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ARTICLE

Acoustic Telemetry Reveals the Complex Nature of Mixed-Stock Fishing in Canada's Largest Arctic Char Commercial Fishery

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Abstract
Climate change is having a myriad of effects on Arctic ecosystems, yet understanding how these changes will influence the spatiotemporal dynamics of harvest in northern commercial fisheries remains unclear. Furthermore, stock mixing continues to complicate fisheries management in Arctic Canada, especially for anadromous stocks, but data on the extent and degree of stock mixing for the majority of northern fisheries are scarce. Here, we used a multiyear (2015–2019) acoustic telemetry data set to test the utility of acoustic telemetry as a potential tool for inferring stock mixing in the Arctic Char *Salvelinus alpinus* commercial fishery in Cambridge Bay (Nunavut). We also assessed the effect of annual variation in environmental variables (river breakup and marine ice conditions) on the potential contribution of discrete stocks to commercial harvest at several fisheries. We found that stock mixing during the commercial harvest is common in both marine and freshwater fisheries during the summer/open-water season, with virtually all stocks potentially being susceptible to harvest at any given commercial fishery. Additionally, in some fisheries, the vulnerability of different stocks to harvest was influenced by annual differences in marine ice and river breakup conditions. We discuss options for fisheries management, including a potential quota-transfer system, and highlight how changing environmental and climatic conditions may have an effect on the commercial harvest of Arctic Char in the region. Overall, the results of this study demonstrate the utility of acoustic telemetry for informing mixed-stock fisheries while highlighting the complex and pervasive nature of stock mixing in Canada's largest Arctic Char commercial fishery.

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Climate warming in the Arctic is outpacing that in most other regions on Earth (Serreze and Barry 2011; IPCC 2014), resulting in significant influences on aquatic ecosystems, including its effects on subsistence and commercial fisheries resources at high latitudes (Galappaththi et al. 2019; Falardeau et al. 2022). For example, climate change has resulted in warming sea surface temperatures and downward trends in marine ice thickness and marine ice duration and it has affected river discharge dynamics in the Arctic (Serreze and Barry 2011; Box et al. 2019). Climate warming has also led to northward range expansions of temperate species (i.e., the "borealization" of Arctic marine habitats; Fossheim et al. 2015; Falardeau et al. 2022), changes in interspecific interactions and marine food web reorganizations (Yurkowski et al. 2018), and phenological changes in animal migrations, especially in anadromous fishes (Reist et al. 2006; Madsen et al. 2020).

These ecosystem-level changes have implications for ecosystem-based fisheries management (Grimm et al. 2013; McMeans et al. 2013), including for anadromous salmonids (Holsman et al. 2019). For example, variability in the timing of migrations between freshwater and marine environments, which is influenced by river breakup and sea ice conditions (Moore et al. 2016; Hammer et al. in press), may be altered under future climatic conditions (e.g., Falardeau et al. 2022). This could potentially affect the vulnerability of discrete stocks (the fundamental unit of management that ideally represents demographically and genetically independent populations or groups of populations; Reiss et al. 2009) to harvest in commercial and subsistence fisheries that are typically restricted in time (i.e., over a matter of days to weeks) and space (i.e., only occurring at a specific water body location). In Arctic Canada, data are scarce and there is a paucity of information on the effects of climate-induced variability in environmental conditions on commercial and subsistence fishery dynamics (Roux et al. 2019; Tallman et al. 2019).

Anadromous fishes support a variety of commercial, recreational, and subsistence fisheries in the Canadian Arctic (Watts et al. 2017; Galappaththi et al. 2019). The concentration of fish both spatially (i.e., in restricted river channels or in restricted foraging and overwintering habitats) and temporally (e.g., during concerted downstream and upstream migrations) results in anadromous fishes being especially susceptible to harvest (e.g., Bradbury et al. 2016). In the Arctic regions of Canada, mixed-stock fishing, the simultaneous harvest of multiple discrete stocks (Utter and Ryman 1993; Manel et al. 2005), is a pervasive issue for fisheries that target anadromous salmonids (Gallagher et al. 2013, 2020; Harris et al. 2016a, 2016b). However, the management of anadromous stocks in the Arctic assumes discrete populations, applying quotas on a river-by-river basis (Roux et al. 2011, 2019). Indeed, quantitative stock assessment models typically assume discrete stock units (i.e., single, homogeneous population), an assumption that is often not met in real-world fishery scenarios (e.g., Hart and Cadrin 2004), which has major implications for model output, certainty, and interpretation (Cadrin 2020). In Canadian Arctic Char *Salvelinus alpinus* populations, for example, there is accumulating evidence that many discretely managed fisheries are in fact mixed-stock fisheries (Moore et al. 2014; Harris et al. 2016a, 2016b), which could affect sustainable resource use (Utter and Ryman 1993; Crozier et al. 2004; Allendorf et al. 2008). Stock mixing can lead to the unintentional overharvesting of less productive stocks (Crozier et al. 2004; VanDeHey et al. 2010), which is undoubtedly a major concern for long-term population persistence and the conservation of intraspecific biodiversity (Hilborn et al. 2003; Schindler et al. 2010). Quantifying the relative contributions of different stocks to commercial and subsistence harvest is thus a priority. Furthermore, the extent of stock mixing could vary between years in relation to differences in climatic or environmental variability that affect fish movements, habitat use, and/or the nature and timing of fishing. For example, the timing of river breakup would influence when Arctic Char could access marine habitats where they would be vulnerable to harvest, and marine ice conditions would influence specific habitat use while at sea (Bégout Anras et al. 1999; Hammer et al. 2022). However, there are limited multiyear data sets that have assessed such possibilities.

Acoustic telemetry has emerged as a powerful tool that is used in fisheries research to investigate spatial and temporal aspects of habitat use, movements, and migrations across several scales from individuals to ecosystems (Hussey et al. 2017). It has provided valuable data that are applicable to habitat management, defining specific areas that warrant protection, and defining management units (Crossin et al. 2017; Hussey et al. 2017; Brooks et al. 2019). However, acoustic telemetry has rarely been used for understanding mixed-stock fishery dynamics (but see Moore et al. 2016; Faust et al. 2019) despite this technology being nonlethal, which allows for potential mixed-stock fishery scenarios that involve single individuals that are tracked over an entire fishery and over multiple years (i.e., over the lifetime of the transmitter battery).

Anadromous Arctic Char have been vitally important to the Inuit across northern Canada, who have relied on this species for millennia (Friesen 2002, 2004). For example, Arctic Char are harvested in every community in Nunavut and continue to be the foundation of food security across the territory (Priest and Usher 2004; Watts et al. 2017). Commercial fisheries for Arctic Char also exist in Nunavut, where they contribute substantially to local economies while providing seasonal and full-time employment to Nunavummiut throughout the year (Kristofferson and Berkes 2005; DFO 2014). The largest commercial fishery for Arctic Char in the territory, with an annual available quota of ~56,000 kgs, takes place near the community of *Iqaluktuuttiaq* (Cambridge Bay) on southern Victoria Island in Nunavut's Kitikmeot Region (Harris et al. 2021). There are currently five active commercial water bodies in this fishery, including (from west to east) areas locally known as Palik (Lauchlan River or Byron Bay), Halokvik (Halokvik River; 30 Mile), Paliryuak (Surrey River), Ekalluktok (Ekalluk River), and Jayko River (Table 1; Figure 1), which is managed based on river- or water-body-specific quotas, assuming that each river represents a discrete stock (Kristofferson and Berkes 2005: DFO 2014).

Arctic Char have a complex life history in that they use multiple habitats throughout their life. Spawning and rearing occurs in freshwater, and at ~4–5 years of age they undertake downstream migrations to marine habitats in late-June and early-July, where they forage for ~45 d (Moore et al. 2016; this study). After foraging in marine habitats, Arctic Char in the region must return to freshwater every fall to overwinter regardless of their reproductive status (i.e., even if they are not going to spawn; Johnson 1980). That is, the upstream migration is composed of individuals who are returning to freshwater for both spawning and overwintering purposes, while some are returning solely to overwinter. Thus, this species is vulnerable to harvest in multiple habitats, including lacustrine spawning and overwintering habitats, riverine downstream and upstream migratory corridors, and marine and estuarine foraging habitats. Existing evidence suggests that stocks of Arctic Char in the Cambridge Bay region mix while foraging at sea (Moore et al. 2016; Harris et al. 2016b). More recently, genomic and telemetry evidence also suggests that the discrete stocks of Arctic Char in the region mix while overwintering in Ferguson Lake (Moore et al. 2017). This is the last lake draining the Ekalluk River system and has the shortest migration distance in the region between summer marine foraging and freshwater overwintering habitats (Moore et al. 2017). Therefore, in terms of overwintering habitat choice, Ferguson Lake is most appealing in nonspawning years given the lower energetic demands of migration needed to access this area. It is also the largest lake on Victoria Island, with depths >30 m recorded (Harris et al. 2020a), suggesting this lake likely has a very large carrying capacity for overwintering Arctic Char. There are likely multiple spawning stocks of Arctic Char in the Ekalluk River system (Kristofferson 2002); therefore, commercial harvest of the downstream and upstream runs at this fishery may also be composed of a mixture of discrete stocks that are natal to this watershed. Finally, it has also been suggested that the Surrey River has a very limited anadromous run of Arctic Char (Kristofferson 2002), so all fish harvested at this fishery are thought to originate from other stocks in the region—namely, the Ekalluk River (i.e., Kristofferson et al. 1984; Dempson and Kristofferson 1987; Moore et al. 2016; Harris et al. 2016b). This hypothesis was initially based on mark–recapture evidence and a failed enumeration (Kristofferson et al. 1984; Dempson and Kristofferson 1987; Kristofferson 2002); however, more recent genetic

TABLE 1. Fishery details for the commercial harvest of Arctic Char in the Cambridge Bay region, Nunavut. Shown are the dates of fishing and commercial harvest at the Lauchlan, Surrey, and Ekalluk river fisheries during 2015–2019 and notes on how each fishery was executed; na = not available.

