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# Environmental and socio-cultural impacts of glyphosate-based herbicides: perspectives from indigenous knowledge and western science

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**Introduction:** For decades, herbicide application in commercial forestry has been a serious concern for First Nations across northern Ontario. To date, the vast majority of studies concerning the impacts of glyphosate-based herbicides have been conducted through a Western scientific lens. Indigenous knowledge systems provide holistic frameworks which acknowledge the interconnectedness of the environment and provide a holistic view of relationships between flora, fauna, environment, and humans. This socio-ecological perspective is key to understanding the wide-ranging impacts of commercial forestry on the wellbeing of Indigenous Peoples.

**Methods:** Through a knowledge sharing workshop, "Connecting Guardians in a Changing World", we interviewed community members from First Nations across the Robinson-Huron Treaty Area and asked them to share their knowledge and concerns regarding herbicide use in commercial forestry. Based on the topics discussed in the workshop, we conducted a literature review to further investigate documented Western scientific evidence on workshop participants' concerns. We then wove the responses of participants and Western Science to identify key concerns of participants regarding the use of glyphosate-based herbicides, identify gaps in current knowledge, and to direct future research.

**Results:** We identified three main research gaps regarding glyphosate-based herbicide impacts used in forestry: 1) research regarding the direct effects of glyphosate-based herbicide toxicity to most of the fauna and flora of the Great Lakes region of northeastern Ontario as well as its environmental persistence, 2) research regarding the indirect effects of glyphosate-based herbicides to the ecosystem and resulting impacts of trophic cascades, and 3) research regarding the impacts of glyphosate-based herbicides to Indigenous culture and community wellbeing.

**Discussion:** By weaving knowledge systems in this way, we can conduct research through an inclusive system which prioritizes the inclusion of multiple ways of knowing, addressing environmental concerns in holistic and inclusive ways which emphasize the interconnectedness of the environment, including humans therein.

KEYWORDS

indigenous knowledge (IK), socioecology, herbicide, glyphosate, forest management

# 1 Introduction

Western Science provides a systematic framework for examining and reporting on ecological phenomena and changes (e.gs., Santillo et al., 1989; Cole et al., 1998). However, traditionally Western Science is often conducted in a piecemeal fashion, simplifying complex ecological systems (Gadgil et al., 1993), by closely examining the quantifiable impact of a specific set of conditions on one (e.g., Benamu et al., 2010; Dai et al., 2018), or a few species of interest (e.g., Cole et al., 1998; Filizadeh and Islami, 2011). This approach, aside from speculative comments, often ignores trophic effects as well as total-ecosystem impacts, and is limited in scope (Gadgil et al., 1993; Peloquin and Berkes, 2009). Though more holistic and socioecological approaches are emerging in Western Science (e.g., Pecl et al., 2017; Thompson et al., 2018) in order to examine impacts on complex ecological systems, these approaches have been at the foundation of Indigenous Knowledge systems since time immemorial (McGregor, 2002; Peloquin and Berkes, 2009). It has been shown that conservation and sustainability efforts led or with more substantive partnerships with Indigenous communities have better outcomes for both the environment and people, and have different objectives, indicators, and outcomes (Thompson et al., 2020; Dawson et al., 2021). Together, Western Science and Indigenous Knowledge can produce research which brings together the benefits of both systems into a comprehensive and holistic approach while maintaining the integrity of each (Bartlett et al., 2012). Inclusive approaches that value multiple ways of knowing are increasingly being used in Western scientific frameworks and management at various levels of government where they can lead to new solutions and mitigation strategies to address longstanding environmental issues (Popp et al., 2018; Buxton et al., 2021).

For decades, aerial forest spraying of herbicides has been a serious concern for First Nations across northern Ontario (Morely, 2019). Of all herbicides used, glyphosate-based formulations are the most common in both the Canadian forestry industry (Thompson and Pitt, 2011) and globally (Duke and Powles, 2008; Tarazona et al., 2017). In forestry operations, glyphosate is used to eliminate competing herbaceous vegetation in the cultivation of coniferous species such as pine (*Pinus* sp.) and spruce (*Picea* sp.). Foresters term this use of glyphosate to eliminate interspecies competition as conifer release (Thompson & Pitt, 2011). Concerns regarding the safety of glyphosate-based herbicides have been largely dismissed on the grounds that glyphosate poses no significant risk to human health (European Food Safety Authority, 2015; Pest Management Regulatory Agency, 2015; United States Environmental Protection Agency, 2016; Pest Management Regulatory Agency, 2017; Health Canada, 2019) or the environment (Thompson and Pitt, 2011). However, several studies and reviews have found contrasting evidence regarding the potential impacts of glyphosate herbicides on wildlife, and ecosystem functionality (e.g., Santillo et al., 1989; Mackinnon and Freedman, 1993; Cole et al., 1997; Cole et al., 1998, Santillo et al., 1998, Howe et al., 2004, Thompson et al., 2004; Relyea, 2005; Relyea and Jones, 2009; Thompson et al., 2014; Abraham et al., 2018; Motta et al., 2018). Additionally, conclusions about potential impacts on human health and safety are highly contentious amongst the academic community (e.g., De Roos et al., 2005; Zhang et al., 2019) and national and international regulators (European Food Safety Authority, 2015; Pest Management Regulatory Agency, 2015; United States Environmental Protection Agency, 2016; International Agency for Research on Cancer, 2017; Pest Management Regulatory Agency, 2017). Neither ecological, nor risk assessment studies have been conducted through an Indigenous Knowledge lens to our knowledge.

As part of the special issue “Conservation Dialogues”, this work addresses the historic and ongoing disenfranchisement of Indigenous Peoples across Canada, particularly with regard to the commercial management of forests. In this work we seek to amplify Indigenous perspectives and ways of knowing in an effort to combat the ongoing disparity within natural sciences, where Western Science is considered to be superior. This work contributes to a growing movement to decolonize approaches to ecological research, and we hope that the findings, as well as our approach lay a basis for further work which prioritizes the needs of Indigenous communities across Canada.

