Life History and Demographic Characteristics of Arctic Cisco, Dolly Varden, and Other Fish Species in the Barter Island Region of Northern Alaska

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Life History and Demographic Characteristics of Arctic Cisco, Dolly Varden, and Other Fish Species in the Barter Island Region of Northern Alaska

Randy J. Brown

Abstract

Arctic cisco *Coregonus autumnalis* and Dolly Varden *Salvelinus malma* are major fishery resources for people in coastal regions of northern Alaska and Yukon Territories. Concerted attempts to document the presence and monitor the relative abundance of these species and others began in the 1970s in response to regional development activities associated with oil exploration and extraction. Numerous sampling projects have taken place in coastal lagoon systems from the Colville River in the west to the Mackenzie River in the east. The U.S. Fish and Wildlife Service conducted an initial four year fyke net sampling program in the Barter Island region from 1988 to 1991 and repeated the sampling program 15 years later, from 2003 to 2005, to examine long-term trends in demographic composition, relative abundance, and body condition of Arctic cisco and Dolly Varden. The relative abundance of Arctic cisco varied widely among years primarily because of the tremendous variation in the number of age 0 fish moving west along the coast. The abundance of mature-size Arctic cisco, the primary demographic group harvested in coastal fisheries, remained relatively stable across years and between the early and late years of the project. Maturity indices, age, tagging, and relative abundance data suggested that Arctic cisco encountered in the Barter Island region come from overwintering habitats in both the Colville and Mackenzie River deltas. Immature Dolly Varden dominated the catch during all sampling years. With few exceptions, the relative abundance of mature Dolly Varden, the primary demographic group harvested in coastal fisheries, remained stable across years and between the early and late years of the project. Catch rates for mature Dolly Varden declined earlier in the season than for immature fish, presumably because of time constraints associated with fall spawning in freshwater habitats. In general, body condition of Dolly Varden improved between early and late summer seasons, as expected. Information regarding other fish species, such as overwintering origins, length frequency data, or relative abundance, is presented with minimal discussion.

Introduction

Arctic cisco *Coregonus autumnalis* and Dolly Varden *Salvelinus malma* are the primary fishery resources harvested by people living in Kaktovik (Craig 1987; Pedersen and Linn 2005), a community located on Barter Island in the Beaufort Sea in northeast Alaska (Figure 1). Most of the annual harvest of these fish, which can amount to 3,000 kg or more per species, occurs in
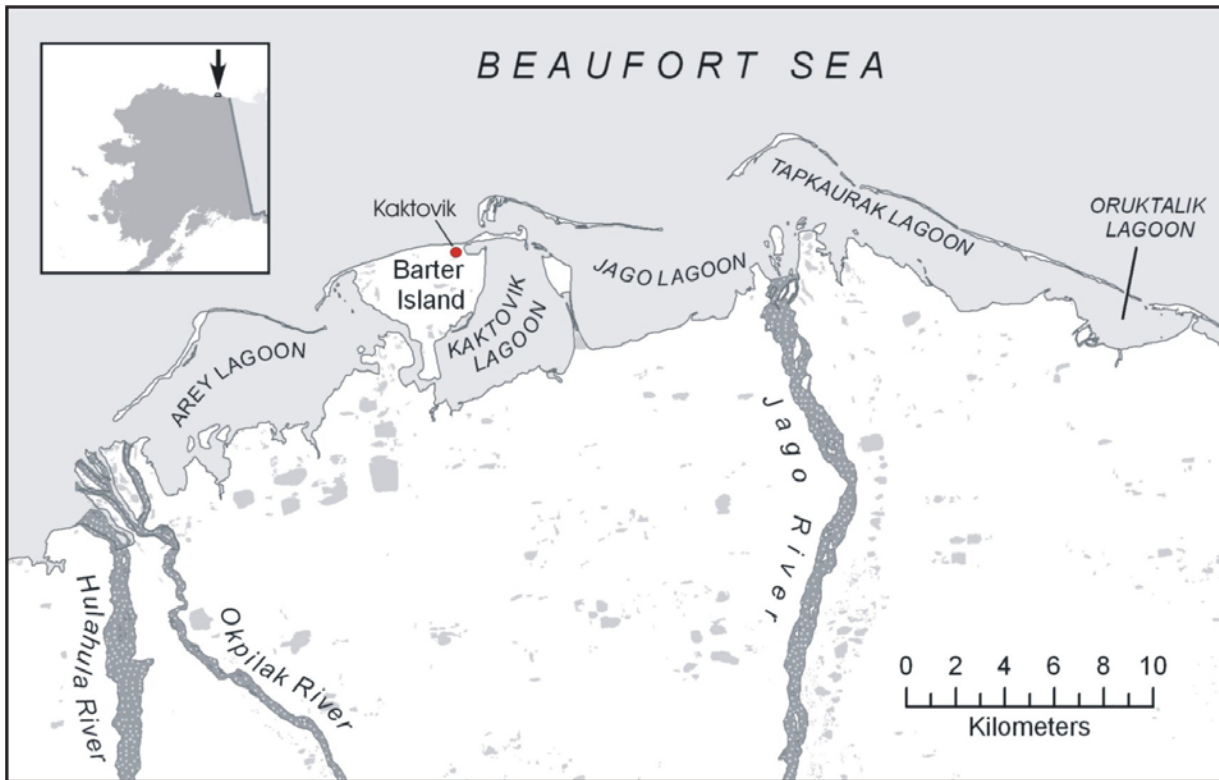
Author: Randy J. Brown is a fisheries biologist with the U.S. Fish and Wildlife Service. He can be contacted at Fairbanks Fish and Wildlife Field Office, 101 12th Ave., Rm. 110, Fairbanks, AK 99701 or randy_j_brown@fws.gov.

Figure 1. The Barter Island region in northeast Alaska.

near-shore marine or lagoon environments during the summer months. A much smaller harvest of Dolly Varden occurs in freshwater habitats during the winter months. Annual harvests of fish are thought to comprise 14% or more of all subsistence food resources harvested by residents of Kaktovik (see discussion in Craig 1987). Arctic cisco and Dolly Varden are considered to be very important subsistence resources to the people of Kaktovik.

Concern over possible impacts of oil development activities on fishery resources in northern Alaska and Canada has inspired several decades of research designed initially to identify species occurrence and distribution and later to understand the ecology of Arctic fish populations and the aquatic systems they lived in (Craig and Haldorson 1981). As a result of this research, a great deal of information, as summarized by Craig (1989), has been gained on origins, demographics, migration routes, and limiting factors on populations. Annual cycles of temperature, salinity, ice-cover, and flow in freshwater, brackish, and marine environments profoundly influence migration timing, overwintering behavior, and geographical distribution of fish (Craig and McCart 1975; McCart 1980; Craig 1984; Jarvela and Thorsteinson 1999; Carmack and Macdonald 2002; Dunton et al. 2006; Fechhelm et al. 2007). Attempts have been made to correlate the relative abundance of fish in certain locations with measurable environmental factors or development activities with some success. Perhaps the most striking example of environmental correlation has been the influence of wind-driven marine currents during summer on the recruitment of age 0 Arctic cisco to the Colville River delta, and the subsequent effects that recruitment has on the fishery several years later (Moulton and Seavey 2004; Fechhelm et al. 2007). Correlating causeway-induced habitat effects in the Prudhoe Bay region, such as localized temperature and salinity anomalies due to changes in along-shore currents, with fish growth, distribution, and relative abundance has been more challenging with less definitive results (e.g., Fechhelm et al. 1989; Gallaway et al. 1991; Griffiths et al. 1992; Martin and

Gallaway 1994; Griffiths et al. 1998; Fechhelm 1999). This may be due to a variety of factors including a lack of correlation, natural variation in fish populations, the confounding of natural and causeway-induced habitat variation, and the difficulty of isolating causes and effects in such a complex environment.

Arctic cisco in the Colville River delta were originally thought to be from local populations like the other coregonid species found there; least cisco *C. sardinella*, humpback whitefish *C. pidschian*, and broad whitefish *C. nasus*. Attempts to find pre-spawning Arctic cisco in the Colville River during the late 1970s and early 1980s, however, failed to identify fish preparing to spawn (McElderry and Craig 1981). These findings, along with the knowledge that there were spawning populations of Arctic cisco in the Mackenzie River drainage, approximately 650 km to the east (Hatfield et al. 1972a, 1972b), led Gallaway et al. (1983) to propose that Colville River Arctic cisco originated in the Mackenzie River. Many of the environmental and ecological details involved in the Arctic cisco life history story have been clarified over the intervening 25 years, but the basic premise of Gallaway et al.'s (1983) proposal still holds true (Fechhelm et al. 2007).

Arctic cisco found in Beaufort Sea coastal waters in northern Alaska originate in the Mackenzie River (Fechhelm et al. 2007), where as many as five spawning populations are thought to exist (Dillinger et al. 1992). They recruit to Alaska waters as age 0 juveniles during years when persistent east winds generate favorable coastal currents during the summer (Fechhelm and Griffiths 1990). During winter, the marine environment gets too cold (approximately -2°C) for salmonid fishes (Black 1957; Craig 1989; DeVries and Cheng 2005). In response, Arctic cisco retreat to brackish environments, but not into fresh water, where reduced salinity prevents such extreme cooling of the water (Craig 1989; Schmidt et al. 1989; Moulton and Seavey 2004). Known overwintering habitats for Arctic cisco are in the Mackenzie River delta region, approximately 350 km to the east of Barter Island, the Anderson River delta even farther east, and in the Colville and Sagavanirktok River deltas, approximately 300 km to the west (Figure 2) (Craig 1984; Schmidt et al. 1989; Bond and Erickson 1992). Rearing Arctic cisco in Alaska disperse along the coast to feed during summer for seven to eight years before maturing and returning to the Mackenzie River to spawn. Rivers between the Mackenzie and Sagavanirktok rivers do not maintain sufficient flow during the winter to produce a brackish water interface with the ocean and do not support overwintering Arctic cisco (Craig 1989; Schmidt et al. 1989). Based on this understanding of Arctic cisco life history, age 0 Arctic cisco captured in the Barter Island region would be migrating west from the Mackenzie River, and older Arctic cisco could be migrating east from the Colville River overwintering region or west from the Mackenzie River overwintering region (Bond and Erickson 1989; Underwood et al. 1995; Wiswar et al. 1995; Fechhelm et al. 2007).

Dolly Varden encountered in the Barter Island lagoon system come from many spawning populations in northern Alaska and Canada; from the Sagavanirktok and Colville rivers in the west to the Firth and Babbage rivers in the east (Craig 1984; Krueger et al. 1999). Anadromous Dolly Varden from Beaufort Sea drainages spawn in freshwater during the fall or early winter and then remain in freshwater through the winter (McCart 1980). Juvenile fish rear in freshwater for one to five years before their initial migration to sea. Yoshihara (1973) found that age 3 and 4 Dolly Varden comprised 95% of all smolts emerging from the Sagavanirktok River. Fechhelm et al. (1997) aged a small sample of Dolly Varden smolts in Prudhoe Bay and found them to be two and three year old fish. Similarly, Underwood et al. (1996) found most smolts in the Barter Island lagoon system to be three to five years old, but, a small number of age 1 and age 2 smolts were also found. Spawning maturity may be attained by five or six years of age and most fish
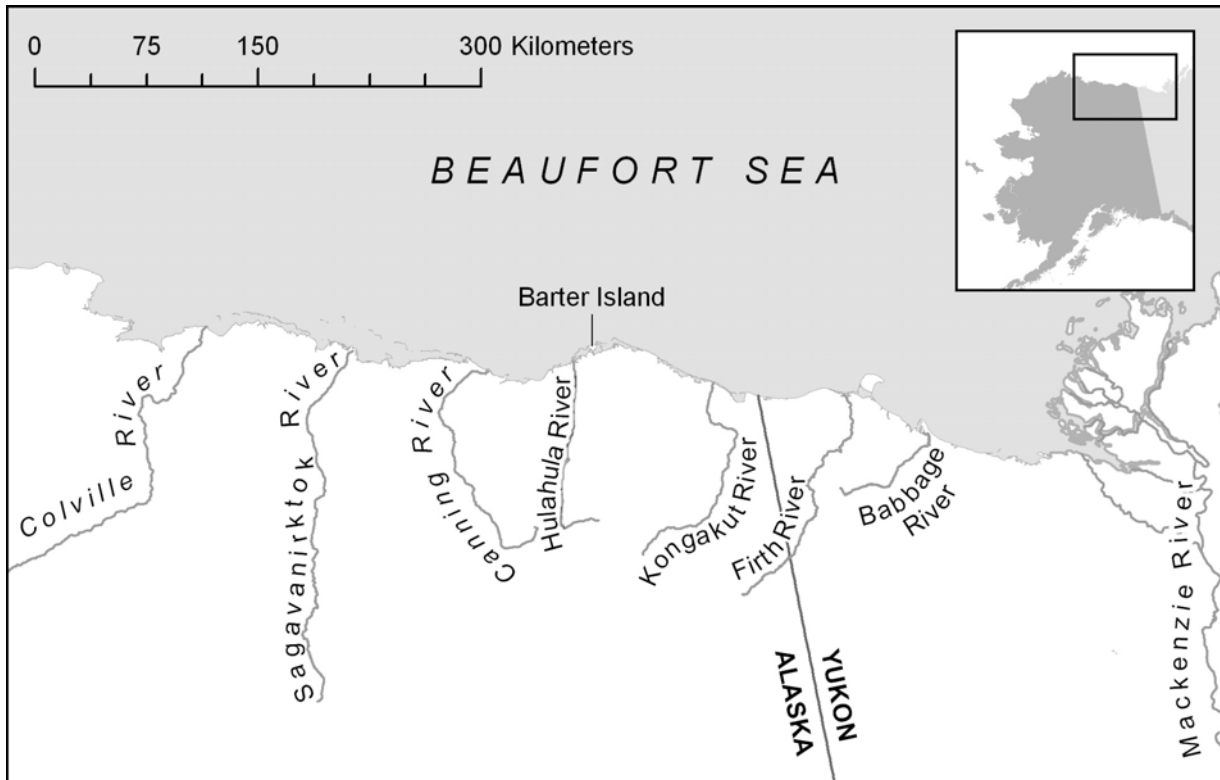
Figure 2. The southern Beaufort Sea coastal region with pertinent geographic features labeled.

are mature by age 8 or 9 (McCart 1980). Dolly Varden tagging studies in various locations have shown that anadromous fish exhibit fidelity to their natal streams for spawning, are widely distributed in the marine and coastal environments during summer, and overwinter during non-spawning years in natal and non-natal streams (McCart 1980). Tagging data reported by Furniss (1975), and more recent genetics work reported by Crane et al. (2005), suggest that mature Dolly Varden in northern Alaska overwinter primarily in their natal streams whether they are spawning or not, which is in contrast to findings in northwest (DeCicco 1985) and southeast Alaska (Armstrong 1974), where during non-spawning years they routinely overwinter in non-natal streams, and possibly even in marine environments (Bernard et al. 1995).

A long-term, fyke net sampling study was conducted in the Barter Island region from 1988 through 1991 to establish baseline fisheries distribution and relative abundance data over time (Underwood et al. 1995). It was expected that these data could be used to improve our understanding of biological processes in the near-shore marine environment, and by so doing, influence development activities to minimize impacts to aquatic habitats and the fish populations that inhabit them. The initial project involved sampling activities in Camden Bay, approximately 60 km west of Barter Island, in the lagoon system near Barter Island, including Jago and Kaktovik lagoons, and in the Beaufort Lagoon area, including Pokok Bay, approximately 60 km east of Barter Island (Figure 3). They focused on anadromous Arctic cisco and Dolly Varden, but also analyzed their catches of three marine species; Arctic cod *Boreogadus saida*, fourhorn sculpin *Myoxocephalus quadricornis*, and Arctic flounder *Pleuronectes glacialis*. Their analyses of Arctic cisco data indicated that relative abundance was highly variable among annual and seasonal time periods, among locations, and among demographic groups. Their catches of age 0 fish were consistent with origins in the Mackenzie River. They had expected that large Arctic cisco were mature and migrating to the Mackenzie River to spawn, but, recaptures of some of
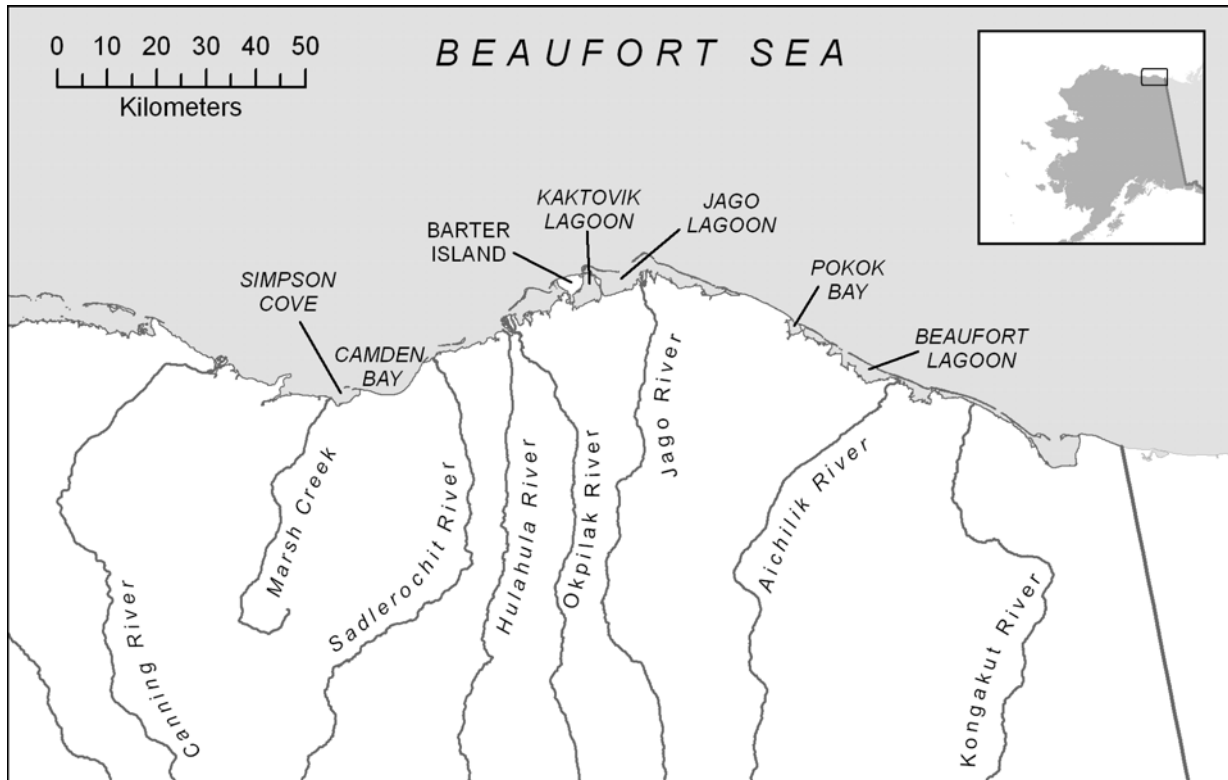
Figure 3. The sampling region of the Beaufort Sea coast in northeast Alaska during the early years.

their tagged fish in the Colville River indicated that at least some large individuals were simply ranging east into the sampling region to feed. Their analyses of Dolly Varden indicated that relative abundance was variable among annual and seasonal time periods, and to a lesser extent among locations. Tagged Dolly Varden were recaptured during summer in coastal waters of Canada to the east and Prudhoe Bay to the west, and in several river systems during fall, indicating that the Barter Island samples were from a multi-stock feeding aggregation. The marine species will be discussed later.

The Barter Island lagoon system sampling study was repeated during the summers of 2003 through 2005 to increase baseline fisheries data for the region and to explore long-term trends in relative abundance, demographics, and condition of Arctic cisco and Dolly Varden. Sampling was limited to sites within Jago and Kaktovik lagoons and did not extend to Camden Bay or Beaufort Lagoon. Sampling methods were similar during the early (1988-1991) and later (2003-2005) years of the study, permitting data analysis between time periods. Arctic cisco and Dolly Varden were the primary focus, but similar to the original study, data were collected on other anadromous and marine species as well. A primary goal of the original study was to correlate environmental factors such as salinity, temperature, ocean currents, and wind, with the relative abundance of fish in the region (Underwood et al. 1995). With few exceptions, however, environmental correlations with the relative abundance of Arctic cisco or Dolly Varden were poor or nonexistent. In the current study, only wind data were considered as they related to age 0 Arctic cisco. Data from all seven years of sampling were considered for statistical analyses.

Study Environment

The Barter Island lagoon system, including Jago and Kaktovik lagoons, is located on the north coast of Alaska midway between the Mackenzie River delta, approximately 350 km to the east, and the Colville River delta, approximately 300 km to the west (Figure 2). The lagoons are bounded on the south by the mainland coast, and on the north by barrier islands, and for Kaktovik Lagoon, by Barter Island as well (Figure 1). Maximum depths of both lagoons are between 4 and 5 m (Hale 1990). Both lagoons become brackish during the summer months due to terrestrial freshwater inputs and hyper-saline during winter when freshwater input ceases and salts become concentrated due to ion exclusion during ice formation (Griffiths et al. 1977). Lagoon ice can reach 2 m in thickness by late winter and the underlying water can become -2°C or colder because the increased salinity depresses the normal freezing temperature of marine water, which is approximately -1.9°C. During the summer, Jago Lagoon is more open to the flow of marine water than Kaktovik Lagoon. In addition, the freshwater flow from the Jago River into Jago Lagoon is much greater than the minor freshwater flows into Kaktovik Lagoon. Tidal amplitude is small, ranging from 10 to 30 cm, and is not a major factor in mixing and exchange between the relatively warm, brackish, lagoon water and the colder, more saline, marine water. Exchange between lagoon and marine water is influenced primarily by wind driven, along-shore currents and storm surges (Griffiths et al. 1977; Hale 1990). These basic environmental features are common to the near-shore environment along the entire coastline between the Mackenzie River in the east and the Colville River in the west (Craig 1989).