Fishery	Year	Fishing dates	Harvest (kg)	Notes
Lauchlan[a] (LAU)	2015	na	na	Gill-net fishery targeting the dowstream run of Arctic Char as they enter marine habitats. Nets are set in the river mouth, estuary and adjacent marine habitats.
	2016	na	na	
	2017	na	na	
	2018	Jul 19–26	3,902	
	2019	Jul 9–20	5,061	
Surrey (SUR)	2015	Jul 6–20	9,082	Gill-net fishery targeting the dowstream run of Arctic Char as they enter marine habitats. Nets are set in the river mouth, estuary, and adjacent marine habitats.
	2016	Jul 12–23	5,739	
	2017	Jul 8–22	8,990	
	2018	Jul 6–20	8,792	
	2019	Jul 5–22	8,792	
Ekalluk (EKA)	2015	Aug 18–Sep 1	18,279	Gill-net fishery targeting Arctic Char in Ferguson Lake after they have returned to freshwater for overwintering subsequent to summer foraging in marine habitats.
	2016	Aug 14–Sep 1	20,011	
	2017	Aug 18–Sep 1	20,001	
	2018	Aug 19–30	16,570	
	2019	Aug 18–Sep 5	16,699	

[a]The Lauchlan River was not commercially harvested during 2015–2017 because the 2,400 kg quota in place at the time was not economically viable. In 2018, the quota was increased to 5,000 kg. The dates that were used to determine the potential for mixed-stock fishing at that site were estimated from historical harvest records (see Methods).

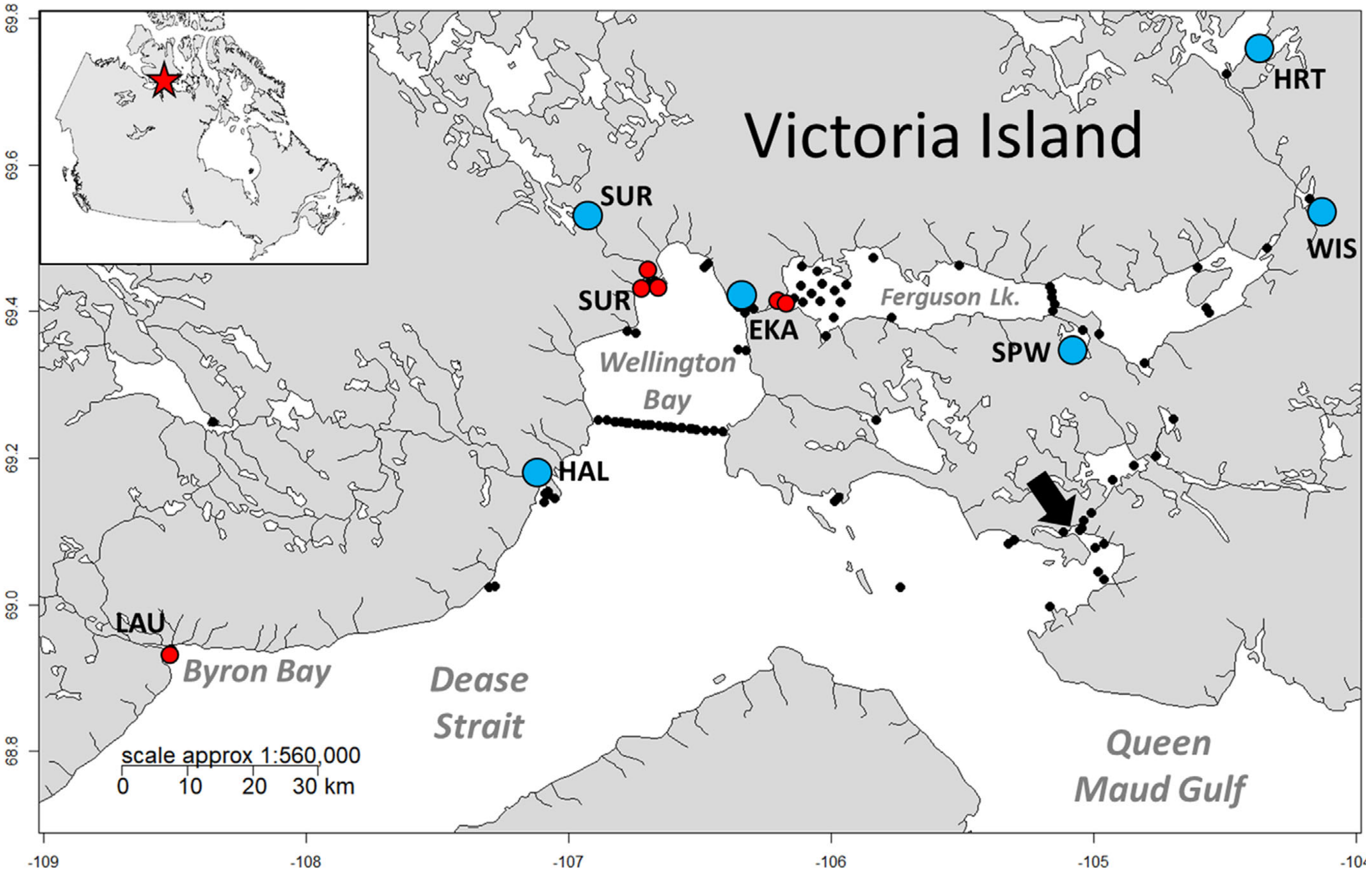

FIGURE 1. Study area on southern Victoria Island within the Kitikmeot Sea region of Nunavut showing all stations within our acoustic telemetry array (black dots), "fishery" stations used for examining the potential contribution of discrete stocks to mixed-stock harvest at commercial fishing locations (red circles), and acoustic tagging locations (blue circles). The location of the community of Cambridge Bay is shown with a black arrow. The commercial fishery and tagging information including the codes that were used in this figure are described in Tables 1 and 2.

and acoustic telemetry evidence has corroborated this idea (Moore et al. 2016; Harris et al. 2016b). Therefore, it is quite clear that stocks of Arctic Char in the Cambridge Bay region likely mix extensively at several locations and at multiple times during the year (i.e., during summer foraging and while overwintering), with potential implications for the river-specific management of Arctic Char that is currently in place in the region (e.g., Reiss et al. 2009).

The purpose of the study was to use an existing data set to test the utility of acoustic telemetry as a tool for mixed-stock analysis of commercial fishery harvest. Specifically, we sought to describe the mixed-stock harvest of Arctic Char in the Cambridge Bay region by using data from an acoustic telemetry array that has been in operation since 2013 and where over 500 individuals have been tracked (Moore et al. 2016, 2017; Harris et al. 2020a). Our major objectives were to (1) determine whether there was mixing of different stocks at commercial fishing locations at the time that commercial fisheries typically operate and whether there were fishing locations where such mixing was more common and (2) to assess the possible effects of year-to-year variation in environmental variables (e.g., date of river breakup and marine ice cover) on stock mixing and contributions to harvest. Given previous genetic (Harris et al. 2016b), genomic (Moore et al. 2017), and tagging data (Dempson and Kristofferson 1987; Moore et al. 2016) available for Arctic Char in the region that suggests that stocks mix at multiple times during the year in multiple habitats, we hypothesized that acoustic telemetry would reveal the mixing of discrete stocks specifically at commercial fishing locations during the commercial harvest. We also predicted that annual variation in river breakup and marine ice conditions, which influence the timing of migration between freshwater and marine habitats and their spatial distribution at sea, respectively, would influence the stock contributions of Arctic Char at commercial fishing locations. For example, a later river breakup may result in Arctic Char accessing marine habitats where commercial fisheries occur after the early-season commercial fisheries (see below for a description of the commercial fisheries in the region) have concluded for some stocks. All told, documenting stock mixing and quantifying its environmental correlates has important practical applications for fishery management in this region.

METHODS

Study area, fishery descriptions, and acoustic array.— This study took place on southern Victoria Island near the community of Cambridge Bay in Nunavut's Kitikmeot region (Figure 1). Here, we have been conducting a long-term (2013–present) acoustic telemetry study in collaboration with the Ocean Tracking Network (Cooke et al. 2011) to better understand the temporal and spatial aspects of Arctic Char migrations and habitat use in both marine and freshwater environments. The marine area in this region, referred to as the Kitikmeot Sea (Williams et al. 2018), is characterized by shallow depths and relatively lower salinity and nutrients compared with other marine areas of the Canadian Arctic (Back et al. 2021).

As described above, there are five active commercial water bodies in the region, four of which occur in Wellington Bay and the surrounding area (note that the Jayko fishery does not occur in the Wellington Bay area). The Lauchlan and Surrey fisheries target the downstream run of Arctic Char in early July, when they are entering marine habitats for summer foraging (Table 1). These are gill-net fisheries, with nets typically set at the river mouths, in estuaries, and in adjacent marine habitats. The Halokvik fishery is a galvanized conduit pipe weir fishery (see Kristofferson et al. [1986] and Harris et al. [2020b] for details) that targets Arctic Char in the river during their upstream return migration in late summer. Finally, the Ekalluk fishery, the largest in the region, is a gill-net fishery that takes place in Ferguson Lake that targets Arctic Char once they have returned to freshwater from marine habitats in the late summer (Table 1).