Through the “Connecting Guardians in a Changing World” workshop, we conducted interviews with First Nations community members about the impacts of glyphosate-based herbicide application on forests within their territories. In addition, we conducted an in-depth Western Science literature review on topics raised by participants. Using this information, we wove together Indigenous and Western Knowledge through an Indigenous-led initiative examining the impacts of glyphosate-based herbicide use in commercial forestry. Throughout this paper, we have provided exemplary quotes from participants, highlighting their concerns, followed by a targetted summary of relevant Western Science literature findings. Our objectives were to identify concerns regarding the use of glyphosate-based herbicides in commercial forestry, summarize the documented impacts of glyphosate-based herbicides through Indigenous Knowledge and Western Science, identify knowledge gaps, suggest paths for future research and advocate for the active involvement of Indigenous Knowledge Holders and inclusion of Indigenous Knowledge in academic research to inform the management of lands and resources.

# 2 Methods

## 2.1 Positionality statement/approach

Our authorship team includes both Indigenous and non-Indigenous researchers from environmental science/studies and law, environmental professionals, and Indigenous Knowledge holders.

The purpose of this work was to share Anishinaabek community members' perspectives, experiences, and knowledge about environmental issues in their territories, and to advocate for the active involvement of Indigenous Knowledge Holders and inclusion of Indigenous Knowledge in academic research to inform the management of lands and resources. Our approach is based on mutual respect, reciprocity, and the building of meaningful relationships between Indigenous and non-Indigenous partners at all stages of research. The project has been Indigenous-led from the outset, including ceremony and respecting cultural protocols and activities during the workshop, and continuous communication between partners throughout the project. Additionally, findings were shared with participants and partners in multiple formats prior to submission of this work for publication, to ensure that our work accurately reflected the knowledge, concerns, and priorities participants expressed throughout the workshop.

This project is one of many that have been undertaken by our research group in direct partnership with Magnetawan First Nation, and other First Nations in northern Ontario. As part of our approach to research, we engage with the communities we work with, ensuring that research topics are of direct relevance and importance to them, and that research is conducted in a way which is respectful of the knowledge and contributions of all parties. It is important to note that these relationships are ongoing and reciprocal.

To our knowledge this approach, aside from an additional paper publishing findings from the same workshop relevant to climate change concerns (Menzies et al., 2022), is novel in its approach to building/establishing relationships, community partnership, weaving knowledge systems and prioritizing Indigenous Knowledge. By directly including quotes from participants, we hope to elevate Indigenous voices, in their own words, with minimal filtering. We hope that this work can serve as an example and a framework for other works which may vary in the specific issues being investigated, but can nevertheless use our approach to relationship building, community engagement/partnership, and continual collaboration through all stages of the research project in order to conduct research in a more equitable way.

## 2.2 Workshop information and ethics

On November 20th and 21st, 2019, a two-day workshop titled "Connecting Guardians in a Changing World" was hosted by Magnetawan First Nation in partnership with Mount Allison University, York University, and the University of British Columbia Okanagan.

Representatives from the Lands Department of 12 First Nation communities in the Great Lakes region of the Robinson-Huron Treaty Area (Figure 1) attended the workshop and were asked to identify and invite one Elder and one youth (aged 18-30) from their community to the workshop. Additionally, individuals from the Georgian Bay Biosphere, the Anishinabek/Ontario Fisheries Resource Centre, and the Toronto Zoo who had previously worked with Magnetawan First Nation on environmental projects were also invited.

The workshop consisted of two days of recorded semi-structured interviews, with the first day focusing on climate change, and the second day focusing on aerial forest spraying (questions posed to participants are available in Appendix 1). Workshop participants from 12 attending First Nations (Figure 1) self-identified as youth (aged 18-30; 15 total), knowledge holders (3 total), and Elders (8 total); 11 participants did not self-identify. Because consent forms were collected for the workshop as a whole, rather than individual days, we cannot concretely state how many people participated in the talks on the second day. The following publication will elaborate on the results related to discussions about aerial forest spraying.

Participants were grouped into four sharing circles of 6 to 8 individuals with a workshop facilitator to lead and record the discussion. Prior to commencing the interviews, consent forms were distributed, and read aloud to all participants to ensure full understanding before signing forms.

Ethics approvals from Mount Allison University (#102582) and the University of British Columbia (H19-01453) were obtained prior to the workshop. Ethics approval from the University of Guelph was also obtained prior to the results sharing session (20-10-014) as the project principal investigator changed affiliation.

## 2.3 Data analysis: transcriptions and quote tables

Interview recordings were first transcribed using Trint (trint.com), and then were manually verified by the research team in order to produce the final transcriptions. Quotes were selected from the transcription documents from each interview and cataloged using tagged keywords (Appendix 2) related to the quote topic(s). General and specific trends in quote subject matter

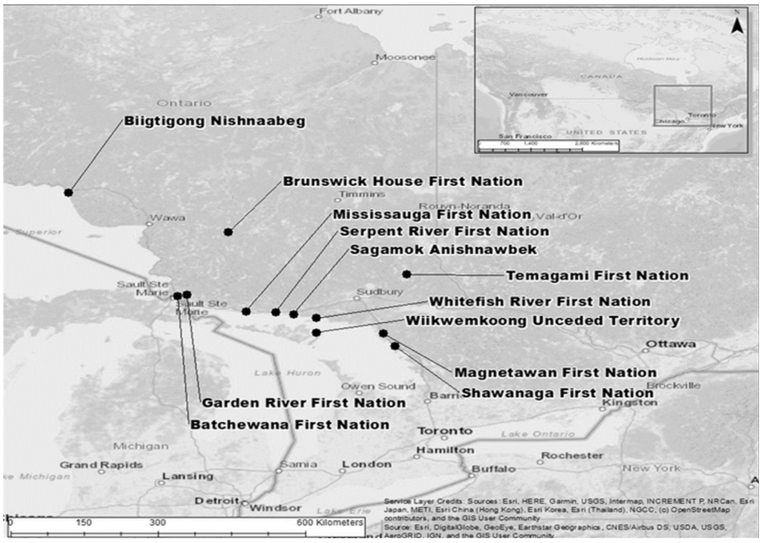


FIGURE 1
Map of first nation communities which had members participate in the Guardians in a changing world workshop.

were identified by the research team and used to identify the key concerns which informed the literature review. Relevant and exemplary quotes are included throughout the paper to amplify the voices of participants in their own words.

