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Tracking Aquatic Biodiversity With Environmental DNA: A Study in Quebec's Mining Region

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ABSTRACT

In Quebec's James Bay region, mining activities pose significant risks to local aquatic biodiversity due to habitat disturbance and potential contaminant release. This study evaluates the efficacy of environmental DNA (eDNA) for detecting and monitoring fish species in areas affected by mining operations, specifically at an active gold mine and a prospective lithium mine. Over two sampling campaigns, eDNA analyses identified the presence of four target fish species, including species of ecological and cultural significance to the Cree communities. The eDNA method proved to be a sensitive and non-invasive tool, capable of detecting species across large aquatic ecosystems and providing insight into species distribution and abundance in relation to environmental changes. Results indicate that certain species, like lake sturgeon or sauger, may be absent or less detectable in mining-impacted areas, potentially due to habitat fragmentation and altered water quality parameters, including low pH and elevated heavy metal concentrations. Our findings support the integration of eDNA as a valuable monitoring tool for assessing biodiversity and establishing species presence baselines in sensitive ecosystems and highlight its potential for community-led environmental management initiatives in Indigenous territories.

1 | Introduction

Biodiversity plays a critical role in the functioning of both terrestrial and aquatic systems. It supports the resilience of these ecosystems against disturbances, maintains essential biological processes, and provides vital services such as climate regulation, water purification, food production, and preserves a healthy and safe environment (Díaz et al. 2019). With 9% of the world's forests, nearly a quarter of its wetlands, and a vast arctic territory, Canada's ecosystems significantly contribute to global biodiversity (Ray et al. 2021). Canada is home to approximately 20% of the world's freshwater, supporting a wide range of aquatic species, and hosts vulnerable species such as polar bears and caribou, which are dependent on polar ecosystems and face a heightened risk of extinction (Woo-Durand et al. 2020). However, this biodiversity faces significant threats from increasing anthropogenic pressures. Among these threats, changes in land use have emerged as the primary driver of biodiversity loss along with overexploitation, climate change, pollution, and invasive species (Ceballos et al. 2015; Díaz et al. 2019; Jaureguiberry et al. 2022). Consequently, localized human activities exert profound effects on biodiversity. In Canada, the integrity of natural habitats is threatened by multiple anthropogenic activities, including hydroelectric dam construction, forest exploitation, agricultural practices, transportation networks, and mining activities (Ray et al. 2021). These disturbances contribute to habitat fragmentation, species isolation, and reduced genetic diversity. Collectively, habitat loss affects 82% of at-risk species within the Canadian territory (Woo-Durand et al. 2020). Among these threats, mining activities stand out due to their extensive land clearing, road construction, and infrastructure development, which exacerbate these impacts. Recent assessments indicate that 11.7% of freshwater species in Canada are considered "at risk," while 37.9% lack sufficient data to evaluate their status (Desforges et al. 2022), emphasizing the need for improved biodiversity monitoring tools.

Indeed, conventional methods for assessing biodiversity, such as direct observation, trapping, and counting individuals, often used to measure species presence and abundance, can be limited. These methods can be time-consuming and costly, often requiring specialized skills. Moreover, they may fail to capture the full extent of biodiversity within an ecosystem, particularly for rare or elusive organisms (Pawlowski et al. 2020). Morphological identification poses additional challenges, especially when distinguishing between similar species or when identifying juvenile stages, which can result in significant omissions during assessments Ficetola et al. (2008). Moreover, adequate biodiversity assessment requires a large volume of data, which is difficult to achieve with traditional methods. In response to these challenges, environmental DNA (eDNA) has emerged as a promising technique (Pawlowski et al. 2020; Langlois et al. 2021; Sahu et al. 2023). eDNA refers to genetic material shed into the environment by organisms, either through the release of cells, tissue fragments, or free-floating DNA. This material originates from macro-organisms (e.g., excrement, skin, scales) and micro-organisms (e.g., viruses, bacteria, protists) alike, allowing for the detection of a wide range of species (Goldberg et al. 2016; Currier et al. 2018; Langlois et al. 2021; Sahu et al. 2023). eDNA can be collected from various habitats, including water bodies like rivers, lakes, and oceans, as well as long-term deposits such as sediment and ice cores. This technique provides a powerful tool for biodiversity monitoring, as it enables the identification of both large organisms (e.g., vertebrates, plants) and smaller ones (e.g., zooplankton, meiofauna) (Deiner and Altermatt 2014; Ardura et al. 2015; Abileva et al. 2023; Duarte et al. 2023; LeBlanc et al. 2020). By detecting trace amounts of degraded DNA, typically under 500 base pairs (bp) in length, eDNA surveys offer a non-invasive and cost-effective alternative to traditional sampling methods Sahu et al. (2023) that could be used for the detection of target species, whether they are rare, protected, or invasive.

In this context, eDNA is being employed to detect the presence of multiple fish species in the Eeyou Istchee James Bay region of Quebec. This area, a traditional Cree territory, has hosted around twenty mining sites over time, mostly for gold and copper extraction. Today, only one mine remains in operation, the Éléonore gold mine, while the Whabouchi project, a prospective lithium mine, is still in development. This study targets these two sites to assess local biodiversity and potential impacts of mining activities on aquatic ecosystems. Freshwater fish were selected as the focal group due to their ecological importance and cultural relevance to local Cree communities. Six species were chosen based on their known presence in the area and their ecological or economic significance: yellow perch (*Perca flavescens*), Northern pike (*Esox lucius*), walleye (*Sander vitreus*), sauger (*Sander canadensis*), brook trout (*Salvelinus fontinalis*), and lake sturgeon (*Acipenser fulvescens*) (Ministry of Natural Resources 2021). Among these, brook trout and lake sturgeon were specifically chosen by local Cree communities for their cultural and economic importance, as they are vital sources of food. Additionally, walleye, sauger, yellow perch, and Northern pike serve as reliable ecological indicators for this study due to their known distribution in the region. These species share several traits, including their significance to both Indigenous populations and the aquatic ecosystems of the James Bay area. Moreover, their differing life histories, habitat preferences, and trophic levels provide a broad understanding of biodiversity and potential environmental impacts. Ultimately, this research aims to assess the relevance and applicability of eDNA as a tool for biodiversity monitoring in remote, mining-affected areas where conventional data are limited or unavailable. The study focuses on establishing a species presence baseline in two key sites—one active and one under development. In such contexts, eDNA provides a practical and scalable solution for monitoring freshwater biodiversity. This study contributes foundational data that can support long-term monitoring and inform environmental assessments in northern resource development zones.