Our specific study area within the Kitikmeot Sea extended from the Lauchlan River, where it enters the ocean at Byron Bay east to Cambridge Bay (Figure 1). Within that area, we have focused extensively on Wellington Bay, where three commercial rivers drain, and on Ferguson Lake, with the intent of monitoring the timing of migrations between freshwater and marine environments of the Ekalluk River stock. The overall spatial coverage of our array is shown in Figure 1.

Since 2013, the acoustic array has had 100 receivers deployed throughout the region considered here. However, for this study, we focused on locations where and when commercial fishing occurred from 2015 to 2019 (Table 1; Figure 1). This included one station in Byron Bay at the mouth of the Lauchlan River, three stations at Surrey River (one within the river proper and two in the estuary), and two stations in Ferguson Lake at the commercial fishing camp (Figure 1). The Halokvik River was not included because we were not able to effectively place an acoustic station within the river near the commercial weir. Detailed descriptions of our array are found in Moore et al. (2016) and Harris et al. (2020a).

Tagging locations and procedure.— We tagged Arctic Char at six locations (i.e., putative contributing stocks) within our study area, including several presumed spawning locations within the Ekalluk River system (Table 2; Figure 1). First, in 2015, we tagged Arctic Char at the mouth of the Ekalluk River ($n = 75$) during the downstream run in early July. The intent was to target Arctic Char from the Ekalluk River system that had just spent the winter in Ferguson Lake and were entering marine habitats for foraging purposes. As described above, however, it is possible that this tagging event could include fish from several different stocks in the region that use Ferguson Lake for overwintering purposes. That same year, also in early July, we tagged Arctic Char at Little Surrey Lake ($n = 42$), which is the last lake draining the Surrey River system (Figure 1). Our intent was to ensure that we were tagging Arctic Char that were natal to the Surrey River system. Tagging Arctic Char at the mouth of the Surrey River during the commercial harvest would likely result in multiple stocks being tagged (Kristofferson et al. 1984). In 2016, we tagged Arctic Char at two spawning locations (Spawning [$n = 23$] and Wishbone [$n = 19$] lakes) in the Ekalluk River system to assess how distinct stocks within this system may mix outside of the spawning season (i.e., when foraging and overwintering). Finally, in 2017, we tagged Arctic Char at a third spawning site (Heart Lake [$n = 19$]) in the Ekalluk River system and at Halokvik River ($n = 19$) in late August during their upstream migration (Table 2; Figure 1). Fish that are tagged at Halokvik River are presumed to be Arctic Char that are natal to that system given the energetic requirements of a 50-km migration to spawning/overwintering areas (i.e., it is unlikely a fish would migrate that distance solely to overwinter; see Moore et al. 2017).

The tagging procedure that was used in this study is described in detail by Moore et al. (2016). Briefly, Arctic Char were captured (1) using gill nets that were continually monitored in order to reduce the time the fish was entangled, (2) using a commercial weir where candidate Arctic Char were removed with a dip net (Halokvik River only), or (3) by angling. Arctic Char that were selected for surgical implantation of transmitters were placed into an anesthetic bath (buffered 75 ppm tricaine methane sulfonate [MS-222] solution). Once anesthetized, the Arctic Char were measured for fork length (to ±1 mm) and round weight (to ±25 g) and were then placed ventral side up in a V-shaped tagging cradle while being provided with

TABLE 2. Summary of Arctic Char tagged in this study, including the location of tagging, location code, year, dates of tagging, and length and weight information for each site. Also indicated here is the number of fish that were tagged at each site and the subsequent number of fish that were detected and used in the analyses. The length and weight data are for all tagged fish.

Location/source	Code	Year	Number tagged	Number detected	Dates	Length (mm) (mean ± SD)	Weight (g) (mean ± SD)
Ekalluk River	EKA	2015	75	66	Jul 9–11	729 ± 83	4,103 ± 1,212
Little Surrey Lake	SUR	2015	42	26	Jul 14–17	697 ± 59	3,603 ± 985
Spawning Lake	SPW	2016	23	18	Aug 14–15	761 ± 62	4,601 ± 1,056
Wishbone Lake	WIS	2016	19	14	Aug 20–21	734 ± 6	4,247 ± 833
Halokvik River	HAL	2017	19	8	Aug 16–17	727 ± 83	4,397 ± 1,246
Heart Lake	HRT	2017	19	5	Aug 22–23	671 ± 52	3,345 ± 698

a constant stream of a maintenance solution (50 mg/L MS-222) over the gills. An incision (~4 cm in length) was made on the ventral side of the fish, anterior to the pelvic fins and just to the left of the fish's center, and the transmitter was then inserted into the body cavity. Simple interrupted stitches (3–0 curved needle, monofilament) were used to close the incision, a T-bar anchor tag was affixed to the left dorsal area of the fish posterior to the dorsal fin, and the fish was placed in a tub of fresh water until it recovered. All surgical tools as well as the transmitters were sterilized in betadine prior to and between each surgery.

The Arctic Char were acoustically tagged with V16 (high power) transmitters (Innovasea). Our acoustic tagging was approved by the Fisheries and Oceans Canada Animal Care Committee for each year of study, and the procedure conforms to all animal care laws in Canada (permit no. FWI-ACC-2015-2019). The acoustic tags had a nominal delay of 30 or 45 s, and the life of the transmitters ranged from 1,533 to 2,233 d, allowing us to track Arctic Char over multiple years. The details for the acoustic tags that were used in this study, including their programming, are shown in Table S1. The detection ranges in our study area are generally above 50% within 500 m of the receivers (Moore et al. 2016).

Environmental data collection.— We compiled river flow and sea ice data for each year of the study that we predicted could have an influence on the spatial and temporal aspects of marine habitat use. We also extracted river flow and sea ice data dating back nearly four decades (1980–2019) to assess how both of these variables have varied over the long term. River breakup would influence transition times between freshwater overwintering and marine foraging habitats. That is, early breakup would allow Arctic Char to access marine habitats earlier, influencing their susceptibility to harvest. Sea ice would influence specific habitat use (vertically and horizontally) when the fish are in the marine environment. River breakup was determined using the daily average flow (discharge) values that are reported from Freshwater Creek gauging station (10TF001) that is operated by the Environment Canada Water Office near the community of Cambridge Bay. The discharge data were extracted from the Environment and Climate Change Canada Historical Hydrometric Data website (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html) on January 21, 2021. Three approaches, listed here in priority order, were used to assign breakup date. (1) The first day of positive daily average flow was used to represent the onset of the melt season for Freshwater Creek for each year of record where the gauging station was operational. The breakup date for 2015 was determined this way. (2) The day of year with the highest daily average flow (peak flow) was used in combination with the breakup dates to perform a linear regression for the period of record (1973–2019). The linear regression model was then used to predict breakup date for years when no data were available at the beginning of the melt season. This method was used for 2016, 2017, and 2019. In 2019, the peak flow date was determined from water-level data, measured using Solinst leveloggers (model 3,001). (3) Field notes were used to approximate a breakup date for 2018 because data were not reported from the Freshwater Creek gauging station during breakup or peak flow in that year. More details on the methods that were used to determine breakup date are available in the supplementary information. Next, we extrapolated the timing of sea ice breakup (i.e., 50% sea ice concentration; Falardeau et al. 2022) in the marine study area from weekly ice charts that are provided by the Canadian Ice Service (https://iceweb1.cis.ec.gc.ca/IceGraph/page1.xhtml?lang=en). Specifically, we used a logistic regression on weekly ice data to estimate the day of year that corresponded to 50% marine ice cover.

Data analysis.— The total number of detections was filtered to remove false and erroneous detections from our study using the OTN SandBox application in R (R Core Team 2018), which employs the White-Mihoff false filtering tool (White et al. 2014). Several fish were identified to have perished (based on the return of tags from fish that were harvested or from immobile tags) and postmortality detections from those fish were removed from all analyses.

The detection data were plotted by date and time for every tag ID to provide a visual depiction of the temporal presence and absence of tagged individuals. The detection data were plotted for each year of the study, focusing on the dates when Arctic Char would be migrating between freshwater and marine habitats (i.e., June 1–September 15) when individuals would be most vulnerable to exploitation. Outside of these dates, commercial fishing is not taking place and Arctic Char would be overwintering in freshwater habitats where they are likely not foraging and have reduced movement activity (Dutil 1986; Mulder et al. 2018). For each plot, the dates for each commercial fishery, date of breakup, and date of 50% ice cover were overlaid on the daily detection data for Arctic Char to assess patterns and associations. Stations were characterized as commercial fishing stations (described above) or grouped into other freshwater or marine stations, not including commercial stations. Duration at sea for individuals was determined following Moore et al. (2016). Marine entry was determined as the first marine detection that occurred after the last freshwater detection, and the date of freshwater return was recorded using the first freshwater detection that occurred after the last marine detection.

We then filtered for detections of Arctic Char at the Lauchlan, Surrey, and Ekalluk fisheries, specifically when the commercial harvest of Arctic Char was occurring for each year of the study (Table 1). For each fishery, we then determined the number of detections and the number of unique individual fish from each contributing stock (Table 2). The Lauchlan River was not commercially fished during 2015–2017, and the dates that were used to determine the potential for mixed-stock fishing at that site were estimated from historical harvest records (i.e., July 6–27; Day and Harris 2013). Our stations were removed from Ferguson Lake in 2019 prior to commercial fishing at this location, so no data were available for that year.

