

# Utility of Pop-Up Satellite Archival Tags to Study the Summer Dispersal and Habitat Occupancy of Dolly Varden in Arctic Alaska

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**ABSTRACT.** In Arctic Alaska, Dolly Varden *Salvelinus malma* is highly valued as a subsistence fish; however, little is known about its marine ecology. New advances in electronic tagging, such as pop-up satellite archival tags (PSATs), provide scientists with a fishery-independent means of studying several aspects of this species' movement and ecology. To evaluate the usefulness of this technology, we attached 52 PSATs to Dolly Varden in the Wulik River, which flows from northwestern Alaska into the Chukchi Sea, to study several characteristics of the marine habits of this species. Overall, PSATs provided unprecedented information about summer dispersal of Dolly Varden, including the first evidence of offshore dispersal in the Chukchi Sea, as well as previously documented dispersal types such as movement to other rivers and southerly nearshore movements in northwestern Alaska. On the basis of minimal observable evidence of tag-induced behavioral effects, as well as movements of more than 450 km by fish at liberty (i.e., between tag deployment and release or recapture), we conclude that PSATs offer an effective alternative method for studying several aspects of Dolly Varden dispersal and ecology in areas where it is not practical or feasible to capture these fish, such as coastal and offshore regions of Arctic Alaska.

**Key words:** Chukchi Sea; dispersal; Dolly Varden; PSATs

**RÉSUMÉ.** Dans l'Alaska de l'Arctique, l'omble du Pacifique, *Salvelinus malma* revêt une grande importance en tant que poisson de subsistance. Toutefois, on en sait peu sur son écologie marine. Les progrès réalisés en matière de traçabilité électronique, notamment en ce qui a trait aux étiquettes de collecte de données par satellite (PSAT) permettent aux scientifiques d'étudier plusieurs aspects des déplacements et de l'écologie de cette espèce sans dépendre de la pêche. Afin d'évaluer l'utilité de cette technologie, nous avons fixé 52 PSAT à des ombles du Pacifique de la rivière Wulik, qui s'écoule depuis le nord-ouest de l'Alaska jusqu'à la mer des Tchoukches, pour étudier plusieurs caractéristiques des habitudes aquatiques de cette espèce. Dans l'ensemble, les PSAT ont permis de recueillir des renseignements sans précédent au sujet de la dispersion estivale de l'omble du Pacifique, y compris la première preuve de dispersion extracôtière dans la mer des Tchoukches et d'autres types de dispersion anciennement documentés, comme les déplacements vers d'autres cours d'eau et les déplacements sublittoraux en direction sud, dans le nord-ouest de l'Alaska. D'après un minimum d'éléments de preuve observables quant aux effets découlant de la présence d'étiquettes sur le comportement ainsi que d'après les déplacements de plus de 450 kilomètres des poissons en liberté (c'est-à-dire entre l'installation des étiquettes et le relâchement ou la recapture), nous concluons que les PSAT présentent une méthode de rechange efficace pour étudier plusieurs aspects de la dispersion et de l'écologie de l'omble du Pacifique dans des endroits où il n'est pas pratique ou réalisable de prendre ces poissons, comme dans les régions côtières et extracôtières de l'Alaska de l'Arctique.

**Mots clés :** mer des Tchoukches; dispersion; omble du Pacifique; PSAT

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## INTRODUCTION

Dolly Varden (*Salvelinus malma*) is found throughout a wide range in northwestern North America and northeastern Asia and is widely distributed in Alaska. While Dolly Varden is not commercially important in Arctic Alaska, it is thought to be the most frequently landed fish in many Arctic Alaska villages (Pedersen and Linn, 2005; Magdanz et al., 2010). For example, in the northwestern Alaskan

villages of Kivalina and Noatak, the harvest of anadromous Dolly Varden in 2007 (30 761 fish) far exceeded the harvest of all species of Pacific salmon *Oncorhynchus* spp. combined (5241 fish; Magdanz et al., 2010).