## 2.4 Literature review

We conducted an intensive literature review of Western Science in order to expand upon the key concerns outlined by workshop participants. Information was gathered from peer-reviewed literature, publicly available government documents and legislation, and press releases. We searched Google Scholar to find literature covering as many aspects of the key concerns as possible, including searches for information on taxa that were specifically discussed by workshop participants, and which are common to the Great Lakes region. Searching was an iterative process, where initial searches were broad (e.g., glyphosate, fish), narrowing to uncover results for specific species, and included 242 search terms (Appendix 3). We manually scanned the titles of the first 20 results from each search, followed by relevant abstracts and full texts. After all avenues had been pursued to access articles, a small subset had to be discarded due to lack of access, though we did not track the final number discarded. Preference was given to sources examining the use and effects of glyphosate in silvicultural applications, over agricultural applications but in situations where no silvicultural research was available, agricultural applications were referenced as analogs. If information on a given topic was lacking based on our Google Scholar searches, in addition, we searched the references of related works tables of contents from key references. No date ranges were specified (so searches extended as far back as publications were completed), nor inclusion or exclusion criteria were used in the search-engine. However, the main search was completed by March 2020, and add-hoc additions to the screened literature were made in response to previous reviews of this manuscript. Preference was given to sources examining the use and effects of glyphosate in silvicultural applications, over agricultural applications in the literature review. In research areas where silvicultural applications had not been examined, or very little research existed, agricultural applications were used as an analog to discuss potential impacts on forest ecosystems. While our literature search did not include multiple databases, we feel that most relevant sources on each of the five areas of concern have been explored in the Western scientific literature.

## 2.5 Dissemination of information and results verification

Indigenous Knowledge and Western Science gained through our described methodology were woven together into a community report. This report was distributed electronically (PDF) to all participants who provided an email address (August 2020), and printed copies were distributed to the Traditional Ecological Knowledge (TEK) Elders group (fall 2020) (http://tekelders.weebly.com/).

A results-sharing session was held via a public Zoom meeting in January 2021. All participants who provided an email address were invited directly, and the session was advertised publicly via the Magnetawan Lands Department social media page(s). At this session, results from the workshop were presented, and feedback was requested on the findings and the validity of our conclusions, to ensure we were properly representing the perspectives of participants. Feedback was overwhelmingly positive, and it was suggested that these results should be shared to a wider audience.

This publication focuses on participant concerns and knowledge gathered from the workshop, and feedback received from project partners and participants regarding the use of glyphosate-based herbicides in aerial forest spraying programs. As per ethics guidelines, all quotes from participants remained anonymous unless the participant explicitly stated they wanted their name associated with that particular quote. We have greatly condensed the Western Science literature component in order to focus on community concerns and priorities. Please see Table A4.1 in Appendix 4 for additional citations on each theme.

# 3 Results and discussion

The following key concerns represent the major themes discussed by participants in response to interview questions (Appendix 1), with exemplary quotes guiding the discussion in each section. We then engage with relevant Western Science literature on each topic. Some key concerns are further subdivided into more specific categories.

## 3.1 Key concern #1: plant biodiversity and health

“The Elders say that if it hurts one blade of grass you can’t use it.”

Plants play key roles in the traditional practices of Indigenous Peoples as medicines, food, and through ceremony and other cultural practices. The impacts of herbicide use on plant species, and the environment as a whole was a concern for participants.

“It affects the environment totally. It doesn’t [just] affect that thing that they’re spraying, it’s that whole area.”

Indigenous Knowledge systems provide holistic perspectives on ecological interactions and the human relationship to nature (McGregor, 2002; Beckford et al., 2010). Results from Western scientific studies vary in the degree of plant community alteration, time frame of recovery, degree of recovery, and the ultimate impact on ecosystem functionality after glyphosate application (Freedman et al., 1993; Boateng et al., 2000; Bell and Newmaster, 2002). Despite shifts in plant community composition and relative abundance (Freedman et al., 1993; Boateng et al., 2000; Bell and Newmaster, 2002), species richness and diversity may remain stable, or in some cases even increase post-treatment (Boateng et al., 2000; Bell and Newmaster, 2002) due to a site being partially repopulated by plant species which may not perform the same ecosystem functions as what existed on the site prior (Freedman et al., 1993; Boateng et al., 2000). Therefore, traditional examinations of species richness and diversity may not accurately reflect impacts to ecosystem functionality.

### 3.1.1 Key plant species of concern

Certain plant species are used more than others by Indigenous Peoples for ceremonial and food purposes (Uprety et al., 2012). Of particular concern for participants in the workshop were the impacts of glyphosate on species of berry-bearing plants, paper birch (*Betula papyrifera*), and eastern white cedar (*Thuja occidentalis*).

“You see that too when you’re trying to pick blueberries every year. One year they’re nice and the next year there’s very few”

Studies vary in their description of the impacts of glyphosate on low-growing berry species from showing no reduction in yield (e.g. highbush blueberries (*Vaccinium corymbosum*) (Hodges et al., 1979), cranberry (*Vaccinium macrocarpon*) (Shawa, 1980; Bewick et al., 1988)) to the contrary (e.g. lowbush blueberry and velvetleaf blueberry (*Vaccinium* sp.) (Moola et al., 1998), barren berry (*Aronia melanocarpa*) (Yarborough and Ismail, 1979; Yarborough and Ismail, 1980), and strawberry plants (*Fragaria* sp.) (Santillo et al., 1998)). Raspberries (*Rubrus* spp.) in particular are often effectively targeted with glyphosate-based herbicides after forest harvest (Pitt et al., 1992; Freedman et al., 1993; Bell and Pitt, 2007) as they are very opportunistic (Donoso and Nyland, 2006); however, they rapidly recolonize the area within a few years post-application (Freedman et al., 1993; Santillo et al., 1998). Other fruit bearing plants successfully targeted using glyphosate include pin cherry (*Prunus pensylvanica*) and elderberry (*Sambucus pubens*) (Pitt et al., 1992).

“With the glyphosate spraying, it’s basically eliminating that [birch trees] resource.”

Paper birch are used not only ceremonially and medicinally by Indigenous Peoples of the Great Lakes region, but also as a material in traditional practices such as the construction of birch bark canoes, baskets, and artwork (Emery et al., 2014). Several participants noted concern for the presence, growth, and health of birch trees, and how glyphosate might impact this species.

Glyphosate-based herbicides effectively kill a variety of broadleaf tree species including paper birch (Sutton, 1978). Death of established trees results in a decline in average tree size, which can directly impact traditional practices.