Given the potential biases that are associated with a few individuals generating the majority of detections at a given station (or commercial fishing location in our case), we also calculated a commercial site residence index ([RI]; e.g., Kessel et al. 2016) to further evaluate the potential contributions of the Arctic Char from Surrey and Ekalluk rivers to the mixed-stock commercial harvest. Specifically, we calculated an RI of the entire contributing stock for both the Surrey and Ekalluk rivers. These stocks were chosen given that they had the largest sample sizes and number of years of data. The mean RI was calculated for each contributing stock as the total number of days that individuals from that stock were detected at a specific station or group of stations, as described above, meant to represent the commercial fishing location divided by the total number of days individuals from that stock were detected anywhere on the entire acoustic array across the study system. The RI values ranged from 0 (indicating no residency near any given station) to 1 (indicating 100% residency at a particular station). For each commercial fishery, we also calculated the RI for the Surrey and Ekalluk river stocks for three periods: (1) 2 weeks prior to commercial fishing, (2) during commercial fishing, and (3) 2 weeks after the commercial fishery. This was done to evaluate how potential contributions to harvest at a commercial fishery may vary temporally within a fishing season and to assess whether specific stocks are more susceptible at different times. Finally, beta regressions were run separately to test the relationship between the RI of an Arctic Char stock during the commercial harvesting period at a fishery (e.g., Surrey River fish RI at the Ekalluk fishery) and 50% marine ice cover or river breakup in separate models. Beta regression was used because RI represents a fraction of time spent in a specific area and therefore provides a continuous proportional value ranging from 0 to 1 (Douma and Weedon 2019). Beta regressions were fit using betareg version 3.1-4 (Zeileis et al. 2021) in *R* with $\alpha \leq 0.05$.

RESULTS

A total of 197 Arctic Char were acoustically tagged from six locations between 2015 and 2017 (Table 2). Eighteen acoustically tagged Arctic Char were recaptured in local commercial and subsistence fisheries, half of which were harvested in the Ekalluk River commercial fishery (Table 3). Of the 197 tagged Arctic Char, 163 were detected at least once within our overall array, generating a total of 5,239,409 detections during the study period: July 10, 2015–August 27, 2019. Filtering the acoustic data set to include only the stations that were located specifically at commercial fishing sites resulted in 99,575 detections and 137 individuals that were used for the subsequent analyses (Table 2).

Environmental Data

The date of river breakup was highly variable, with a 25-d difference between the earliest (May 29, 2015) and latest date (June 23, 1986 and 2003) from 1980 to 2019 (Figure 2). There was no significant trend in the breakup date during the study period ($P = 0.5$), although later years tended to have earlier breakup dates. The date of 50% sea ice concentration was also highly variable among years, with the earliest and latest date differing by 34 d (from July 6 in 2017 to August 9 in 1986; Figure 2). The marine ice cover trended significantly toward earlier breakup throughout the entire marine ice time series (Figure 2, $P <$ 0.01). The date of 50% marine ice cover and date of river breakup were also correlated ($r = 0.48$, $P < 0.01$).

TABLE 3. Summary of acoustically tagged Arctic Char that were recaptured in commercial and subsistence fisheries during this study. All recaptured individuals were removed from the analyses once harvested.

			Fishery recapture location			
Tagging location/fishery	Number tagged	Number recaptured	Lauchlan	Surrey	Ekalluk	Other
Ekalluk River	75	7	0	0	4	3
Little Surrey Lake	42	5	0	2	3	0
Spawning Lake	23	4	0	2	1	0
Wishbone Lake	19	1	0	0	1	0
Halokvik River	19	1	0	0	0	1
Heart Lake	19	0	0	0	0	0

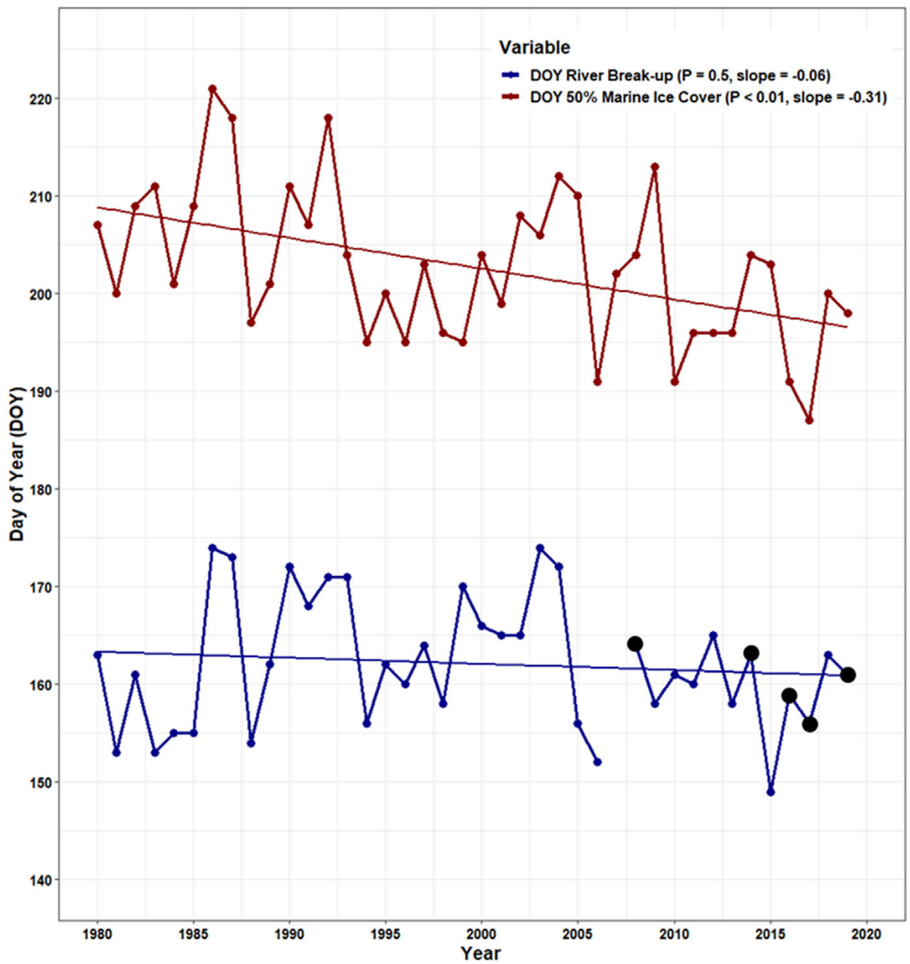

FIGURE 2. Marine ice and river breakup conditions in our study area. Shown are the date (day of year [DOY]) of 50% marine ice cover and date of river breakup from 1980 to 2019 (see the Supplementary Material for details). The black circles for DOY for river breakup represent data points that were estimated using regression analysis or from field notes (see Methods).

Acoustic Detections and Stock Mixing

Our acoustic telemetry data suggested that multiple stocks contribute to the Cambridge Bay Arctic Char commercial fishery and that there was some variation in potential contributions to harvest depending on the year and where the fish were being harvested. The results for daily detections across all years are shown in Figures S1–S9. Generally, Arctic Char that were tagged in this study from each discrete stock were detected at each of the commercial fisheries during the commercial harvest (Figure 3).