Methods

Sampling

Fish were sampled with fyke nets (nets) each summer during the course of this project in lagoon systems near Barter Island, in northeast Alaska (Figure 1). The nets were set approximately 60 m offshore, the entrance facing shore, a perpendicular lead from shore to each net, and 15 m wings off the sides of each frame to guide fish moving along shore into the nets. Additional net details can be found in Underwood et al. (1995). Two nets each were fished in Kaktovik and Jago lagoons from early July to mid-September during the years 1988 to 1991 and 2003 to 2005. Nets were checked daily except when severe weather prevented sampling. Initial net locations were adjusted at times in response to ice flow patterns and human activity. Additional sampling took place during the early years (1988-1991) at Camden Bay, approximately 60 km to the west of Barter Island, and Beaufort Lagoon, approximately 60 km to the east of Barter Island (Figure 3). The current study does not focus on data from Camden Bay or Beaufort Lagoon, however, some sampling data from these sites were used to improve our understanding of the origins of fish captured in the vicinity of Barter Island.

All fish captured were identified to species, counted, and representative samples were measured for fork length (FL, mm) or total length (TL, mm), as appropriate for the species, and weighed (g). The number of fish of a given species in unusually large catches was estimated using a process detailed by Craig and Haldorson (1981) whereby the average number of individuals in three subsamples (defined by volume) was multiplied by the total number of subsamples in the catch. Length data were collected for six primary species, Arctic cisco (FL), Dolly Varden (FL), fourhorn sculpin (TL) Arctic flounder (TL), Arctic cod (TL), and saffron cod *Eleginus gracilis* (TL), and for two relatively rare species, broad whitefish (FL) and least cisco (FL). All individuals of these species were measured in every sampling event unless unusually large

catches occurred. Unusually large catches of any species were composed of the smallest demographic group. When these events occurred, all of the larger fish were measured as well as a subsample of the smallest, most numerous cohort. Early (July 15 or before) and late (August 25 or later) season subsamples of measured Arctic cisco and Dolly Varden were weighed to evaluate fish condition and explore length weight relationships. Weights were collected from subsamples of five to eight fish within each 10 mm length category represented in seasonal catches of Arctic cisco and within each 25 mm length category of Dolly Varden. A small percentage of fish died during capture and handling, a few were sacrificed for aging and demographic purposes, and most were released offshore to reduce the probability of recapture.

The demographic group containing the largest Arctic cisco in the Barter Island region during the early years (Underwood et al. 1995) was similar in size to the largest fish captured in the Colville River fishery (Moulton and Seavey 2004) and to mature Arctic cisco ascending the Mackenzie River to spawn (Hatfield et al. 1972b). These fish were initially thought to be engaged in a spawning migration from the Colville to the Mackenzie River, but, some tagged fish were recaptured in the Colville River fishery the following winter, suggesting this was not entirely true (Underwood et al. 1995). To test this hypothesis, a sample of fish from the mature-size demographic group was sacrificed between mid-July and early September in 2005 to determine age and obtain gonadosomatic index (GSI) data. Otoliths from 60 fish were collected for aging. They were thin-sectioned in the transverse plane and annuli were identified using a compound microscope (Chilton and Beamish 1982). Historical data presented by Moulton and Seavey (2004) suggested that most rearing Arctic cisco in the Colville River delta became mature and left as seven, eight, or nine year old fish. Consistent with this observation, Arctic cisco migrating up the Mackenzie River to spawn were found to be age 7 or older (Stein et al. 1973). Finding age 7 or older fish in the Barter Island sample would be one line of evidence in support of the spawning migration hypothesis.

Maturity indices can provide strong evidence of spawning preparation in coregonid species by late July of a spawning year (Bond and Erickson 1989; Lambert and Dodson 1990). Gonadosomatic index (GSI) values were calculated for 95 female Arctic cisco captured between mid-July through early September as: GSI = (egg weight · whole body weight^{-1})100. Beginning in early July, egg skeins of fish preparing to spawn increase in relative mass from typical non-spawning levels, which are generally less than 3% of total body weight, to spawning levels in late September or October of 20 to 30% of total body weight (Bond and Erickson 1989, 1997; Brown 2004; Brown et al. 2007). VanGerwen-Toyne et al. (2008) presented GSI data from the spawning run of Arctic cisco in the Peel River. They calculated the maturity index with the weight of somatic tissue in the denominator (whole body - egg weight) rather than whole body weight. For comparison with our data, their values were adjusted algebraically with the following equation:

$$GSI_{whole\,body} = \left(\frac{GSI_{somatic}}{100 + GSI_{somatic}} \right) 100 \,.$$

Their adjusted mean July, August, September, and October (spawning season) GSI values were approximately 7%, 9%, 14%, and 26% respectively, for Arctic cisco preparing to spawn in the Peel River. Brown et al. (2007) prepared a GSI from a spawning run of Bering cisco *Coregonus laurettae* in the Yukon River and found a similar seasonal trend at slightly higher levels. Bering and Arctic ciscos are very closely related (McPhail 1966), so GSI values from the Barter Island Arctic cisco were compared with the least squared linear regression of GSI versus Julian date for

Bering cisco to determine if Arctic cisco GSI values fell within the 95% prediction interval of the Bering cisco GSI. Values within or above the interval would support the spawning migration hypothesis, while values below the interval would not support the hypothesis.

CPUE

The relative abundance of a given species or demographic group was calculated as the number of fish captured per unit of fishing effort (CPUE). One unit of fishing effort was defined as one net fished for one day (net-day). Fishing effort for each net during daily sampling events was calculated as the elapsed time between current and previous events in hours (HH.hh) divided by 24. Four seasonal periods within each year of sampling were defined as: 1) the first day of sampling in early to mid-July through July 31; 2) August 1 through August 15; 3) August 16 through August 31; and 4) September 1 through the last day of sampling, which was during the second or third week of September. Mean daily CPUE data within the four periods were used to identify seasonal trends in relative abundance. In the original work, trends in sample site specific and right or left side of the net CPUE were evaluated (Underwood et al. 1995). In this investigation, however, capture and effort data from all four sampling sites were pooled and the focus was on temporal trends in CPUE for the Barter Island lagoon system as a whole.

Temporal CPUE data for Arctic cisco and Dolly Varden were used to evaluate trends in relative abundance. They were analyzed with a general linear model with "years" and "sample periods nested within years" as factors. Daily CPUE (CPUE + 1) were Log_{10} (Log) transformed to normalize data and equalize variances among the different groups prior to analysis. Tukey's HSD method of multiple comparisons, with an adjusted family error rate of 0.05, was used for individual contrasts following significant results. The null hypothesis for all contrasts was that the mean CPUE of one temporal unit was equal to the mean CPUE of another temporal unit. Contrast matrices were prepared with significant contrasts shaded. Annual and seasonal trends in relative abundance were illustrated with bar-graphs and discussed.

Arctic cisco daily CPUE data collected from Beaufort Lagoon, Barter Island, and Camden Bay sampling sites during the early years of the project were plotted as X (date) Y (CPUE) area graphs to illustrate gradients of relative abundance along the 120 km reach of coastline. Likely overwintering origins of the different demographic groups of Arctic cisco encountered in the Barter Island region were proposed based on east west gradients in relative abundance assuming the greatest abundance would be observed closest to the overwintering origin.

Broad whitefish and least cisco are occasionally encountered in the Barter Island region (Craig 1984; Underwood et al. 1995). Similar to Arctic cisco, the nearest overwintering habitats for these coregonid species are in the Mackenzie River delta to the east of Barter Island, and the Sagavanirktok River delta to the west. CPUE data for broad whitefish and least cisco captured during the early years of the project were calculated for Beaufort Lagoon, Barter Island, and Camden Bay as total catch divided by total effort pooled across years. These data for each sample region were plotted with bar graphs to illustrate gradients of relative abundance. Likely overwintering origins of broad whitefish and least cisco were proposed based on east west trends in relative abundance.

Relative abundances of fourhorn sculpin, Arctic flounder, Arctic cod, and saffron cod were calculated as total catch divided by total effort (net-days) for each sampling period. Bar-charts illustrating general trends in seasonal abundance, among years, and between the early and late

years of this project were presented and discussed. No statistical analyses of CPUE data were conducted for these species.

Wind Vectors

Recruitment success of age 0 Arctic cisco to the Colville River is highly correlated with prevailing winds in the region during the ice-free months (Fechhelm et al. 2007). To illustrate annual winds in the region and compare them with the relative abundance of age 0 Arctic cisco in the Barter Island region, long-term wind speed and direction data from Herschel Island, Barter Island, and the airport at Deadhorse, Alaska were retrieved from the on-line database of the National Climate Data Center (2008). Data from the airport at Deadhorse are presented as representing region-wide trends because they encompassed the entire time period of this project and were highly correlated with the more limited data from Herschel Island and Barter Island. Average daily wind speed and direction vectors were illustrated in X (east west coordinate) Y (north south coordinate) plots for each year of the project, color coded by month for the June through September period.

Length Frequency

Annual length frequency histograms were created for the six primary species to illustrate and identify the presence of length-specific cohorts among years. Arctic cisco and Dolly Varden histograms were analyzed more intensively than fourhorn sculpin, Arctic flounder, Arctic cod, or saffron cod. Length frequency histograms were also created for broad whitefish and least cisco pooled across years because of low capture numbers.

Three Arctic cisco demographic groups; age 0, immature (mostly ages one to three), and mature-size fish (understanding that not all were actually mature), were identified based on distinctive peaks at characteristic lengths as discussed by Hatfield et al. (1972b), Bond and Erickson (1989), Fechhelm et al. (1996), and Moulton and Seavey (2004). These demographic groups were thought to be engaged in different life history activities and were considered independently. The presence, seasonal timing, and abundance of age 0 Arctic cisco west of the Mackenzie River are dependent on prevailing winds, ice pack, and probably on the annual strength of spawning stocks within the Mackenzie River drainage (Fechhelm and Fissel 1988; Fechhelm and Griffiths 1990; Bond and Erickson 1989; Fechhelm et al. 2007). Seasonal growth of this cohort is rapid and measurable (Fechhelm et al. 1996). As a result, this cohort was smaller during years when it arrived early in the Barter Island region and larger during years when it arrived late. Annual length frequency histograms were therefore used to identify the age 0 cohort by length for each year. The immature group was defined as being all fish larger than the age 0 cohort, which varied by year, up to 250 mm, which was arbitrarily selected because there were few or no fish of this length in any sampling year. The mature-size group was defined as being all fish larger than 250 mm.

Dolly Varden length frequency histograms were primarily used to illustrate the length distributions of the catch and to identify the presence and location of the smolt peak each year. Fechhelm et al. (1997) determined that the initial length frequency peak in histograms of Dolly Varden captured in Prudhoe Bay were smolts emerging from the Sagavanirktok River at ages 2 and 3. Underwood et al. (1996) presented data from the early years of this project indicating that most smolts in the Barter Island region were age 3, with a smaller component of age 1 and 2 fish. Gonadosomatic indices of Dolly Varden captured in coastal waters indicated that maturity was

attained at a length of approximately 400 mm. Similar methods employed by Yoshihara (1973) with anadromous Dolly Varden in spawning tributaries of the Sagavanirktok River produced similar results. Based on these data, Dolly Varden <400 mm FL were classified as immature and fish ≥400 mm FL were classified as mature. Craig and Haldorson (1981) fished with a variety of gear in Simpson Lagoon, between the mouths of the Colville and Sagavanirktok rivers, during the late 1970s. They found that fyke nets were more efficient at catching immature Dolly Varden while gillnets were more efficient at catching mature Dolly Varden. We therefore analyzed the CPUE of immature and mature Dolly Varden separately. The relative strength of the smolt peak, as well as the two broader demographic groups, were discussed regarding general trends among years and between the early and late years of this project.

Fish Condition

Seasonal and annual trends in Arctic cisco and Dolly Varden condition were investigated by analyzing residuals of least-squared linear regressions of Log transformed length and weight data (Pope and Kruse 2007). Age 0 Arctic cisco were not included in these analyses because of the annual variability of their timing and abundance in the Barter Island region. Additionally, it was thought that factors determining the condition of the age 0 cohort were different than for older cohorts, an issue discussed by Fechhelm et al. (1996). Data from all years and seasonal periods were considered together for each species. Outlying data points often have high influence on the regression slope and intercept parameters. In the length and weight data sets for Arctic cisco and Dolly Varden they were rare (<3% of all records) and thought to result from abnormally stout or frail fish or errors in measurement or data entry. In either case they were not considered to be representative of the general population. In a manner similar to Fechhelm et al. (1995), outliers were censored from these analyses by deleting standardized residuals >3 and <-3 following an initial least-squared linear regression. Studentized residuals from a subsequent regression were analyzed with a general linear model with "years" and "seasonal periods nested within years" as factors. Tukey's HSD method of multiple comparisons, with an adjusted family error rate of 0.05, was used for individual contrasts following significant results. The null hypothesis for all contrasts was that the mean value of studentized residuals of one temporal unit was equal to the mean value of studentized residuals of another temporal unit. Contrast matrices were prepared with significant contrasts shaded. Annual and seasonal trends in relative condition were illustrated with boxplots and discussed. All boxplots in this paper include the median line, an interquartile range box, and whiskers encompassing >95% of data with no outliers shown.

Results

Overview

Sampling began in early to mid-July and stopped in early to mid-September during all years of the project (Table 1). Total effort for most years was between 200 and 250 net-days. In 2003 and 2004, however, total effort was less than 200 net-days. Overall, 22 fish species were captured and identified (Table 2). Seven species were captured at average rates greater than one fish per day per net throughout the entire project. Other species were either comparatively rare or occasional in the catches. A general comparison of overall CPUE between Kaktovik and Jago lagoons for the seven most abundant species suggested a similar pattern of use by most species (Figure 4), although, Arctic cisco and ninespine stickleback *Pungitius pungitius* were captured at almost twice the rate in Jago Lagoon than in Kaktovik Lagoon.

Table 1. Sampling days and total fishing effort in the Barter Island lagoon system during the seven years of the project.

Year	Start day	End day	Net-days
1988	July 12	September 14	230.76
1989	July 12	September 14	246.39
1990	July 8	September 14	221.45
1991	July 11	September 13	229.85
2003	July 15	September 8	117.45
2004	July 7	September 6	192.47
2005	July 7	September 7	262.52

Table 2. Fish species captured and identified during the seven years of sampling in the lagoons near Barter Island, Alaska. Species are listed in order of overall relative abundance in the catch (CPUE = fish per net-day). CPUE in this table was calculated as the total number of fish of a given species captured during the project divided by the total number of net-days fished.

| Family	Species	Common name	CPUE
Cottidae	*Myoxocephalus quadricornis*	Fourhorn sculpin	69.797
Salmonidae	*Coregonus autumnalis*	Arctic cisco	64.154
Pleuronectidae	*Pleuronectes glacialis*	Arctic flounder	27.229
Gasterosteidae	*Pungitius pungitius*	Ninespine stickleback	23.077
Gadidae	*Eleginus gracilis*	Saffron cod	13.676
Gadidae	*Boreogadus saida*	Arctic cod	13.211
Salmonidae	*Salvelinus malma*	Dolly Varden	7.485
Osmeridae	*Mallotus villosus*	Capelin	0.910
Osmeridae	*Osmerus mordax*	Rainbow smelt	0.892
Cottidae	*Myoxocephalus scorpioides*	Arctic sculpin	0.638
Salmonidae	*Coregonus sardinella*	Least cisco	0.269
Stichaeidae	*Lumpenus fabricii*	Slender eelblenny	0.202
Clupeidae	*Clupea pallasii*	Pacific herring	0.047
Salmonidae	*Coregonus nasus*	Broad whitefish	0.045
Cottidae	*Gymnocanthus tricuspis*	Arctic staghorn sculpin	0.033
Salmonidae	*Oncorhynchus gorbuscha*	Pink salmon	0.023
Gasterosteidae	*Gasterosteus aculeatus*	Threespine stickleback	0.009
Percophidae	*Ammodytes hexapterus*	Pacific sand lance	0.007
Salmonidae	*Thymallus arcticus*	Arctic grayling	0.006
Liparidae	*Liparis tunicatus*	Kelp snailfish	0.003
Salmonidae	*Oncorhynchus keta*	Chum salmon	0.003
Salmonidae	*Coregonus pidschian*	Humpback whitefish	0.001
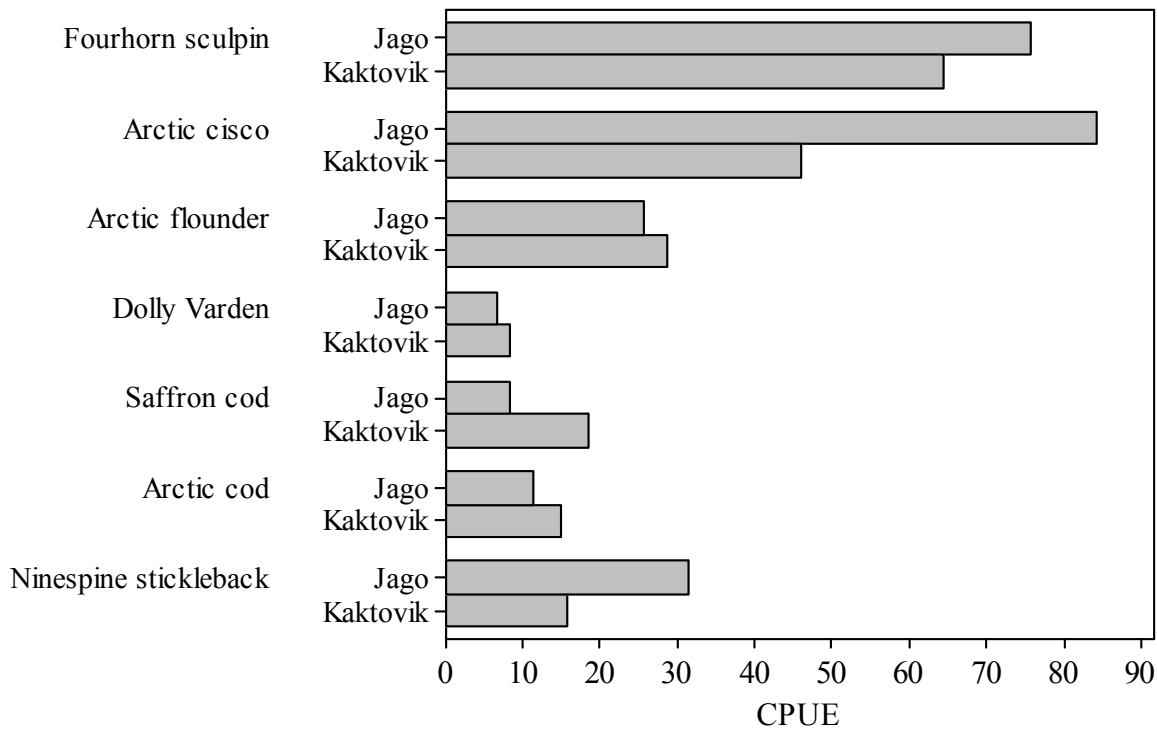
Figure 4. Overall CPUE of the seven most abundant species by lagoon.

Arctic Cisco

Length frequency—Annual length frequency histograms of Arctic cisco illustrated considerable variation in the presence and relative strengths of the three major size categories (Figure 5). The age 0 cohort was relatively strong during 1988, 1989, 1990, 2004, and 2005, and was poorly represented during 1991 and 2003. Maximum size of the age 0 cohort varied among years. The immature group of fish, predominantly age 1 to 3, were present during all years but were relatively rare during 2004 and 2005 compared to other years. The mature-size group of fish, those greater than 250 mm FL, were present in all years, but were rare in 1990 compared to the smaller demographic groups.

The length distributions of mature-size Arctic cisco from Barter Island during the early years and the later years grouped separately, the largest group of Arctic cisco captured in the Colville River fishery between 1986 and 2003 (Moulton and Seavey 2004), and of Arctic cisco sampled during the spawning migration in the Mackenzie River during 1971 (Hatfield et al. 1972b) were illustrated with boxplots (Figure 6). Barter Island fish larger than 250 mm averaged larger in the early years (368 mm) than in the later years (329 mm) of this project. The mean length from Barter Island in the early years was similar to that of the mature spawning Arctic cisco in the Mackenzie River (374 mm). The mean length from Barter Island in the later years was similar to that of the larger group of fish from the Colville River (323 mm), which were immature fish likely to mature in one or two years. It was possible, based on these length data, that at least some members of the mature-size group of Arctic cisco were migrating east in preparation to spawn.