2 | Material & Methods

2.1 | Sampling Area & Sampling Methodology

The study area includes two mining sites in the James Bay region of Québec, Canada. The first is Éléonore, a major gold mine operated since 2014 by Goldcorp Inc., then acquired by Newmont in 2019 and now owned by Dhilmar Ltd. since November 2024. The second is Whabouchi, a prospective lithium mine owned by Nemaska Lithium. Water samples were collected over two sampling campaigns, with station information presented in Table S1. Sampling was conducted at eight stations at the gold mine site both in August 2022 and August 2023, and at 12 stations at the lithium mine site in July 2022 and August 2023. Stations were selected based on their proximity to the mining facilities, and two stations, between 5 and 10 km upstream of each mining site, were also sampled as field control. The water bodies sampled varied in nature and flow, from rivers to small bodies of water, and several water parameters (temperature, pH, conductivity, etc.) were recorded with a YSI multiparameter probe (Tables S3 and S4).

Water samples were collected from shore using a portable water pump system carefully disinfected with a 10% bleach solution and conditioned with water downstream of the area sampled at each station. Samples were filtered on-site and DNA was retained on 0.45 μm nitrocellulose filters-funnels (Nalgene, 0974030 K). Each station was sampled in triplicate, and 1 L was collected when possible (e.g., filter saturation), and the volume sampled was recorded (Table S1 for the lithium mine and Table S2 for the gold mine). One liter of bottled water was also filtered every sampling day as a field blank. The filters were then folded and stored in individual paper envelopes inside a sealable plastic bag for each station along with silica gel beads to dry them and prevent cross-contamination as described by (Allison et al. 2021). Samples were stored at −20°C until extraction.

2.2 | eDNA Extraction

For each sample, a quarter of filter was incubated overnight at 56°C in 280 μL of lysis buffer (ATL) and 20 μL of Proteinase

K from DNeasy Blood and Tissue Kit (Qiagen, 69,506) on a ThermoMixer (Eppendorf) at 1000 rpm. On the following day, the extraction was performed with DNeasy Blood & Tissue kits (Qiagen) and Qiashredder columns (Qiagen) by following the manufacturer protocol. The final sample was eluted in 150 μL and stored at −20°C until further analysis. All steps were conducted in a laminar hood; the working space was decontaminated with a 10% bleach solution (Clorox). Protocols used followed the Canadian Standard Association (CSA) guidelines (CSA W214 2021; CSA W219 2023).

2.3 | Quantitative PCR

Samples were first screened in 4 replicates with ePlant5 primers/probe set to check the presence of PCR inhibitors (Hobbs et al. 2019; Robinson et al. 2022). Samples in which 50% of their replicates are amplified after 27 Ct were cleaned with OneStep PCR Inhibitor Removal Kit columns (Zymo Research, D6030, Cedarlane) by following the manufacturer protocol. Six targets freshwater fish species-specific primers/probe sets used in this study are listed in Table 1. Assays for *Perca flavescens*, *Sander canadensis*, *Salvelinus fontinalis*, and *Acipenser fulvescens* were developed by Langlois et al. (2025), while those for *Esox lucius* and *Sander vitreus* were designed by Lopez et al. (2023). All assays targeted mitochondrial regions due to their high copy number, small size, and high interspecific variability, which improve both sensitivity and specificity in environmental samples Allison et al. (2023).

All primers and probes (5′FAM reporter dye and 3′ZEN/Iowa Black FQ quencher) were ordered from Integrated DNA Technologies (IDT, USA). Targeted DNA was amplified by qPCR using a CFX96 thermocycler (Bio Rad Laboratories) with 2 μL of each sample in a total of 15 μL total reaction volume (7.5 μL H2O, 1.5 μL primer/probe mix 10X, 3.75 μL QIAcuity Probe 4X (Qiagen, 250,103)). The thermocycler was set for an initial activation step at 95°C followed by 50 cycles of 15 s for denaturation at 95°C, 30 s for annealing at 64°C, and 30 s for extension at 72°C. A signal before 50 Ct is considered a hit. The detection threshold for the presence/absence of targeted species DNA test was set at 1/8 for 1 out of 3 water bottles. To avoid false positives and ensure the qPCR performance, a blank field, NTC, and positive controls with 20 copies of the gene fragment of the species of interest (gBlock, IDT) were inserted for every qPCR run.

2.4 | Data Treatment

When all eight technical replicates were positive (8/8), DNA concentration was calculated using the standard curve (copies per reaction) and then converted to copies per liter based on the total volume of water filtered and the volume of DNA extract used per qPCR reaction. For partial detections (< 8/8), we used the eLowQuant model, a probabilistic method designed for low-concentration eDNA quantification. It provides a more robust estimate of DNA copy number in cases where standard curve interpolation is unreliable due to stochastic amplification (Lesperance et al. 2021, Table S5).

The probability of detection for each fish species in each station was calculated from the following equations, considering that only one positive assay leads to a detection for a sample and only one positive sample leads to a detection for a station:

$$PSample = 1 - (1 - Passay)n\ assay \tag{1}$$

TABLE 1 | Primers and probe nucleotide sequences for *P. flavescens*, *E. lucius*, *S. vitreus*, *S. canadensis*, *S. fontinalis*, *A. fulvescens* from (Langlois et al. 2025; Lopez et al. 2023).

Species	Code	Gene	Sequences
Perca flavescens	ePEFL1	mt-d-loop	Forward: CTCCCATGTTAAAACTGC Reverse: TCAGGTTCAGGAAGTTAC Probe: TTCTTAGTCAGCCTTCTTCCGTTATT
Esox lucius	eESLU1	mt-cyb	Forward: TCTCCACAGCCTTCTCATC Reverse: CCGCCTCAGATTCATTGG Probe: CTCCTCCTAACAATAATAACCGCCTTCGT
Sander vitreus	eSAVI2	mt-nd1	Forward: CTCGGGATCTTGTTTCTA Reverse: CTGATACTAATTCGGATTCG Probe: CCTATCAAGCCTAGCAGTCTACTCTATTCT
Sander canadensis	eSACA1	mt-nd2	Forward: CTCTCTCTCAGCCGATAG Reverse: AGCCTAAGTCTCTTAACG Probe: ATTCTTCTACTACCAATAACTCCAGCCATT
Salvelinus fontinalis	eSAFO6	mt-d-loop	Forward: GCATCATAGAAGGAGAGC Reverse: GGCTTCGTAATACTCCAT Probe: CGTCCAAGCTCTTACTCTCACCATC
Acipenser fulvescens	eACFU	mt-nd1	Forward: TGGCAATTTCACTCTACAC Reverse: TTGGCGTATTCAGCTAAG Probe: AACTGGTCTCCGGCTTCAACGTAGAATATG