Because of the logistical challenges of capturing fishes in the Arctic Ocean, as well as the lack of commercial fisheries there, most research on Dolly Varden in Arctic Alaska has focused on its freshwater biology and ecology. For example, studies have attempted to locate spawning

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and overwintering sites, ascertain the timing of freshwater immigration and emigration, and identify the geographic distribution, mixing of stocks, and relative abundance of this species (Yoshihara, 1972; Furniss, 1975; Craig, 1977; McCart, 1980; DeCicco, 1985, 1989, 1996, 1997). In Arctic Alaska, beginning at two to five years of age, anadromous Dolly Varden start their annual migration to the ocean, where they feed each summer, returning to freshwater to overwinter (Armstrong and Morrow, 1980). After two or three marine migrations for summer feeding, Dolly Varden individuals reach maturity and return to their natal river to spawn in the fall (DeCicco, 1989). Additionally, results from conventional tagging and genetic studies show that Dolly Varden in Arctic Alaska demonstrate complex migration patterns, in which individuals may overwinter in mixed stocks and move across boundaries between Alaska, Canada, and the Russian Far East (DeCicco, 1992, 1997; Krueger et al., 1999; Crane et al., 2005). As a result, significant mixing of Dolly Varden stocks occurs in this area during both marine and freshwater phases, and subsistence fishers often target fish natal to multiple drainages.

Previous studies of the marine ecology of Dolly Varden suggested that the species remains in nearshore habitats while in the ocean (Armstrong and Morrow, 1980); however, several lines of evidence now suggest that Dolly Varden may occupy offshore habitats (DeCicco, 1992; Volkov et al., 1996; Fechtel et al., 1997; Morita et al., 2009). For example, bycatch data from offshore Pacific salmon research fisheries south of the Bering Strait indicate that Dolly Varden is distributed throughout a wide range of the Pacific Ocean that includes nearshore and offshore waters of the Japan Sea, the Bering Sea, the Okhotsk Sea, and the Gulf of Alaska (Morita et al., 2009). However, it is not known whether individuals occupy offshore areas of the Arctic Ocean because summer fisheries there are very limited. Fishery-independent data collection is therefore critically important for understanding the habits of Dolly Varden.

Electronic fish tags provide opportunities to examine aspects of marine biology and ecology of fishes, including marine dispersal, behavior, habitat occupancy, and mortality (Arnold and Dewar, 2001; Thorstad et al., 2014). One tag type, the pop-up satellite archival tag (PSAT), measures and records depth, temperature, and ambient light intensity while attached to a fish. On a pre-programmed date, the tag releases itself from the fish, floats to the surface of the ocean, and transmits the archived information to a series of ARGOS satellites, from which project investigators can retrieve it. Initially, PSATs were limited to large-bodied marine species, including Atlantic bluefin tuna *Thunnus thynnus* (Block et al., 2005), white marlin *Tetrapturus albidus* (Horodysky et al., 2007), tiger sharks *Galeocerdo cuvier* (Holland et al., 2001), and Pacific halibut *Hippoglossus stenolepis* (Seitz et al., 2003), because of the large size and weight of tags. As the size of tags has become miniaturized, PSATs have been successfully used to describe habitat occupancy and movements of smaller fishes

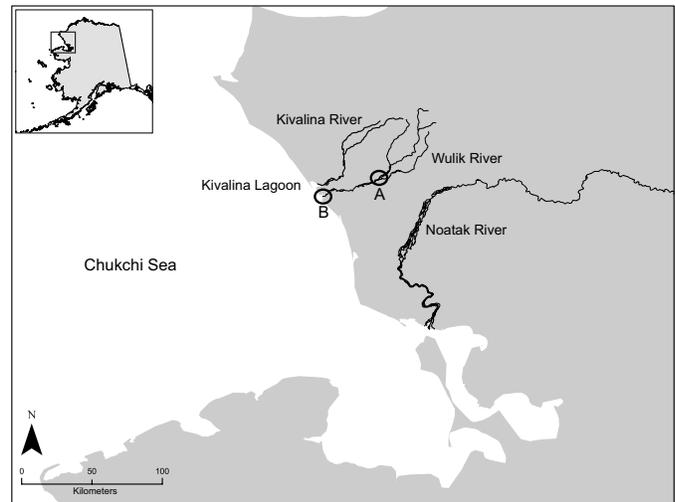


FIG. 1. Sampling locations (circles) where Dolly Varden were tagged in A) the Wulik River, Alaska, in 2012, and B) Kivalina Lagoon in 2013.