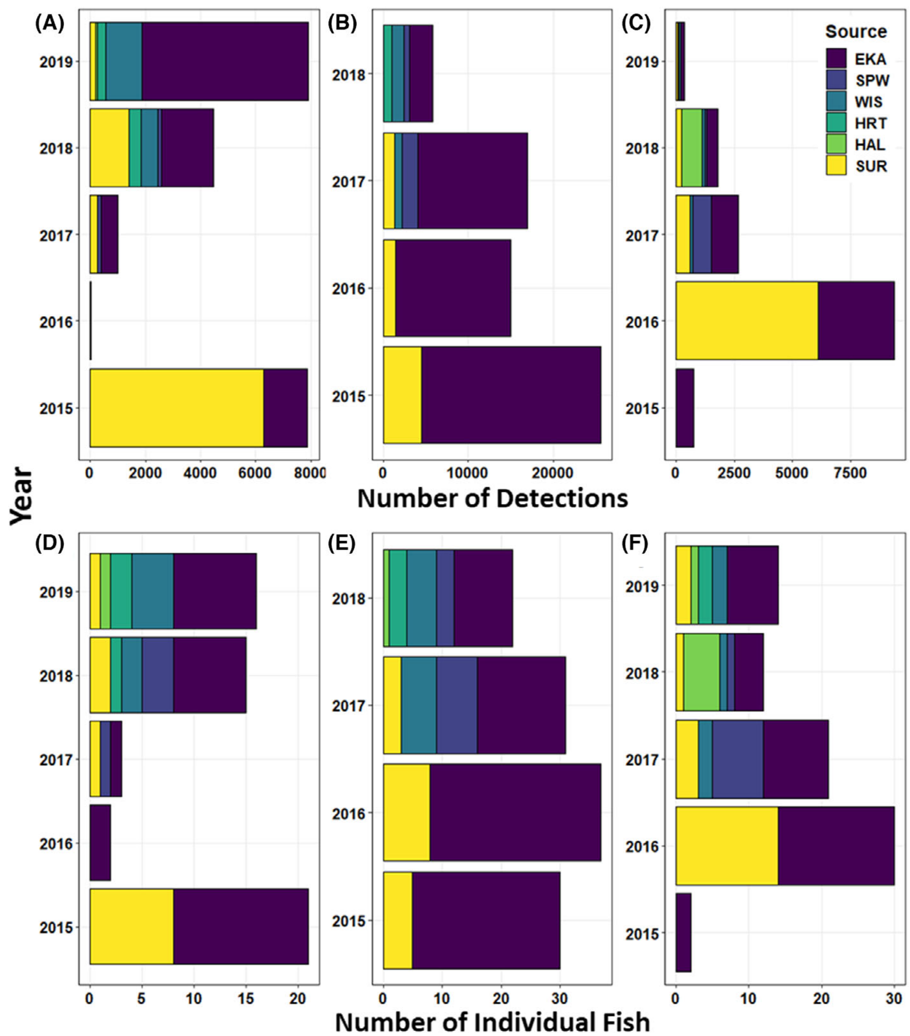

FIGURE 3. Potential contributions of discrete stocks of Arctic Char in **(A, D)** the Cambridge Bay region to the Surrey River commercial fishery, **(B, E)** the Ekalluk River fishery, and **(C, F)** the Lauchlan River fishery. Shown for each fishery are the potential contributions by the number of detections (top) and by the number of individual fish. The commercial fishery and tagging information including the codes that were used in this figure are described in Tables 1 and 2.

Arctic Char were never detected in the marine environment before river breakup, and the majority of daily detections corresponded to the dates of presumed marine entry and return to freshwater. The earliest date of marine entry across the entire study was June 17 (in 2017), and the latest date of freshwater return was September 15 (in 2018). Among individual fish, the number of days spent in marine habitats varied from 5 to 78 (mean duration at sea across all individuals/years = 48.8 d).

The number of detections and individual fish potentially contributing to each fishery in each year of the study is shown in Table 4, and the proportion of potential contributions of each stock (by detections and individual fish) is shown in Table S2. At each commercial fishing location, multiple stocks were detected almost every year of fishing. At the Surrey River commercial fishery, Arctic Char that were tagged at the Ekalluk River and at discrete spawning sites within that system dominated the potential contributions to harvest (Table 4; Figure 3A, D). For example, the tagged fish from Ekalluk River and those that were tagged at discrete spawning locations in this system, combined, constituted between 61.9% (2015) and 100% (2016) of the fish that were detected during the Surrey River fishery (Table S2). Anadromous Arctic Char that were tagged in Little Surrey Lake contributed between 0.00% (2016) and 38.1% (2015) of fish that were detected during the Surrey River fishery (Table 2). The potential contributions from this site also decreased from 2015 to 2019 at the Surrey River fishery. Arctic Char from Halokvik River that were tagged in 2017 were detected during this fishery in 2018.

TABLE 4. Shown are the number of detections and corresponding number of individual fish from each contributing stock (i.e., tagging locations) recorded at each commercial fishing location during the commercial fishery. See Table 2 for the location codes. The Lauchlan River was not commercially harvested during 2015–2017 and dates that were used to determine the potential for mixed-stock fishing at that site were estimated from historical harvest records (see Methods), as indicated by an asterisk (*).

		Contributing stock (number of detections)						Contributing stock (number of individual fish)					
Fishery	Year	EKA	SUR	SPW	WIS	HRT	HAL	EKA	SUR	SPW	WIS	HRT	HAL
Lauchlan	2015*	757						2					
	2016*	3,286	6,084					16	14				
	2017*	1,173	615	797	94			9	3	7	2		
	2018	458	233	105	82		901	4	1	1	1		5
	2019	190	67		54	56	2	7	2		2	2	1
Surrey	2015	1,606	6,277					13	8				
	2016	43						2					
	2017	632	273	113				1	1	1			
	2018	1,882	1,418	132	625	427		7	2	3	2	1	
	2019	6,027	183		1,298	313	86	8	1		4	2	1
Ekalluk	2015	21,063	4,542					25	5				
	2016	13,497	1,492					29	8				
	2017	12,798	1,299	1,934	874			15	3	7	6		
	2018	2,649		688	1,460	943	47	10		3	5	3	1

At the Ekalluk River fishery, the only lake fishery, stock mixing was also observed (Table 4; Figure S10; Table S2). Across all years, tagged Arctic Char from Ekalluk River dominated the potential harvest at this fishery (Table 4; Figure 3B, E). Arctic Char that were tagged at Little Surrey Lake were detected during 2015–2017, contributing 9.7% (2017) to 21.6% (2016) of detected Arctic Char (Figure 3B, E; Table S2). The discrete spawning stocks that were tagged in the Ekalluk River system (Spawning, Wishbone, and Heart lakes) were also detected during the commercial fishery in 2017 and 2018 (Figure 3B, E; Table S2). One tagged Arctic Char from Halokvik River was detected during the Ekalluk River commercial fishery in 2018 (Figure 3B, E; Table S2). Finally, individuals from all contributing stocks were detected at the Lauchlan River commercial fishery at least once during the commercial harvest (Table 4; Figure 3C, F). Arctic Char that were tagged in Ekalluk River were detected the most during this fishery, recorded in all years of the study. The Arctic Char that were tagged at Little Surrey Lake were detected every year, with the exception of 2015 (Table 4; Figure 3C, F). Tagged Arctic Char from Halokvik River constituted over 51% of Arctic Char ($n = 5$) detected at the Lauchlan fishery in 2018 (Table S2).

Across all years, RI values (for the Ekalluk and Surrey stocks) during each of the commercial fisheries ranged from 0.00 to 1.00 (0.50 ± 0.30 [mean ± SD]; Table 5). The RI values were typically higher for the potential contributions of the Ekalluk River stock to each of the commercial fisheries (Table 5). Overall, the highest RI values were calculated for the potential Ekalluk stock contribution to the Ekalluk fishery, followed by the Ekalluk stock to the Lauchlan fishery (Table 5). The RI value for each of the stocks also varied temporally at each of the fisheries (Figures 4–7; Table S3; Figures S10–S11). That is, both the Ekalluk and Surrey River stocks appeared to be potentially vulnerable to harvest before, during, and after commercial harvest at each of the fisheries during some years, but differences among years were observed (Figures 4–7; Table S3; Figures S10–S11). For example, Arctic Char from Surrey River were potentially vulnerable to harvest during the Surrey River fishery in 4 of 5 years, whereas they were potentially vulnerable to harvest at this site pre- and postfishery 1 and 2 of 5 years, respectively (Figure 4C; Table S3). Arctic Char from Ekalluk River were potentially vulnerable to harvest at the Surrey River fishery during each year of the study but were only vulnerable 2 weeks before and after the fishery in 2 of the 5 years (Figure 5C; Table S3).

There were also several significant relationships between yearly RI of the Ekalluk or Surrey stocks during the commercial harvest at several fisheries and yearly marine ice and river breakup conditions. First, there was a significant ($R^2 = 0.66$, $P < 0.01$) negative relationship between RI for Arctic Char from Surrey River at the Surrey River commercial fishery and date of river breakup (Figure 4B). That is, in years when the river breakup was earlier, fish from Surrey River were more vulnerable at the Surrey River fishery. Interestingly, at the Lauchlan River commercial fishery, there was a significant ($R^2 = 0.66$, $P < 0.01$) positive relationship between RI for Arctic Char from Surrey River and date of river breakup

TABLE 5. Residency index (RI) values for the Ekalluk and Surrey River source stocks (tagging locations) at each of the commercial fisheries during the time of commercial harvest. Also shown for each year of the study are dates (day of year [DOY]) of river breakup (Breakup) and 50% marine ice conditions (50 ice); na = not available.

		Fishery				
Contributing stock	Year	Surrey	Lauchlan	Ekalluk	Breakup (DOY)	50 ice (DOY)
Surrey	2015	1.00	0.00	0.76	149	203
	2016	0.00	0.67	0.35	159	191
	2017	0.24	0.22	0.76	156	187
	2018	0.18	0.70	0.00	163	200
	2019	0.11	1.00	na	161	198
Ekalluk	2015	0.75	0.56	1.00	149	203
	2016	0.29	0.73	0.57	159	191
	2017	0.18	0.18	0.82	156	187
	2018	0.53	0.90	0.57	163	200
	2019	0.53	0.36	na	161	198

(Figure S10B). Therefore, the later the breakup, the more vulnerable were the Arctic Char from Surrey River to this fishery, as inferred from RI values. There was also a significant ($R^2 = 0.97$, $P < 0.01$) positive relationship between date of 50% marine ice cover and RI for Arctic Char from Ekalluk River at the Surrey River commercial fishery (Figure 5A). Finally, there was a significant relationship ($R^2 = 0.87$, $P < 0.01$) between river breakup and RI for Arctice Char from Ekalluk River at the Ekalluk River commercial fishery (Figure 7B). It should be noted that there was a lack of a strong relationship between stock RI and the two environmental variables that were assessed in the majority of the statistical tests (i.e., 7 of the 12 tests resulted in an $R^2 < 0.5$).