Little research has been done with regards to glyphosate’s impact on eastern white cedar, a culturally significant species about which participants expressed concern. One study found that glyphosate application reduced first-year volume growth and damaged the foliage of eastern white cedar seedlings (Noland et al., 2015).

“They’re [forest plants] adapting to the change. But how much can they take? How much can our plants and trees take? Yes, they are very resilient, and yes, they find their own ways, but how much can they take before it’s too much for them?”

## 3.2 Key concern #2: animal biodiversity and health

“So, we were having a discussion about how everything has a place and a reason and how it contributes. So, when we eliminate something that nature has put forth, you’re taking away medicine and food for another. Or for the animals, the bugs that might be around. [ … ] We are wanting to get back to our respect of everything has a place in this journey.”

### 3.2.1 Invertebrates (pollinators, insects, arthropods)

Concerns have been raised increasingly by Indigenous communities, academia, and the public about the potential impacts of pesticides and herbicides on pollinators and other insects (Herbert et al., 2014; Balbuena et al., 2015; Helmer et al., 2015; Goñalons and Farina, 2018; Zgurzynski and Lushington, 2019). Concerns were also raised during the workshop.

"It [aerial forest spraying] kills all the pollinators."

Studies examining the direct toxicity of glyphosate to different bee species (Superfamily: *Apoidea*) show variable results, and are often controversial (e.g., Thompson et al., 2014; Abraham et al., 2018; Eler Seide et al., 2018). Documented negative effects vary from acute toxicity (Abraham et al., 2018), to various sub-lethal effects which may have negative impacts on overall colony survival and success (Herbert et al., 2014; Balbuena et al., 2015; Dai et al., 2018; Goñalons and Farina, 2018; Motta et al., 2018; Vazquez et al., 2018; Zgurzynski and Lushington, 2019). These findings are contradicted by studies which report no adverse effects on adult bee health or bee brood development (Thompson et al., 2014).

Glyphosate's impact on other insect pollinator species in Canada, and terrestrial arthropods in general, are seldom examined. Many studies rely on plant community composition and habitat structure rather than direct exposure impacts. For example, studies often highlight the adverse effects of glyphosate on milkweed impacting monarch butterfly (Hartzler, 2010; Pleasents and Oberhauser, 2012; Pleasents, 2017).

### 3.2.2 Birds

Concerns regarding the impact of glyphosate-based herbicides and other industrial pollutants on birds were expressed during the workshop.

"When we'd go to bait or pluck [the geese] you'd see the lumps underneath their feathers."

No studies were found examining the direct toxicity of glyphosate to any bird species, though several studies have reported shifts in avian species composition following herbicide spraying, usually lasting from one to three years post-treatment (Santillo et al., 1989; Mackinnon and Freedman, 1993; Betts et al., 2013). These shifts have been attributed to resulting changes in food availability (Betts et al., 2013) and nesting habitat availability (Stoleson et al., 2011). Typically, bird species that favor coniferous habitats would be expected to thrive, while those which directly or indirectly depend on deciduous species may be challenged.

"There's a definite decline in the whippoorwill population. Back home, and the surrounding area around Sagamok, I remember in our younger years, in the early evenings and the mornings you can hear them. You don't hear that no more. You just don't, it's gone."

"I've started to kind of keep an eye out for oak stands, because one of the experts that I was talking to, to kind of build our project was saying that they [eastern whippoorwills] like to nest around oak stands because they eat the moths there. So now I'm wondering if they're focusing on pines for the forestry with the glyphosate that's also a direct impact on that?"

### 3.2.3 Herpetofauna

"I have to imagine that anything being sprayed on an animal who breathes through its skin is just not good."

Western scientific methods have found varying degrees of toxicity of glyphosate and its formulations on amphibians. For example, studies examining frogs (order: *Anura*) have shown varying impacts depending on the herbicide formulation, species under study (Howe et al., 2004), life-stage (Howe et al., 2004; Relyea, 2005), pH, suspended sediments in water, and exposure level (Wojtaszek et al., 2004). These impacts range from mortality (Relyea, 2005), to morphological changes, changes in the time to metamorphosis, and gonadal abnormalities (Howe et al., 2004), to negligible impacts (Wojtaszek et al., 2004). Salamanders are generally less sensitive to glyphosate than anurans (Relyea and Jones, 2009), and a field study showed no difference in capture rates on glyphosate-treated plots when compared to other disturbed sites (Cole et al., 1997). However, UV light exposure has been shown to influence the impacts of glyphosate exposure (Levis and Johnson, 2015).

Reptiles are under-represented in the literature regarding the impacts of glyphosate-based herbicides on their populations and habitats. Freshwater turtles were the only reptiles for which we found a Western scientific study, and glyphosate exposure led to negative fitness effects, but results could not be translated to wild-relevant conditions (Sparling et al., 2006).

### 3.2.4 Fish

Several studies have examined potential impacts of glyphosate-based herbicides on fish, though few focus on fish in temperate freshwater environments (Morgan and Kiceniuk, 1992; Filizadeh and Islami, 2011; Webster and Santos, 2015). Studies have noted the role that ecological conditions play in toxicity, suggesting that temperate species may be less sensitive compared to their tropical counterparts (Filizadeh and Islami, 2011). Studies evaluating the impacts of glyphosate-based herbicides on salmonids and sturgeon (brown trout (*Salmo trutta*) (Webster and Santos, 2015), rainbow trout (*Oncorhynchus mykiss*) (Morgan and Kiceniuk, 1992), and sturgeon (*Huso huso*, *Acipenser stellatus*, and *A. persicus*) (Filizadeh and Islami, 2011)) generally showed negative effects from glyphosate exposure, but the magnitude and duration of these effects varied.

### 3.2.5 Mammals

"I've spoken to some trappers, and they say that animals don't usually come back on their traps line for a couple years after it has been sprayed."

We found no studies that examined direct toxicity of glyphosate or glyphosate-based herbicides to wild small, or medium-sized mammal populations. Studies have shown potential toxicity, and other negative impacts including endocrine disruption, and negative reproductive effects (Dallegrave et al., 2007; Romano et al., 2012) in laboratory mice (*Mus musculus*) and rats (*Rattus* sp.). However, the results of these studies have been contradicted by others (Greim et al., 2015; European Food Safety Authority, 2017).