(52–112 cm) such as the striped bass *Morone saxatilis* (Graves et al., 2009) and Atlantic salmon *Salmo salar* (Chittenden et al., 2013a; Lacroix, 2013; Godfrey et al., 2015).

Because Dolly Varden in Arctic Alaska can attain sizes equivalent to those of striped bass and Atlantic salmon, we hypothesized that PSATs might be an effective tool for collecting fishery-independent information about the marine ecology of this species, including whether it occupies offshore areas of the Arctic Ocean. Since Dolly Varden is an important subsistence species for many Alaska Natives, this information is directly pertinent to future management decisions of Native fishers, as well as those of biological resource managers, mineral and energy developers, and regulators. This study therefore aims to evaluate the utility of using PSATs to study the distribution, dispersal, and habitat occupancy of Dolly Varden in the marine environment of Arctic Alaska. For this evaluation, we examined the following metrics: tag reporting rates and percentage of retrieved depth and temperature data; Dolly Varden summer distribution and dispersal patterns; and trends in behavior and survivorship of tagged Dolly Varden. Detailed analyses of depth and temperature data are not included in this paper, but can be found in a companion manuscript that describes the marine habitat occupancy and behaviors of Dolly Varden in nearshore and offshore waters of the Arctic Ocean (Courtney et al., 2015).

## METHODS

### Study Site

Fish were obtained from the Wulik River, located in northwestern Alaska (67°43'24" N, 164°31'24" W; Fig. 1). The Wulik River contains the largest known overwintering aggregation of Dolly Varden in Arctic Alaska; annual abundance estimates, produced by periodic aerial surveys

from 1969 to 2008, are commonly more than 100 000 fish (Scanlon, 2011). The Wulik River drainage is a clearwater system that drains a 2280 km<sup>2</sup> watershed. Beginning at the Delong Mountains, the river flows westward approximately 145 km before entering the Chukchi Sea portion of the Arctic Ocean near the village of Kivalina, Alaska.

### *Fish Capture*

In early to mid-June of 2012 and 2013, Dolly Varden that overwintered in the Wulik River were captured and tagged with PSATs (n = 52). In 2012, Dolly Varden (n = 20) were captured between 3 and 5 June using a beach seine (70 × 2.4 m, with 0.05 m mesh) in the main stem of the Wulik River (67°52'40.91" N, 163°40'23.28" W) approximately 45 km upstream from where it enters Kivalina Lagoon (Table 1; Fig. 1). In 2013, we captured Dolly Varden (n=32) with gill nets in Kivalina Lagoon near the confluence of the lagoon and the Chukchi Sea (67°43'24" N, 164°31'24" W) on 13 and 14 June (Table 1; Fig. 1). This change was made to reduce the number of tagged fish incidentally captured in subsistence and recreational fisheries before leaving the Wulik River. When gill nets were deployed, we monitored them constantly, and upon capture of a Dolly Varden (indicated by bobbing floats), we removed the fish immediately from the gill net. Dolly Varden that had fork length greater than 60 cm (measured to the nearest cm) and were deemed appropriate for tagging (i.e., no visible bleeding or injuries) were carefully removed from the nets with a knotless-mesh dip net and placed in a small-mesh holding pen (1.2 × 2.4 m, 70 cm water depth). While fish were in the holding pen, we assessed their health for up to four hours before tagging. Each fish was monitored for signs of stress or abnormal behavior, including visual injuries and bleeding, loss of equilibrium, abnormal coloration, frayed fins, and rapid opercular movement. Only fish deemed to be healthy according to these metrics were tagged. After accumulating several large fish in the holding pen, we removed individuals one at a time. We placed each fish in a custom-made tagging cradle that contained river water, blindfolded it, and attached the PSAT tag.