Age 0   Ages 1 to 3   Age 4 and up
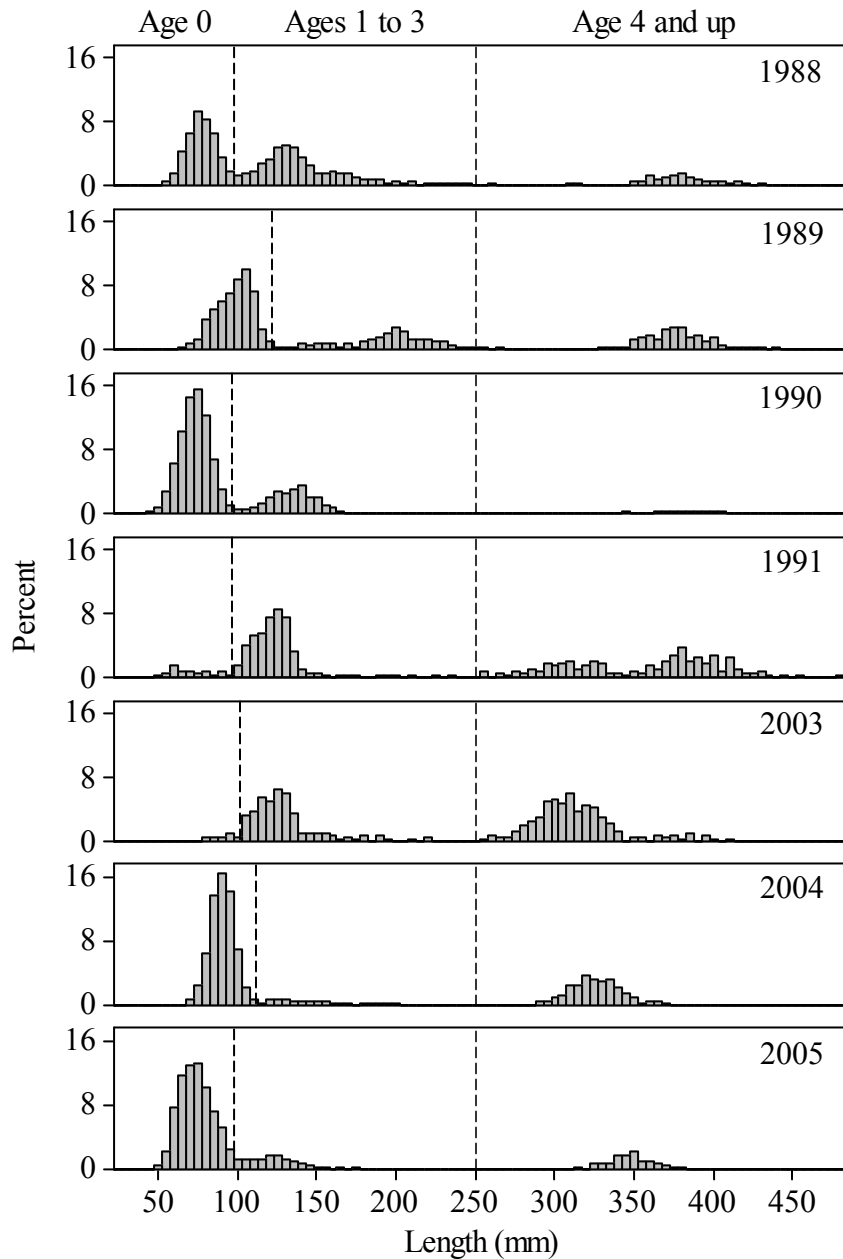
Figure 5. Arctic cisco length histograms for all seven years of the project. Note that the age 0 cohort is identified as the initial peak of small fish below the first dashed lines. The position of these lines is variable because the age 0 cohort arrived early to the Barter Island lagoons during some years and late during other years. Early arriving fish tended to be smaller than later arriving fish reflecting their different growing periods. They were noticeably present in 1988, 1989, 1990, 2004, and 2005, and they were poorly represented in 1991 and 2003. The intermediate-size category, primarily fish from one to three years of age, were present in all years to some extent. The largest size category, those greater than 250 mm FL, were primarily mature-size fish.
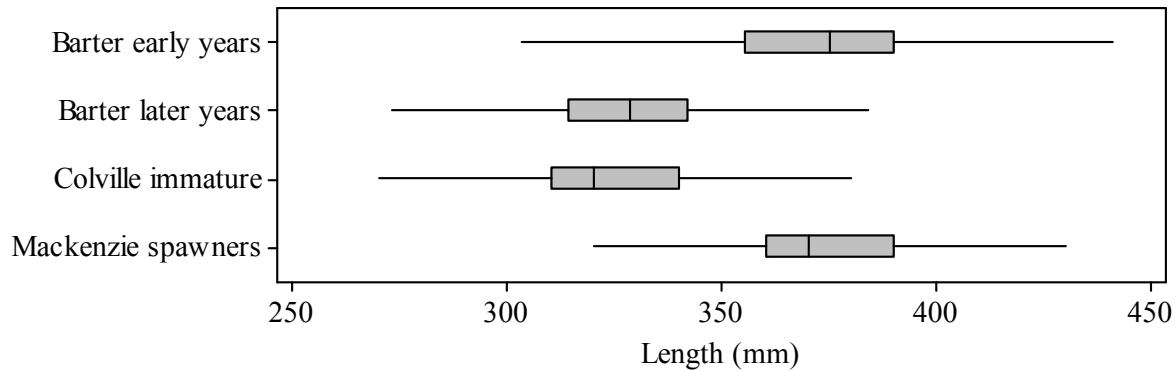
Figure 6. Boxplots of the length distributions of the large Arctic cisco (>250 mm FL) of unknown demographics from the early (1988-1991) and late (2003-2005) years of the sampling project in the Barter Island lagoon system, the largest of the immature Arctic cisco caught in the Colville River, and mature Arctic cisco sampled during their spawning migration up the Mackenzie River.

Age and maturity indices—Age data for our sample of mature-size male and female Arctic cisco and maturity indices for mature-size females from the Barter Island lagoon system in 2005 indicated that most were minimum age of maturity or older, but, were not preparing to spawn during the year of capture. Sixty aged fish ranged from 272 to 444 mm and from age 5 to 10. A majority of fish were age 8 (n = 35) with a slightly smaller component age 7 (n = 21). Maturity indices from 95 female Arctic cisco ranged from 0.1 to 5.8% and averaged 1.1%. All except one of these values fell below the lower 95% prediction interval of a maturity index created from a spawning migration of Bering cisco from the Yukon River, and only three would have exceeded the lower 95% prediction interval for spawning Arctic cisco in the Peel River (Figure 7). These data indicate that very few mature-size Arctic cisco captured in the Barter Island region were intending to spawn during the year of capture.

CPUE—The relative abundance of Arctic cisco in the Barter Island lagoon system varied considerably among years, sample periods, and demographic groups. Age 0 fish were the most abundant demographic group during 1988, 1989, 1990, 2004, and 2005, and were essentially missing in 1991 and 2003 (Figure 8). In 1990, the age 0 cohort was extraordinarily strong, with peak catches much greater than any other year. The relative strength and duration of winds from the east (Figure 9) appeared to be favorable for age 0 recruitment in 1990, 1991, and 2005, mediocre in 1988 and 2004, and poor in 1989 and 2003. Despite favorable winds in 1991 very few age 0 Arctic cisco were observed that year. In a similar but opposite contrast, age 0 fish were observed in 1988, 1989, and 2004 despite mediocre to poor winds.

The relative abundance of age 0 Arctic cisco was significantly different among years and seasonal periods within years (P < 0.0005 in both cases). Individual contrasts of mean daily CPUE within seasonal periods nested within years revealed distinct patterns of significant differences (Table 3). The extremely high CPUE values in 1990 (Figure 8) resulted in 75 significant contrasts among seasonal periods, the highest number of significant contrasts of any year. Some years and many seasonal periods had few or no age 0 Arctic cisco. Individual contrasts between those periods and periods with high CPUE values were all significant. During years when age 0 Arctic cisco were present, they were usually rare in July (seasonal period 1) and increased in relative abundance in August (seasonal periods 2 and 3). The ANOVA r^2 value of 65.5% reflects the annual consistency of this pattern. Their relative abundance during September (seasonal period 4) was variable among years.
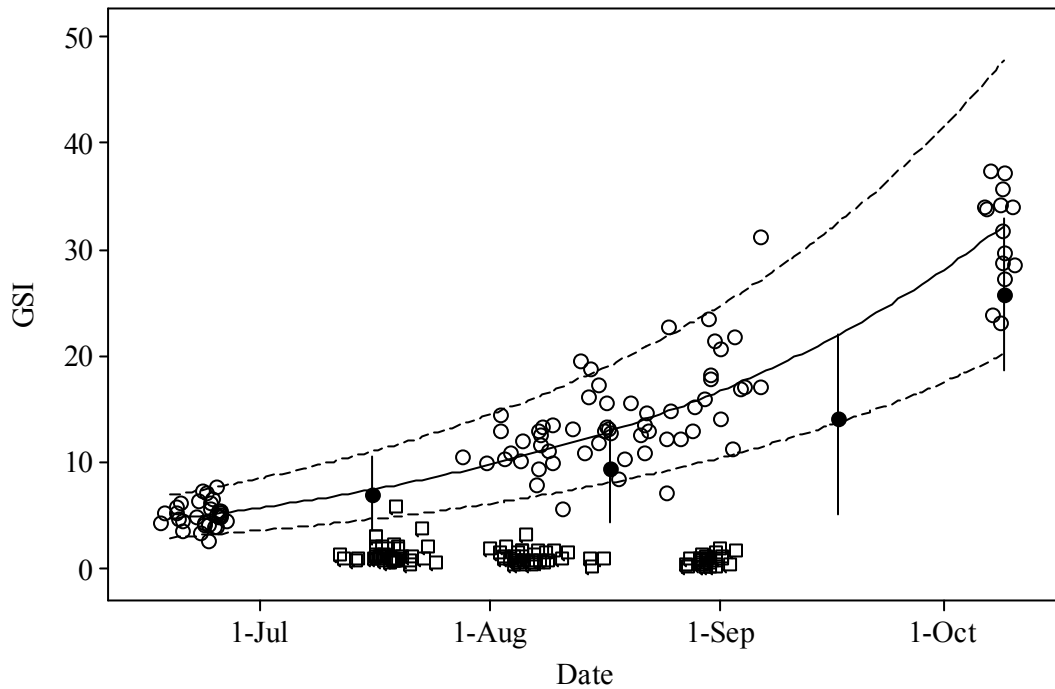
Figure 7. Maturity index (GSI) take from the Bering cisco *Coregonus laurettae* spawning migration in the Yukon River, Alaska (open circles), highlighting the increasing trend as they approach spawning time in mid-October. The center curved line is the least squared linear regression of Log transformed GSI data versus the Julian date and the upper and lower curved lines encompass the 95% prediction intervals of GSI across the season for spawning Bering cisco. The solid circles and vertical lines are adjusted mean monthly GSI values and 95% confidence intervals from the spawning run of Arctic cisco in the Peel River within the Mackenzie River drainage (VanGerwen-Toyne et al. 2008; mean monthly values with standard deviations provided by M. VanGerwen-Toyne, Canada Department of Fisheries and Oceans). The GSI from Barter Island Arctic cisco (squares) are, with one exception, clustered below the lower 95% prediction interval for the Bering cisco GSI, indicating that few were preparing to spawn during the capture year.

The relative abundance of the immature group of Arctic cisco was significantly different among years and seasonal periods within years (P < 0.0005 in both cases). Individual contrasts of mean daily CPUE within seasonal periods nested within years revealed certain patterns of significant differences (Table 4). Mean daily CPUE values in the third periods in 1988 and 1989, and periods one and two in 1990, were significantly greater than most other periods (see Figure 8 and Table 4). No other strong patterns of significant contrasts were apparent. The immature group of Arctic cisco were present during all years and in most but not all seasonal periods. No particularly strong seasonal pattern of abundance was observed, except that they were usually rarer during September (seasonal period 4) than earlier in the summer. The ANOVA r^2 value of 55.6% reflects this weak seasonal pattern.

The relative abundance of the mature-size group of Arctic cisco was significantly different among years (P = 0.002) and seasonal periods within years (P < 0.0005). Individual contrasts of mean daily CPUE within seasonal periods nested within years revealed few patterns of significant differences (Table 5). Mean daily CPUE values in the first periods in 1989 and 2004, and the second period in 2003, were significantly greater than most other periods (see Figure 8 and Table 5). No other strong patterns of individual contrasts were apparent. The mature-size group of Arctic cisco were present during all years and all seasonal periods. No particularly
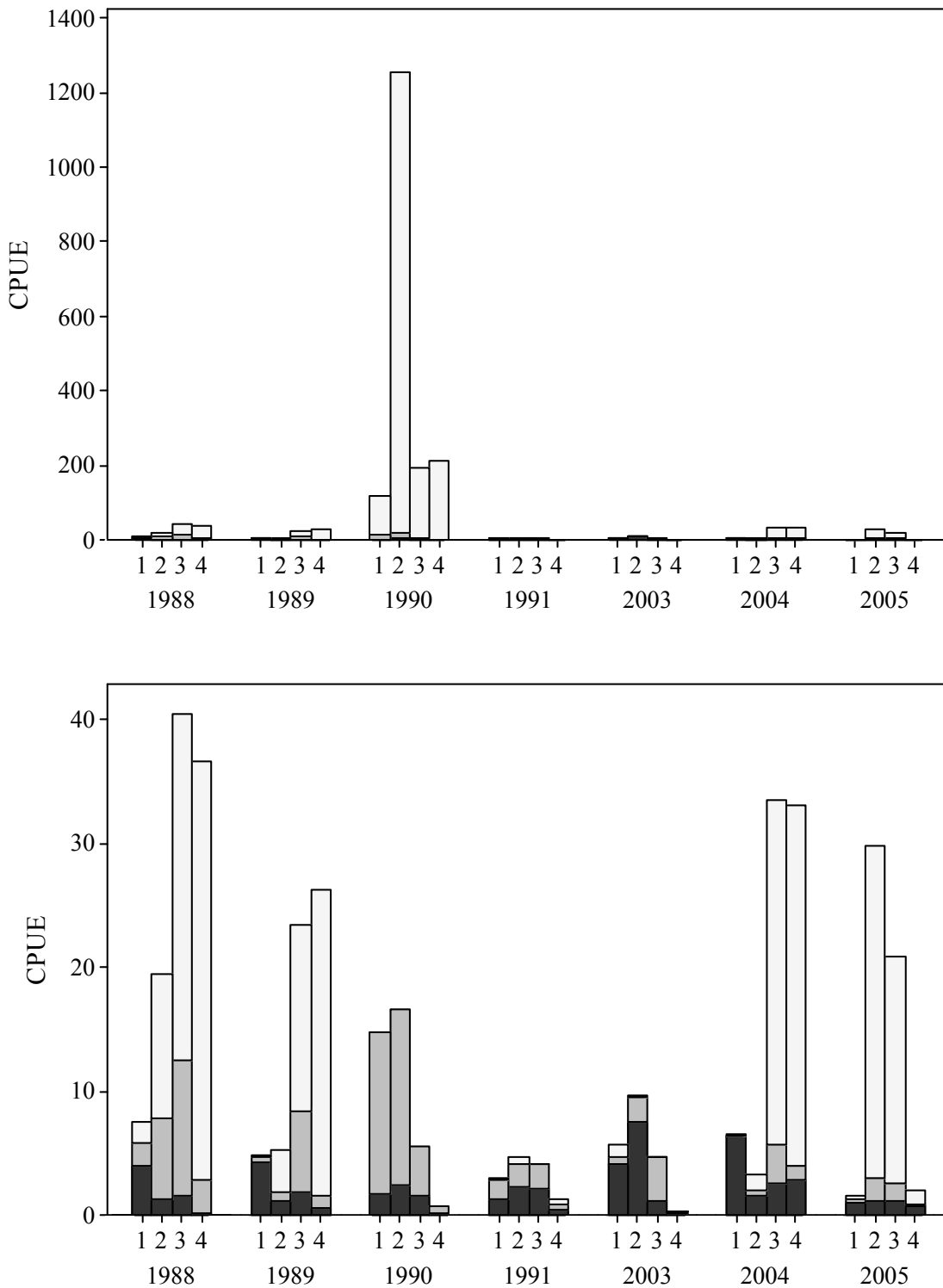
Figure 8. Arctic cisco CPUE (mean daily) organized by year, seasonal period, and demographic group. The CPUE of the mature-size group, those age 4 and older, are represented by the dark bars, the immature group, predominantly ages 1 and 2, are represented by the grey bars, and the age 0 cohort are represented by the light bars. The age 0 cohort in 1990 was extremely abundant (top chart), so they were removed in the bottom chart to highlight other data trends.
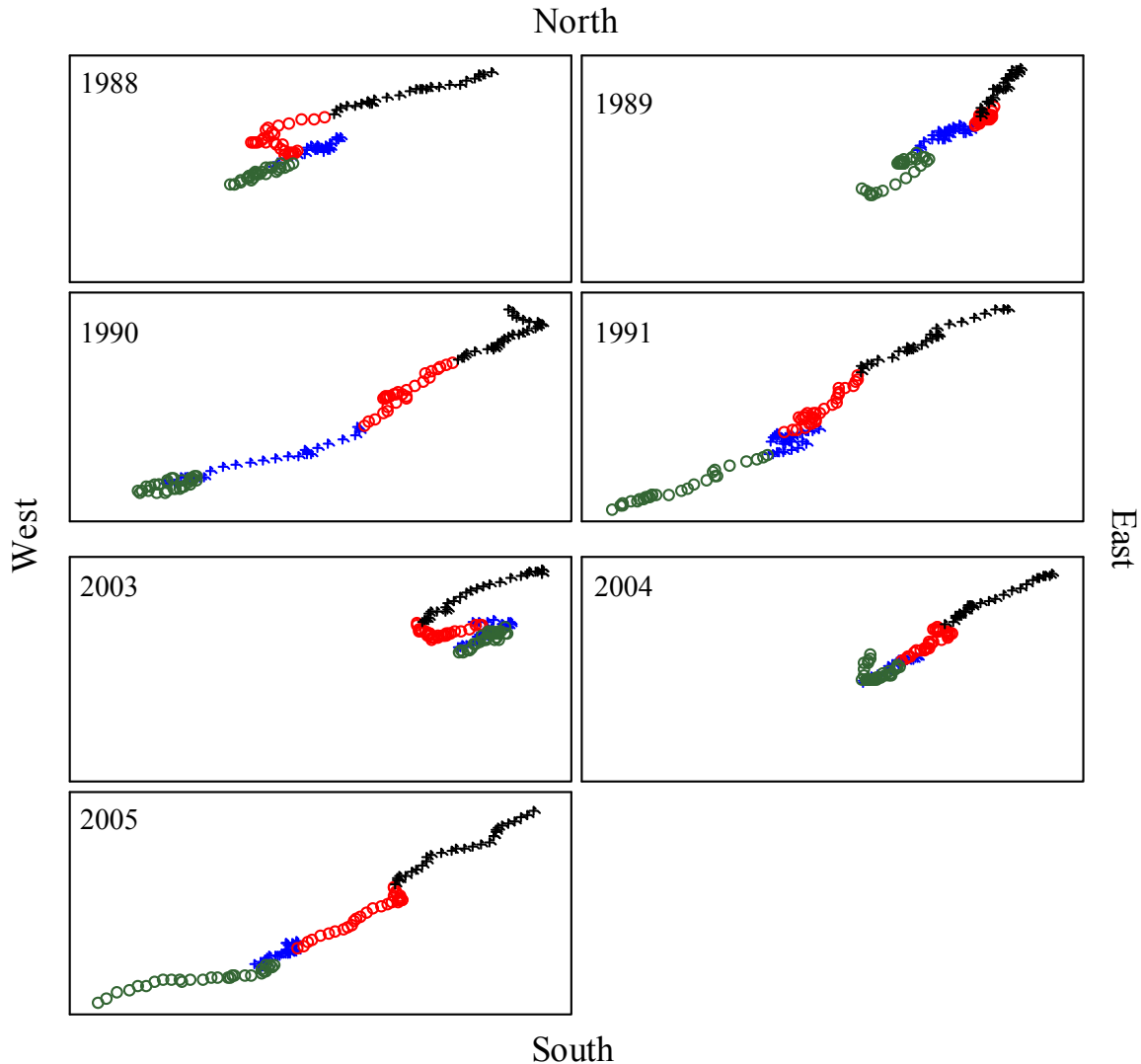
Figure 9. Relative wind vector diagrams from data collected at Deadhorse, Alaska during June (black crosses), July (red circles), August (blue crosses), and September (green circles) during the years 1988 through 1991 and 2002 through 2005. Daily averages were calculated from wind direction and velocity records archived by the National Climate Data Center. June 1 is in the northeast corner of each plot.

strong seasonal pattern of abundance was observed, except that they were usually rarer during September (seasonal period 4) than earlier in the summer. The ANOVA r^2 value of 33.2% reflects the very weak seasonal pattern of relative abundance.

Area graphs of daily CPUE for age 0, immature, and mature-size Arctic cisco from the Beaufort Lagoon, Barter Island, and Camden Bay sampling sites during the early years suggested that relative abundance was not equal among sites and east west relative abundance gradients were apparent most years for the three demographic groups. During 1988, winds were mediocre for age 0 fish migration west (Figure 9). Daily CPUE of age 0 fish were lowest in Beaufort Lagoon, relatively high in Barter Island and present through the sampling period, and low in Camden Bay except for a very high (>1,000 fish per net-day) but brief CPUE spike in late July (Figure 10). Immature fish were present in all three sampling regions through most of the sampling period. A relative abundance gradient was apparent, with the highest levels in Camden Bay and lowest

Table 3. P-values, adjusted based on a family error rate of $\alpha = 0.05$, for comparisons of daily CPUE data for the age 0 Arctic cisco group by sample period nested within years using a General Linear Model with individual contrasts conducted with Tukey's HSD test. Significant contrasts are indicated with shaded cells.

		1988				1989				1990				1991			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1988	1																
	2	1.00															
	3	0.00	0.18														
	4	0.00	0.10	1.00													
1989	1	1.00	0.42	0.00	0.00												
	2	1.00	1.00	0.00	0.00	1.00											
	3	0.05	0.95	1.00	1.00	0.00	0.02										
	4	0.00	0.04	1.00	1.00	0.00	0.00	1.00									
1990	1	0.27	1.00	0.82	0.64	0.00	0.16	1.00	0.36								
	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
	3	0.00	0.00	0.19	0.49	0.00	0.00	0.01	0.90	0.00	0.00						
	4	0.00	0.00	0.07	0.23	0.00	0.00	0.00	0.65	0.00	0.01	1.00					
1991	1	1.00	0.47	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00				
	2	1.00	0.78	0.00	0.00	1.00	1.00	0.00	0.00	0.01	0.00	0.00	0.00	1.00			
	3	1.00	0.40	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00		
	4	1.00	0.96	0.00	0.00	1.00	1.00	0.02	0.00	0.14	0.00	0.00	0.00	1.00	1.00	1.00	
2003	1	1.00	0.90	0.00	0.00	1.00	1.00	0.00	0.00	0.03	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	2	1.00	0.88	0.00	0.00	1.00	1.00	0.01	0.00	0.09	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	3	1.00	0.50	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	4	1.00	0.85	0.00	0.00	1.00	1.00	0.01	0.00	0.09	0.00	0.00	0.00	1.00	1.00	1.00	1.00
2004	1	1.00	0.34	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	2	1.00	0.99	0.00	0.00	1.00	1.00	0.03	0.00	0.17	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	3	0.00	0.28	1.00	1.00	0.00	0.00	1.00	1.00	0.92	0.00	0.09	0.03	0.00	0.00	0.00	0.00
	4	0.01	0.26	1.00	1.00	0.00	0.00	1.00	1.00	0.77	0.00	1.00	1.00	0.00	0.00	0.00	0.00
2005	1	1.00	0.47	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00
	2	0.06	0.97	1.00	1.00	0.00	0.03	1.00	0.98	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	3	0.00	0.61	1.00	1.00	0.00	0.00	1.00	1.00	0.99	0.00	0.14	0.05	0.00	0.00	0.00	0.00
	4	1.00	1.00	0.31	0.21	1.00	1.00	0.84	0.11	0.99	0.00	0.00	0.00	1.00	1.00	1.00	1.00

		2003				2004				2005			
		1	2	3	4	1	2	3	4	1	2	3	4
2003	1												
	2	1.00											
	3	1.00	1.00										
	4	1.00	1.00	1.00									
2004	1	1.00	1.00	1.00	1.00								
	2	1.00	1.00	1.00	1.00	1.00							
	3	0.00	0.00	0.00	0.00	0.00	0.00						
	4	0.00	0.00	0.00	0.00	0.00	0.00	1.00					
2005	1	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00				
	2	0.01	0.02	0.00	0.02	0.00	0.03	1.00	0.99	0.00			
	3	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	1.00		
	4	1.00	1.00	1.00	1.00	1.00	1.00	0.39	0.20	1.00	0.88	0.55	

Table 4. P-values, adjusted based on a family error rate of $\alpha = 0.05$, for comparisons of daily CPUE data for the immature group of Arctic cisco by sample period nested within years using a General Linear Model with individual contrasts conducted with Tukey's HSD test. Significant contrasts are indicated with shaded cells.

