.d.), and the Tri-Agency (i.e., Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, and Social Sciences and Humanities Research Council of Canada) (Government of Canada 2022) are also driving collaborative research and monitoring by providing opportunities, resources, and subprograms for Indigenous and community-engaged focused research that supports the inclusion of Indigenous ways of knowing. For example, the Tri-Agency aims to support Indigenous research and research training that contributes to reconciliation through four strategic directions: self-determination, decolonization of research, accountability, and equitable access for Indigenous students and researchers, thus encouraging researchers to engage in collaborative and community-led work (Government of Canada 2022).

Challenges, barriers, and harms

Despite the benefits of weaving knowledge systems, this type of work also presents challenges, barriers, and the potential to cause harm to those involved. Due to the complex nature of weaving multiple knowledge systems challenges relating to "different world views, identities, practices, and ethics" can and will be faced (Tengö et al. 2017). When beginning any collaborative endeavours with Indigenous and non-Indigenous Canadians, it is critical to acknowledge the context in which research is being built upon. To a great degree, this refers to the historical legacy of research which has been exploitative, assimilating, racist, unjust, and "has largely functioned as a tool of colonialism" (Simpson 2001*a*; Simpson 2001*b*; Liboiron et al. 2021). According to David-Chavez and Gavin (2018), researchers hold ethical responsibilities to promote benefits and reduce harm to Indigenous communities and community members.

One barrier to weaving knowledge research is time constraints, which are often dictated by graduate degrees or funding cycles. This can be a challenge because building the foundations of collaborative research and trusting relationships takes time and are crucial to the success of any project. Consequently, the fast pace of academia may be unrealistic for these types of projects resulting in early engagement falling "largely outside of established funding structures" (Ban et al. 2018; Stiegman and Castleden 2015). Due to funding and time constraints of research, the Western academic agenda places emphasis on data analysis and scientific publications which can clash with the priorities of Indigenous communities which are often related to social issues, education, land management, and economic development (Gérin-Lajoie et al. 2018). To avoid perpetuating the status quo in natural science research, long-term funding is essential for collaborative research with Indigenous communities and thus, funding bodies must adapt and change their approaches to funding (Gérin-Lajoie et al. 2018; Wong et al. 2020). Naturally, each way of knowing has its strengths and weaknesses, but ultimately the benefits of a multifaceted approach outweigh the limitations of individual perspectives (Abu et al. 2019).

Despite harms caused by research most often being unintentional, they can be a result of power imbalances between Western-trained, non-Indigenous academics and Indigenous Peoples (Tri-Council Policy Statement, Article 9.21, 2018). For example, some Indigenous ways of knowing are sacred and thus sharing this knowledge outside of families and communities may not be culturally appropriate, possible, or wanted (Sanderson et al. 2015). In addition, some research is not meant for academic or outsider consumption (Tuck and Yang 2014). This can present challenges for data ownership, sovereignty, and power structures and thus holds the potential to cause harm, especially in cases where Western-trained, non-Indigenous academics have a legal obligation to report findings (e.g., avian influenza) (Cáceres et al. 2017; World Organisation for Animal Health 2022). In the context of wildlife health, Boyd et al. (2019) found that communicating findings on contamination in traditional foods can lead to the avoidance of these foods and thus result in negative impacts on economic, health, cultural, and spiritual well-being of Indigenous Peoples (Boyd et al. 2019). To avoid harm Western-trained, non-Indigenous academics should continuously self-reflect and discuss findings and implications with research partners, recognizing that research goals and objectives can be ever evolving.

Conclusion and recommendations

Weaving knowledge systems can provide a unique way to solve challenging environmental problems related to ecotoxicology and wildlife health. We systematically reviewed 17 studies from the peer-reviewed and grey literature that wove knowledge systems to study environmental contaminants and wildlife health. Through our study we offer some suggested guidance and information to ecotoxicologists, wildlife health experts, and those working in conservation science on approaches to conducting respectful collaborative research with Indigenous Peoples that responds meaningfully to the calls for reconciliation in Canada. Due to the scope of the project, we excluded collaborative management and decision-making studies related to wildlife health and ecotoxicology. We also acknowledge the heavily peer-reviewed focused literature search that was conducted, which gives rise to the possibility of grey literature studies conducted by consultants, non-governmental organizations, Indigenous organizations, governing bodies, or communities that may have gone undiscovered. We recommend future work that involves a wide range of grey literature databases to yield more results and a fuller understanding of collaborative ecotoxicology and wildlife health related studies. There is no single way to weave knowledge systems (Abu et al. 2019), and thus it is critical to remember, each project, community, and individual are unique and relationship building must be met with humility, respect, curiosity, and compassion (Adams et al. 2014; Johnson et al. 2016). By acknowledging their privilege, being flexible, challenging the status quo, and meaningfully working together with Indigenous Peoples, Western-trained, non-Indigenous natural scientists, social scientists, and wildlife health experts can create shared research goals and outcomes across every stage of the research process

(Adams et al. 2014; Johnson et al. 2016; Kutz and Tomaselli 2019; Tomaselli et al. 2018) ultimately improving ecotoxicology, wildlife monitoring, and management in Canada.

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Community involvement

This project was initiated through conversations with our partners (CH and LK) at GCT3, the governing body of the Anishinaabe Nation in Treaty #3. Our original intent was to co-design and co-execute research on environmental contaminants in freshwater lakes in Treaty #3 ("*Spirit of the Lakes*" project), but our partners at GCT3 wanted us to first work together to scan the literature (as was done here) and develop a protocol for collaborative research (in progress). The findings of this review, coupled to a series of interviews with GCT3 community members currently on-going by our team, will feed into the research protocol for GCT3. Our team shares findings with community members through GCT3-organized Research Engagement events.

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Data analyzed during this study are available from the corresponding author by email (diane.orihel@queensu.ca).

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Heather Castleden served as an Editorial Advisory Board Member for *Environmental Reviews* at the time of manuscript review and acceptance and did not handle peer review and editorial decisions regarding this manuscript.

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Competing interests

The authors declare there are no competing interests.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/er-2022-0087.

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