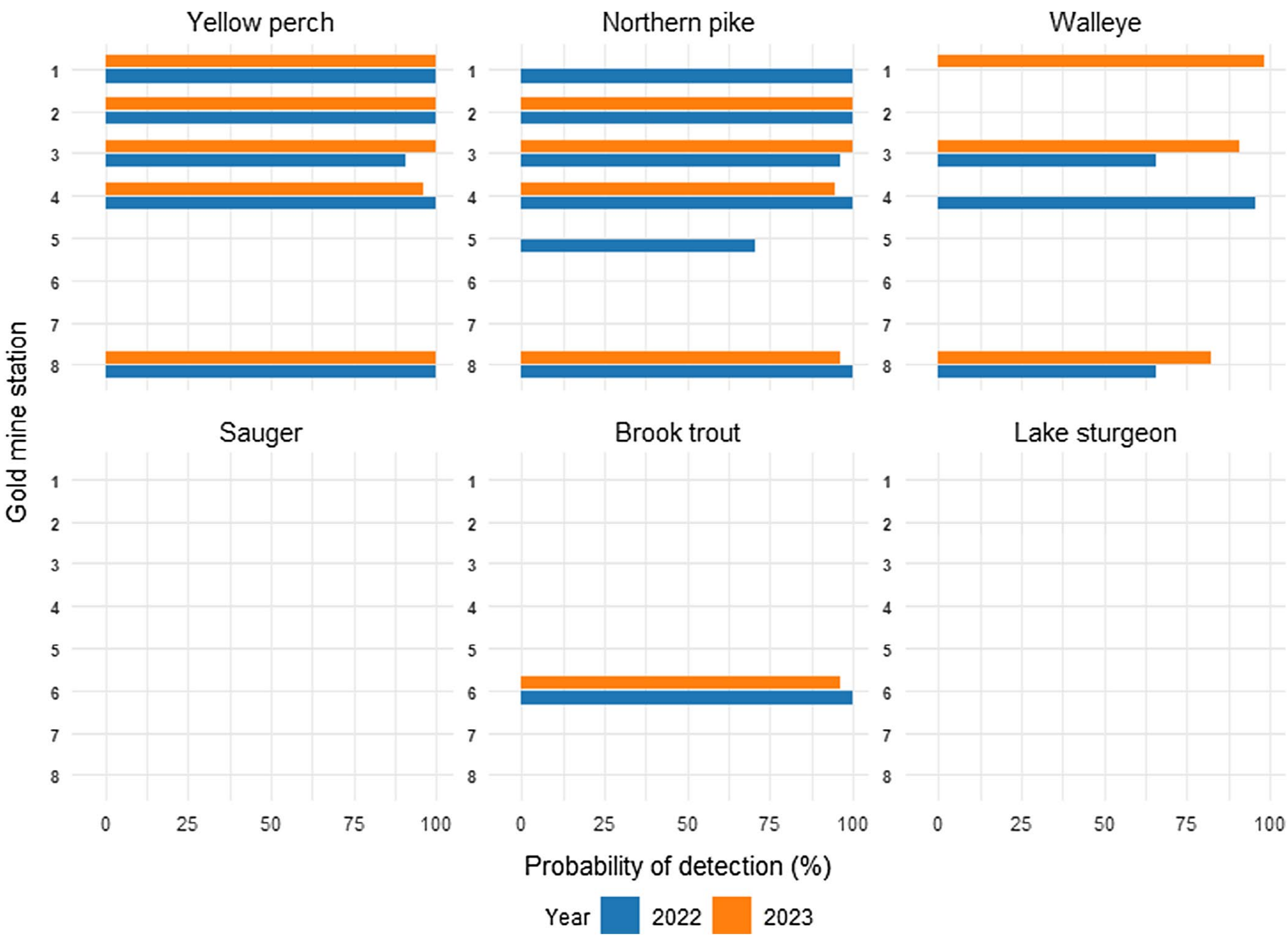

FIGURE 1 | Detection probability of fish species in stations around gold mining site.

where n is the number of qPCR assays per sample (eight in our experimental design).

$$PStation = 1 - (1 - PSample)n\ sample \quad (2)$$

where n sample is the number of samples per station (three in our experimental design).

2.5 | Water Parameters

Physico-chemical parameters were recorded by the mining companies and included both field measurements and laboratory analyses. In situ variables comprised maximum depth, temperature, pH, conductivity, dissolved oxygen, and water transparency. Laboratory analyses covered general water quality indicators such as alkalinity (as $CaCO_3$ at pH 4.5), turbidity, total hardness, BOD_5, COD, TSS, TDS, and total solids. Carbon fractions (DIC, DOC, TOC) and nutrient concentrations (NH_4^+/NH_3, NO_2^-, NO_3^-, total N [TKN], and total P) were also quantified. Elemental analysis included a wide range of trace and major metals: Al, Sb, Ag, As, Ba, Cd, Ca, Cr, Co, Cu, Fe, Li, Mg, Mn, Hg, Mo, Ni, Pb, K, Se, Na, Sr, Ti, W, U, V, and Zn. Rare earth elements (Ce, Dy, Gd, La) were analyzed via ICP-MS/MS. Chlorophyll ɑ concentrations were used to assess primary production, while petroleum hydrocarbons (C10–C50) indicated hydrocarbon contamination. Radioactivity was monitored through Ra-226 measurements.

3 | Results

Out of a total of 134 samples collected over the two summers for the two mining sites, all samples passed the IntegritE-DNA test before or after the inhibitor clean-up. Detailed detection results are presented in Table S2,S3.

At the gold mine site, the yellow perch, Northern pike, walleye, and brook trout were consistently detected both in 2022 and 2023 throughout the four sampling campaigns, while sauger and lake sturgeon were never detected under the conditions and methodological framework of this study. There was almost no variation in species presence between 2022 and 2023 Figure 1. Yellow perch and Northern pike were consistently detected at five of the eight sampling stations in both 2022 and 2023. Brook trout was only detected at one control station upstream of the mine. Species distribution at the gold mining site in 2022 and 2023 is shown in Figure 2.