		1988 1	1988 2	1988 3	1988 4	1989 1	1989 2	1989 3	1989 4	1990 1	1990 2	1990 3	1990 4	1991 1	1991 2	1991 3	1991 4
1988	1																
	2	0.19															
	3	0.00	0.49														
	4	1.00	0.99	0.00													
1989	1	0.21	0.00	0.00	0.00												
	2	0.92	0.00	0.00	0.14	1.00											
	3	0.00	1.00	1.00	0.30	0.00	0.00										
	4	1.00	0.01	0.00	0.66	1.00	1.00	0.00									
1990	1	0.00	0.82	1.00	0.00	0.00	0.00	1.00	0.00								
	2	0.00	0.34	1.00	0.00	0.00	0.00	0.99	0.00	1.00							
	3	0.94	1.00	0.01	1.00	0.00	0.01	0.75	0.18	0.03	0.01						
	4	0.81	0.00	0.00	0.09	1.00	1.00	0.00	1.00	0.00	0.00	0.01					
1991	1	1.00	0.01	0.00	0.92	0.85	1.00	0.00	1.00	0.00	0.00	0.40	1.00				
	2	1.00	0.34	0.00	1.00	0.29	0.93	0.00	1.00	0.00	0.00	0.98	0.84	1.00			
	3	1.00	0.51	0.00	1.00	0.15	0.82	0.01	1.00	0.00	0.00	1.00	0.67	1.00	1.00		
	4	0.84	0.00	0.00	0.15	1.00	1.00	0.00	1.00	0.00	0.00	0.02	1.00	1.00	0.86	0.73	
2003	1	0.55	0.00	0.00	0.03	1.00	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.98	0.61	0.42	1.00
	2	1.00	0.19	0.00	0.99	1.00	1.00	0.00	1.00	0.00	0.00	0.84	1.00	1.00	1.00	1.00	1.00
	3	1.00	0.33	0.00	1.00	0.29	0.94	0.00	1.00	0.00	0.00	0.98	0.84	1.00	1.00	1.00	0.86
	4	0.59	0.00	0.00	0.07	1.00	1.00	0.00	1.00	0.00	0.00	0.01	1.00	0.95	0.62	0.46	1.00
2004	1	0.00	0.00	0.00	0.00	1.00	0.97	0.00	0.82	0.00	0.00	0.00	1.00	0.06	0.00	0.00	1.00
	2	0.41	0.00	0.00	0.02	1.00	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.94	0.47	0.30	1.00
	3	0.99	1.00	0.00	1.00	0.00	0.03	0.38	0.35	0.00	0.00	1.00	0.02	0.65	1.00	1.00	0.05
	4	1.00	0.40	0.00	1.00	1.00	1.00	0.03	1.00	0.00	0.00	0.93	1.00	1.00	1.00	1.00	1.00
2005	1	0.04	0.00	0.00	0.00	1.00	1.00	0.00	0.99	0.00	0.00	0.00	1.00	0.41	0.07	0.03	1.00
	2	1.00	0.19	0.00	1.00	0.59	0.99	0.00	1.00	0.00	0.00	0.92	0.96	1.00	1.00	1.00	0.96
	3	1.00	0.19	0.00	1.00	0.80	1.00	0.00	1.00	0.00	0.00	0.90	0.99	1.00	1.00	1.00	0.99
	4	0.94	0.02	0.00	0.46	1.00	1.00	0.00	1.00	0.00	0.00	0.19	1.00	1.00	0.94	0.88	1.00

		2003 1	2003 2	2003 3	2003 4	2004 1	2004 2	2004 3	2004 4	2005 1	2005 2	2005 3	2005 4
2003	1												
	2	1.00											
	3	0.62	1.00										
	4	1.00	1.00	0.62									
2004	1	1.00	0.71	0.00	1.00								
	2	1.00	1.00	0.48	1.00	1.00							
	3	0.00	0.95	1.00	0.02	0.00	0.00						
	4	1.00	1.00	1.00	1.00	0.99	1.00	0.98					
2005	1	1.00	0.95	0.07	1.00	1.00	1.00	0.00	1.00				
	2	0.85	1.00	1.00	0.81	0.03	0.75	0.99	1.00	0.20			
	3	0.95	1.00	1.00	0.91	0.09	0.90	0.98	1.00	0.40	1.00		
	4	1.00	1.00	0.94	1.00	1.00	1.00	0.30	1.00	1.00	0.98	0.99	

Table 5. P-values, adjusted based on a family error rate of $\alpha = 0.05$, for comparisons of daily CPUE data for the mature-size group of Arctic cisco by sample period nested within years using a General Linear Model with individual contrasts conducted with Tukey's HSD test. Significant contrasts are indicated with shaded cells.

		1988				1989				1990				1991			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1988	1																
	2	0.78															
	3	0.52	1.00														
	4	0.00	0.70	0.71													
1989	1	1.00	0.03	0.00	0.00												
	2	0.17	1.00	1.00	0.96	0.00											
	3	1.00	1.00	1.00	0.07	0.53	1.00										
	4	0.01	1.00	1.00	1.00	0.00	1.00	0.60									
1990	1	0.99	1.00	1.00	0.04	0.08	1.00	1.00	0.57								
	2	1.00	1.00	0.98	0.01	0.98	0.81	1.00	0.16	1.00							
	3	0.89	1.00	1.00	0.39	0.04	1.00	1.00	0.97	1.00	1.00						
	4	0.00	0.74	0.75	1.00	0.00	0.97	0.09	1.00	0.06	0.01	0.44					
1991	1	0.36	1.00	1.00	0.68	0.00	1.00	1.00	1.00	1.00	0.95	1.00	0.72				
	2	1.00	1.00	1.00	0.01	0.71	0.95	1.00	0.29	1.00	1.00	1.00	0.02	1.00			
	3	1.00	1.00	0.99	0.01	0.87	0.85	1.00	0.17	1.00	1.00	1.00	0.01	0.97	1.00		
	4	0.03	1.00	1.00	1.00	0.00	1.00	0.76	1.00	0.77	0.29	0.99	1.00	1.00	0.48	0.32	
2003	1	0.98	1.00	1.00	0.25	0.13	1.00	1.00	0.90	1.00	1.00	1.00	0.29	1.00	1.00	1.00	0.96
	2	0.98	0.04	0.02	0.00	1.00	0.00	0.44	0.00	0.13	0.91	0.07	0.00	0.01	0.59	0.74	0.00
	3	0.26	1.00	1.00	0.94	0.00	1.00	1.00	1.00	1.00	0.88	1.00	0.95	1.00	0.98	0.91	1.00
	4	0.02	0.98	0.99	1.00	0.00	1.00	0.53	1.00	0.54	0.16	0.91	1.00	0.99	0.29	0.18	1.00
2004	1	0.39	0.00	0.00	0.00	1.00	0.00	0.02	0.00	0.00	0.30	0.00	0.00	0.00	0.03	0.08	0.00
	2	0.37	1.00	1.00	0.92	0.00	1.00	1.00	1.00	1.00	0.93	1.00	0.94	1.00	0.99	0.96	1.00
	3	1.00	1.00	1.00	0.05	0.23	1.00	1.00	0.59	1.00	1.00	1.00	0.07	1.00	1.00	1.00	0.77
	4	1.00	1.00	1.00	0.14	1.00	0.96	1.00	0.54	1.00	1.00	1.00	0.15	0.99	1.00	1.00	0.63
2005	1	0.22	1.00	1.00	0.86	0.00	1.00	1.00	1.00	1.00	0.87	1.00	0.89	1.00	0.98	0.91	1.00
	2	0.21	1.00	1.00	0.98	0.00	1.00	1.00	1.00	1.00	0.83	1.00	0.98	1.00	0.96	0.87	1.00
	3	0.29	1.00	1.00	0.99	0.00	1.00	1.00	1.00	1.00	0.86	1.00	0.99	1.00	0.97	0.90	1.00
	4	0.90	1.00	1.00	1.00	0.29	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00

		2003				2004				2005			
		1	2	3	4	1	2	3	4	1	2	3	4
2003	1												
	2	0.15											
	3	1.00	0.01										
	4	0.82	0.00	1.00									
2004	1	0.00	1.00	0.00	0.00								
	2	1.00	0.01	1.00	1.00	0.00							
	3	1.00	0.24	1.00	0.53	0.00	1.00						
	4	1.00	1.00	0.98	0.42	1.00	0.99	1.00					
2005	1	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.98				
	2	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.96	1.00			
	3	1.00	0.01	1.00	1.00	0.00	1.00	1.00	0.97	1.00	1.00		
	4	1.00	0.18	1.00	1.00	0.04	1.00	1.00	0.99	1.00	1.00	1.00	
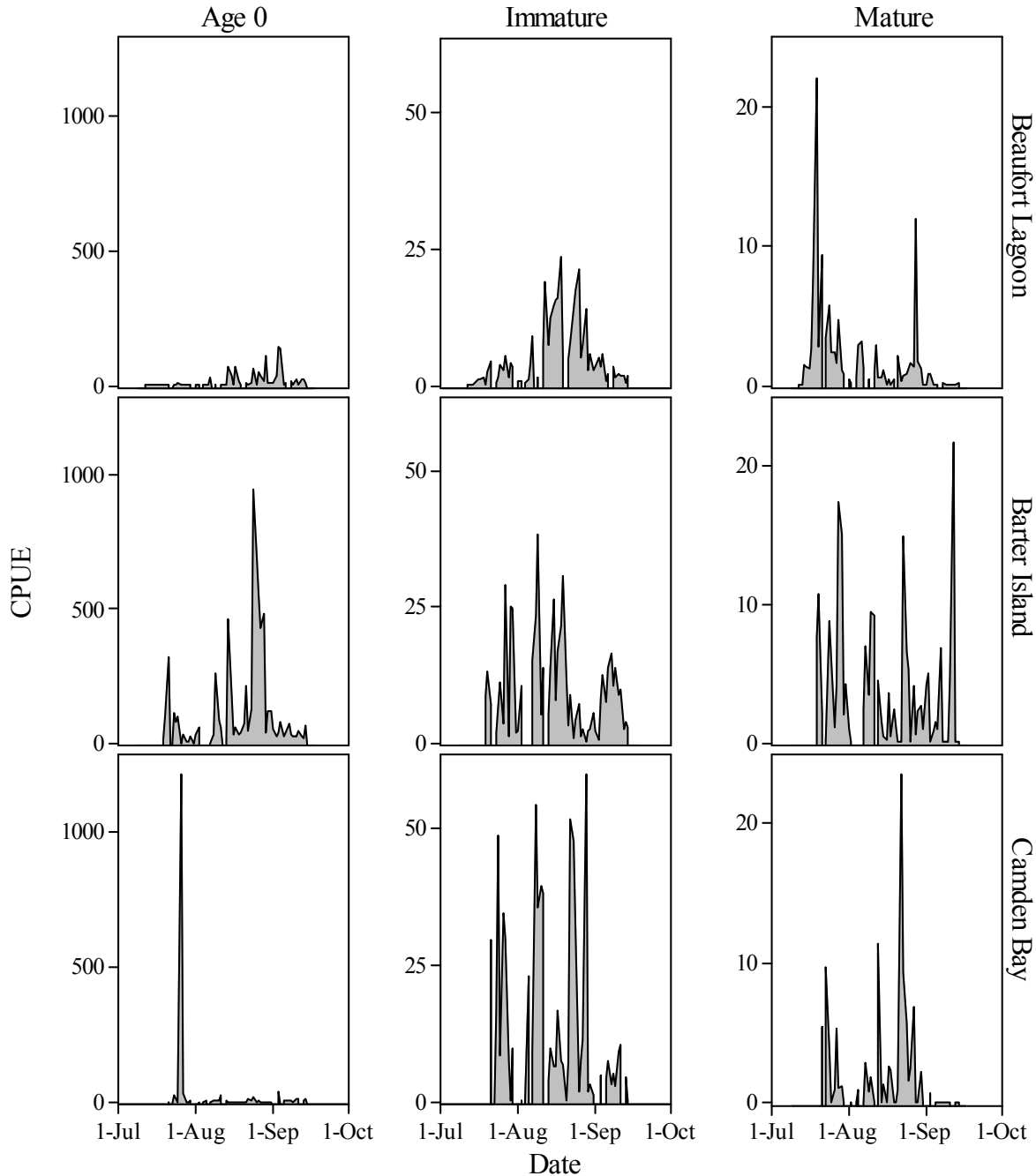
Figure 10. Daily CPUE (fish per net-day) of Arctic cisco during 1988.

levels in Beaufort Lagoon, suggesting a Colville River overwintering origin for the immature group. Mature-size fish were present in all three sampling regions through most of the sampling period. The relative abundance in the Barter Island region appeared to be the greatest overall, however, no strong gradient was apparent and it was not possible to assign a probable overwintering origin to mature-size fish.

Sampling in the Beaufort Lagoon region during 1989 was intermittent so there were large gaps in the daily CPUE area graphs for that region. Sampling in Barter Island and Camden Bay regions
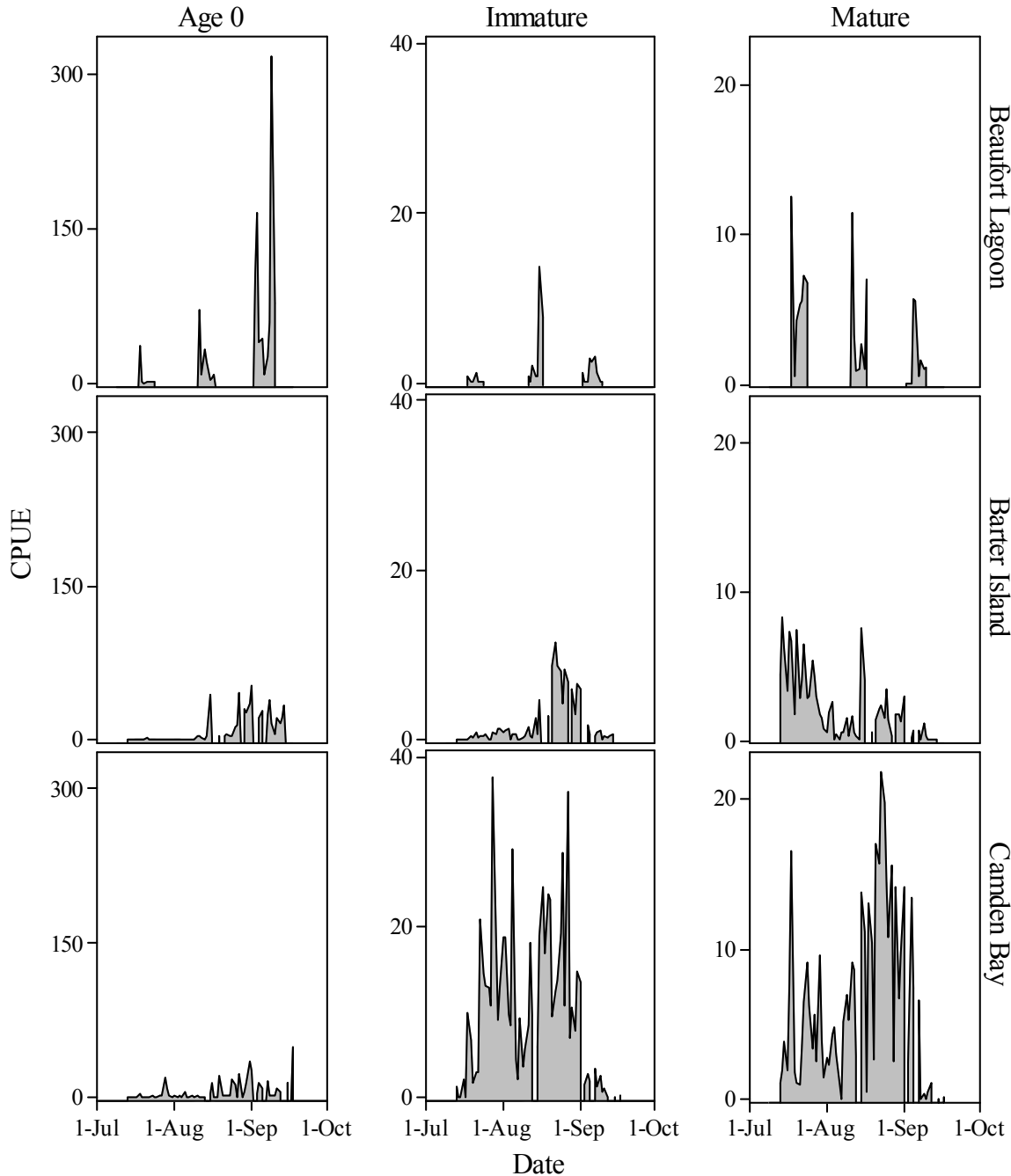
Figure 11. Daily CPUE (fish per net-day) of Arctic cisco during 1989.

was reasonably continuous. During 1989, winds were poor for age 0 Arctic cisco migration west (Figure 9). Daily CPUE of age 0 fish were highest in Beaufort Lagoon, relatively low in Barter Island, and lowest in Camden Bay (Figure 11). Immature and mature-size fish were present in all three sampling regions through most of the sampling period. A similar relative abundance gradient was apparent for both size groups, with the highest levels in Camden Bay and lower levels in Barter Island and Beaufort Lagoon, suggesting a Colville River overwintering origin for both groups.
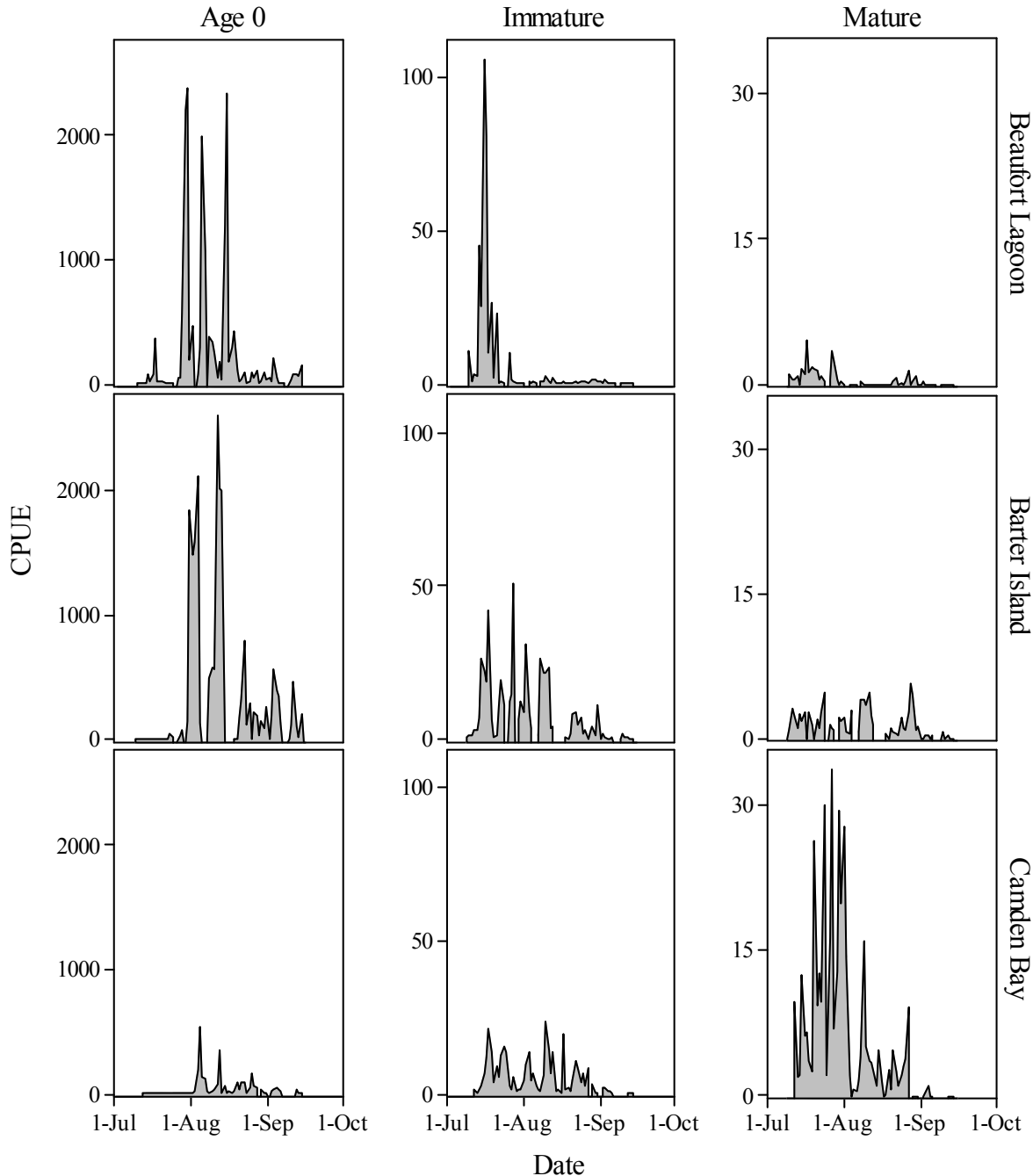
Figure 12. Daily CPUE (fish per net-day) of Arctic cisco during 1990.