Similar to other taxa, generalist small-mammal species, or species that occupy coniferous habitats generally remain relatively unimpacted by herbicide-induced habitat changes, while those which directly or indirectly depend on deciduous plants may suffer (Cole et al., 1998, Santillo et al., 1998). Wild animals may take refuge on untreated patches and return once their habitat recovers, resulting in only transient shifts in community composition (Santillo et al., 1998). If sufficient refuges exist in the surrounding areas, certain populations may not experience adverse impacts (e.g., snowshoe hare, *Lepus americanus*: Sullivan, 1994; Sullivan, 1996, De Bellefeuille et al., 2001).

Large mammals, particularly ungulates, were a great source of concern for workshop participants.

"Hunters are seeing the deformities. They are seeing the sickness. So, it is there."

Several participants noted changes in the health of white-tailed deer (*Odocoileus virginianus*) and moose (*Alces alces*) being hunted, including white spots on the liver, abnormal growth, and hermaphroditism. At times, these factors made meat unconsumable for the participants. Additionally, several participants commented on how glyphosate-based herbicides may be impacting moose population decline:

"The moose used to have triplets often even quadruplets. And now you rarely see that. And they say it's a miracle now, that's not a miracle. They poisoned everything. So, we're talking about, it also causes miscarriages. So, has anybody done any research on how many times a moose has a miscarriage?"

Generally, workshop participants suspected glyphosate-based herbicides and other industrial pollutants to be the cause of these abnormalities, however, participants were far from certain due to lack of resources for investigation.

"We haven't looked into it [whether the spraying of herbicides is causing observed impacts in deer]. But we're saying it definitely could be a huge factor."

"We don't have the resources to look into it [whether the spraying of herbicides is causing observed impacts in deer]."

While no studies were found directly examining the health impacts of glyphosate-based herbicides on ungulates, adverse impacts observed in small mammals exposed to glyphosate under lab conditions (Dallegrave et al., 2007; George et al., 2010; Romano et al., 2012) may support workshop participants' assertions.

"You also have the effect of the different levels of plant growth and sort of a structure to all those sapling trees that the moose rely on or the deer. Those would all be gone too so it's sort of affecting all the wildlife and the food chain, food cycle."

Glyphosate-based herbicides have been shown to significantly reduce browse for moose (Eschholz et al., 1996; Raymond et al., 1996; Milner et al., 2013) and white-tailed deer (Vreeland et al., 1998). However, browse has been shown to return to control levels several years post-treatment (Eschholz et al., 1996; Raymond et al., 1996; Vreeland et al., 1998).

"Even bears [could be affected by herbicide spraying] - bears eat berries."

Though a significant part of their diet is made up of vegetation (Brown et al., 2000), we found no studies examining the impacts of glyphosate-based herbicide habitat alteration on the health or habitat of large omnivorous mammals such as black bears (*Ursus americanus*), though Brown et al. (2000) did speculate that reductions in fruit and nut bearing plants may adversely impact bear populations.

"The moose and bears are all coming into the community because there's nothing left to eat up in the bush."

Participants also noted a concern regarding the impacts of glyphosate-based herbicides on large carnivorous mammals such as wolves (*Canis lupus*).

"It [glyphosate-based herbicides] affects behavior. They've talked about how they've noticed wolves behaving differently. So, it's actually doing something."

Brown et al. (2000) suggested that changes in populations of small to medium sized mammals may indirectly impact carnivorous mammal populations, but no studies were found examining the direct impacts of exposure.

"So, [wolf] behavior is now different. Way more scary to be around in the bush when the wolves are there because they're not behaving in packs like they normally do. They're way more aggressive"

### 3.2.6 Ecosystem biodiversity

"To our people, the smallest little insect, all the way to the biggest one is so important to our people. And it's so important to our environment. I would say even the smallest ones we can't see still play a part within our environment, on our lands, our mother."

Regardless of taxon, the literature has consistently shown that certain species that are more generalist are more likely to survive, and may even thrive, in areas that have been logged or treated with glyphosate-based herbicides (Cole et al., 1997; Cole et al., 1998; Santillo et al., 1998), whereas other species that directly rely on species whose populations suffer from forestry and glyphosate-based herbicides may in turn be impacted negatively (Santillo et al., 1989; Santillo et al., 1998).

## 3.3 Key concern #3: movement through the environment and persistence

A key concern when discussing any substance being released or applied in the environment is its mobility and persistence.

### 3.3.1 Mobility

Several concerns were raised by workshop participants regarding the movement of glyphosate via drift.

"Somewhere along the line where they're spraying [herbicides] it's blowing elsewhere."

In its 2015 re-evaluation of glyphosate, Health Canada concluded that spray buffer zones and weather guidelines are necessary when using glyphosate in order to mitigate potential risks to non-target organisms from spray drift (Pest Management Regulatory Agency, 2015). Despite this, there are concerns that these buffer zones are not being followed during application or are insufficient.

"You can look at the MNRF [Ministry of Natural Resources and Forestry] maps and it shows the areas where they're going to spray and then it has [ … ] a red line and that's the boundary, and then has orange where they're supposed to spray. They're not supposed to spray on windy days. You're flying in a plane. You're really going to be able to guess that you're staying away from the water and whatever?"

Drift can cause unintended plant death and injury outside of the targeted spray zone. Sub-lethal doses of glyphosate have been shown to impair photosynthesis in certain species of trees and algae by preventing the synthesis of chlorophyll (Hernando et al., 1989; Stasiak et al., 1992; Gomes et al., 2016).

"How can they respect the boundaries anyways when it's picked up by the water, by the mist and everything, and then moved all over the place?"

Glyphosate has been shown to remain mobile in the air post-application but is estimated that these residues have a short residency time, with the vast majority being removed by precipitation (Chang et al., 2011). This could potentially cause further impacts beyond the intended spray zone through run-off (Chang et al., 2011; Battaglin et al., 2014).

"It's a mobile pollutant. It's meant to be sprayed over an area. So, you can't guarantee that it's not going to get into a stream [ … ] There's no guarantees that it's going to go where it's supposed to go, and that where it's supposed to go isn't going to go somewhere else if it links up to water."

Studies and reviews have highlighted rainfall as a key factor in leaching of glyphosate from soils (Borggaard and Gimsing, 2008) and washing off foliage (Sundaram, 1990).