At the lithium mine, yellow perch, Northern pike, walleye, and brook trout were also detected in the two sampling years, but no major differences in species distribution were observed

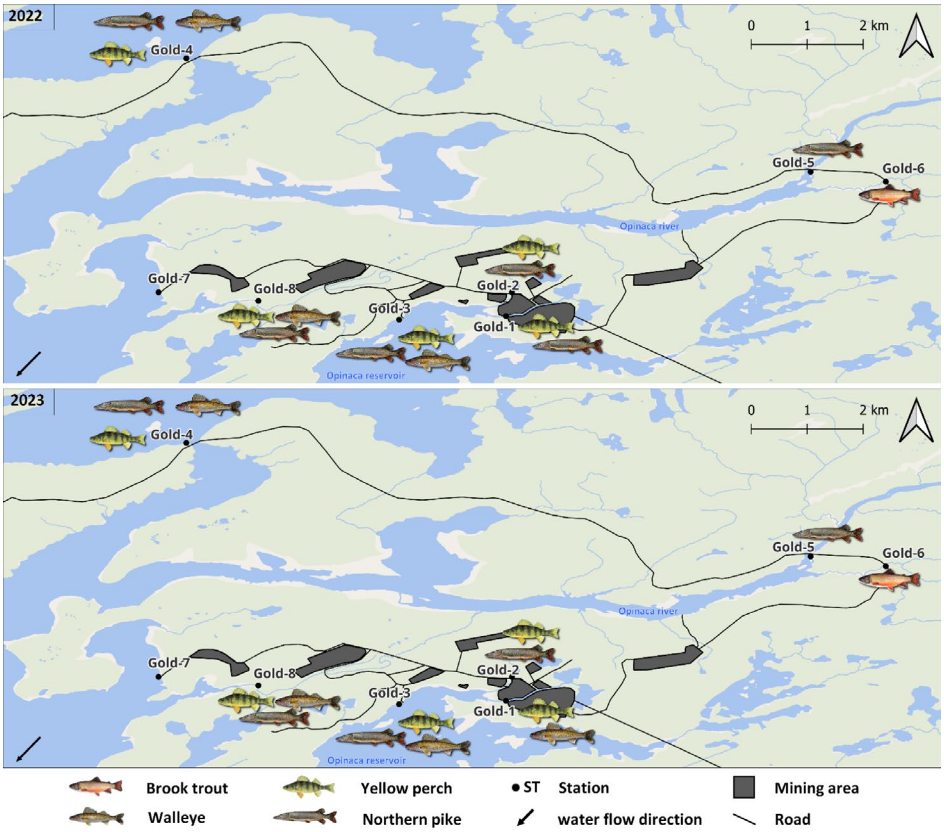

FIGURE 2 | Distribution of fish species around gold mining site. The map was produced using the free software QGIS v3.38.3. The base map was obtained from the Quebec government's public imagery service. The species represented on the map correspond to those detected at nearby sampling stations in 2022 and 2023.

between 2022 and 2023 Figure 3. The most represented species is Northern pike, with over 50% detection (7/12 stations in 2022, 10/12 stations in 2023), followed by yellow perch, with around 35% detection, with 2/12 detections in 2022, and 10/12 detections the next year, showing a change in the distribution of this species in 2023. Species distribution at the future lithium mining sites is shown in Figure 4 for the 2 years.

The physico-chemical parameters are presented in Tables S3 and S4. Based on the Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs (MELCCFP) and Canadian Council of Ministers of the Environment (CCME) resources, several parameters at the gold mine site appear to exceed recommended thresholds (Table S6). For example, the pH levels were consistently low (acidic) across all sites sampled in both 2022 and 2023, with similarly low pH observed near the lithium mine site in 2023. Low dissolved oxygen levels, consistent with the low pH, were also observed at several sites. In 2023, all stations around the prospective lithium mine (except for station Lithium#10) and stations Gold#2, Gold#5, and Gold#11 around the gold mine were below the thresholds established by CCME and MELCCFP for the protection of aquatic life. At the site of the prospective lithium mine, high concentrations of aluminum were observed, exceeding aquatic life protection thresholds at all stations. Elevated iron levels were recorded at station Lithium#10, and high lead concentrations at station Lithium#4. These exceedances do not appear to be isolated, as similar physicochemical conditions were observed during other field campaigns, including data collected in October of the same year, which also showed elevated values for these elements at multiple locations.

4 | Discussion

4.1 | Impact of Mining Sites on Water Quality

Mining activities can impact the local environment by altering natural habitats through infrastructure development and by affecting water composition, particularly through mine effluents resulting from refining processes and waste management (Ray et al. 2021). While mine effluents represent a key pathway for water contamination, other processes such as contact water runoff, dewatering activities, and seepage from waste storage facilities can also contribute to changes in surface and groundwater quality. For example, according to the mine's technical report (Goldcorp Inc. 2018), gold extraction involves crushing and grinding the ore, which produces large amounts of waste rock. The ore undergoes flotation to separate the gold from other minerals, followed by cyanidation to dissolve the gold. Lead nitrate is added to improve gold recovery, and calcium hydroxide is used to adjust the pH of the solutions. Despite measures such as storing flotation sludge, cyanide tailings in lined facilities, and treating contact water in an industrial plant, several substances are released in the final effluent from the gold mine, including chlorides, As, Cr, Cu, Fe, Ni, U, Hg, Zn, Cd, and Pb (Goldcorp Inc. 2018). In 2022, the average concentration of Cu,