During 1990, winds were favorable for age 0 fish migration west (Figure 9). Overall daily CPUE of age 0 fish were greatest in Beaufort Lagoon where they apparently arrived first, high in Barter Island where they arrived next, and relatively low in Camden Bay where they arrived last (Figure 12). Immature and mature-size fish were present in all three sampling regions through most of the sampling period. The greatest relative abundance of immature fish was in Beaufort Lagoon, where a brief CPUE spike exceeded 100 fish per net-day early in the season and low levels were observed through the rest of the summer. Progressively lower CPUE levels were observed in Barter Island and Camden Bay, suggesting the Mackenzie River overwintering
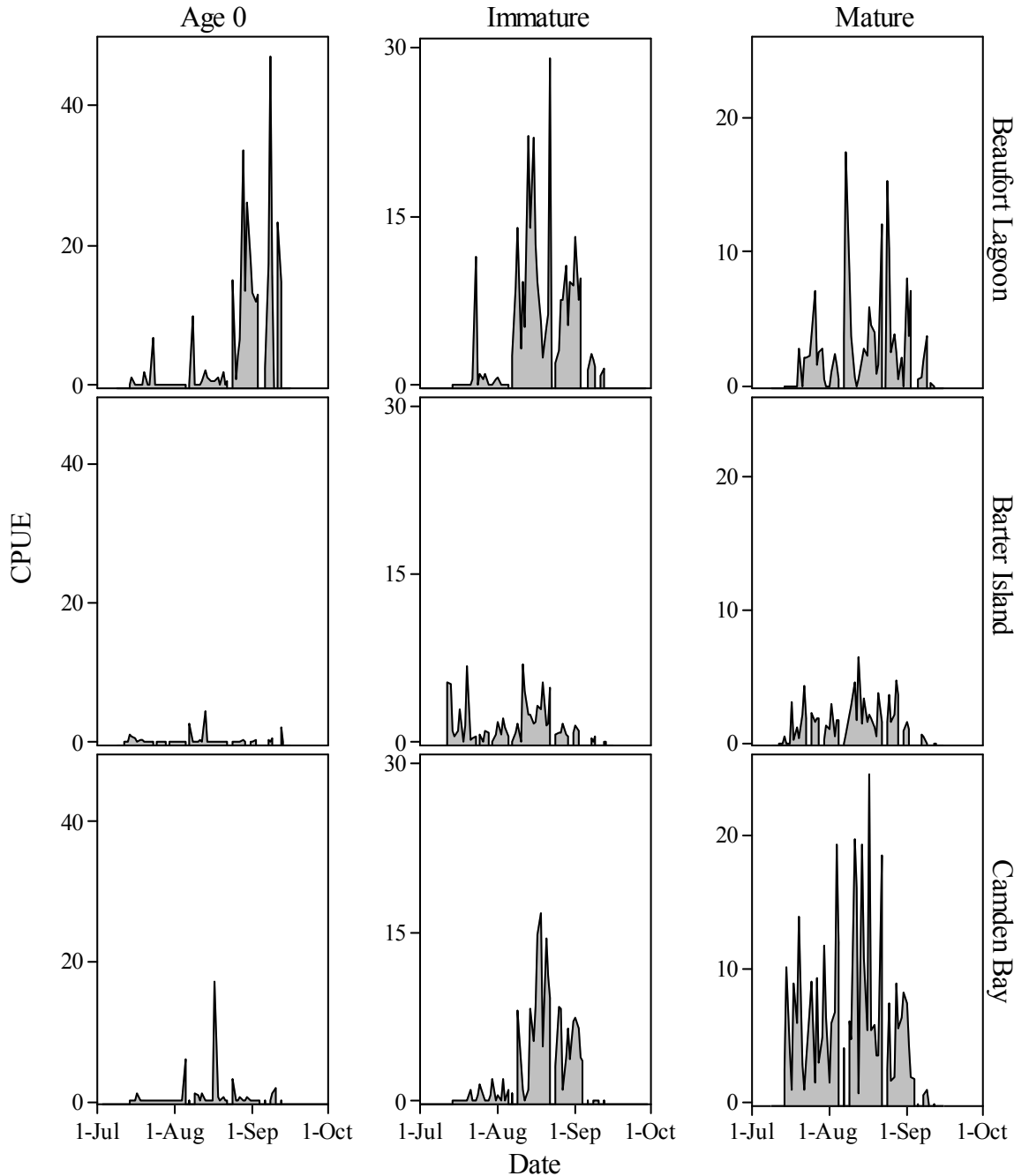
Figure 13. Daily CPUE (fish per net-day) of Arctic cisco during 1991.

origin for the immature group in 1990. An opposite relative abundance gradient was apparent for mature-size fish suggesting the Colville River as their overwintering origin.

During 1991, winds were favorable for age 0 fish migration west (Figure 9). Overall daily CPUE of age 0 fish were greatest in Beaufort Lagoon where they were present throughout the sampling period with the highest levels late in the season. By comparison, relative abundance of age 0 fish was very low in both Barter Island and Camden Bay (Figure 13). Immature and mature-size fish were present in all three sampling regions through most of the sampling period. For both groups, the lowest relative abundance level was in Barter Island with distinctively

higher levels in Beaufort Lagoon to the east and Camden Bay to the west. These CPUE gradients suggest that immature and mature-size fish captured in Barter Island originated in both the Mackenzie and Colville River overwintering habitats in 1991.

Condition—With all sample years (1989-1991 and 2003-2005, comparable samples were not collected in 1988), and both early and late season samples pooled, there were 957 records of length and weight for immature and mature-size Arctic cisco (age 0 fish were not included). Nine records (~0.9% of the data) were censored during a preliminary least squared linear regression of Log transformed data because their standardized residuals were either >3 or <-3. A subsequent regression with the remaining data had a significant positive slope (P < 0.0005) and length was positively correlated with weight (r^2 = 99.1%) (Figure 14). Years was a significant factor in the GLM model (P = 0.002) and seasons nested within years was a more significant factor (P < 0.0005). Individual contrasts of mean studentized residuals (proxy data for relative fish condition) for seasons nested within years did not exhibit strong seasonal trends during most years (Table 6). The mean condition of fish sampled during the early season was less than of fish sampled during the late season only in 1989 and 2005 (P < 0.05, adjusted for a family error rate of 0.05 among all 66 contrasts) (Figure 15); for all other years mean seasonal conditions were not significantly different. Mean condition during the early season of 1989 and 1991 were significantly less than for many other seasons during other years (P < 0.05). There were a few other significant contrasts among seasons nested within years, but, no other strong trends in relative condition were observed (Table 6).

$$Log(Weight) = -5.591 + 3.257 \, Log(Length)$$
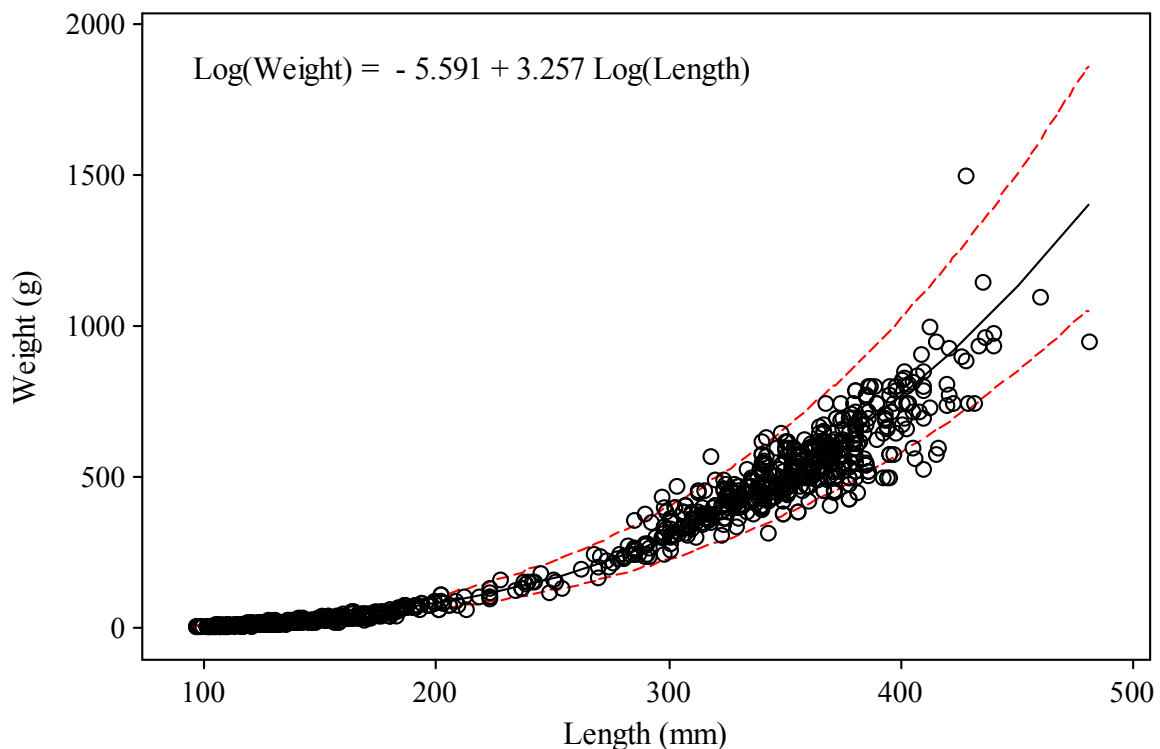
Figure 14. Least squared linear regression of Log transformed weight and length data of Arctic cisco older than age 0 displayed in normal units with fitted line and associated 95% prediction intervals (dashed lines). Length was highly predictive of weight (r^2 = 99.1%).

Table 6. Matrix of individual contrasts among seasons nested within years for Arctic cisco older than age 0. Shaded cells indicate significant differences of condition between paired samples.

		1989		1990		1991		2003		2004		2005	
		early	late	early	late	early	late	early	late	early	late	early	late
1989	early												
	late	0.00											
1990	early	0.11	0.34										
	late	0.49	0.71	1.00									
1991	early	0.96	0.00	0.01	0.06								
	late	1.00	0.04	0.87	0.97	0.64							
2003	early	0.05	0.84	1.00	1.00	0.00	0.60						
	late	0.00	1.00	0.25	0.81	0.00	0.02	0.91					
2004	early	0.00	0.83	0.96	1.00	0.00	0.23	1.00	0.88				
	late	0.00	0.99	0.53	0.98	0.00	0.05	1.00	1.00	1.00			
2005	early	0.87	0.05	0.95	1.00	0.16	1.00	0.72	0.01	0.18	0.03		
	late	0.00	0.97	0.64	0.99	0.00	0.07	1.00	1.00	1.00	1.00	0.04	
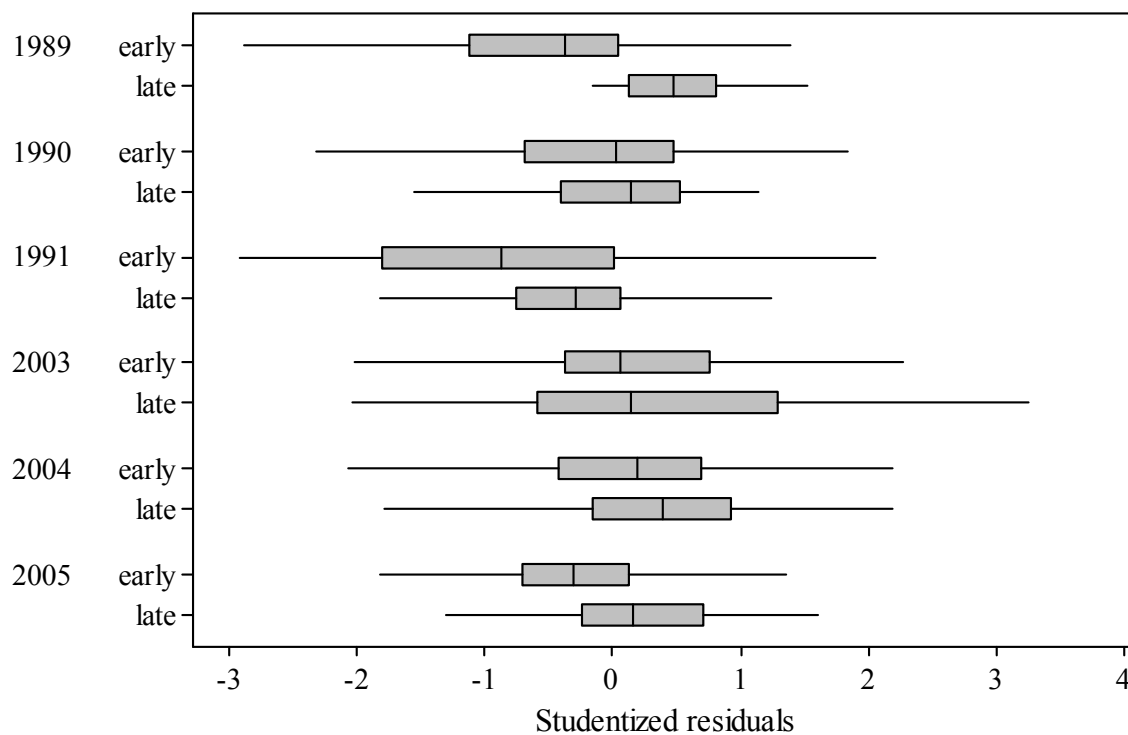
Figure 15. Boxplots illustrating seasonal trends in relative condition of Arctic cisco older than age 0 as represented with the distributions of studentized residuals of the length weight regression.

26

Dolly Varden

Length frequency—Immature Dolly Varden dominated the sampled population during all sampling years of the project (Figure 16). Annual length frequency histograms varied considerably among years; from being unimodal in 1989 and 2003, bimodal in 1988 and 1991, and without distinct modality during 1990, 2004, and 2005. The primary smolt cohort was identified in 1988, 1989, 1991, and 2003 by the modal length frequency peak at approximately 200 mm. Dolly Varden ≤120 mm and mature Dolly Varden (≥400 mm) were both sampled at low frequency during all years of the project.

CPUE—The relative abundance of immature Dolly Varden in the Barter Island lagoon system varied significantly among years and seasonal periods nested within years (P < 0.0005 in both cases), with years explaining more overall variation than seasonal periods nested within years (Figure 17). The relative abundance was similar during 1988, 1989, and 1990, as evidenced by only eight of 66 (12%) individual contrasts being significantly different (P ≤ 0.05) among seasonal periods nested within those years (Table 7). In 1991, the relative abundance of immature Dolly Varden in the Barter Island region was very high resulting in 18 of 48 (38%) significant contrasts (P ≤ 0.05) among seasonal periods nested within the years 1988, 1989, and 1990, and 33 of 48 (69%) significant contrasts (P ≤ 0.05) among seasonal periods nested within the years 2003, 2004, and 2005. The relative abundance of immature Dolly Varden during the later years was generally less than during the early years with the exception of the second period during 2003, which was comparable to the highest mean CPUE values during 1991, and the first period during 2004, which was comparable to mean CPUE values during 1988, 1989, and 1990 (Figure 17). Mean CPUE values for the fourth seasonal period was less than for the earlier periods during most years.

The relative abundance of mature Dolly Varden in the Barter Island lagoon system varied significantly among years and seasonal periods nested within years (P < 0.0005 in both cases), with seasonal periods nested within years explaining more overall variation than years (Figure 17). In general, the relative abundance of mature Dolly Varden was similar, with only a few exceptions, during all years and seasonal periods nested within years (Table 8). During the first sample period in 1991 the relative abundance of mature Dolly Varden was significantly greater than in any other sample period throughout the project (P ≤ 0.05). The mean CPUE of the first sample period in 1990 was also higher than most other sample periods, resulting in 19 of 27 (70%) significant contrasts (P ≤ 0.05). Mature Dolly Varden followed a general trend of being in greatest relative abundance during July (sample period 1) and declining through the summer to lowest relative abundance by September (sample period 4).

Condition—With all sample years (1989-1991 and 2003-2005, comparable samples were not collected in 1988), and both early and late season samples pooled, there were 1,040 records of length and weight for Dolly Varden. Twenty-five records (~2.4% of the data) were censored during a preliminary least squared linear regression of Log transformed data because their standardized residuals were either >3 or <-3. A subsequent regression with the remaining data had a significant positive slope (P < 0.0005) and length was positively correlated with weight (r^2 = 98.5%) (Figure 18). Years and seasons nested within years were both significant factors in the GLM model (P < 0.0005). Individual contrasts of mean studentized residuals (proxy data for relative fish condition) revealed that Dolly Varden sampled during the early season in 1991 were in significantly poorer condition than in all other seasonal periods (P < 0.05 for all 11 contrasts), and that Dolly Varden sampled during the late season in 2003 were in significantly better condition than in all other seasonal periods except the late season in 2004 (P < 0.05 for 10 of 11
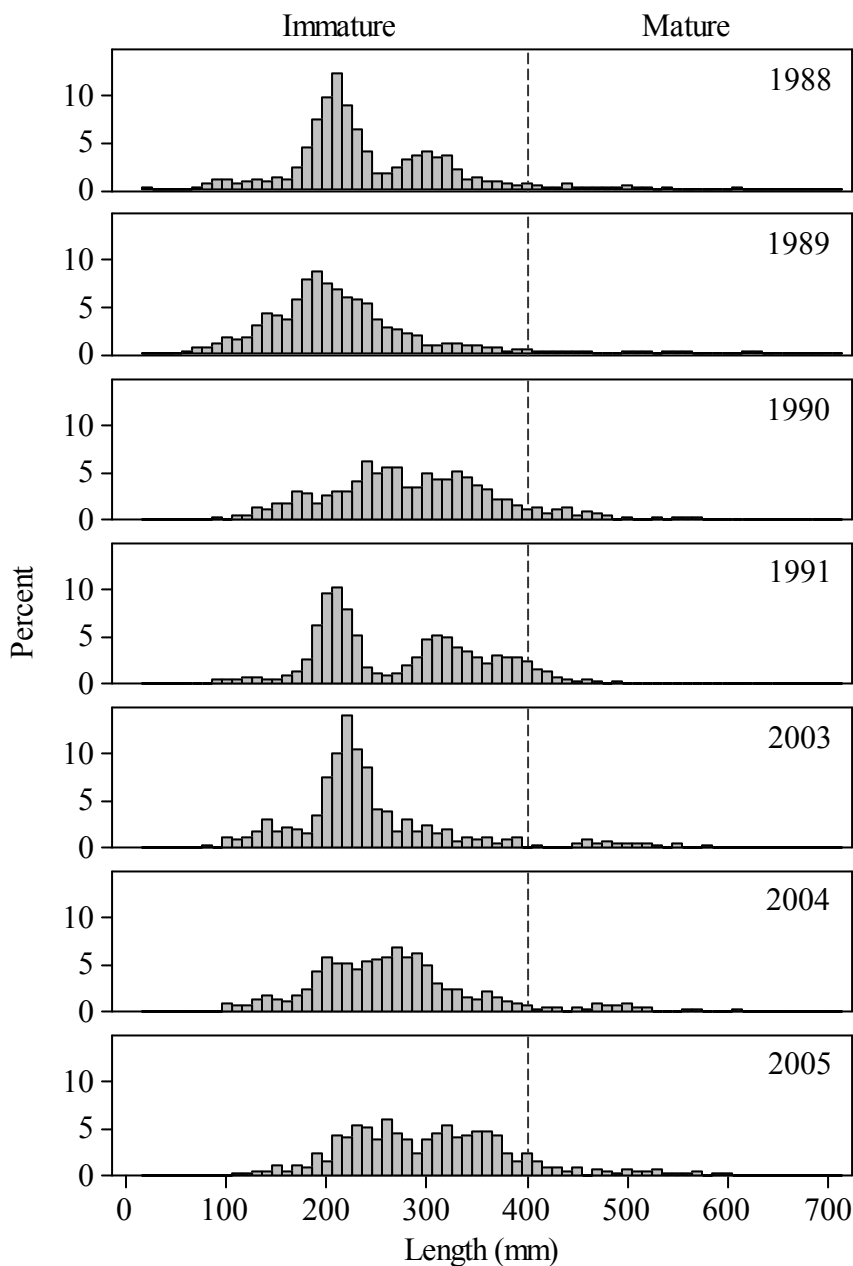
Figure 16. Dolly Varden length frequency histograms for all seven study years. Fish 400 mm or more in length (dashed line) were considered to be reproductively mature and fish less than 400 mm in length were considered to be immature. The dominant peak evident during some years between 200 and 250 mm is thought to represent the most common size at first migration to sea.

contrasts) (Table 9). Fish sampled late in the season during 1991, 2003, 2004, and 2005 were in significantly better condition than fish sampled early in the season ($P < 0.05$), but during 1989 and 1990, early and late sampled fish were in similar condition (Figure 19).
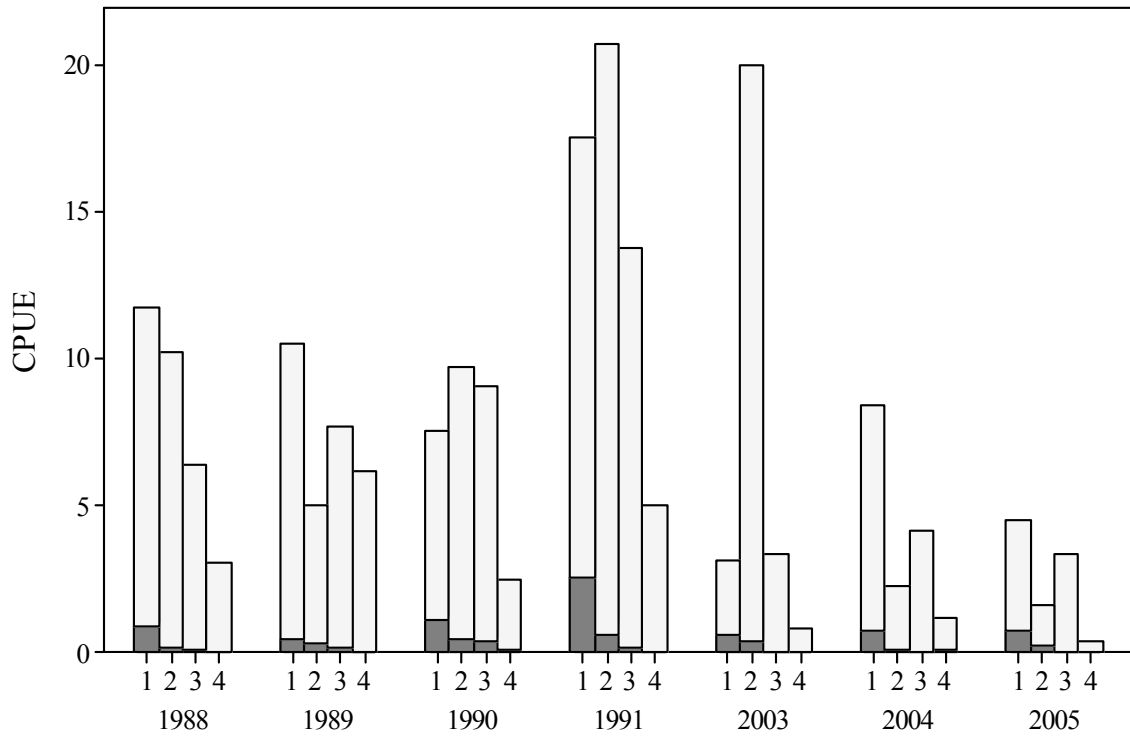
Figure 17. Dolly Varden CPUE (mean daily) by year, seasonal period, and demographic group. The CPUE of mature-sized individuals (those ≥400mm FL) are represented by the dark bars, and immature-sized individuals (those <400mm FL) are represented by the light bars stacked above.