DISCUSSION

In this study, we used multiple years of acoustic telemetry data to demonstrate the ubiquity of mixed-stock fishing in Canada's largest commercial fishery for Arctic Char near Cambridge Bay, Nunavut. This is the first study to quantify specific contributions of discrete stocks to commercial harvest in the region and the first to assess how interannual variation in stock mixing may vary with changing environmental and climatic conditions. For most of the years assessed, individuals from multiple discrete stocks were detected at each fishing location during the time of the commercial harvest, including in both marine/estuarine and freshwater fisheries. Our acoustic data highlight the importance of the Ekalluk River stock in contributing to the harvest of most commercial fisheries in the region. Our data also suggested that environmental variables such as river breakup date and marine ice conditions may influence the susceptibility of some stocks to harvest at certain locations, thus potentially offering management options for predicting interannual variation in relative stock contributions to specific fisheries. We do acknowledge that in some years, our sample sizes for the RI calculations used to assess potential contributions to commercial harvest were low and unbalanced, especially toward the end of the study. Larger sample sizes and a more balanced study design consisting of similar sample sizes across tagging locations and years and including fish that are all tagged during the first year would undoubtedly improve the precision and accuracy of these estimates. Taken together, however, our data do highlight the ubiquitous nature of stock mixing in the Cambridge Bay Arctic Char commercial fishery and provide initial insights into environmental variables that influence the susceptibility of some stocks to commercial harvest in the region.

Acoustic Telemetry Reveals the Potential for Inferring Mixed-Stock Fisheries

Acoustic telemetry has great potential for informing fisheries management (Hussey et al. 2017) and offers a powerful tool to assess potential stock contributions to harvest in mixed-stock fishing scenarios (Smith et al. 2015; Faust et al. 2019). Despite the increasing use of acoustic telemetry for management-driven studies, multiyear quantifications of stock mixing remain rare (but see Kneebone et al. 2014 for an example). The complex migratory behavior of Arctic Char needs to be included in fishery management (DFO 2014; Moore et al. 2014; Harris et al. 2021), but there are still few estimates of relative stock contributions to harvest in northern commercial and subsistence fisheries. Harris et al. (2016a) used microsatellite DNA to assess Arctic Char stocks that contribute to a subsistence fishery in the Darnley Bay area of the Northwest Territories and found extensive stock mixing, with temporally varying contributions to harvest. Layton et al. (2020) also used microsatellites and single nucleotide polymorphisms to estimate contributions to harvest in an Arctic Char fishery in Labrador and highlighted

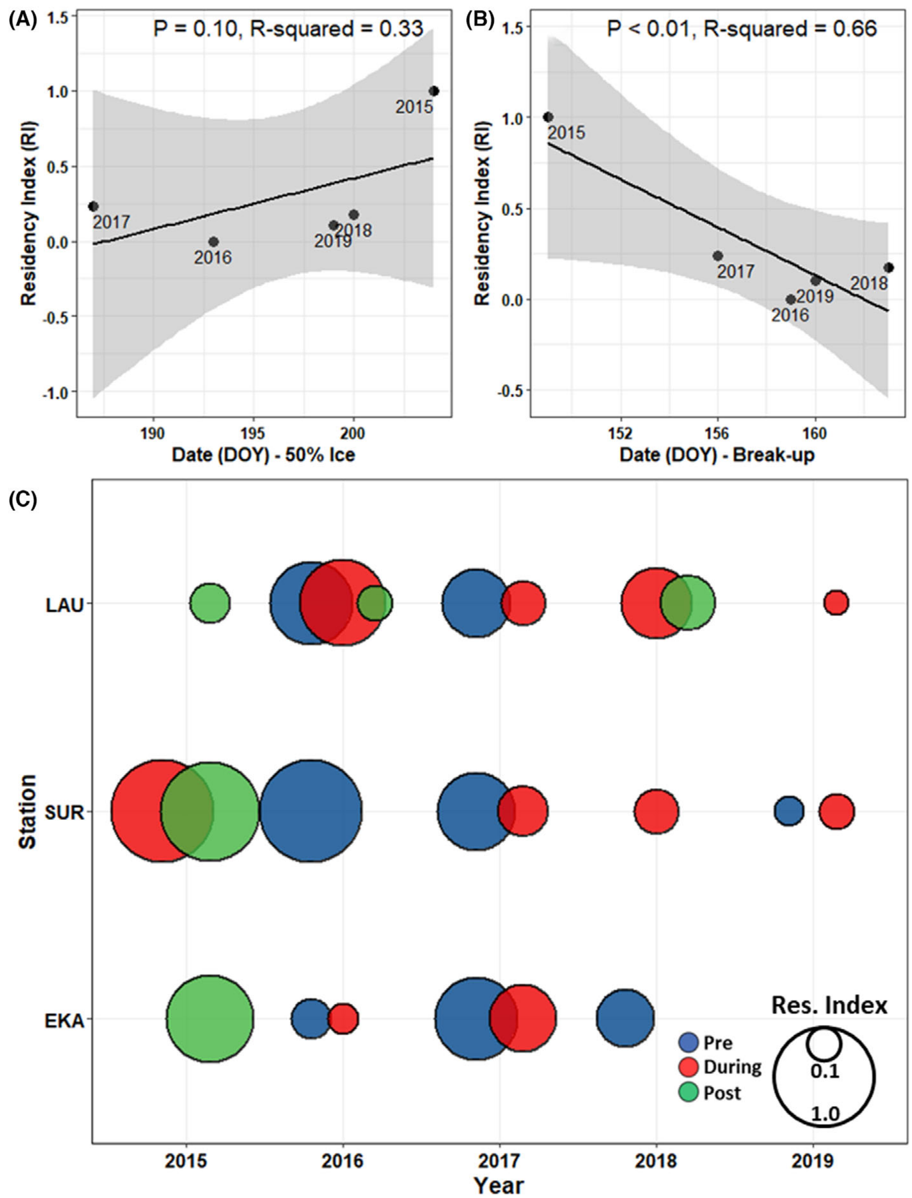

FIGURE 4. Potential contributions (inferred from RI values; see Methods) of the Surrey River stock during the period of the Surrey River commercial harvest for each year assessed. Shown are **(A)** the relationship between the yearly RI for the Surrey River stock at the Surrey River commercial fishery during the commercial harvest and date (day of year [DOY]) of 50% marine ice conditions (50% Ice) and **(B)** the relationship between yearly RI and date of river breakup (Break-up). Also shown for each year are **(C)** the RI values for the Surrey River stock, calculated for three periods around the Surrey River fishery, including the 2 weeks prefishery ("Pre" = blue circles), the dates of the Surrey River fishery ("During" = red circles), and 2 weeks postfishery ("Post" = green circles). The RI values for the Surrey River stock for these periods are shown for the receivers that represent the Ekalluk (EKA), Surrey (SUR), and Lauchlan (LAU) commercial fisheries.

the ubiquitous nature of mixed-stock fishing in marine habitats, which aligns with results from this study. Other efforts that specifically target Arctic Char from the Cambridge Bay region also offer perspective and further support on our findings. During the late 1970s, Kristofferson et al. (1984) tagged 1,630 Arctic Char in the Ekalluk River with T-bar anchor tags, and recaptures occurred at every commercial fishery in the region. Extending this work, Dempson and Kristofferson (1987) tagged fish from all stocks in the region, and Arctic Char from each distinct tagging location were also recaptured in subsequent years at each of the fisheries. For example, between 8% and 54% of Arctic Char that were tagged at the Ekalluk, Halokvik, and Lauchlan rivers were recaptured at one of the other fisheries, highlighting the marine intermixing of these stocks. More recently, acoustic telemetry (Moore et al. 2016) and