"How long does it take to break down? If it does break down? [ … ] They spray it during a dry season, but then if it rains and it gets picked up by water, then there's no point. It does matter when you spray because it's still gonna be moved."

Studies examining runoff of glyphosate-contaminated water have shown that the highest concentration of glyphosate is found the days immediately following treatment, though lower concentrations of glyphosate have been detected up to four months post-treatment (Edwards et al., 1980). Detection rates in lakes, ponds, and wetlands are typically lower than rivers, streams, and drainage ditches, potentially due to sediment adsorption of the herbicide (Battaglin et al., 2014).

Studies generally dismiss the risk of ground water pollution by glyphosate because it readily binds with sediment in the water column and is rapidly degraded by micro-organisms (Borggaard and Gimsing, 2008; Battaglin et al., 2014). This is supported by field studies, which have found low levels of glyphosate and its degradation product, aminomethylphosphonic acid (AMPA), in groundwater samples (Battaglin et al., 2014).

### 3.3.2 Persistence and impact on wild forage

"It's something that the hunters, like the trapper that I'm with, does worry about. Because he's eating that all the time [ … ] you might want to consider limiting how much additional foods you eat because in our area, you might be accumulating that."

We did not find any studies documenting the potential acute or chronic dietary exposures of people who rely on wild forage for sustenance to glyphosate-based herbicides or its metabolites. However, the Pest Management Regulatory Agency has concluded that exposures of the public from residues of glyphosate and its metabolites in agricultural crops and drinking water are not of concern to human health (Pest Management Regulatory Agency, 2017). We reason that it is likely that these findings would be consistent with residues found in wild forage as the glyphosate application rate in forestry (Thompson et al., 2004) is comparable to a typical application rate in agricultural studies (Sprankle et al., 1975a), though different formulations may be used.

"We talk about this stuff [spraying of herbicides and pesticides] that's happening, how it affects the food chain. [ … ] The food chain goes all the way up to us, and when you affect the chain somewhere in between, it breaks the whole cycle. When something happens, it messes things up. And this is what's happening with this whole thing."

Glyphosate is not thought to bioaccumulate in animals, and therefore is thought to pose a low risk to humans eating wild fish and game exposed (Newton et al., 1984; Lautenschlager, 1992), though existing studies are limited and dated.

Beyond residues present in wild forage, is the actual presence and availability of wild forage.

"[Aerial forest spraying impacts] food sovereignty. Like, for people that rely more on sustenance food, it's like a food desert."

No studies were found which specifically examined the quantity and quality of wild foods and medicines in and around sprayed areas through an Indigenous lens; or how alterations in species composition may impact large scale food web structures of the entire ecosystem, up to and including humans.

Several workshop participants expressed concern about movement of animals that may have been impacted by glyphosate-based herbicides in and out of the application site, increasing the impact zone for those looking to hunt or trap.

"Look how far the animals migrate. So, we are spraying, and we are leaving a sprayed area, and they're going back up north, going on their migration pattern, they're taking that with them."

No studies were found examining the long-term movement of animals through sprayed and unsprayed areas. Particularly when examining the impact of glyphosate-based herbicides on Indigenous traditional practices, as well as hunting and trapping as a whole this factor should be further analyzed.

### 3.3.3 Persistence in soil

"Then [glyphosate] gets into your soil and gets into the water ways and all the systems."

Several studies have shown that glyphosate and AMPA are quickly degraded in soil (Sprankle et al., 1975a; Sprankle et al., 1975b), but the rate of degradation is highly dependent on site conditions such as pH, phosphate concentration, soil type, organic matter content, and the presence of certain metal ions (Sprankle et al., 1975a; Sprankle et al., 1975b; Borggaard and Gimsing, 2008; Rampazzo et al., 2013; Battaglin et al., 2014). Few studies have been conducted in and around the Great Lakes region of Ontario. Studies conducted in boreal soils have suggested that glyphosate and its metabolite AMPA have a relatively long persistence (Laitinen et al., 2009).

Uptake of glyphosate in agricultural plants have been observed to be very low, possibly due to microbial degradation, chemical degradation, adsorption to the soil, lack of plant absorption, or a combination of these factors (Sprankle et al., 1975a). Glyphosate has been shown to translocate throughout plant tissues of a variety of species and may even be transferred from root tissues to soils after application (Green et al., 1992; Laitinen et al., 2007).

## 3.4 Key concern #4: human safety and wellbeing

### 3.4.1 Physical health

The toxicity and risk to human health posed by glyphosate and its formulations is an obvious concern to the general public including Indigenous communities, and a highly contentious issue amongst academics, and international regulators. Human health risk assessments have been conducted on glyphosate and/or its formulations by both academic researchers (De Roos et al., 2005; Zhang et al., 2019) and various regulatory agencies (European Food Safety Authority, 2015; Pest Management Regulatory Agency, 2015; United States Environmental Protection Agency, 2016; International Agency for Research on Cancer, 2017), with discrepancies in results. These studies range in their conclusions from linking glyphosate with cancers such as non-Hodgkin's lymphoma (Zhang et al., 2019), to claiming no ill effects (De Roos et al., 2005; Greim et al., 2015).

Health Canada's Pest Management Regulatory Agency (PMRA) launched a routine re-evaluation of glyphosate in 2009 (Pest Management Regulatory Agency, 2010). A report outlining the PMRA's decision was released in 2015 based on available information provided by the manufacturer of the pesticide, published scientific literature, environmental monitoring information (e.g. groundwater and surface water monitoring), as well as reviews conducted by other regulatory authorities (Pest Management Regulatory Agency, 2015; Pest Management Regulatory Agency, 2017), ultimately ruling that glyphosate and its approved product formulations do not present unacceptable risks to human health when used according to label directions (Pest Management Regulatory Agency, 2015; Pest Management Regulatory Agency, 2017). However, new risk reduction measures are now required for products registered in Canada (Pest Management Regulatory Agency, 2015). The results of the Health Canada re-evaluation of glyphosate are consistent with other contemporary reviews by the Unites States Environmental Protection Agency (United States Environmental Protection Agency, 2016), with whom Health Canada partnered for their review of glyphosate (Pest Management Regulatory Agency, 2017), as well as the European Food Safety Authority (EFSA) (European Food Safety Authority, 2015). However, in 2015, the World Health Organization's International Agency for Research on Cancer (IARC) conducted a review of the potential carcinogenic effects of five pesticides, including glyphosate (International Agency for Research on Cancer, 2017). The panel concluded that based on what they deemed limited evidence of carcinogenicity in humans and sufficient evidence of carcinogenicity in animals that glyphosate be classified as "probably carcinogenic to humans" (2A) (International Agency for Research on Cancer, 2017). The panel also concluded that there was evidence of genotoxicity for both glyphosate itself and glyphosate formulations such as commercial herbicides (International Agency for Research on Cancer, 2017).

