Canadian Journal of Fisheries and Aquatic Sciences

OPEN ACCESS | Communication

# Potential loss of salmonid spawning habitat in the Arctic due to rusting rivers

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## Abstract

Permafrost thaw is a disturbance impacting high-altitude and high-latitude environments. In northern Alaska, permafrost thaw is driving the mobilization of metals from soils and degrading the water quality of Arctic rivers. Due to the weathering of sulfide mineral deposits, river reaches can appear orange due to iron oxides either suspended in the water or deposited on the substrate creating the appearance of rusting rivers. A primary concern about rusting rivers is the negative effect on spawning habitat due to increasing metal concentrations above toxicity thresholds in surface waters or altering hyporheic flow. We examined the spatial overlap between spawning habitat of Dolly Varden (*Salvelinus malma*) and rusting river degradation in northwest Alaska using a time-series of satellite imagery. Annual overlap between total Dolly Varden spawning area and degraded habitat ranged from 0% to 21% from 1986 to 2024. Spatial overlap of degraded water and spawning habitat varied temporally amongst watersheds. Spatial and temporal variability in the overlap of degraded water and spawning habitat indicates a complex interaction between rusting rivers, fish, and aquatic food webs.

**Key words:** spawning habitat, rusting rivers, Dolly Varden (*Salvelinus malma*), permafrost thaw, acid rock drainage

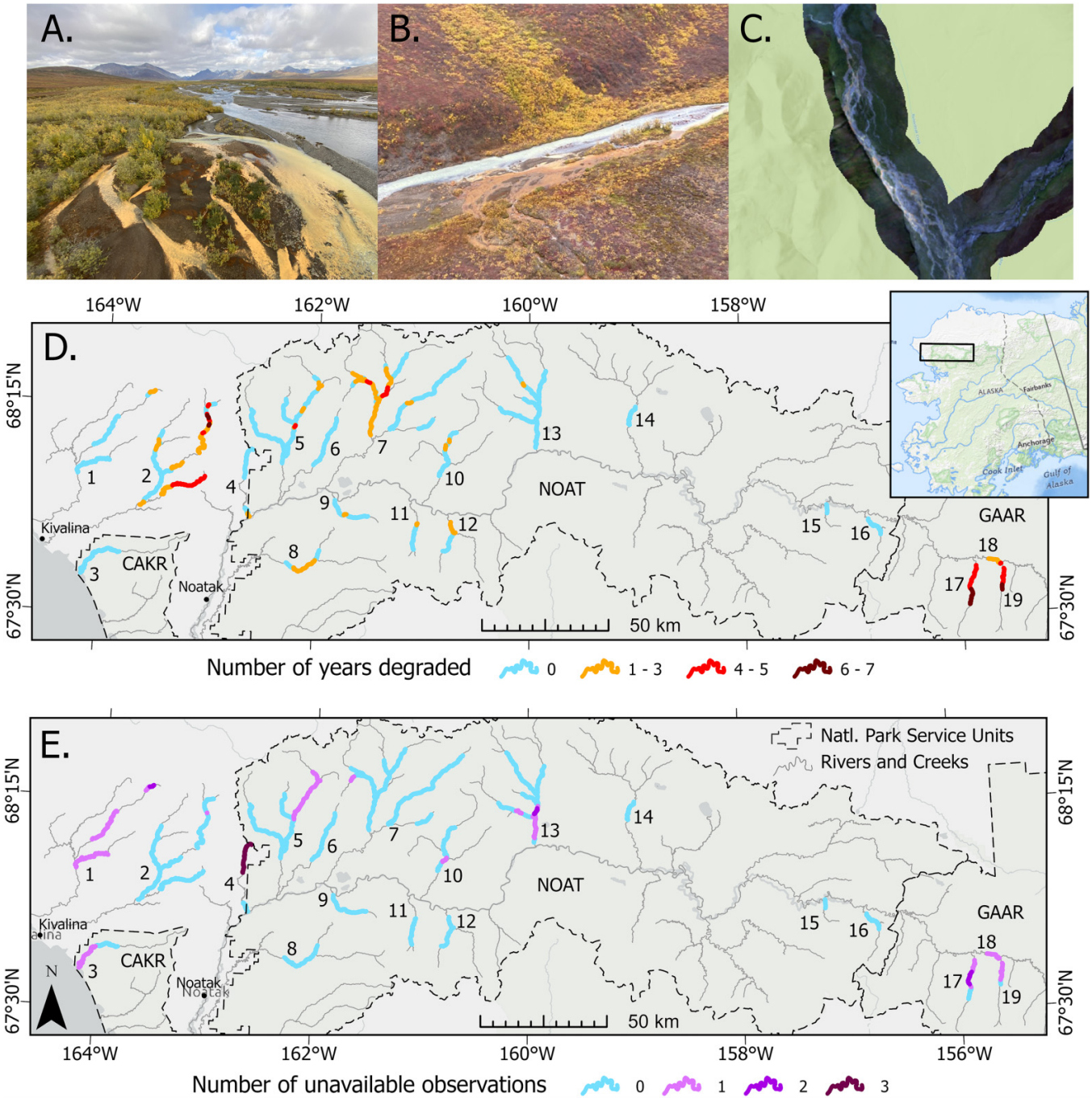
## Introduction

Permafrost thaw is a pervasive disturbance in the Arctic impacting surface waters (Smith et al. 2015; O'Donnell et al. 2024). Changes in stream hydrology and chemistry from permafrost thaw can have myriad effects on aquatic food webs (O'Donnell et al. 2024; Carey et al. 2025). A recent thaw-driven phenomenon is the rusting of Arctic rivers in which abrupt changes in the color and clarity of river reaches occur, reflecting a dramatic shift in water quality with consequences for food webs (O'Donnell et al. 2024; Figs. 1A and 1B). The change in water quality is due to subsurface metals and other ions being transported from the surrounding catchment to rivers. Metals concentrations can exceed U.S. Environmental Protection Agency chronic exposure thresholds for toxicity to aquatic life (Sullivan et al. 2025). While the spatial extent, landscape processes, and potential toxicity have been documented, there are many concerns about the impact of rusting rivers on Arctic ecosystems.