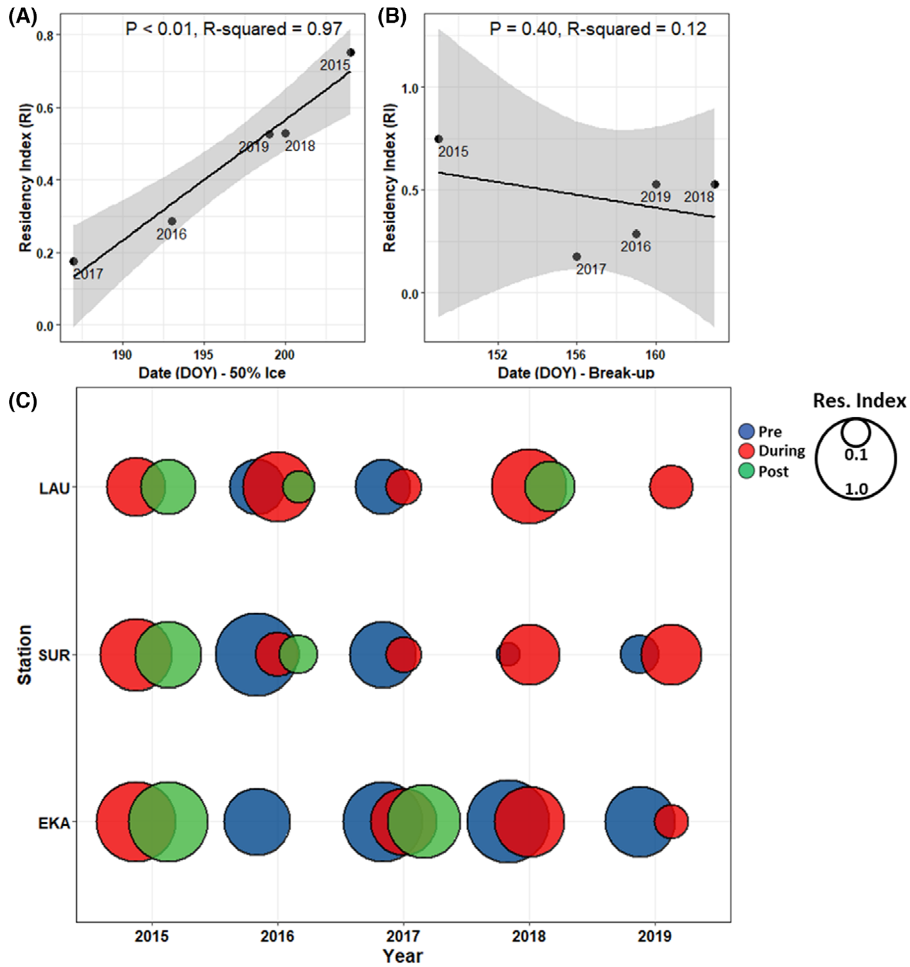

FIGURE 5. Potential contributions (inferred from RI values) of the Ekalluk River stock during the period of the Surrey River commercial harvest for each year assessed. Shown are **(A)** the relationship between the yearly RI for the Ekalluk River stock at the Surrey River commercial fishery during the commercial harvest and date (day of year [DOY]) of 50% marine ice conditions (50% Ice) and **(B)** the relationship between yearly RI and date (DOY) of river breakup (Break-up). Also shown for each year are **(C)** the RI values for the Ekalluk River stock, calculated for three periods around the Surrey River fishery, including the 2 weeks prefishery ("Pre" = blue circles), the dates of the Surrey River fishery ("During" = red circles), and 2 weeks postfishery ("Post" = green circles). The RI values for the Ekalluk River stock for these periods are shown for the receivers that represent the Ekalluk (EKA), Surrey (SUR), and Lauchlan (LAU) commercial fisheries.

genetic (Harris et al. 2016b; Moore et al. 2017) evidence also highlighted possible stock mixing in the region, including at commercial fishing locations in both marine and freshwater environments. All told, the above studies highlight the pervasiveness and complexity of Arctic Char stock mixing in the Cambridge Bay region in both marine foraging and freshwater overwintering habitats. However, these previous efforts did not assess each stock that was studied here and did not specifically quantify the proportional contributions of discrete stocks to harvest in the Cambridge Bay commercial fishery. Mixed-stock fishery analyses based on genomic data are currently in development for this region and should show promise for improving our understanding of mixed-stock fishing, including shedding additional light on interannual variation in contributions to harvest.

Environmental Correlates of Stock Mixing

Managing mixed-stock fisheries is complex and challenging, especially if the relative contributions of distinct stocks to a fishery vary from year to year (Hilborn et al. 2003). Identifying environmental drivers of this annual variation could offer potential solutions to managers who are attempting to predict relative stock contributions to a fishery. For example, in years when river breakup was earlier, the RI values for the Surrey River fish stock were higher at the Surrey River fishery during the commercial harvest (Figure 4A); however, earlier breakup resulted in lower RI values for this stock at the Lauchlan River fishery (Figure S10B). Previous studies (Harwood et al. 2013; Hammer et al. in press) and results presented here show that Arctic Char typically access marine habitats as the

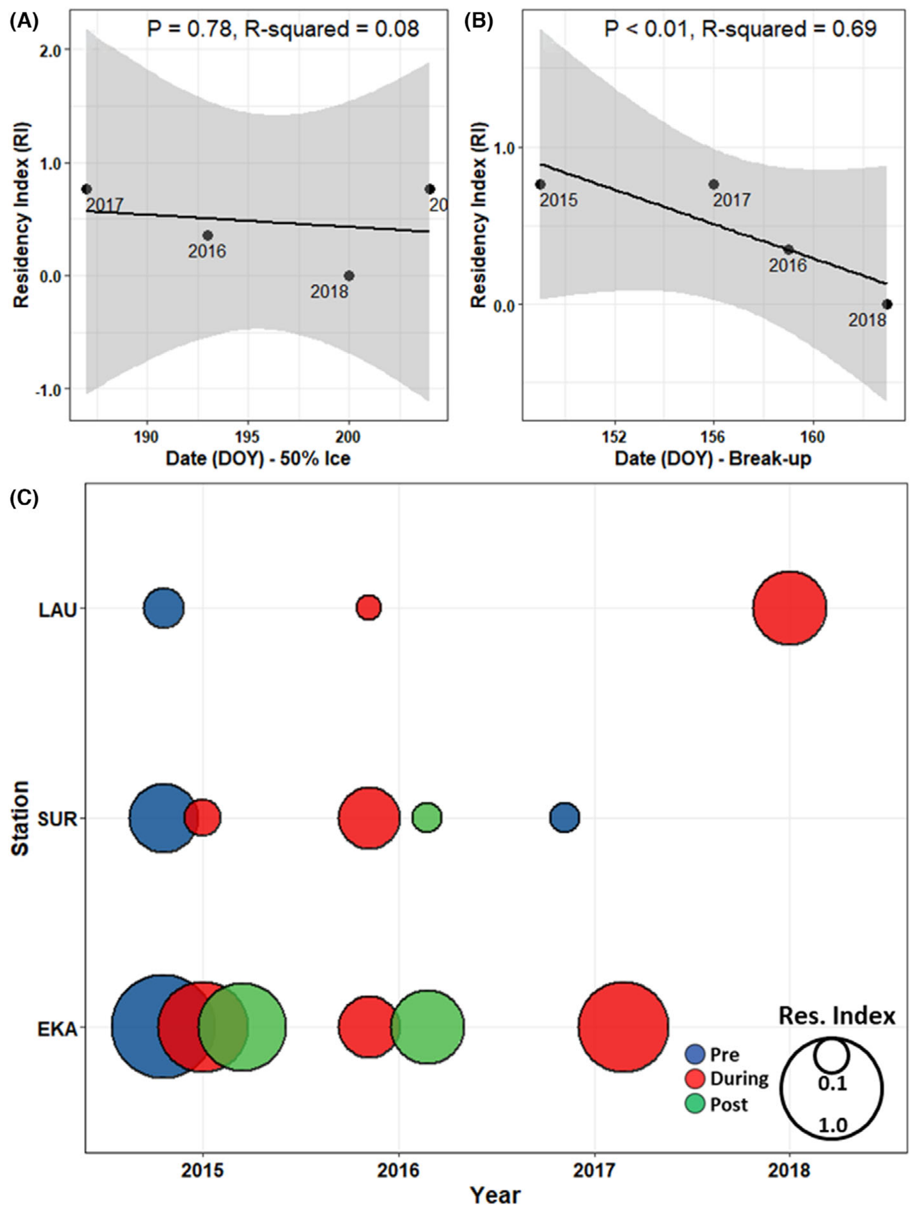

FIGURE 6. Potential contributions (inferred from RI values) of the Surrey River stock during the period of the Ekalluk River commercial harvest for each year assessed. Shown are **(A)** the relationship between the yearly RI for the Surrey River stock at the Ekalluk River commercial fishery during the commercial harvest and date (day of year [DOY]) of 50% marine ice conditions (50% Ice) and **(B)** the relationship between yearly RI and date (DOY) of river breakup (Break-up). Note that neither relationship was significant. Also shown for each year are **(C)** the RI values for the Surrey River stock, calculated for three periods around the Ekalluk River fishery, including the 2 weeks prefishery ("Pre" = blue circles), the dates of the Ekalluk River fishery ("During" = red circles), and 2 weeks postfishery ("Post" = green circles). The RI values for the Surrey River stock for these periods are shown for receivers that represent the Ekalluk (EKA), Surrey (SUR), and Lauchlan (LAU) commercial fisheries.

rivers break or shortly thereafter. The date of river breakup thus has implications for the timing and duration of marine foraging, but how this variable specifically influences distribution at sea, marine habitat use, and potential vulnerability in coastal marine areas remains unclear. Some of our previous work (Moore et al. 2016) and local knowledge (F. Hamilton, Dal Aviation, personal communication) suggest that Arctic Char in the region generally move east to west in the spring around Wellington Bay, residing in the Surrey and Lauchlan River estuaries, where the commercial fisheries operate. These estuarine coastal fisheries consistently take place during early- to mid-July (~days of year 185–200) regardless of the date of breakup (Day and Harris 2013), and river ice breakup appears to influence the susceptibility of nonlocal Arctic Char to the fishery: later river ice breakup leads to the fishery taking