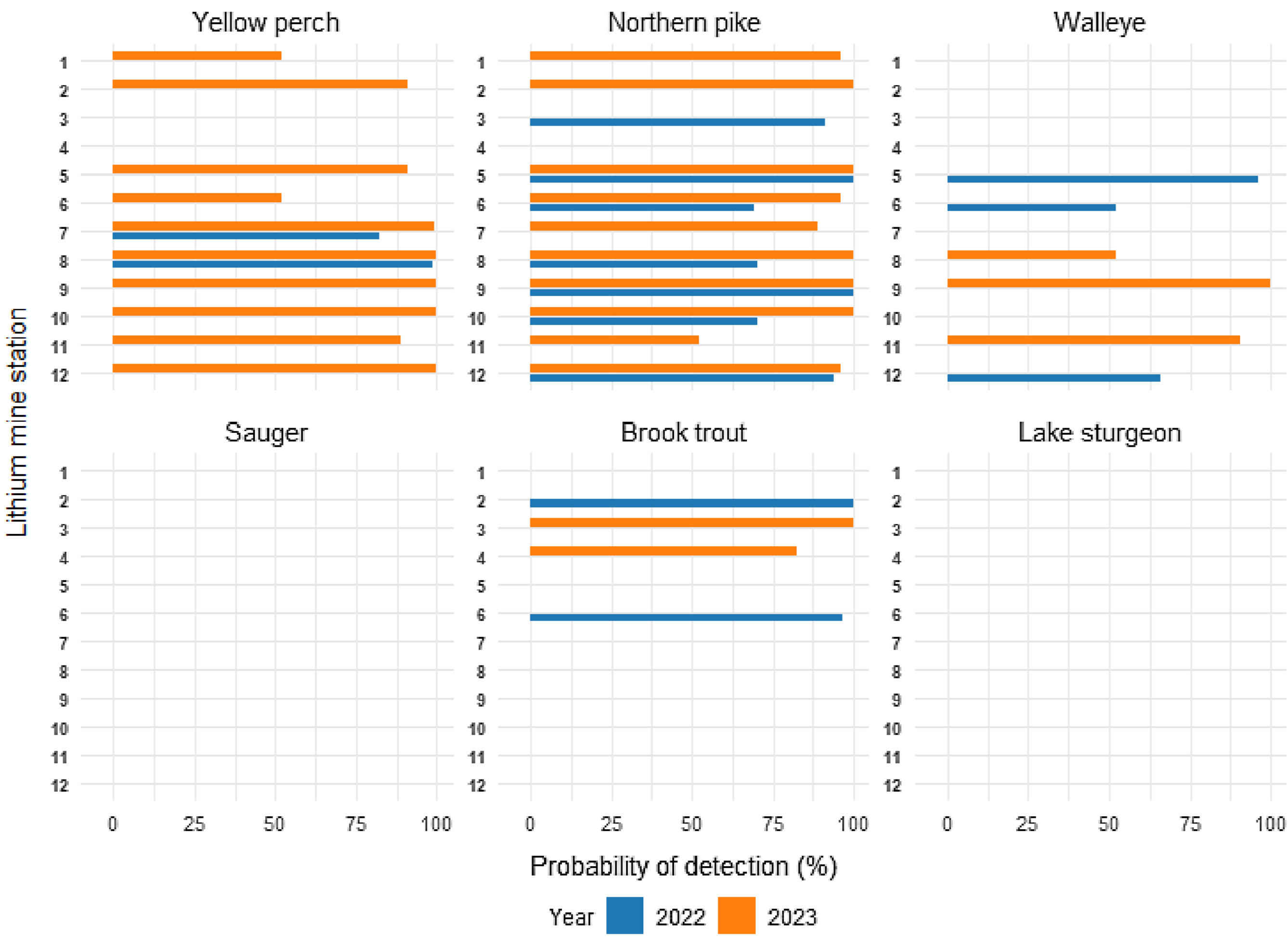

FIGURE 3 | Detection probability of fish species in stations around the lithium mining site.

Hg, Zn, Cd, and Pb exceeded protection criteria established by the MELCCFP and CCME in Opinaca reservoir (artificial reservoir immediately downstream of Éléonore mine) (Kaweshekami environnement 2023). Lithium extraction follows a different process, starting with the crushing of spodumene ore (a lithium-rich mineral), followed by flotation and treatment with sulfuric acid to produce lithium carbonate or lithium hydroxide (Livent Corporation 2023). Although the mine was not yet operational during the data collection for this study, 19,000 tons of spodumene were extracted during 2017 testing campaigns and remain stored on-site. No exceedances were found in relation to thresholds, which suggests that the current containment and control measures for the storage of raw mineralized spodumene on-site are effective. However, further monitoring is needed to confirm long-term effectiveness and ensure no potential impacts to aquatic ecosystems.

Mining activities are often associated with the potential for acid mine drainage (AMD), which can lower the pH of surrounding water bodies through the oxidation of sulfides found in extracted ores, including gold and lithium-associated minerals, leading to sulfuric acid formation (Simate and Ndlovu 2014). AMD can also reduce dissolved oxygen levels by consuming oxygen in chemical reactions and releasing metals such as lead (Pb), cadmium (Cd), and mercury (Hg), which may oxidize and further deplete oxygen levels in the water (Simate and Ndlovu 2014). However, at the study sites, all contact water and runoff undergo treatment at the mine's water treatment plant, where pH levels are adjusted before being released back into the environment. In addition, sulfate levels remained below 100 mg/L, which does not suggest significant acidification beyond what is expected from natural water conditions. pH levels at the upstream reference stations were also low, suggesting that the observed low pH may be attributable to the region's natural geochemical background—particularly given that the landscape is predominantly made up of wetlands, which are common in the boreal ecosystems, and play a significant role in soil acidity. The accumulation of organic matter and the production of humic and fulvic acids in water-saturated soils naturally lower pH levels, further influencing regional water chemistry (Calvo-Polanco et al. 2017). Furthermore, high chemical oxygen demand (COD) levels observed near the gold mine suggest the presence of organic material. Naturally occurring acidic cations in the soil, such as aluminum (Al^{3+}) and iron, can contribute to water acidification (Kopáček et al. 2009; Calvo-Polanco et al. 2017). These elements are present in significant concentrations at several stations, reflecting the region's geochemical composition. Moreover, the James Bay region of northern Quebec experiences some of the largest and most frequent fires across the North American boreal forest Boulanger et al. (2014); Ministère des Ressources naturelles et des Forêts (2024), with exceptional burned areas recorded in the area during the summer of 2023

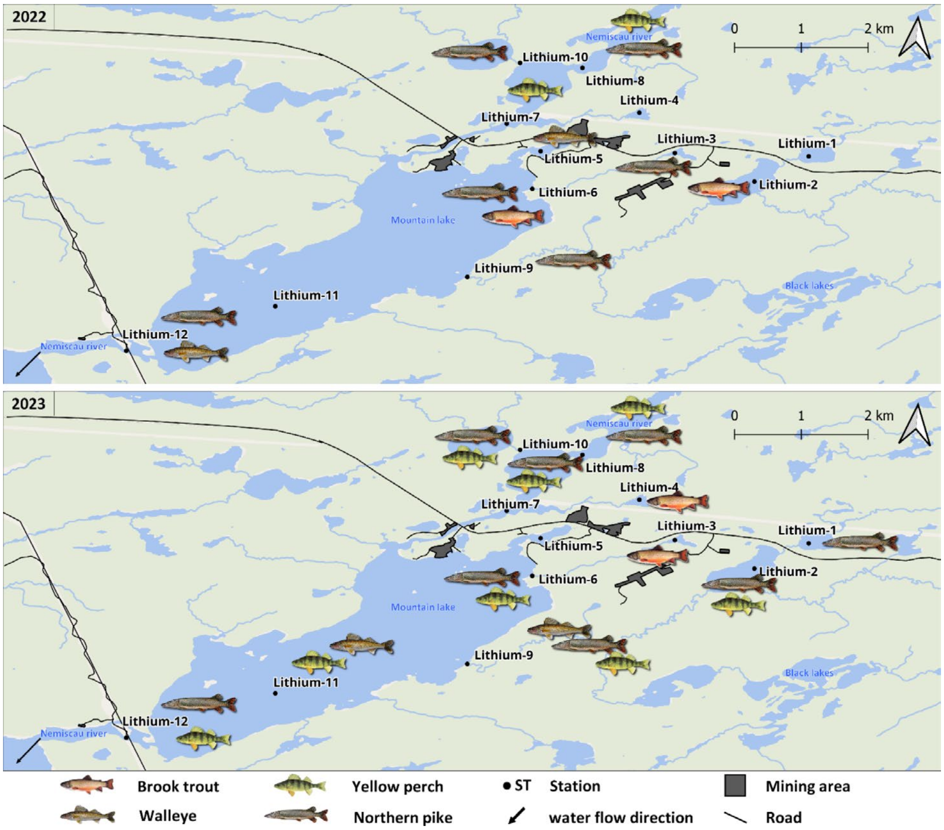

FIGURE 4 | Distribution of fish species around the lithium mining site. The map was produced using the free software QGIS v3.38.3. The base map was obtained from the Quebec government's public imagery service. The species represented on the map correspond to those detected at nearby sampling stations in 2022 and 2023.