Table 7. P-values, adjusted based on a family error rate of $\alpha = 0.05$, for comparisons of daily CPUE data for immature Dolly Varden by sample period nested within years using a General Linear Model with individual contrasts conducted with Tukey's HSD. Significant contrasts are indicated with shaded cells.

		1988				1989				1990				1991			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1988	1																
	2	1.00															
	3	1.00	1.00														
	4	0.01	0.07	0.85													
1989	1	1.00	1.00	0.96	0.00												
	2	0.23	0.56	1.00	1.00	0.09											
	3	1.00	1.00	1.00	0.24	1.00	0.87										
	4	0.75	0.93	1.00	1.00	0.50	1.00	1.00									
1990	1	0.85	0.98	1.00	0.95	0.57	1.00	1.00	1.00								
	2	1.00	1.00	1.00	0.29	1.00	0.90	1.00	1.00	1.00							
	3	1.00	1.00	1.00	0.30	1.00	0.92	1.00	1.00	1.00	1.00						
	4	0.00	0.00	0.21	1.00	0.00	0.99	0.02	0.94	0.33	0.03	0.02					
1991	1	0.91	0.94	0.03	0.00	0.98	0.00	0.68	0.00	0.00	0.73	0.40	0.00				
	2	0.24	0.35	0.00	0.00	0.43	0.00	0.12	0.00	0.00	0.15	0.04	0.00	1.00			
	3	0.99	1.00	0.16	0.00	1.00	0.00	0.92	0.02	0.02	0.94	0.76	0.00	1.00	1.00		
	4	0.95	0.99	1.00	1.00	0.84	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.04	0.00	0.14	
2003	1	0.00	0.00	0.05	1.00	0.00	0.85	0.00	0.71	0.09	0.00	0.00	1.00	0.00	0.00	0.00	0.89
	2	1.00	1.00	0.96	0.02	1.00	0.23	1.00	0.60	0.73	1.00	1.00	0.00	1.00	1.00	1.00	0.82
	3	0.01	0.08	0.87	1.00	0.00	1.00	0.25	1.00	0.96	0.30	0.31	1.00	0.00	0.00	0.00	1.00
	4	0.00	0.00	0.00	0.46	0.00	0.05	0.00	0.03	0.00	0.00	0.00	0.95	0.00	0.00	0.00	0.09
2004	1	0.94	1.00	1.00	0.84	0.73	1.00	1.00	1.00	1.00	1.00	1.00	0.17	0.00	0.00	0.03	1.00
	2	0.00	0.01	0.29	1.00	0.00	1.00	0.03	0.97	0.43	0.04	0.03	1.00	0.00	0.00	0.00	0.99
	3	0.28	0.63	1.00	1.00	0.11	1.00	0.91	1.00	1.00	0.93	0.95	0.96	0.00	0.00	0.00	1.00
	4	0.00	0.00	0.02	0.86	0.00	0.33	0.00	0.23	0.04	0.00	0.00	1.00	0.00	0.00	0.00	0.35
2005	1	0.01	0.10	0.93	1.00	0.00	1.00	0.32	1.00	0.99	0.38	0.39	1.00	0.00	0.00	0.00	1.00
	2	0.00	0.00	0.00	0.94	0.00	0.22	0.00	0.15	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.37
	3	0.01	0.05	0.71	1.00	0.00	1.00	0.16	1.00	0.87	0.19	0.20	1.00	0.00	0.00	0.00	1.00
	4	0.00	0.00	0.03	0.77	0.00	0.29	0.00	0.20	0.04	0.00	0.00	0.99	0.00	0.00	0.00	0.29

		2003				2004				2005			
		1	2	3	4	1	2	3	4	1	2	3	4
2003	1												
	2	0.00											
	3	1.00	0.03										
	4	0.99	0.00	0.39									
2004	1	0.03	0.84	0.86	0.00								
	2	1.00	0.00	1.00	0.88	0.24							
	3	0.75	0.27	1.00	0.03	1.00	0.98						
	4	1.00	0.00	0.82	1.00	0.02	0.99	0.26					
2005	1	1.00	0.03	1.00	0.21	0.92	1.00	1.00	0.67				
	2	1.00	0.00	0.89	1.00	0.00	1.00	0.14	1.00	0.66			
	3	1.00	0.01	1.00	0.72	0.70	1.00	1.00	0.96	1.00	1.00		
	4	1.00	0.00	0.72	1.00	0.03	0.97	0.23	1.00	0.58	1.00	0.90	

Table 8. P-values, adjusted based on a family error rate of $\alpha = 0.05$, for comparisons of daily CPUE data for mature Dolly Varden by sample period nested within years using a General Linear Model with individual contrasts conducted with Tukey's HSD. Significant contrasts are indicated with shaded cells.

		1988				1989				1990				1991			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1988	1																
	2	0.86															
	3	0.28	1.00														
	4	0.12	1.00	1.00													
1989	1	1.00	0.98	0.58	0.31												
	2	1.00	1.00	1.00	0.99	1.00											
	3	0.81	1.00	1.00	1.00	0.97	1.00										
	4	0.24	1.00	1.00	1.00	0.50	1.00	1.00									
1990	1	0.45	0.00	0.00	0.00	0.14	0.00	0.00	0.00								
	2	1.00	1.00	0.92	0.74	1.00	1.00	1.00	0.85	0.30							
	3	1.00	1.00	0.99	0.94	1.00	1.00	1.00	0.98	0.02	1.00						
	4	0.47	1.00	1.00	1.00	0.77	1.00	1.00	1.00	0.00	0.97	1.00					
1991	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
	2	1.00	0.53	0.09	0.03	1.00	0.93	0.47	0.08	0.97	1.00	1.00	0.19	0.00			
	3	0.81	1.00	1.00	1.00	0.97	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.45		
	4	0.50	1.00	1.00	1.00	0.75	1.00	1.00	1.00	0.00	0.94	0.99	1.00	0.00	0.23	1.00	
2003	1	1.00	0.99	0.75	0.49	1.00	1.00	0.99	0.66	0.34	1.00	1.00	0.88	0.00	1.00	0.99	0.84
	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.04	1.00	1.00	1.00	0.00	0.96	1.00	1.00
	3	0.16	1.00	1.00	1.00	0.40	1.00	1.00	1.00	0.00	0.82	0.97	1.00	0.00	0.05	1.00	1.00
	4	0.63	1.00	1.00	1.00	0.84	1.00	1.00	1.00	0.00	0.97	1.00	1.00	0.00	0.33	1.00	1.00
2004	1	1.00	0.28	0.02	0.01	1.00	0.77	0.23	0.02	0.89	1.00	0.98	0.06	0.00	1.00	0.20	0.11
	2	0.32	1.00	1.00	1.00	0.61	1.00	1.00	1.00	0.00	0.93	0.99	1.00	0.00	0.11	1.00	1.00
	3	0.06	1.00	1.00	1.00	0.20	0.99	1.00	1.00	0.00	0.65	0.90	1.00	0.00	0.02	1.00	1.00
	4	0.96	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.04	1.00	1.00	1.00	0.00	0.81	1.00	1.00
2005	1	1.00	0.21	0.01	0.00	1.00	0.65	0.17	0.01	1.00	1.00	0.93	0.04	0.00	1.00	0.15	0.08
	2	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	0.81	1.00	1.00
	3	0.24	1.00	1.00	1.00	0.50	1.00	1.00	1.00	0.00	0.86	0.98	1.00	0.00	0.08	1.00	1.00
	4	0.97	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.09	1.00	1.00	1.00	0.00	0.86	1.00	1.00

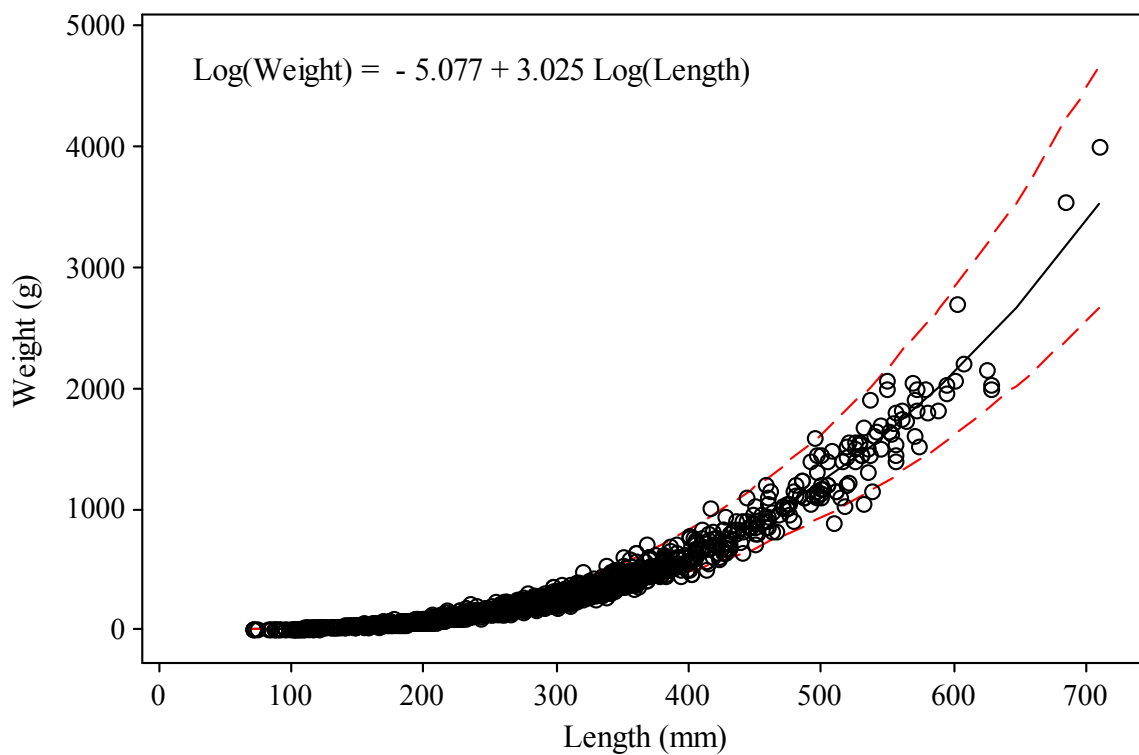|		2003				2004				2005			
		1	2	3	4	1	2	3	4	1	2	3	4
2003	1												
	2	1.00											
	3	0.59	1.00										
	4	0.90	1.00	1.00									
2004	1	1.00	0.91	0.01	0.20								
	2	0.77	1.00	1.00	1.00	0.03							
	3	0.37	1.00	1.00	1.00	0.00	1.00						
	4	1.00	1.00	1.00	1.00	0.71	1.00	1.00					
2005	1	1.00	0.82	0.01	0.14	1.00	0.02	0.00	0.60				
	2	1.00	1.00	1.00	1.00	0.58	1.00	1.00	1.00	0.46			
	3	0.66	1.00	1.00	1.00	0.02	1.00	1.00	1.00	0.01	1.00		
	4	1.00	1.00	1.00	1.00	0.80	1.00	1.00	1.00	0.70	1.00	1.00	

Figure 18. Least squared linear regression of Log transformed weight and length data of Dolly Varden displayed in normal units with fitted line and associated 95% prediction intervals (dashed lines). Length was highly predictive of weight (r^2 = 98.5%).

Table 9. Matrix of individual contrasts among seasons nested within years. Shaded cells indicate significant differences of condition between paired samples.

		1989		1990		1991		2003		2004		2005	
		early	late	early	late	early	late	early	late	early	late	early	late
1989	early												
	late	0.58											
1990	early	1.00	0.62										
	late	0.99	1.00	0.99									
1991	early	0.00	0.00	0.00	0.00								
	late	0.67	0.02	0.75	0.26	0.00							
2003	early	1.00	0.95	1.00	1.00	0.00	0.58						
	late	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
2004	early	1.00	0.79	1.00	1.00	0.00	0.42	1.00	0.00				
	late	0.00	0.31	0.00	0.10	0.00	0.00	0.00	0.91	0.00			
2005	early	0.12	0.00	0.25	0.06	0.00	1.00	0.20	0.00	0.02	0.00		
	late	0.97	1.00	0.97	1.00	0.00	0.17	1.00	0.00	1.00	0.13	0.02	
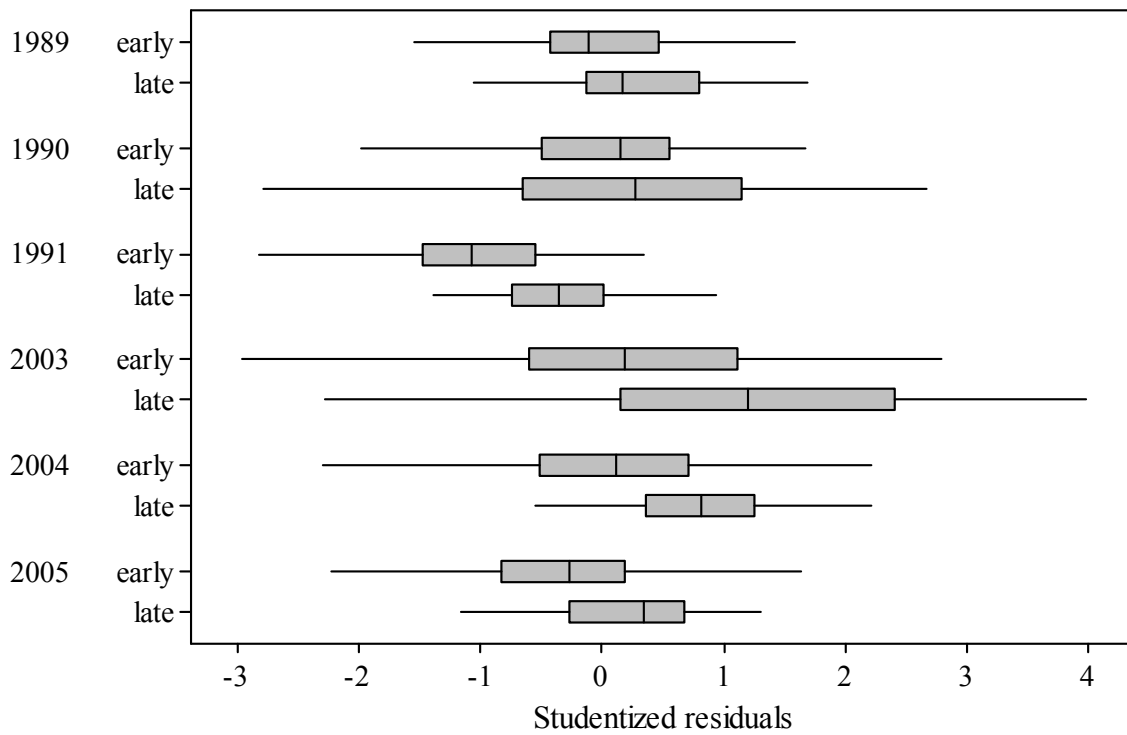
Figure 19. Boxplots illustrating seasonal trends in relative condition of Dolly Varden as represented with the distributions of studentized residuals of the length weight regression.

Broad Whitefish and Least Cisco

CPUE—One hundred twenty-nine broad whitefish and 1,242 least cisco were captured in Beaufort Lagoon, Barter Island, and Camden Bay, combined, during the sampling years 1988 through 1991. Relative abundances (CPUE) of both species were greatest in the Camden Bay region, least in the Beaufort Lagoon region, and intermediate in the Barter Island region, suggesting that both species originated in western rather than eastern overwintering locations (Figure 20). Minimum length at maturity for broad whitefish is commonly reported to be between 400 and 450 mm (Alt 1976; Bond 1982; Treble and Tallman 1997; Shestakov 2001; Brown 2004) and for least cisco between 250 and 300 mm (Hatfield et al. 1972a; Moulton et al. 1997; Brown 2004). Maturity was not evaluated directly for broad whitefish or least cisco in this sampling study, but based on these other data sources, broad whitefish ≥425 mm and least cisco ≥275 mm were considered to be mature. Length frequency histograms of all broad whitefish (n = 144) and least cisco (n = 1,276) captured during the seven sampling years of the project revealed that approximately 92% of broad whitefish and 59% of least cisco were immature (Figure 21).
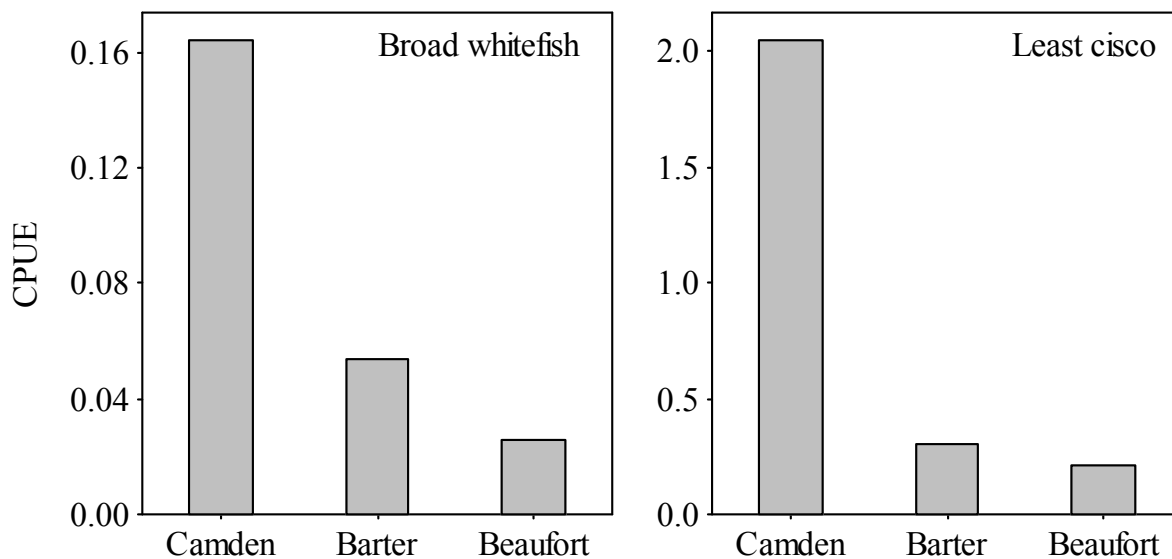
Figure 20. Overall CPUE (fish captured per net-day) of broad whitefish (n = 129) and least cisco (n = 1,242) captured between 1988 and 1991 in three sampling areas along the eastern Beaufort Sea coast in Alaska: Camden Bay, which is closest to the Sagavanirktok and Colville rivers overwintering region; Barter Island, which is approximately midway between the two overwintering regions; and Beaufort Lagoon, which is closest to the Mackenzie River overwintering region.

Marine Species

Fourhorn sculpin was the most abundant species encountered during the seven years of sampling in the Barter Island region (Table 2). Length frequency histograms were tri-modal during the early years of the sampling project, with modes at approximately 75, 120, and 190 mm, and bimodal during the later years, with modes at approximately 75 and 120 mm (Figure 22). The large demographic group was comparatively rare in the Barter Island region during the later years. Relative abundance of fourhorn sculpin varied among years, and among some sampling periods within years, but no strong trends were apparent (Figure 23). They were generally more
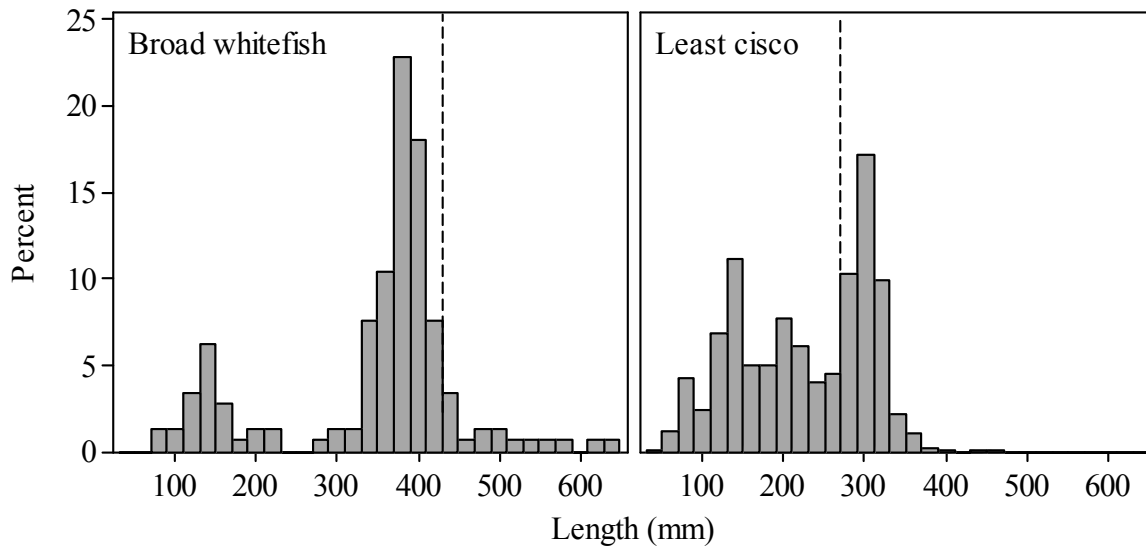
Figure 21. Length frequency histograms of broad whitefish (n = 144) and least cisco (n = 1,276) captured in sampling areas along the eastern Beaufort Sea coast in Alaska during seven years of sampling between 1988 and 2005. The vertical lines indicate commonly reported minimum lengths of maturity for broad whitefish (425 mm) and least cisco (275 mm). Based on these length criteria, approximately 92% of broad whitefish and 59% of least cisco encountered in the sampling region were immature.

abundant during 1989 and 1990 than in other years. The pattern of CPUE by sample period during 1988 was very similar to that in 2005, and the CPUE pattern in 1991, with the exception of the high first sampling period, was very similar to that in 2004. No major population trends were apparent from these data except the reduced representation of large fourhorn sculpin in the later years compared to the early years.