Several reviews have been conducted analyzing how regulatory bodies could come to such drastically different conclusions around the same substance. These differences in rulings between regulatory agencies have largely been attributed to methodological differences in the evaluation of available evidence, as well as reliance on different data sets between regulatory bodies (Tarazona et al., 2017; Benbrook, 2019). Criticisms have been launched on the methodologies and final decisions of each regulatory body by different reviewers.

Some criticisms of the classification of glyphosate as a probable human carcinogen by the IARC state that typical exposure levels to glyphosate are low enough that there is no risk to the public (Solomon, 2016; Williams et al., 2016; Tarazona et al., 2017). This has been countered by others who state that glyphosate use and human exposure is increasing globally, making typical exposure estimates outdated, and increasing the risk of accidental high-exposure events (Bai & Ogbourne, 2016; Peterson Myers et al., 2016; Vandenberg et al., 2017; Benbrook, 2019). Additionally, the IARC has been criticized for drawing conclusions based on what some consider to be statistically or methodologically flawed studies, or results which were inconsistent across studies (Williams et al., 2016).

Other reviews criticize the US EPA (Benbrook, 2019) and EFSA (Portier et al., 2016), supporting the findings of the IARC. These reviews criticize the examination of glyphosate on its own rather than in formulations (Benbrook, 2019), existing exposure estimates used by regulatory bodies (Benbrook, 2019), the predominant use of industry-sourced unpublished data rather than peer-reviewed literature in drawing final conclusions (Portier et al., 2016; Benbrook, 2019), and the dismissal of peer-reviewed studies on what reviewers consider relevant and valid (Portier et al., 2016; Benbrook, 2019).

Many reviews, both of the processes of regulatory bodies and of the existing body of literature, suggest that there is not enough unbiased peer-reviewed research regarding glyphosate, its formulations, and its metabolites and their mechanisms of action in order to make informed decisions regarding its potential impacts on human health (Peterson Myers et al., 2016; Vandenberg et al., 2017; Davoren & Schiestl, 2018; Benbrook, 2019). Even further, some studies suggest that data that regulations are currently dependent on are outdated and no longer valid due to increasing prevalence of glyphosate use (Peterson Myers et al., 2016; Vandenberg et al., 2017).

### 3.4.2 Mental health and cultural wellbeing

One commonly overlooked aspect of human health when considering the impacts of resource extraction, is the impact on mental and social wellbeing of communities. Indigenous Peoples often find themselves on the frontlines of environmental degradation (Simpson, 2004; Beckford et al., 2010), as their close ties with the natural environment make them the first to be impacted by industrial practices. This brings a perspective beyond the physical impacts of sustenance living, to an emotional wellbeing supported by the environment.

Ecological grief has been defined as “the grief felt in relation to experienced or anticipated ecological losses, including the loss of species, ecosystems and meaningful landscapes due to acute or chronic environmental change” (Cunsolo and Ellis, 2018). While the limited literature on this topic generally surrounds the issue of climate change (Cunsolo et al., 2013; Cunsolo and Ellis, 2018), ecosystem alteration through forestry practices can result in the same feelings of despair amongst Indigenous Peoples. While underappreciated within Western Science, this concept is not novel. Several participants alluded to these feelings of grief in relation to industrial development and alteration of lands, but often did not specifically use the term ecological grief.

“The Elders have always been saying that, [they] just they never called it ecological grieving”

Many cultural practices, including hunting, trapping, gathering medicines, and ceremony are inherently tied to an individual’s identity and their role in the community.

“For me to come back home and to be reintroduced to my community and to know my role as a as a woman there, how can I do that when I can’t access my own medicines or berries?”

Artificial changes to the environment induced by forest management which change the availability of plants and animals impact community social structure and function. Several participants commented that this relationship is being altered and damaged by industrial practices such as forestry.

“It’s like further colonization of our people, another form of it. It’s affecting our food and medicines so we can’t eat them.”

Further, many workshop participants expressed concern that these impacts are being magnified in younger generations.

“It makes me emotional to think that if I want to raise my own child, how am I going to do all of our ceremonies when we can’t even find a place to find our bearings? To find our medicines? So, when we talk about our traditional way of life, maybe you should also put our bodies too. Because we are of the land, we are the voices of the land.”

Land-based learning is a key aspect of Indigenous cultures. Since time immemorial, knowledge of the land and its inhabitants has been passed through intergenerational knowledge transfers from Elders and knowledge holders to youth. Often, intergenerational knowledge transfer can only be done effectively on the land through experiential learning (Simpson, 2014).

“As much as I could learn from this book, it doesn’t mean anything if I don’t know about my own land.”

Several participants expressed concern that knowledge transfer is inhibited, if not entirely stopped, by alterations to the ecosystem which prevents the execution of traditional practices.

“Even if you don’t realize what you’re learning, through hunting or trapping or fishing, you’re learning so much about the land, about the animals, about your culture [ … ] if you can’t do any of those things, you’re losing or you have to find a new way to get those teachings.”

Overall, participants highlighted a sense of environmental dispossession from their territories based on perceived contamination from herbicide use in forestry, ultimately preventing them from practicing traditional land-based activities. This type of dispossession has been shown to negatively impact both the physical and the cultural wellbeing of Indigenous Peoples as their wellbeing is tied directly to the wellbeing of the land (Big-Canoe and Richmond, 2014; Tobias and Richmond, 2014).

## 3.5 Key concern #5: awareness and transparency

In addressing knowledge gaps in herbicide research, additional barriers must be overcome for research to move forward in a meaningful way with Indigenous communities.

One barrier to conducting and dissemination research findings is a distrust in existing academic research due to real or perceived conflicts of interest especially with regard to industry-based studies.