One of the largest concerns of rusting rivers is the impact of metals on fishes, especially species such as Dolly Varden (*Salvelinus malma*) that are important for recreational and subsistence harvest (DeCicco 1985; Brown et al. 2023). Dolly Varden populations are susceptible to water quality degradation due to rusting rivers (O'Donnell et al. 2024) because of the freshwater stages of its life history (Carey et al. 2021 and references therein). Dolly Varden spawn in freshwater streams and anadromous fish remain for two to five years before migrating to coastal areas where they grow more rapidly (Carey et al. 2021). Thereafter, they feed annually in saltwater during summer and migrate to freshwater each fall to overwinter or spawn, following a facultatively anadromous life history strategy. This anadromous strategy can include skipping an ocean migration to remain in freshwater to spawn the following fall, a strategy that becomes more common with age (Bond et al. 2015; Gallagher et al. 2018). Dolly Varden also have freshwater resident populations (Carey et al. 2021).

The different life history strategies and stages create several instances in which Dolly Varden could be affected by elevated concentrations of metals as shown for other salmonids (Sergeant et al. 2022). Direct toxicity to adult fish returning to spawn or freshwater residents could occur from iron accumulation on gills and in tissue leading to structural impairment of the gills, DNA damage, and decreased survival (Egnew et al. 2021). Other metals such as cadmium, aluminum, zinc, and copper can be acutely toxic (Mebane 2006; Monette and McCormick 2008). Further, the mineral weathering reactions

**Fig. 1.** Images of differences in degradation across channels in the Kugururok River (A), degraded water quality including aluminum precipitation (milky, blue color) in the Salmon River in the Kobuk River drainage (B), and a satellite composite image of the Kugururok River (Sentinel-2 - image courtesy of European Space Agency, ESRI topographic basemap) (C). Map of study region (D) in northwest Alaska, USA showing the number of years of degradation of spawning habitat. A year of degradation was considered for 1986, 2002, 2010, 2016, 2018, 2019, 2020, 2023, and 2024. The rivers identified with Dolly Varden spawning habitat (color segments) by DeCicco (1985) are [1]Kivalina River, [2]Wulik River, [3]Omikviorok River, [4]unnamed tributary at Noatak River km 158, [5]Kelly River, [6]Avan River, [7]Kugururok River, [8]Eli River, [9]Kivivik Creek, [10]Kaluktavik River, [11]Akikukchiak Creek, [12]Nakolik River, [13]Nimiuktuk River, [14]Anisak River, [15]Spring Creek, [16]Kavachurak Creek, [17]Igning River, [18]upper Noatak River, and [19]Kugrak River. The map indicates the national parklands in the region Cape Krusenstern National Monument (CAKR), Noatak National Preserve (NOAT), and Gates of the Arctic National Park and Preserve (GAAR), AK. Map of the rivers and spawning habitat (E) indicating the number of years observations were unavailable in remote sensing imagery. For (D) and (E), base maps from Esri and its licensors, copyright 2026. Select hydrography from USGS National Hydrography Dataset. Park boundary from USGS National Boundary Dataset (NBD) in Alaska. Alaska Albers projection, North American Datum of 1983 (2011), latitude–longitude coordinate system.