(Boulanger et al. 2024, see Table S7). Wildfires have a substantial impact on the acidification of water bodies, primarily due to the increase in sulfate (SO_4^{2-}) levels in aquatic environments. This rise is largely attributed to the oxidation of sulfur compounds present in the soil and ash, which can dramatically elevate sulfate concentrations (Moazeni and Cerdà 2024). Low pH can impair fish growth and reproduction and may increase the solubility of heavy metals such as lead, cadmium, or copper, making them more bioavailable (Baldisserotto 2011). Although the species detected in this study generally prefer a pH range of 6.5 to 8.5, some like brook trout and yellow perch can tolerate these lower pH values (Table S6); however, their survival may be influenced by water hardness. Fish in low-hardness waters can experience physiological stress, as the low calcium and magnesium concentrations alter ion regulation Val et al. (1998). In this study, the total water hardness was very low at both sites, and survival rates for teleosts in acidic, soft waters are notably lower than in harder water conditions (Baldisserotto 2011).

Overall, aside from low pH levels, no significant contamination was detected in the physicochemical analyses despite the presence of mining sites and a geologically metal-rich background in the region. However, mining activities may still impact wildlife presence due to land-use changes that alter habitat structure. The analysis of eDNA successfully identified the yellow perch, Northern pike, walleye, and brook trout at both the gold mine and future lithium mine sites over two consecutive years; however, lake sturgeon and sauger were not detected. To further interpret eDNA presence results, several factors influencing species detection were investigated, including physical factors (hydrological, human construction), species-specific biological factors (preferred habitats, physicochemical parameter tolerance ranges, seasonality, and migration patterns), as well as environmental interactions (resource availability, inter- and intra-species competition).

4.2 | Presence of Species Around Mining Sites

Before the establishment of mining activities, various fish species were documented in the affected areas. Environmental reports prepared by Geodefor-Envirocree Ltd. for state agencies on the lithium mine indicate the presence of several fish species, including walleye, sauger, Northern pike, lake sturgeon, and brook trout, investigated in the present study, and also lake whitefish (*Coregonus clupeaformis*) and lake trout (*Salvelinus namaycush*) (Geodefor-Envirocree Itée 2011). Additionally, fishing surveys conducted for the gold mine technical report—prepared for Goldcorp Inc., —highlight that the most abundant species are lake whitefish, Northern pike, and walleye, with burbot (*Lota lota*), cisco (*Coregonus artedi*), longnose sucker (*Catostomus catostomus*), white sucker (*Catostomus commersonii*), and yellow perch also frequently found near the shoreline (Goldcorp Inc. 2018).

Two fish species were not detected at any of the sites (Figures 1 and 3). Lake sturgeon was not detected at either of our sites in 2022 or 2023, despite its historical presence in northern Quebec, including the James Bay watershed (Goldcorp Inc. 2018). Between 1974 and 1979, over 2000 sturgeons were harvested annually by local Indigenous communities in the region (Macdonald 2014). Regarding the lithium mine, the pre-exploitation report mentions the presence of sturgeon in nearby lakes and systems but not within the area of the mining site (Geodefor-Envirocree Itée 2011)). At the gold mine, however, the lake sturgeon is a special case, as mining authorization was granted in 2011 by the MELCCFP, on condition that the lake sturgeon population in the river flowing through the site be monitored. Lake sturgeon is also of great importance to the Cree Nation as an integral part of their traditional diet and cultural practices. The species is of special concern under the federal Species at Risk Act (SARA) and is listed as a "species susceptible to being designated as threatened or vulnerable" under Quebec's Ministère des Ressources naturelles et des Forêts (1989). Sturgeon populations are experiencing significant declines worldwide, primarily due to overfishing for meat and caviar, which has historically depleted their numbers beyond sustainable limits (COSEWIC Report 2006). In the James Bay and Northern Quebec Agreement (JBNQA) Territory, lake sturgeon belong to the federally designated Southern Hudson Bay—James Bay populations and face multiple contemporary threats. Hydroelectric development has significantly altered watersheds, reducing habitat connectivity, flooding critical areas, and disrupting sturgeon behavior. Additionally, forestry, mining, and unsustainable harvesting contribute to cumulative impacts that may further threaten populations and habitats (Cree Nation/DFO Threat Management Plan, 2025; UNEP, Appendix II 2021). In our study area, the construction of the mining site and the upstream hydroelectric dam, which created the artificial reservoir (Opinaca Reservoir) shown in Figure 2 near Station Gold#3, are further complicating their migration, as anthropogenic barriers are known to impede sturgeon movement Pfleger et al. (2016). However, it is important to note that the lake sturgeon is a reserved species for the Cree Nation, and non-Cree harvesting is prohibited in the James Bay Territory under Section 24 of the James Bay and Northern Quebec Agreement (JBNQA). The baseline report for the sturgeon monitoring program was completed in 2013, with population monitoring updates provided in 2016 and 2022 (Kaweshekami environnement 2023). The last surveys, conducted in July 2022, recorded a total of 12 sturgeon caught, fewer than in previous campaigns held in June. Three sturgeons were caught at station Gold#5 (Figure 2). Sturgeon primarily inhabits the river during the spawning period, when water temperatures range from 10°C to 16°C (Kaweshekami environnement 2023). The sampling campaigns in this study were conducted in August, likely after the spawning period, even though recorded water temperatures were around 16°C. Any remaining sturgeon presence may have been harder to detect due to their low numbers.