“They give them the answers they want to hear, not the actual truth.”

While various studies regarding the mechanisms and potential impacts of glyphosate-based herbicides exist, in many cases, no true consensus seems to have been reached by the academic community or governing bodies. Lack of agreement amongst regulatory agencies can understandably cause confusion.

“How are we supposed to reduce the impacts when we don’t know what they are?”

We propose that further research that is implemented independent of industry or special interest groups must be conducted to address these concerns. Ensuring researchers have minimal or no conflict of interest is critical in these efforts.

Often distrust extends to government and regulatory bodies who assess and control the use of industrial chemicals such as glyphosate-based herbicides.

“What it comes down to with them, it’s just dollars.”

Several participants cited concerns that government and industry prioritize economy over ecology when making decisions regarding forest management.

“They want to farm the forests.”

Often a lack of trust is due to the history of colonial relationships in academic studies due to inequitable political relationships and narrow views of Indigenous Knowledge where various aspects of Indigenous Knowledge, particularly those relating to intangibles such as spirituality, ceremony, ancestral teachings, story telling, and cultural values are often dismissed (Reo et al., 2017; Thompson et al., 2020). Because of this, few studies have been performed through a holistic lens which acknowledges and respects these intangibles. Meaningful engagement among industry, government, and Indigenous nations is critical to making progress. Weaving of knowledge systems can result in new and innovative solutions to environmental issues.

“So that question has to go back to the other side to say, what can you do? Because we’ve already done everything possible to work with people that come into our territories.”

## 4 Conclusion

In conclusion, the environmental and sociocultural impacts of glyphosate-based herbicides used in forestry are vast and complex, especially in those thematic areas of concern identified by First Nations and Elders in the Robinson Huron Treaty areas: plant biodiversity and heath, animal biodiversity and health, movement through the environment and persistence, human safety and wellbeing, and awareness and transparency.

Several gaps in Western scientific literature exist, and further research is needed regarding the impacts of glyphosate-based herbicide use in commercial forestry in northeastern Ontario. Through the combination of concerns shared during the workshop, and a review of Western scientific literature, we identified three main gaps in research regarding glyphosate-based herbicide impacts used in forestry:

1. Very little research has been done to explore the direct effects of glyphosate-based herbicide toxicity to most of the fauna and flora of the Great Lakes region of northeastern Ontario as well as the persistence in the environment.
2. The indirect effects of glyphosate-based herbicides to ecosystems in the Great Lakes region are generally poorly understood, as are the resulting impacts of trophic cascades.
3. Research regarding the impacts of glyphosate-based herbicides used in forestry to Indigenous culture and community wellbeing conducted from an Indigenous perspective have, in general, lacked. Additionally, research that uses Indigenous research methods, is led by Indigenous Peoples, or responds to the questions of Indigenous Peoples is lacking.

Research directly examining the direct effects of glyphosate-based herbicide toxicity to most of the fauna and flora of the Great Lakes region of northeastern Ontario as well as glyphosate's persistence in the environment are key to understanding the unique effects of glyphosate-based herbicides experienced by all life residing in the Great Lakes region of northeastern Ontario. The unique climatic, geological, ecological, and cultural context of this region warrants it's own investigation into the toxicity, persistence and transport of glyphosate-based herbicides and their metabolites in this region. Similarly, research regarding the indirect effects of glyphosate-based herbicides including impacts on local food webs, animal behaviour, and health specific to the ecosystems of this region is needed in order to address the place-based concerns raised in this paper. However, conducting research that investigates these concerns without consideration and prioritization of the needs, wellbeing, and lived experience of Indigenous Peoples in this region will fall short of addressing the knowledge gaps identified in this paper.

Research that brings together a holistic framework, acknowledging and incorporating the interconnectedness of the environment (including humans therein) is greatly needed (Whyte et al., 2016). Community-led research that weaves Indigenous and Western Knowledge systems is critical to a comprehensive assessment of ecological and socio-cultural impacts (Latulippe and Klenk, 2020). In this context, weaving knowledge systems implies bringing together Indigenous Knowledge and Western Science at any stage of the research process, as desired by Indigenous community partners, in a way that respects the integrity of each knowledge system (Kimmerer, 2002; Johnson et al., 2015; Henri et al., 2021). By weaving Indigenous and Western Knowledge systems, these knowledge gaps can be addressed in a way that holistically considers the interconnectedness of the environment and humans. Inclusive approaches that value multiple ways of knowing can lead to collaborations where new solutions and mitigation strategies can address longstanding environmental issues. In this work, we present participants words as our guide, and then contextualize these words within Western scientific literature. This approach was intentional and aimed at elevating the voices of our Indigenous community partners. We feel that the methodological approach used in this paper, and the publication resulting from the first day of the workshop focused on climate change (Menzies et al., 2022) provide a novel approach to weaving knowledge systems. We hope approach can be applied and further developed by others in approaching a variety of environmental and scientific concerns in a holistic and equitable way which recognizes the inherent value of Indigenous Knowledge Systems.

"That's one of the advantages of traditional knowledge is there is hope."

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, after discussion about proposed use, and in consideration of OCAP principles.

## Ethics statement

The studies involving human participants were reviewed and approved by Mount Allison University (#102582), University of British Columbia (H19-01453) and University of Guelph (20-10-014). The patients/participants provided their written informed consent to participate in this study, and provided written informed consent for the use of the knowledge they shared in this article.

## Author contributions

Conceptualization: JP, CK. Methodology: JP, DM, CK, EB, HP. Software: HP. Validation: JP, DM, CK, EB, HP. Formal analysis: HP, EB, JP. Investigation: HP, EB, JP. Resources: HP, EB, JP. Data curation: HP, EB, JP. Writing – original draft preparation: HP, EB, JP. Writing – review & editing: HP, EB, JP, DM, SC, CK. Visualization: HP. Supervision: JP. Project administration: JP, EB, CK, HP. Funding acquisition: JP, DM. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2023.1186399/full#supplementary-material

APPENDIX 1
Questions asked to participants at the Connecting Guardians in a Changing World Workshop.

APPENDIX 2
List of tagged keywords used to code quotes from interviews.

APPENDIX 3
Search terms used in the literature search.

APPENDIX 4
Additional citations on each theme discussed in this manuscript, that were removed to reduce the length and complexity of the manuscript, with metadata associated with that citation.

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