that release metals also produce sulfuric acid, which can dramatically lower the pH of tributaries in northern Alaska (O'Donnell et al. 2024); pH levels below 5 are typically harmful for fish, and the acidification increases metal toxicity (Smith et al. 2015). Rusting rivers may also impede upstream migration to overwintering or spawning habitats as fish avoid toxic conditions (Sergeant et al. 2022). For other life-history stages, egg mortality could occur due to metal toxicity or altering hyporheic flow by interstices restriction and/or armoring sediments, both of which could reduce the flow of oxygen and nutrients, while emerging fry could be exposed to lethal conditions from metal toxicity when entering the surface water of a degraded river (Sergeant et al. 2022). This study represents a first step in assessing the influence of rusting rivers on Dolly Varden by evaluating the spatial and temporal overlap between degraded water and spawning habitat.

## Methods

*Remote sensing*: Spawning habitat of Dolly Varden was estimated by digitizing maps developed by DeCicco (1985) that inventoried Dolly Varden habitat in the Brooks Range of Alaska; these maps comprise the only available dataset. While the spatial extent has not been reassessed, spawning by Dolly Varden continues to be observed in the watersheds (Schwanke and Johnson 2016). The spatial extent of spawning habitat was derived by selecting line segments from the National Hydrograph Data (U.S. Geological Survey 2023) flow path vector dataset. We identified locations and historical coverages of degraded reaches across rivers using a time-series of satellite imagery. Degradation, defined as any discolored water or stained sediment, was manually detected in natural color composite images (red, green, and blue) by visually identifying changes in color over time (Baughman et al. 2025; Supplement). Degraded water and stained sediment can be recognized by high reflectance in the red, orange, or yellow tones associated with precipitation of iron oxides (Fig. 1A, Supplement). In limited cases, white or milky blue colors represent precipitation of aluminum (Caraballo et al. 2019; Fig. 1B). Previous water quality measurements have documented that high levels of metals occur with the observed discoloration (O'Donnell et al. 2024). Next, the spatial extent of degradation was recognized using contrast in color associated with stained sediment or surface-waters. We conservatively did not classify downstream reaches as degraded if there were not obvious color tones and change over time.

Cloud-free composite images (Fig. 1C) were derived in Google Earth Engine (Gorelick et al. 2017) from Landsat satellite scenes (https://www.usgs.gov/landsat-missions/landsat-satellite-missions) for years between 1986 and 2010 and Sentinel-2 satellite imagery (https://sentinels.copernicus.eu/web/sentinel/copernicus/sentinel-2) after 2016. Landsat is the best resource for providing multispectral images to assess historical degradation, while Sentinel's superior resolution is better after 2016. Scenes were included between day of year 213–258 when summer thaw is most pronounced (O'Donnell et al. 2024 and references therein). Some Dolly Varden spawning also occurs during this time (DeCicco 1985). We validated accuracy of Landsat- and Sentinel-based interpretation by comparing degradation classification to independent high resolution satellite imagery (Baughman et al. 2025; Supplement). Further details on image selection criteria and compositing can be found in Baughman et al. (2025).

To evaluate spawning habitat degradation across years and rivers, we calculated the ratio of degraded and clearwater river segments within spawning habitat across the region and within individual rivers (Fig. 1D). Our conservative approach assumed missing observations were clearwater. Next, we qualitatively assessed changes in degradation of spawning habitat exploring spatial and temporal patterns amongst rivers.

## Results

Dolly Varden spawning habitat identified by DeCicco (1985) was estimated to be 692.3 (±3.9) km of river length. The proportion of river reaches available varied annually with the least visible amount in 1986 (Table 1). Missing observations were distributed throughout the region except for multiple missing years in one tributary (Fig. 1E). The total percentage of degraded spawning habitat in each year observed ranged between 0% and 21% across the region and varied amongst rivers (Table 1). For example, a maximum of 51% of the spawning habitat was degraded in the Wulik River, 29% of the spawning habitat was degraded in Kugururok River, and other longer spawning areas such as the Kelly River had less than 8% degraded spawning habitat amongst years (Table 1). Similarly, shorter spawning areas were variable; Kivivik Creek that had a maximum of 6% degraded spawning habitat, while the spawning habitat in the Igning and Kugrak Rivers became completely degraded (Table 1). Other rivers like the Nimiuktuk and Omikviorok Rivers did not show degraded water in the spawning areas.