Sauger was also not detected at either sampling site, and no mention of this fish was found at the gold mine in the fishing campaign conducted in 2022 as part of the sturgeon monitoring program (Goldcorp Inc. 2018; Kaweshekami environnement 2023). This absence could be linked to the species' distribution, as government data suggest that sauger populations are primarily located further south of the studied mining sites (Ministère de l'Environnement, de la Lutte contre les Changements Climatiques, de la Faune et des Parcs 2021). Sauger is the most migratory percid in North America and depends on a variety of habitats, making it vulnerable to habitat fragmentation (Bozek et al. 2011; Loukmas 2023). This fragmentation is often caused by dams and infrastructure that block access to historical spawning sites, change the river's temperature and flow patterns, and reduce sediment levels Bellgraph et al. (2008). Similarly, mining activities can alter water currents. The sauger is physiologically adapted to low-light environments, thanks to its highly advanced light-gathering retina. Since turbidity is a key component of its habitat, changes in water clarity caused by mining or other developments can disrupt these conditions, potentially posing a significant threat to the species (Loukmas 2023). Sauger populations also face pressure from hybridization, which can affect their genetic integrity and viability Bozek et al. (2011). Sauger and walleyes compete due to significant overlap in their diets and habitat use, particularly during spring and summer when food resources are limited, but saugers are less tolerant of water quality changes, and environmental changes may favor walleyes and give them a competitive advantage Bellgraph et al. (2008). Given that walleye have been detected at both mining sites and that environmental changes are occurring due to human activities, it is plausible to consider that these factors may be responsible for the absence of sauger. Moreover, the northern pike, a predator of sauger, is abundant in the study area. Sauger DNA may also be less detectable as they tend to inhabit much greater depths, sometimes found at over 50 m Bozek et al. (2011). In contrast, our samples were collected at depths ranging from 0 to 10 m (see Tables S3 and S4).

Some species were detected at only a subset of the sampling stations. Brook trout is one of the least frequently detected fish in our study, and it is notably quite sensitive to alterations in environmental conditions. Indeed, brook trout require high levels of dissolved oxygen, with an increasing demand as water temperatures rise, a common trait among ectothermic organisms (Durhack et al. 2021), which is limiting at our mining sites. They are also highly sensitive to aluminum in acidic media, also the case in the studied mining area, as it can disrupt gill function by precipitating on the gill surfaces Teears et al. (2016). Additionally, brook trout populations are declining within their native range, strongly linked to human activities. One important factor contributing to their decline is deforestation, which can lead to increased sedimentation, higher water temperatures, and habitat fragmentation Thorn et al. (2016). Notably, the mining reports for the study sites indicate significant deforestation as part of the site preparation and infrastructure development (Geodefor-Envirocree Itée 2011; Goldcorp Inc. 2018). This habitat modification may explain why brook trout were found only upstream of the gold mine (Figure 2) but were more present around the lithium mine site (Figure 4). As mentioned earlier, forest fires are also common in the James Bay area, making the area even less favorable for this species.

Walleye was also partially detected in both mining sites and was also noted in the 2022 lake sturgeon monitoring report downstream of station Gold#4 (Figure 2) at the gold mine (Kaweshekami environnement 2023). Walleye shares a similar ecological niche with sauger but is more competitive, potentially contributing to the absence of sauger at certain sites Bozek et al. (2011). They can tolerate up to 2 mg/L of dissolved oxygen Bradford et al. (2008) and can consume fish approximately half their body length, demonstrating a versatile and opportunistic feeding strategy that allows them to maintain dominance in their habitat Baldwin et al. (2003). However, walleye faces significant predation pressure from piscivorous fish such as Northern pike, which can affect their population dynamics and distribution Bradford et al. (2008). The competition with Northern pike and changes in environmental conditions, such as water turbidity altered by mining activities, can influence the presence and detectability of walleye in these aquatic systems.

The Northern pike is one of the most frequently detected fish in our study, aligning with reports from technical documents for both mining sites (Geodefor-Envirocree Itée 2011; Goldcorp Inc. 2018). It was also observed during the 2022 lake sturgeon monitoring study at the gold mine, particularly at stations #4 and #5 (Kaweshekami environnement 2023). As a species of significant interest to humans, it has likely been translocated to new regions for centuries. It has largely expanded beyond its native range through both stocking efforts by natural resource agencies and some unauthorized introductions Bradford et al. (2008). This species acclimates well to a variety of conditions, with a thermal tolerance ranging from 0.1°C to 29.4°C and a notable resilience to variations in dissolved oxygen and pH levels, which pose no constraints on its presence at the sites studied (Bradford et al. 2008; Harvey 2009). Being non-migratory, it can be detected all year round Bradford et al. (2008).

The other most frequently detected species in our study is yellow perch, considered as invasive in some regions but a native species in the James Bay area. While it has difficulty navigating barriers due to being a poor swimmer, its adaptability and human-facilitated introduction have cemented its presence in many freshwater systems (Brown et al. 2009). Yellow perch shows remarkable resilience to challenging environmental conditions, tolerating low pH levels (documented as low as 3.9 in Ontario) and low dissolved oxygen concentrations (Brown et al. 2009). Predatory fish like Northern pike and walleye help regulate yellow perch populations Bradford et al. (2008) but their high thermal tolerance allows them to escape predation from less heat-tolerant species during warmer months, reducing the efficacy of native predators (Brown et al. 2009). Moreover, Northern pike hunt other planktivorous prey fishes, which leads to an increase in the abundance of zooplankton and benthic invertebrates in certain environments, to the benefit of yellow perch Bradford et al. (2008).

4.3 | eDNA As an Innovative Monitoring Tool

The presence of the various species monitored in this study seems to be explained by environmental parameters and interactions between the different species. Analyzing multiple fish species using eDNA provides insights into the dynamics between different fish species and their ecosystems. Studying trophic relations inside multitrophic communities with eDNA has already been documented and shows correlation between prey and predator species but also with aquatic pollution and land use (Qin et al. 2023; Riaz et al. 2023).

In the case of sturgeon, the use of eDNA has been widely explored in the literature for the detection of several species, including *Scaphirhynchus suttkusi*, *Acipenser oxyrinchus desotoi* Pfleger et al. (2016), *Acipenser oxyrhynchus* Plough et al. (2021), *Acipenser sinensis* (Yu et al. 2021), *Acipenser transmontanus* Crossman et al. (2024), *Acipenser medirostris* Bergman et al. (2016), *Acipenser ruthenus*, and *Acipenser stellatus* Abileva et al. (2023). Recent literature shows sturgeon detections with eDNA frequently align with seasonal migratory patterns for spawning (Abileva et al. 2023; Yu et al. 2021). Our campaigns failed to detect sturgeon, likely due to sampling late in the season. This monitoring approach could be integrated during spawning periods to track the presence and abundance of sturgeon. Some studies have also highlighted difficulties in detecting sturgeon, given that they are highly migratory and capable of covering hundreds of miles. It is therefore crucial to ensure an extensive detection range and reinforce spatial sampling efforts. Plough et al. (2021) noted that detections were weaker in deepwater habitats, which may further complicate monitoring. The authors also reported that shedding rates for eDNA were comparable to those of other fish species, suggesting that weak field detections are not necessarily due to low eDNA shedding rates but rather to factors such as migration timing, low abundance, or DNA degradation. (Crossman et al. 2024) demonstrated that sturgeon DNA can be detected in water up to 7 days, though this was observed under controlled laboratory conditions. However, in natural environments, DNA degradation occurs more rapidly, depending significantly on the differences between lotic (flowing water) and lentic (still water) systems Balasingham et al. (2017). While degradation occurs in both, factors such as dilution and transport via water flow can make detection more challenging in a lotic environment, as the flow can both dilute eDNA and facilitate its breakdown Balasingham et al. (2017). On the other hand, the homogenization of DNA in the water column is facilitated by the mixing of water in lakes, which can affect the persistence of eDNA (Hervé et al. 2022). Moreover, several factors accelerate eDNA degradation, such as microbial activity, high temperature, low pH, and UV exposure (Joseph et al. 2022; Hunter et al. 2017; Sahu et al. 2023; Strickler et al. 2015).