Arctic flounder was the third most abundant species encountered during the seven years of sampling in the Barter Island region (Table 2). Length frequency histograms were highly variable among years (Figure 22). A small mode (less than 100 mm) dominated during 1990 and 1991, was present during 2005, and was essentially missing during 1988, 1989, 2003, and 2004. During the early years there appeared to be a large mode centered at approximately 200 mm, while during the later years there appeared to be two, less distinctive modes centered at approximately 140 and 200 mm. Relative abundance of Arctic flounder was lowest in 1988 and was very similar during all other years (Figure 24). Arctic flounder were most abundant during the first or second sample period every year and were more abundant during the first sample period of 1990 than in any other sampling period. A distinct seasonal trend of declining CPUE by sampling period was evident during sample years 1990-1991, and 2003-2005. The relative abundance of Arctic flounder was lowest during the fourth sample period of every year.

Arctic cod was the sixth most abundant species encountered during the seven years of sampling in the Barter Island region (Table 2). Length frequency histograms were relatively stable among years (Figure 25). A single mode was evident during all years. During 1989 the mode was approximately 125 mm, and during all other years it was approximately 100 mm. Relative abundance of Arctic cod varied greatly among years (Figure 26). The only apparent seasonal pattern was that during the first sampling period each year they were absent or rare compared to other sampling periods.
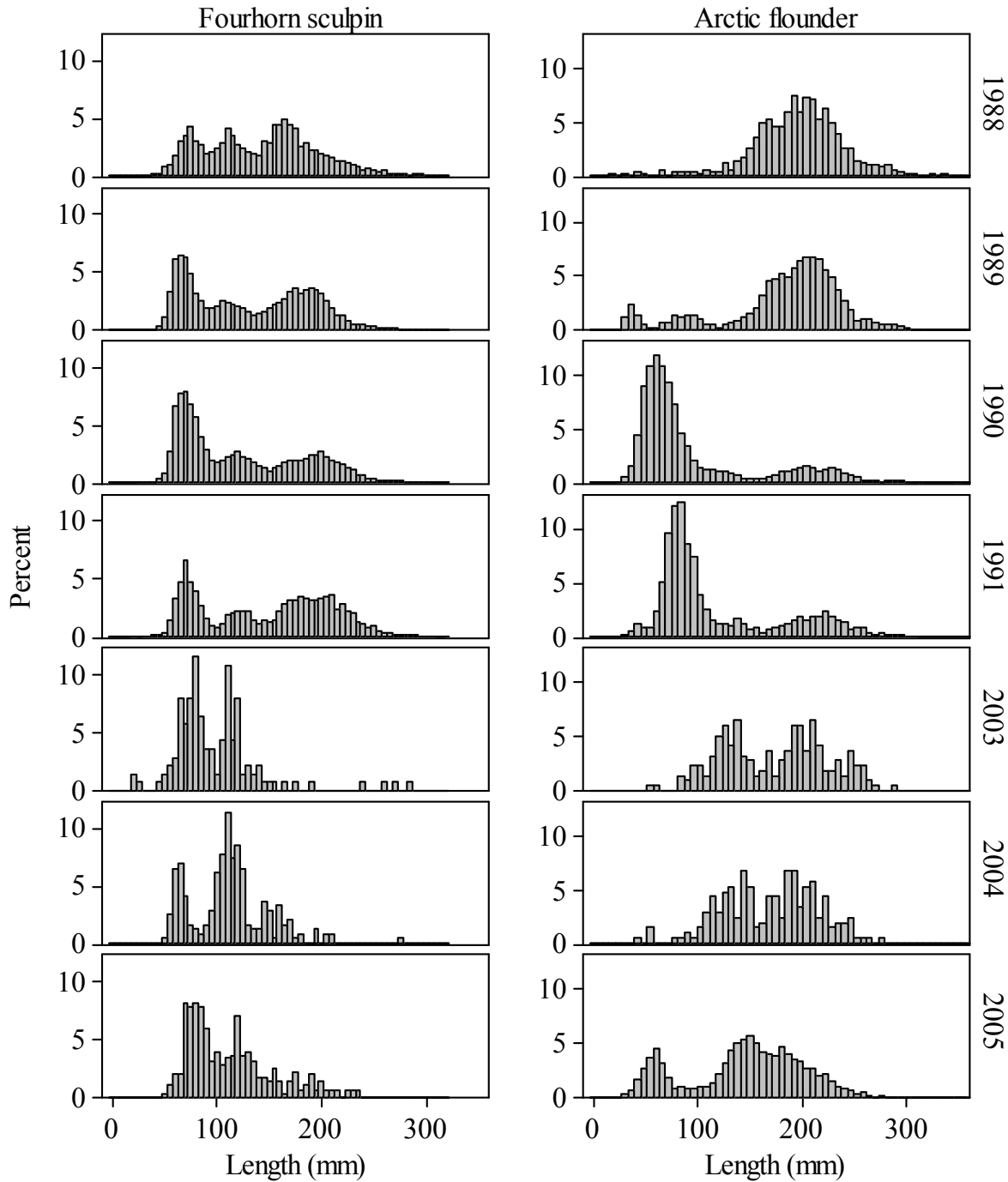
Figure 22. Length frequency histograms of fourhorn sculpin and Arctic flounder for all seven study years.

Saffron cod was the fifth most abundant species encountered during the seven years of sampling in the Barter Island region (Table 2). Length frequency histograms were highly variable among years with from one to three modes being present (Figure 25). A large mode centered between 350 and 400 mm was present only during 2003 and 2004. A strong mode at approximately 180 mm was present during 1989, 1991, and 2004. A small mode near 100 mm was present during 1988, 1990, 1991, 2003, and 2005. These modes are thought to represent age cohorts with variable annual representation in the Barter Island region lagoon systems. The relative
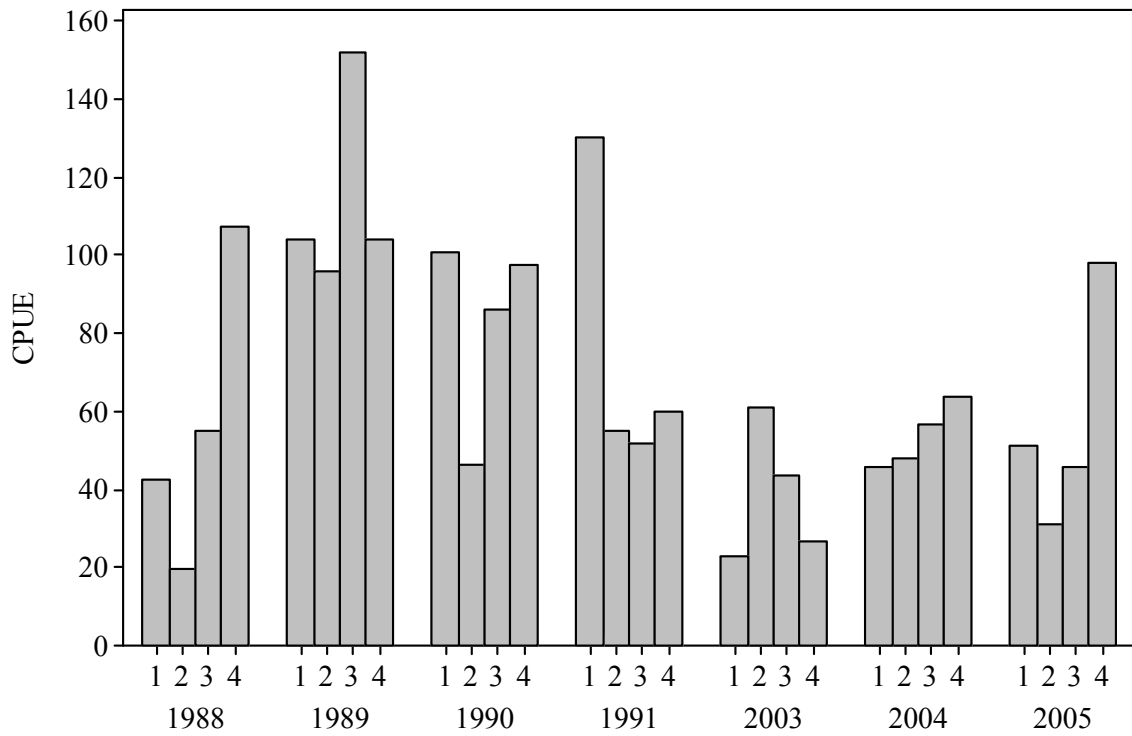
Figure 23. Fourhorn sculpin CPUE by year and seasonal period.
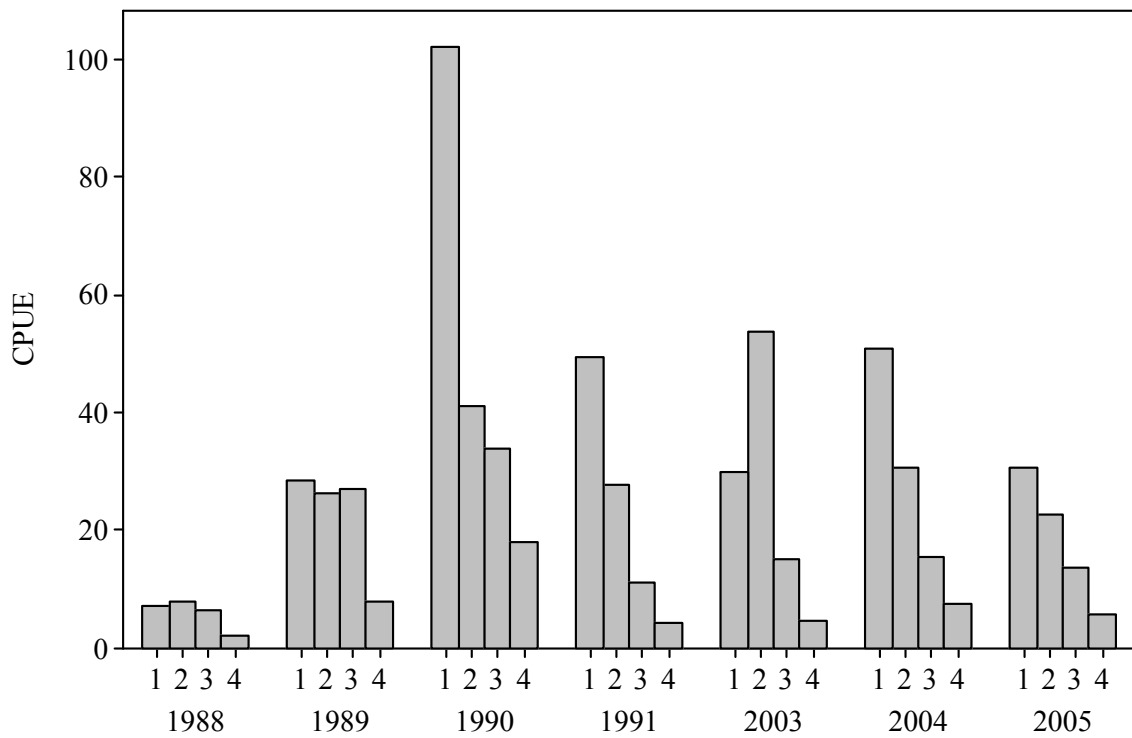
Figure 24. Arctic flounder CPUE by year and seasonal period.
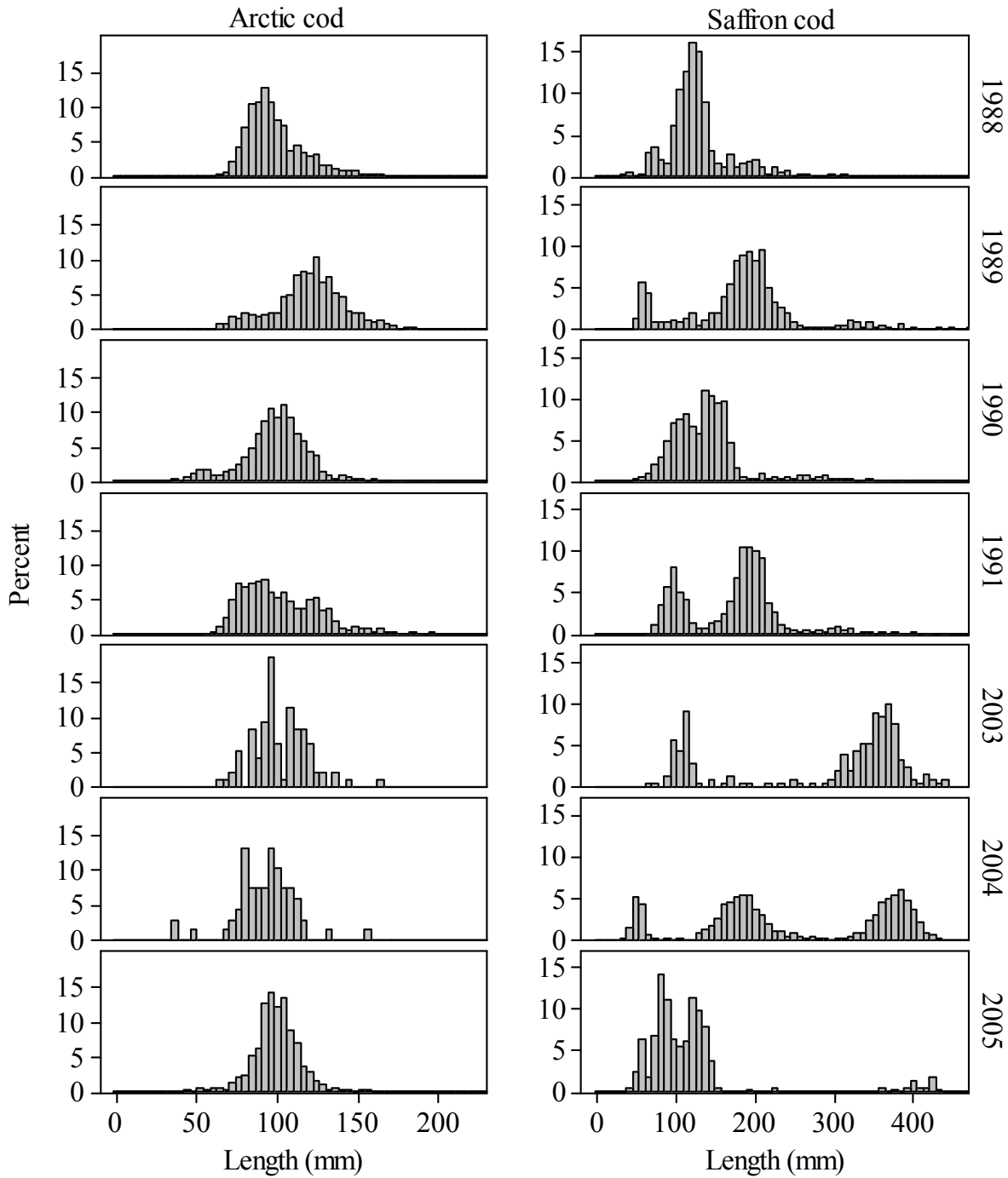
Figure 25. Length frequency histograms of Arctic and Saffron cod for all seven study years.

abundance of saffron cod was similar among years during the early years of the project, and among years during the later years of the project, but was substantially greater during the later years than the early years (Figure 27). The CPUE during the first sampling period of all years except 2003 was less than during later sampling periods, suggesting some seasonality to their use of the Barter Island region lagoon system.
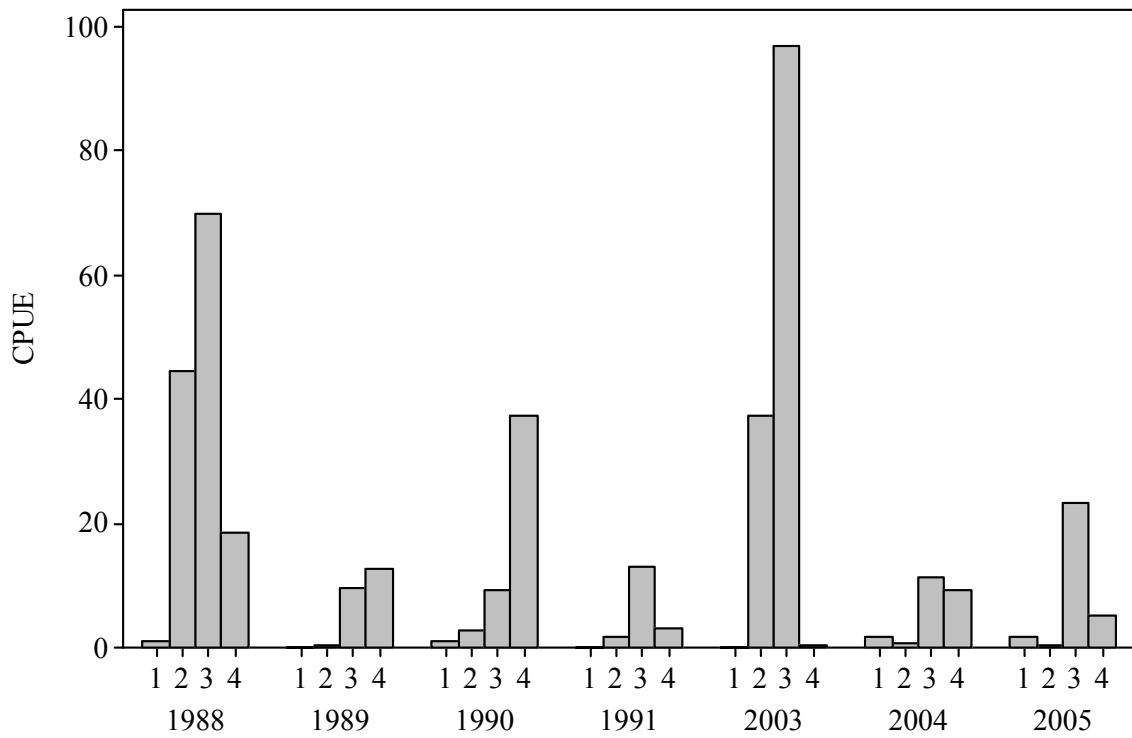
Figure 26. Arctic cod CPUE by year and seasonal period.
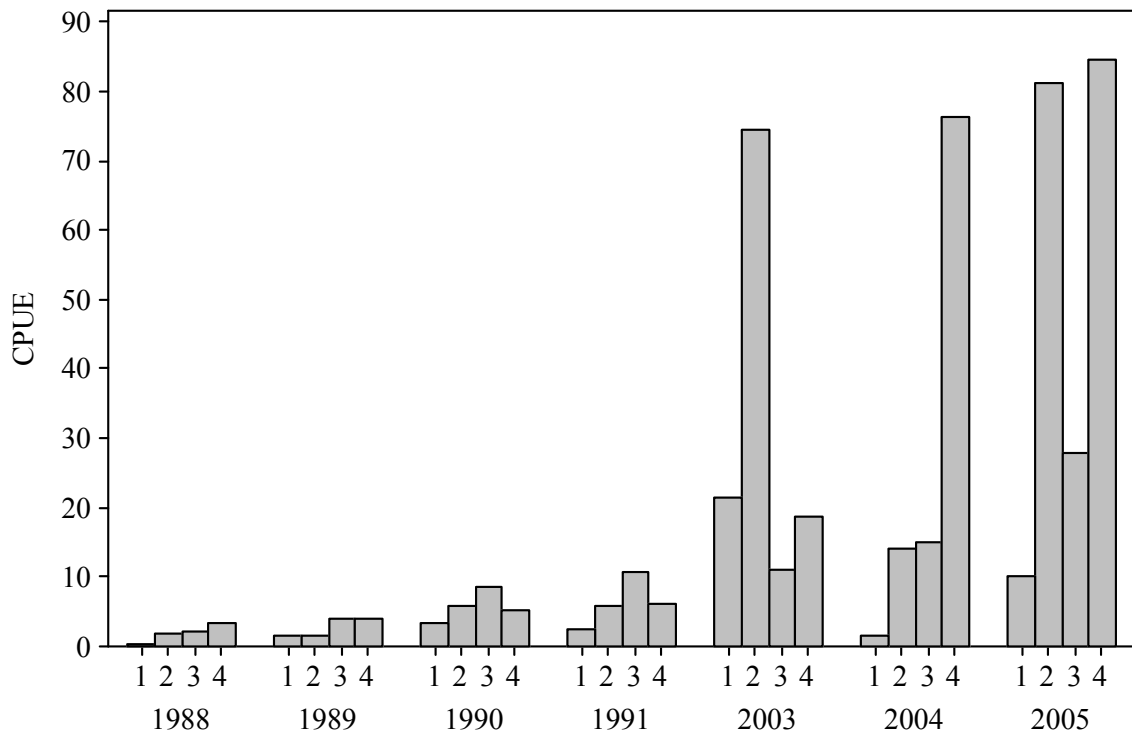
Figure 27. Saffron cod CPUE by year and seasonal period.