Imagery from 2010 shows the onset of initial degradation of spawning habitat with progressive increases in coverage that reach maxima in 2020 across multiple rivers (Table 1). Degraded spawning habitat decreased in 2023 and 2024 from the maxima in 2020 (Table 1). The first degraded locations were identified in the Wulik River and Igning River in 2010 and then observed in the Kugrak River in 2016 (Table 1). The spatial extent of degraded water expanded in 2019 to include spawning habitat in the Kivalina River, Kelly River, and Kugururok River. In total, 15 of the 19 rivers had degraded spawning habitat in at least one year. Across the region with available observations, 123.5 km (17.8%) are degraded 1–3 years, 47.2 km (6.8%) are degraded 4–5 years, and 10 km (1.4%) are degraded for 6–7 years (Fig. 1D). The reaches found to be degraded 6–7 years are the initial observations of degraded spawning habitat.

Changes amongst rivers showed different temporal patterns in the extent spawning habitat was degraded within a river (Table 1). For instance, increasing degradation occurred in the upper Noatak River that increased from 0% in 2018 to 75% degradation in 2024. In contrast, recovery occurred within the Eli River, where 54% of the spawning habitat degraded in 2020, but recovered to clearwater conditions in 2023 and 2024. In the Wulik River, the percentage of de-

**Table 1.** Overlap of degraded water from rusting rivers on Dolly Varden (*Salvelinius malma*) spawning habitat (DeCicco 1985) in northwest Alaska.

| | Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1986 | 2002 | 2010 | 2016 | 2018 | 2019 | 2020 | 2023 | 2024 |
| Observed spawning area (692.3 km) | 88 | 91 | 97 | 96 | 100 | 100 | 100 | 99 | 100 |
| Impaired spawning area | 0 | 0 | 1 | 2 | 5 | 12 | 21 | 18 | 11 |
| (1) Kivalina River (43.63 km) | 0 | 0 | 0 | 0 | 0 | 7 | 5 | 0 | 0 |
| (2) Wulik River (107.97 km) | 0 | 0 | 3 | 2 | 5 | 28 | 48 | 51 | 19 |
| (3) Omikviorok River (31.04 km) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (4) Unnamed Tributary* (23.71 km) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 |
| (5) Kelly River (92.25 km) | 0 | 0 | 0 | 0 | 1 | 2 | 8 | 3 | 1 |
| (6) Avon River (23.27 km) | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| (7) Kugururok River (127.94 km) | 0 | 0 | 0 | 0 | 1 | 12 | 29 | 27 | 12 |
| (8) Eli River (20.02 km) | 0 | 0 | 0 | 0 | 0 | 0 | 54 | 0 | 0 |
| (9) Kivivik Creek (20.24 km) | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 |
| (10) Kaluktavik River (24.78 km) | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 11 | 3 |
| (11) Akikukchiak Creek (12.29 km) | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 0 | 0 |
| (12) Nakolik River (16.01 km) | 0 | 0 | 0 | 0 | 0 | 0 | 36 | 36 | 5 |
| (13) Nimiuktuk River (90.2 km) | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| (14) Anisak River (9.56 km) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (15) Spring Creek (3.79 km) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (16) Kavachurak Creek (10.7 km) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (17) Igning River (18.33 km) | 0 | 0 | 13 | 100 | 100 | 100 | 100 | 95 | 100 |
| (18) Upper Noatak R. (6.8 km) | 0 | 0 | 0 | 0 | 0 | 6 | 6 | 19 | 75 |
| (19) Kugrak River (9.83 km) | 0 | 0 | 0 | 100 | 100 | 100 | 100 | 100 | 100 |

**Note:** The total percentage of spawning habitat observed by remote sensing is indicated for each year along with the percentage of degraded spawning habitat for each river across years. The length of the spawning habitat is indicated for each river next to each river name in parentheses. The orange shading highlights years degraded water was observed in the spawning area and within individual rivers. The darker shade of orange indicates the maxima of observed degradation across years.
*Unnamed tributary on Noatak River at 152 river km from mouth.

graded spawning habitat increased from 3% to 51% between 2010 and 2023, followed by a decrease in 2024 to 19%. Reaches of the Wulik River displayed different temporal patterns with consistent historical degradation (i.e., close to headwaters and degraded 6–7 years) versus reaches with fewer but more recent years of degraded water (Table 1) due to the downstream expansion of degraded spawning habitat (Fig. 1D). The spatial expansion of degraded habitat also occurs in the Kugururok River and Igning River. The difference in the Kugururok River from the Wulik and Igning Rivers is the expansion upstream.