eDNA also facilitates the monitoring of invasive species, with effectiveness proven across multiple species in the literature. Comparative studies between traditional methods and eDNA demonstrate strong concordance in detecting invasive species (Jerde et al. 2011; LeBlanc et al. 2020; Dubreuil et al. 2022). Due to its high sensitivity, eDNA can enable rapid identification of new introductions, even at low population densities, which could be particularly relevant in the context of climate change and increasing human activities in northern ecosystems (Jerde et al. 2011; Ardura et al. 2015). This is particularly valuable, as invasive species pose a significant threat to ecosystems and can have substantial negative impacts on recreational and commercial activities in coastal communities (LeBlanc et al. 2020). Currently, few invasive species have been reported in Eeyou Istchee, but some species with expanding distributions, such as Northern pike, walleye, brook trout, and yellow perch, have been translocated beyond their historical ranges due to human activities (Baldwin et al. 2003; Bradford et al. 2008; Brown et al.

2009; Bozek et al. 2011). The use of eDNA has already been demonstrated for monitoring walleye, sauger (Dysthe et al. 2017), Northern pike (Dunker et al. 2016), brook trout (Nolan et al. 2023) and yellow perch (Bradley et al. 2022). These species show high adaptability, which can lead to their becoming invasive in non-native habitats, thereby causing ecological imbalances. While these species are native to parts of Quebec, their introduction into new habitats can disrupt ecological balances, particularly when they act as top predators or competitors. Top predators like Northern pike and walleye significantly reshape fish communities and alter food web dynamics (Baldwin et al. 2003; Bozek et al. 2011). Northern pike, for instance, exerts strong predatory pressure, reducing prey and competing species, including sensitive salmonid populations (Bradford et al. 2008). Similarly, yellow perch disrupts plankton communities, creating cascading ecosystem effects and competing with salmonids like brook trout for resources (Bradford et al. 2008). The use of eDNA for long-term monitoring could provide valuable insights into potential future shifts in species distributions, particularly in response to environmental changes and anthropogenic pressures such as mining.

The simplicity of water sampling makes eDNA an accessible and time-effective tool. In the context of mining facilities, where water sampling is already part of environmental protocols, it would be feasible for companies to set aside water samples for both chemical and eDNA testing. Storing water on filters requires minimal space and maintains sample integrity, making eDNA monitoring highly adaptable for industries like mining. This method's ease of use, requiring only a water sample, also makes it suitable for community-led monitoring efforts. Indigenous communities, for example, could easily adopt eDNA sampling, allowing them to play a hands-on role in conservation, as in Canada, biodiversity is deeply connected to Indigenous cultures that rely on natural resources for both sustenance and cultural practices (Vogel and Bullock 2021). For example, for the Cree of Eeyou Istchee, lake sturgeon holds historical and cultural significance, used in its entirety for various purposes, underscoring its role in Cree traditions (COSEWIC Report 2006). Other fish species, such as brook trout, remain a dietary cornerstone, reflecting the importance of these resources in Cree cuisine and culture Limoges (2019).

5 | Conclusion

This study provides a first environmental DNA (eDNA) baseline of fish biodiversity at two sites under mining pressure in northern Quebec. Across four sampling campaigns, we detected several culturally and ecologically important fish species, including yellow perch, Northern pike, walleye, and brook trout, while others such as lake sturgeon and sauger were not detected under our sampling conditions. While no clear signal of widespread contamination was found in surface waters, occasional exceedances of heavy metal concentrations in mine effluents, combined with naturally acidic soils and recurring wildfires, suggest that the region's aquatic ecosystems are subject to complex environmental pressures.

Rather than conducting a methodological assessment of eDNA, this study demonstrates its practical application as a tool to establish species presence in remote or logistically challenging areas, where conventional surveys are limited or absent. By focusing on species of concern near mining operations, eDNA allowed the detection of fish in ecosystems with altered hydrology and water quality, where physical sampling may be impractical or ecologically disruptive.

Despite its strengths, eDNA remains limited in the ecological information it provides—notably on demographic structure, age, health, or the status (alive or dead) of individuals at the time of sampling. These gaps could be addressed by other techniques, such as environmental RNA (eRNA) or transcriptomic, which have the potential to provide additional insights into population health and ecosystem conditions, particularly for microorganisms that are difficult to track with other methods. Additionally, eDNA does not yet allow for precise individual quantification; although semi-quantitative estimates can be made relative to standards. The use of eRNA may help resolve this limitation, enabling better quantification of target species. While still in development, eRNA is a promising complement to eDNA for monitoring biodiversity, especially in areas impacted by human activities. Moreover, eDNA has been chosen for its high sensitivity and precision in detecting target species. However, this approach requires selecting specific species to monitor; whereas techniques like metabarcoding could offer a broader screening of biodiversity, allowing for the detection of a wider range of organisms in a given environment.

In conclusion, this study highlights the value of targeted eDNA monitoring for documenting species presence in remote regions where conventional surveys are scarce. The results contribute to establishing a biodiversity baseline near mining sites and emphasize the relevance of eDNA as a decision-support tool for conservation. Including indicator species—organisms particularly sensitive to environmental changes—could further strengthen the monitoring of ecosystem health in such contexts. These species can serve as early warning signals of environmental degradation, such as changes in water quality or habitat integrity. Such approaches can be integrated into long-term monitoring programs to better anticipate ecological shifts and support the sustainable management of natural resources essential to local communities.

Author Contributions

F.S. have made major contributions to the analysis, the interpretation of the data and writing of the manuscript. T.A.T. have made major contributions to the conception or design of the study, the acquisition and analysis. J.C. have made major contributions to the conception or design of the study, the acquisition and analysis. A.C.B. have made major contribution to the interpretation of the data. V.S.L. have made major contributions to the conception or design of the study.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

In accordance with the journal's data-sharing policies, qPCR data are provided as Supporting Information in the manuscript appendices, while raw data are available upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information