Discussion

Arctic Cisco

Mature-size group—Underwood et al. (1995) initially assumed the largest Arctic cisco were migrating to spawn, but, some of their tagged fish were recaptured during the winter in the Colville River demonstrating that at least some migrated to the west after capture instead of east to Mackenzie River spawning destinations. The mature-size group of Arctic cisco sampled in the Barter Island region from mid-July through early September were evidently not preparing to spawn during the year of capture despite most being of size and age distributions consistent with spawning Arctic cisco in the Mackenzie River (Hatfield et al. 1972a, 1972b). The GSI values for at least 92 of 95 females sampled were too low given their capture dates for them to progress to spawning condition by fall (Figure 7). Griffiths et al. (1977) examined egg size of female Arctic cisco from the Barter Island lagoons and concluded that only a few fish captured early in the season could possibly be preparing to spawn. Bond (1982) and Bond and Erickson (1989) observed that Arctic cisco preparing to spawn became rare in coastal waters by the end of July and they speculated that by that time most had begun their upstream migrations to spawning destinations in the Mackenzie River drainage. Arctic cisco overwintering in the Colville River must migrate east to the Mackenzie River to spawn. Sampling data, as presented above, indicate that they avoid capture in the coastal lagoon sampling project as they migrate past the Barter Island region either because they avoid the lagoon systems during their spawning migration or their migration occurs before the sampling project begins.

Tagging, aging, and CPUE data along the Beaufort Sea coast suggest that mature-size Arctic cisco encountered in the Barter Island region are coming from the Colville and the Mackenzie River overwintering groups. In 1988 Bond and Erickson (1989) tagged several hundred mature-size Arctic cisco during summer sampling activities at Phillips Bay, approximately 225 km east of Barter Island and 125 km west of the Mackenzie River delta. One of their tagged fish was recovered later the same summer in the Barter Island lagoons, suggesting that fish overwintering in the Mackenzie River delta range at least as far west as the Barter Island region to feed. Underwood et al. (1995) found approximately 7% of Arctic cisco aged in the Barter Island region during the early years of this study were age 10 or older. Mature fish in this age range are thought to have spawned previously. While they are not uncommon in the Mackenzie River system (Hatfield et al. 1972a; Stein et al. 1973; Reist and Bond 1988), they are almost never encountered in the Colville River fishery (Moulton and Seavey 2004). These data are consistent with the concept of Mackenzie River overwintering origins for some mature-size Arctic cisco in the Barter Island region. Plots of daily CPUE at Beaufort Lagoon, Barter Island, and Camden Bay during the early years of this project (Figures 10, 11, 12, and 13), admittedly qualitative and weak data by themselves, also suggest that mature-size Arctic cisco come to the Barter Island region from both Colville and Mackenzie River overwintering locations. Provided these indicators reflect the actual situation, the relative abundance of mature-size Arctic cisco in the Barter Island region would not be expected to correlate with harvest levels in the Colville River winter fishery. In fact, during the seven years for which data were available for comparison (albeit a rough comparison) between mean daily CPUE in the Barter Island lagoon system and the CPUE of the previous winter's subsistence fishery in the Nigliq Channel of the Colville River, as reported by Daigneault and Reiser (2007), the correlation was non-significant ($\rho = -0.392$, $P = 0.384$; Figure 28).
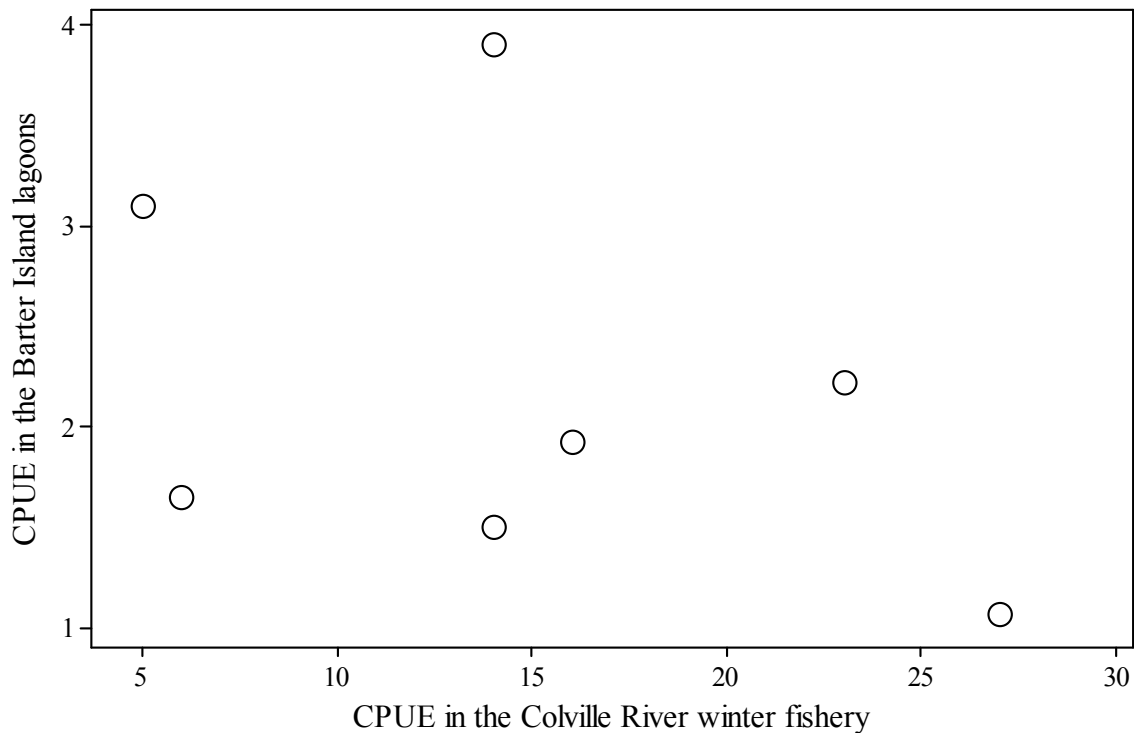
Figure 28. Scatterplot illustrating the lack of correlation between mean daily CPUE of mature-size Arctic cisco in the Barter Island lagoons and the CPUE in the Colville River subsistence fishery the winter before. Pearson's correlation coefficient was -0.392, which was non-significant ($P = 0.384$).

The relative abundance of the mature-size group of Arctic cisco was the least variable of the three size categories considered in this study. There were comparatively few patterns of significant CPUE contrasts among seasonal periods nested within years (Table 5). Notable exceptions were the relatively high CPUE values observed in the first period of 1989, the second period of 2003, and the first period of 2004, which were significantly greater than a large fraction of the other seasonal periods. Despite these individual seasonal periods of significantly higher abundance, the overall presence and relative abundance of mature-size Arctic cisco, which are the demographic group captured in the fishery, appear to be relatively stable across the seven years of sampling during this project (Figure 8).

Immature group—Similar to the mature-size group, CPUE data along the Beaufort Sea coast suggest that immature Arctic cisco encountered in the Barter Island region are coming from the Colville and the Mackenzie River overwintering groups. Plots of daily CPUE at Beaufort Lagoon, Barter Island, and Camden Bay during the early years of this project (Figures 10, 11, 12, and 13) suggest that immature Arctic cisco come to the Barter Island region from Colville and Mackenzie River overwintering locations. These data suggest that during some years fish might come from both overwintering sources (1991, Figure 13) and during other years fish might come primarily from either the Colville (1988, Figure 10; 1989, Figure 11) or the Mackenzie River (1990, Figure 12). Annual overwintering origins of the immature cohorts may not necessarily be the same as for the mature-size group, as illustrated during 1990, when the immature group appeared to come primarily from the east while the mature-size group appeared to come primarily from the west (Figure 12), suggesting that different factors influence their summer

feeding forays, or possibly that the abundance ratios of the two demographic size groups vary by overwintering region. In a similar manner to the mature-size group, the relative abundance of immature Arctic cisco in the Barter Island region would not be expected to reliably correlate with previous recruitments to the Colville River.

The relative abundance of the immature group of Arctic cisco was less variable than the age 0 cohort and more variable than the mature-size group. In general there was a relatively low level of abundance of immature Arctic cisco during most sampling periods nested within years. Significantly higher levels of CPUE were observed during several sampling periods including periods two and three in 1988, period three in 1989, and periods one and two in 1990 (Table 4). These five high-abundance sample periods were significantly greater than most other sample periods within years (Figure 8).

Age 0 cohort—Overall variability in relative abundance of Arctic cisco in the Barter Island lagoon system was dominated by the age 0 cohort (Figure 8). The presence of age 0 Arctic cisco was generally correlated with the prevalence of east winds (Figure 9), as has been documented previously in the Prudhoe Bay region (Fechhelm et al. 2007). The annual patterns of relative abundance of the age 0 cohorts in the Barter Island region (Figure 8) were very similar to those presented by Fechhelm et al. (2006) for the Prudhoe Bay region, with the cohort being in greatest abundance in 1990, essentially missing in 1991 and 2003, and of more moderate abundance during the other years.

While favorable winds may generate the along-shore current (Dunton et al. 2006), the mechanism that transports age 0 Arctic cisco to the west, annual variation in CPUE among years with similarly favorable wind conditions suggests that other factors may be more influential of the magnitude of the recruitment. Favorable winds during July (sampling period 1) should strongly influence the arrival of age 0 Arctic cisco in the Barter Island region during early August (sampling period 2). Equally favorable July winds (Figure 9, red circles) were observed in 1990, 1991, and 2005, yet, the average daily CPUE of this cohort during early August ranged from over 1,200 in 1990, less than 2 in 1991, and about 25 in 2005 (Figure 8). This same pattern of relative abundance for these three years was also observed in Prudhoe Bay (Fechhelm et al. 2006). The relative abundance of age 0 Arctic cisco declined somewhat during late August and September in 1990, although, they were still very abundant compared to other years. Age 0 Arctic cisco were essentially missing during late August and September in 1991, and remained at similar levels of abundance throughout August in 2005, declining to relatively low levels during September. The variability in relative abundance of age 0 Arctic cisco during years of similarly favorable wind conditions may indicate variable spawning success within the Mackenzie River populations, as discussed by Fechhelm et al. (2007), the presence of heavy coastal pack ice dampening the wind-driven coastal current, which may have been a factor in 1991 (Underwood et al. 1996; Jarvela and Thorsteinson 1999), or possibly a more easterly distribution of the cohort in the Mackenzie River delta, making them less likely to be carried west by the coastal current.

Condition—Evidence of Arctic cisco growth and improved body condition between early and late seasons of the summer was expected given their annual life history pattern; heavy feeding in the warm coastal waters during the brief summer season and long months of minimal feeding in cold brackish waters during the winter season (Craig 1989; Schmidt et al. 1989). Fechhelm et al. (1996) examined seasonal body condition for 76 different year-class groups of Arctic cisco sampled during 12 years in Prudhoe Bay and found that body condition improved significantly over the course of the summer in 80% of the cases. Significant seasonal body condition improvement in this study was observed in only two of six years (33%) (Table 6, Figure 15).

Similar to Fechhelm et al. (1996), age 0 Arctic cisco were censored from these analyses, and the GSI data (Figure 7) suggested that almost all mature-size Arctic cisco that were included in the Barter Island body condition analyses were not developing gonads. Age classes of Arctic cisco could not be isolated in this study as they were in Fechhelm et al. (1996) because the length histograms did not consistently reveal age class cohorts beyond age 0 (Figure 5) and length and weight sampling was not directed to obtain cohort-specific samples. Mean studentized residuals of immature and mature-size Arctic cisco were not significantly different in this study so they were pooled and analyzed together. It is possible that fish condition did improve between early and late seasons every year and that the lack of cohort-specific data prevented us from detecting it. An alternative explanation, however, may be that cohorts from different overwintering origins migrated in and out of the Barter Island lagoon system relatively quickly, confounding the detection of growth of any one group of fish. Presumably all Arctic cisco encountered in the Prudhoe Bay region overwinter in the Colville or Sagavanirktok River deltas and experience more uniform growth conditions than the mixed overwintering groups that are encountered in the Barter Island region. In any case, body condition indices would be more useful if influential environmental variables such as salinity, temperature, ocean currents, coastal ice-flow density, prey abundance, etc., were systematically measured during the course of summer sampling, which was done during the early years of this project (Underwood et al. 1995) but not during the later years.

Dolly Varden

Most Dolly Varden captured during the fyke net sampling study in the Barter Island lagoon system were immature fish (Figures 16 and 17). Very few immature fish are large enough to be captured by the gillnet or angling methods employed in the regional fishery (Pedersen and Linn 2005), which targets the mature demographic group almost exclusively. The annual smolt peaks identified in the length frequency histograms (Figure 16) were much less distinctive than those from the Prudhoe Bay region, as presented by Fechhelm et al. (1997). In fact, no discernable smolt peak could be identified during the years 1990, 2004, and 2005. The reason for this apparent difference is thought to be related to the proximity of the two sampling regions to rivers maintaining spawning populations of Dolly Varden. Genetics research and tag return data have shown that Dolly Varden from many source populations are found in coastal sites across northern Alaska and Yukon Territories (Craig 1984; Krueger et al. 1999). Additionally, Krueger et al. (1999) showed that fish originating in nearby rivers were proportionately more abundant than those originating in more distant rivers. The closest rivers to the Barter Island lagoon system with known Dolly Varden populations are the Aichilik River, approximately 60 km to the east of Barter Island, and the Hulahula River, approximately 20 km to the west (Figure 3). By contrast, the Sagavanirktok River, a major producer of Dolly Varden in northern Alaska (Yoshihara 1973; Viavant 2005), empties into the sea at the eastern edge of Prudhoe Bay. If smolts range less widely along the coast than older fish, they would be expected to be proportionately more abundant in Prudhoe Bay than in the Barter Island lagoons, and would therefore produce more distinct peaks in length frequency histograms in Prudhoe Bay sampling sites.

Craig and Haldorson (1981) conducted a multi-year sampling study in Simpson Lagoon, which is located between the mouths of the Sagavanirktok and Colville rivers in northern Alaska (Figure 2). They fished a variety of gear including fyke nets, multiple-mesh gillnets, and beach seines. They contended, based on species-specific length frequency data from simultaneous sets of different gear, that all sampling methods were highly selective. Of particular interest relative to

Dolly Varden was a fyke net versus gillnet comparison they conducted in 1977. They presented length frequency histograms (Figure 46, page 177 of their report) that depict the fyke net catch, which was unimodal, similar to that of the 2003 catch in Figure 16 of this paper, and the gillnet catch, which was bimodal with a smolt mode at a similar length to that from the fyke net catch, and a larger mature fish mode at approximately 540 mm. They concluded that fyke nets were much more efficient at catching immature than mature Dolly Varden and gillnets were more efficient at catching mature Dolly Varden. Fyke net derived CPUE data may be useful for comparing the relative abundance of mature Dolly Varden among years or seasons, although, a more efficient capture method would provide better resolution of changes, analogous to weighing fish to the nearest 100 g versus weighing them to the nearest 1 g. Based on the findings of Craig and Haldorson (1981), fyke net derived CPUE data cannot be used to compare the relative abundance of immature versus mature Dolly Varden.

The relative abundance of mature Dolly Varden averaged about one fish per net day during one or two sampling periods during every year except 1991, when they approached three fish per net day during July (Figure 17). Underwood et al. (1996) reported that 1991 was a year of heavy pack ice and relatively cold water temperatures in the nearshore marine environment in northeastern Alaska. They hypothesized that these environmental conditions concentrated Dolly Varden that might normally have been more broadly dispersed in the coastal band of warm brackish water. Jarvela and Thorsteinson (1999) reported that heavy pack ice and colder water temperatures occurred in 1988 as well as 1991, but the relative abundance of Dolly Varden in the Barter Island lagoon system did not appear to increase in 1988. Further, Craig et al. (1985) captured only a small number of Dolly Varden on the seaward side of the barrier islands relative to a much larger catch within the barrier island lagoon system, suggesting that most Dolly Varden normally feed within the barrier islands. They were uniformly rare or absent during September (sample period 4) in all years, consistent with our understanding that they must migrate into the river systems where they will spawn and then overwinter (McCart 1980). Immature Dolly Varden apparently extend their feeding season by remaining in the marine environment somewhat longer, as evidenced by their continued presence in the fyke net catches in September.

Condition—Evidence of improved body condition of Dolly Varden between early and late seasons of the summer was expected given their annual life history pattern; heavy feeding in the warm coastal waters during the brief summer season and long months of minimal feeding in river systems during the winter season (Craig 1989; Schmidt et al. 1989). Underwood et al. (1997) investigated expected differences in body condition of Dolly Varden captured in Beaufort Lagoon, Barter Island, and Camden Bay using data from the early years of this project. They compared slope and intercept parameters of least-squared linear regressions among sample groups and found no significant differences between male and female Dolly Varden, but, they did observe a significant seasonal improvement of condition between early and late season samples for three of four paired sample sets, a significant decline in condition between late season samples of one year to early season samples of the next for two of three paired sample sets, and significant differences in condition among sample locations and years. The relatively poor condition of Dolly Varden in 1991, also identified in the current analyses (Table 9; Figure 19), was attributed to the effects of persistent coastal pack ice that year.

Fechhelm et al. (1997) examined seasonal growth of Dolly Varden smolts during 10 years of sampling in Prudhoe Bay. They identified the smolts by length as the major distinctive peak in length frequency histograms. They reasoned that smolts were a distinct size group in the same stage of life, despite being composed of multiple age classes, and should display similar growth

patterns in the common environment of the coastal lagoons. They simply tracked the seasonal advancement of the mean length of the smolt group to estimate summer growth. They found that Dolly Varden smolt grew slowly in the early and late periods of the summer and more rapidly during mid-summer.

In this study, changes in seasonal body condition were estimated with residual analyses of length weight regressions of Dolly Varden of all age classes and demographic groups. Unlike the Arctic cisco case, where significant seasonal improvement in body condition was detected during only two of six sample years (Figure 15), Dolly Varden showed significant seasonal improvement during four of six sample years, with 1989 and 1990 being the exceptions (Figure 19). Underwood et al. (1997) found significant differences between early and late season samples during 1989 and 1990, but, they pooled seasonal data from the three sampling regions (the current work is limited to samples from the Barter Island region only) and both sampling region and year factors were significant in separate analyses. Seasonal improvement in body condition was probably experienced by most fish in all years, despite these results. Our inability to consistently detect it may not be because our method was inappropriate, but more that we sampled from mixed-stock and mixed-demographic aggregates of fish engaged in feeding migrations east and west along the coast, and in and out of lagoon systems. It is, therefore, likely that the growth histories of samples collected at different times were different. Given the mobile life history of anadromous Dolly Varden in the southern Beaufort Sea, as summarized by McCart (1980), Craig (1984, 1989), and others, it is thought that condition indices will always be an ineffective way to measure the effects of small-scale spatial or temporal environmental variables. They may become useful for gauging the effects of larger-scale events that are expected with climate warming such as reduced summer sea ice cover, progressively longer summer seasons, or a steady increase in average summer sea temperatures. For these types of analyses the baseline data collected here may become extraordinarily valuable.

General Linear Model

A general linear model with Tukey's HSD method of multiple comparisons was used to compare relative abundance (CPUE) and fish condition (studentized residuals) among years and seasonal periods nested within years. Combined with associated graphics (bar graphs and boxplots) and tables containing contrast P-value matrices, they allowed any contrast of interest to be examined for significance. Tests of homogeneity in relative abundance involved 378 individual contrasts (see Tables 3, 4, 5, 7, and 8) and tests of homogeneity in body condition involved 66 individual contrasts (see Tables 6 and 9). Adjusted for a family error rate of 0.05, individual contrasts were significant at approximately $P<0.0002$ and $P<0.001$ respectively, which was insensitive to small differences. Significant differences were therefore very different. Refining the questions to limit the number of contrasts would improve our ability to detect smaller differences in relative abundance or body condition among groups. But, this may be a moot point at this time because there is no clear understanding of what a significant difference means about fish populations. Nor are there established critical values beyond which some inference about a population can be made (i.e., the population is healthy, the population is doing poorly, there is a cohort failure, etc.). In fact, we are still in a descriptive mode attempting to understand how the system works. The statistical analyses at this point are simply methods of describing our temporal and geographic findings and putting them in context with the findings at other times and places. As such, the general linear model with Tukey's HSD method of multiple comparisons appears to have worked reasonably well.

Conclusion

Based on harvest data and the life history accounts discussed above, we know that Arctic cisco and Dolly Varden captured in the Barter Island fishery are primarily mature-size fish of mixed-stock origins. It would not be appropriate to consider them as independent populations or individual stocks with common survival histories. Many human influenced and natural factors, including development activities, fisheries across their ranges, timing of spring breakup, river flow patterns, prevailing winds, ice cover on the sea, population levels of marine predators and competitors, and more, influence their seasonal presence and relative abundance in the region. Arctic cisco originating from the Laird River population and overwintering along the Tuktoyaktuk Peninsula would experience different survival challenges than those originating from the Peel River population and overwintering in the Colville River delta, yet both may contribute to the Barter Island fishery (Bond 1982; Bond and Erickson 1989; Bickham et al. 1992; Moulton and Seavey 2004). While the Colville River winter fishery for Arctic cisco may be highly correlated with recruitment of age 0 fish five to eight years prior (Fechhelm et al. 2007), the Barter Island summer fishery is apparently not. The relative abundance of mature-size Arctic cisco in the Barter Island lagoon system appears to be relatively stable across the years (Figure 8), suggesting more than just the Colville River source population, which is highly variable because of periodic annual recruitment failures of age 0 fish from the Mackenzie River (Moulton and Seavey 2004). Similar to the Arctic cisco situation, Dolly Varden originating from a Sagavanirktok River population would experience different survival challenges than those originating from a Firth River population, yet both certainly contribute to the Barter Island summer fishery (Underwood et al. 1995; Krueger et al. 1999). The winter fishery for Dolly Varden up the Hulahula River is a completely different case (Craig 1987; Pedersen and Linn 2005), being directed primarily at a single population.

The large geographic scope of the aquatic system, the many contributing populations, the multiple options for rearing, and environmental variability across marine and freshwater environments, may be viewed together as a grand buffering mechanism for the coastal fishery. Some populations may be at low levels while others are high. Coastal feeding migration from the east may be reduced one year because of ice-pack along shore while migration from the west may be clear and open. On another year the situation might be reversed. The Barter Island fishery would be relatively successful when survival was high for many populations across the region and would be relatively poor when survival was low for many populations. While the mixed-stock nature of the Barter Island fishery makes it impossible to monitor and manage as a discrete stock, it also reduces the risk of depletion of any single population. Major changes in coastal development, fishing effort, or harvest methods, however, should be carefully considered, as these may alter what appears to be a sustainable system.

Acknowledgments

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