## Discussion

We documented spatial overlap between known spawning areas of Dolly Varden and degraded water quality from rusting rivers; however, degraded spawning habitat exhibited spatial variability amongst rivers, with a gradient from rivers with completely degraded spawning habitat to clearwater. Spatial variability is likely driven by local factors within watersheds such as mineral and soil lithology, geomorphology, and groundwater hydrology with metal loads often sourced from hillside seeps that impact mainstem rivers directly or through tributaries (O'Donnell et al. 2024).

The overall temporal trend of increased degraded water in spawning habitat of Dolly Varden is concurrent with the timing of rusting rivers observed throughout the region (O'Donnell et al. 2024) with recent, increasing degradation in spawning habitat peaking in 2020. Several of the spawning areas follow this pattern, but there is spatial and temporal variability in the timing of degradation and apparent recovery (e.g., Eli River). Determining if the expansion within rivers is due to increasing downstream effects from the same source or increasing sources could help understand mechanisms driving the expansion of rusting rivers. Multiple drivers of temporal variation are likely, including differences in permafrost thermal state, groundwater, and precipitation (O'Donnell et al. 2024). Overall, the spatial variability within and across spawning areas interacts with processes driving temporal changes creating a complex pattern that needs to be understood to assess the consequences of rusting rivers for fish populations.

The goal of this study was to assess the overlap of rusting rivers with Dolly Varden spawning habitat. We used a conservative approach to visually characterize degraded spawning habitat that likely underestimated the amount of degraded spawning habitat. Our classification was limited to bold, perceivable color change likely related to iron precipitation. We classified locations as degraded when these conditions were pronounced and assume that some portion of downstream reaches is still degraded but not apparent. Metals can accompany iron precipitation but also remain in solution as pH climbs, iron precipitation ceases, leading to clearer water (O'Donnell et al. 2024). Thus, the system becomes visu-

ally clear water but may still contain elevated metal concentrations. We also assumed that spawning habitat above a degraded reach was still available to spawners; however, we suspect that fish in highly degraded rivers may be prevented from accessing upstream spawning habitat due to poor water quality creating a barrier to fish passage. Lastly, there are areas and years missing observations due to unavailable remote sensing imagery, which were considered clear water in the comparison across years and amongst watersheds. Even if degraded spawning habitat is underestimated, population level effects could occur if the loss of spawning habitat from rusting rivers is commensurate with reduced spawning success.

Future research could further quantify changes in water quality from remote sensing via automated approaches, examining the response of each life history stage, and assessing how spawning fish respond to fine scale spatial differences in degraded spawning habitat such as in the Kugururok River, where braided river channels differ in degradation (Fig. 1A). Furthermore, it is unknown whether Dolly Varden could switch to previously unused habitat and maintain similar levels of spawning success. Addressing the temporal and spatial variability and consequences of rusting rivers for Dolly Varden could also inform predictions for other species in the region. For instance, Chum Salmon (*Oncorhynchus keta*) use these same watersheds and are important subsistence and commercial species (DeCicco 1985).

## Acknowledgements

Project support included USGS-NPS Natural Resources Partnership Program, the USGS Ecosystems Mission Area, and the National Park Service's Arctic Network. We thank Chris Sergeant for insights on a previous version and Chris Zimmerman for helping conceptualize the project. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

## Article information

### History dates

Received: 3 March 2026
Accepted: 14 July 2026
Version of record online: 20 August 2026

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### Data availability

All data are available at Baughman, C.A., Carey, M.P., and Koch, J.C. 2025, Historical extent of metal mobilization within Dolly Varden (*Salvelinus malma*) spawning habitat of the Noatak River drainage based on Landsat and Sentinel data, 1986-2024: U.S. Geological Survey data release, https://doi.org/10.5066/P13MQRCB.

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### Competing interests

The authors declare there are no competing interests.

## Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2026-0061.

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