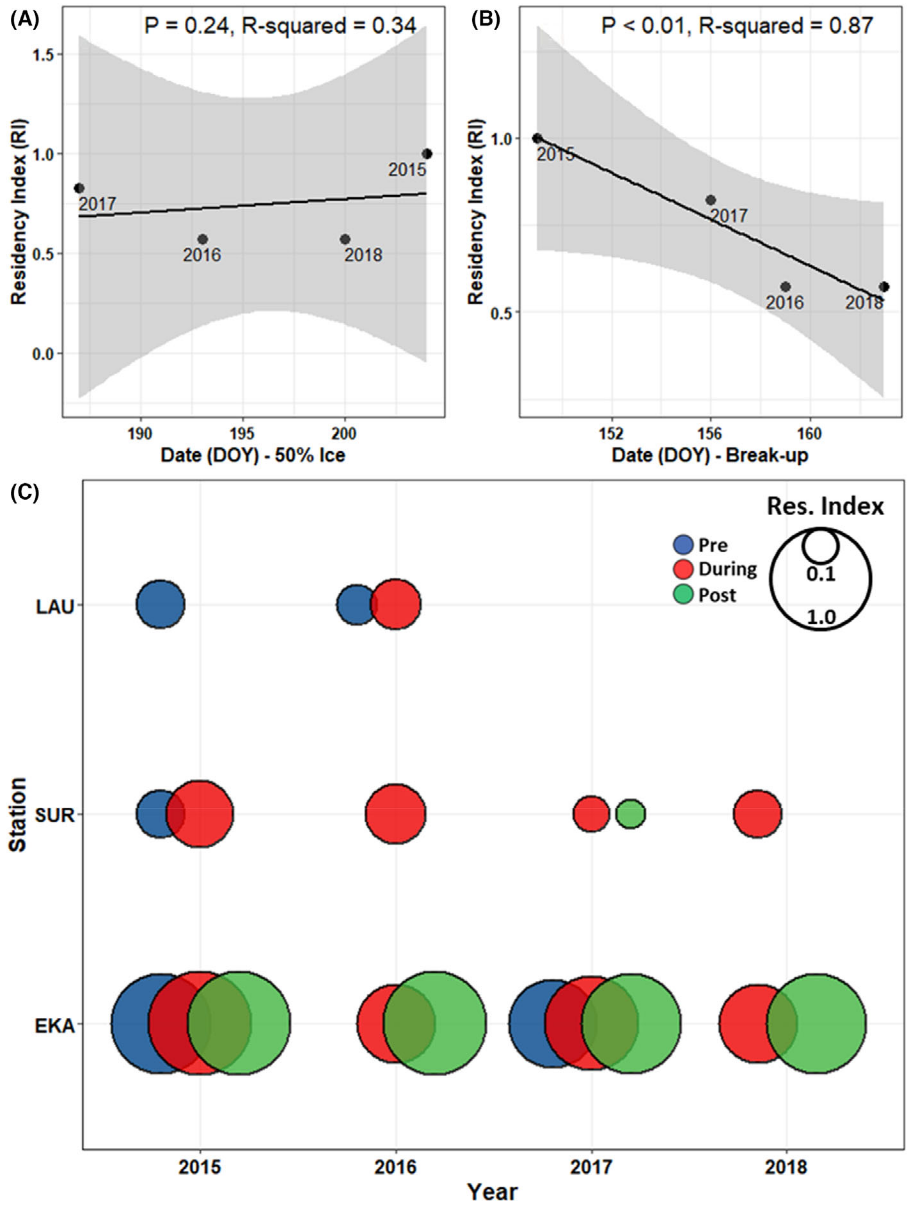

FIGURE 7. Potential contributions of the Ekalluk River stock during the period of the Ekalluk River commercial harvest for each year assessed. Shown are **(A)** the relationship between the yearly RI for the Ekalluk River stock at the Ekalluk River commercial fishery during the commercial harvest and date of 50% marine ice conditions (50% Ice) and **(B)** the relationship between yearly RI and date of river breakup (Break-up). Note that neither relationship was significant. Also shown for each year are **(C)** the RI values for the Ekalluk River stock, calculated for three periods around the Ekalluk River fishery, including the 2 weeks prefishery ("Pre" = blue circles), the dates of the Ekalluk River fishery ("During" = red circles), and 2 weeks postfishery ("Post" = green circles). The RI values for the Ekalluk River stock for these periods are shown for receivers that represent the Ekalluk (EKA), Surrey (SUR), and Lauchlan (LAU) commercial fisheries.

place after the local Surrey River fish have already started their migration toward the Lauchlan River estuary, which in turn increases their contribution to that other fishery.

We also found a significant negative relationship between date of river breakup and RI for the Ekalluk River stock at the Ekalluk fishery in Ferguson Lake (Figure 7). As mentioned above, Arctic Char access the ocean as the river breaks, and our results as well as previous work (Dutil 1986; Moore et al. 2016) suggest they feed in marine habitats for ~50 d before returning to freshwater. This relatively consistent duration of time spent foraging at sea suggests that earlier breakup should result in an earlier migration back into freshwater for overwintering purposes. The Ekalluk fishery takes place in the freshwater at the outlet of Ferguson Lake during the return migration. We posit that a later breakup potentially results in a later return to freshwater that would coincide with the end of the fishery, thus decreasing the susceptibility of the Ekalluk River stock. Finally, we found a significant positive relationship between RI for the Ekalluk River stock at the Surrey River fishery and 50% marine ice cover. Marine ice conditions are known to influence the distribution and abundance of forage species (Steiner et al. 2019), thereby influencing horizontal and vertical habitat use in Arctic Char (Harris et al. 2020a). Ice-covered marine habitats are also colder and have higher salinity than do adjacent ice-free estuarine habitats with freshwater input (Harris et al. 2020a), which influences the spatial distribution of Arctic Char at sea in that individuals remain closer to shore when ice is still present (Bégout Anras et al. 1999). Thus, it is plausible that when marine ice is still prevalent, Arctic Char from Ekalluk River reside in the nearby ice-free estuary where the Surrey River fishery takes place. It is worth noting that far more of the relationships that we tested between RI and river breakup were statistically significant (4 of 6) compared with significant relationships between RI and marine ice (1 of 6). This suggests that the river breakup date plays a more important role than marine ice conditions in influencing the susceptibility of stocks being harvested at certain fisheries. It is clear, however, that the timing of downstream migration is tightly linked to river breakup (Hammer et al. 2022) subsequently influencing the timing of access to the estuaries where the marine fisheries occur. Much less is known regarding how marine ice conditions influence the spatial distribution of Arctic Char at sea, and further work exploring how sea ice conditions influence Arctic Char behavior would be relevant for this system.

Implications for Commercial Fishery Management in a Changing Arctic

The Integrated Fisheries Management Plan for Cambridge Bay Arctic Char highlights the need for understanding stock contributions to the commercial harvest (DFO 2014). Recent stock assessments that were conducted on fisheries in the region (Harris et al. 2021; Zhu et al. 2021), as well as studies elsewhere (Moore et al. 2014; Harris et al. 2016a; Layton et al. 2020), have also highlighted the need for mixed-stock fishery analyses for understanding the proportions of stocks being harvested. Indeed, others have previously argued that the Cambridge Bay Arctic Char commercial fishery should be managed as a mixed-stock fishery (Kristofferson and Berkes 2005). In the Cambridge Bay region, one natural strategy would be to regionally manage the fishery through the implementation of area-based quotas given that multiple stocks are harvested at any given commercial fishing location. However, area-based approaches have proven problematic in the past: an area-based quota for Wellington Bay resulted in the concentration of fishing effort at the Ekalluk River commercial fishery that threatened the sustainability of that stock and resulted in a decrease in average weight over that period (from 3.4 to 1.4 kg; Kristofferson et al. 1984). The fishery was subsequently closed to allow the stock to recover. Thus, until more information becomes available on stock mixing, contributions to harvest, and straying among stocks, we recommend that Arctic Char stocks in the region continue to be managed following the current river-by-river strategy, which has a demonstrated record of success (Moore et al. 2014). Another option proposed by Harris et al. (2016b) would be to maintain river-specific quotas but allow for potential transfers of quotas if some systems are underharvested. For example, if the Surrey River early summer fishery was unsuccessful, potentially more Arctic Char could be harvested at the Ekalluk River fishery later in the summer. This would facilitate the increased use of fishery resources in the region without compromising the sustainability of the fishery as a whole. The addition of genetic or genomic tools to annually monitor and quantify mixed-stock fishing in the region will be valuable for refining potential adaptive management strategies moving forward to ensure the long-term sustainability of this culturally and commercially important resource.

As the Arctic continues to warm, there will be marked changes to sea surface temperatures, marine ice conditions, and river breakup dynamics. The multidecade data that we present here and the work of others (e.g., Harwood et al. 2013) clearly show that marine ice is melting faster during the spring and early summer. A clear trend is not yet evident in the river breakup date around Cambridge Bay but can be expected based on models and observations of other river systems (Prowse et al. 2007). Our results suggested that the timing of where Arctic Char are spatially (particularly with respect to harvest sites) depends more on river ice conditions than on marine ice conditions. If a trend toward earlier river ice breakup does emerge, this combined with longer ice-free seasons in the Kitikmeot Sea (Falardeau et al. 2022) will provide longer foraging opportunities for Arctic Char (Bégout Anras et al. 1999; Moore et al. 2016; Hammer et al. in press). It is not clear exactly how this will affect fishery dynamics, but these changes will influence the timing of when Arctic Char can access the ocean and their use of space in marine, estuarine, and freshwater environments. This may potentially have implications for their vulnerability to commercial fisheries with continued climate change and increasing environmental unpredictability (Mann et al. 2017). With earlier access to the ocean and earlier marine ice retreat, perhaps Arctic Char will spend less time in estuaries where the majority of fisheries are executed, thereby increasing the amount of fishing effort to reach quotas. Therefore, it seems logical that the fisheries would have to be adjusted accordingly (i.e., executed earlier).

Finally, the longer ice-free season could allow Arctic Char to forage in the ocean later into the fall, potentially returning to freshwater after commercial fishing has ceased. However, a longer feeding season could result in Arctic Char returning in better condition (Harwood et al. 2013), and if the timing of the fishery could be adjusted accordingly, this could have positive effects on harvest. Additional work in the region and subsequent years of data may help us further understand the relationships between these environmental variables, vulnerability of discrete stocks to commercial harvest, and effects on stock mixing. All told, the results of this work highlight the utility of acoustic telemetry methods for inferring contributions of discrete stocks to harvest in mixed-stock fisheries. We also improve the insights on the ubiquitous nature of stock mixing in Canada's largest Arctic Char commercial fishery and how contributions may change depending on marine ice and river breakup conditions.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.