### *Tag Attachment*

Tags were attached to Dolly Varden using a “tag backpack” system formerly developed for Atlantic salmon (Chittenden et al., 2013a; Fig. 2). The backpack system included two components: the “straps” (a harness attachment system that was affixed through the dorsal musculature of the fish) and the “pack” (the transmitter, which was attached to the harness). The straps consisted of two custom-fabricated plastic plates (each one 1.0 cm wide × 5.0 cm long × 0.2 cm thick and protected on one side by a silicon pad 0.2 cm thick), which were affixed to both ends of a 15 cm length of 80 lb. test Dacron fishing line. The middle of this line was then secured to a corrodible link on the transmitter using a cow hitch knot. Each tag backpack was affixed

to a fish by placing the silicon-padded side of each plastic bar approximately 2 cm below and on opposite sides of the dorsal fin. Once in place, the “tag backpack” was secured by threading a 20 cm long U-shaped piece of stainless steel wire first through two small holes in one of the plastic bars, then through the dorsal musculature of the fish, and finally out two small holes in the second plastic bar on the opposite side of the fish. The ends of the wire were secured to each other using a haywire twist, which was trimmed to a 1 cm tag-end and pushed to lie flat against the plastic bar to prevent detachment of the tag backpack. Each tagged fish was released near its capture site. All fieldwork was conducted under University of Alaska Fairbanks, Institution of Animal Care and Use Committee assurance #308584 and State of Alaska Fisheries Research Permit SF-ECP-2007-87.

### *PSAT Tag Specifications, Settings, and Data Acquisition*

Each PSAT tag (X-tag, Microwave Telemetry Inc.) weighed 40 g in air and was buoyant with the complete harness attached. While attached to a fish, the tag measured and recorded depth, temperature, and ambient light readings every two minutes (specifications available at <http://www.microwavetelemetry.com/fish/Xtag.cfm>). The exact timing of return to freshwater was unknown, and the PSATs need to be in water with salinity of at least 5 psu for their release mechanism to function. We therefore used a staggered pop-up schedule, in which tags were programmed to pop up at two-week intervals (from 1 July to 1 September in 2012, and from 1 July to 1 October in 2013). This pop-up schedule was developed as a compromise between maximizing the duration of tag data records and maximizing the tag-reporting rate. Since we had no previous knowledge of the vertical range of Dolly Varden in marine waters, no constant depth release function to indicate mortality was activated on the PSATs.

On the predetermined dates, the tags released from the fish, floated to the surface of the sea, and transmitted archived temperature and depth data and daily sunrise and sunset times (based on light readings) via satellite. While the tag was transmitting, its location was determined from the Doppler shift of the transmitted radio frequency in successive uplinks received during one Argos satellite pass (Keating, 1995). Because of the large amount of data collected by the tags, limited data reception by Argos satellites, and short tag-battery life, only a subset of temperature and depth data, recorded at 15-minute intervals, was transmitted. However, if the tags were recovered while still attached to the fish (i.e., from fish recaptured in subsistence or sport fisheries), the complete data set recorded at two-minute intervals was obtained. Daily sunrise and sunset times (calculated by PSATs) transmitted to satellites were sent to the tag manufacturer (Microwave Telemetry, Inc., Columbia, Maryland) and used to calculate daily geolocation estimates during post-processing of the raw data.

The end locations of tags were determined as follows. For tags that popped up and transmitted to satellites on

TABLE 1. Deployment and end location information for pop-up satellite archival tags (PSATs) attached to 52 Dolly Varden in the Wulik River, Alaska, in June 2012 and in Kivalina Lagoon in 2013. End dates and locations represent when and where a fish reported to satellites or was physically recaptured. An asterisk (\*) denotes a fish that died prior to its pop-up date.

Fish ID	Length (cm)	Tagging location and year	End date <sup>1</sup>	Time at liberty (days)	Minimum distance (km)	% data obtained <sup>2</sup>	End location
107988	78	Wulik 2012	7/1/12	26	45	84	Kivalina Lagoon
107989	76	Wulik 2012	7/7/12	32	13	100	Wulik River
107990	82	Wulik 2012	7/1/12	26	319	100	Russian Chukchi
107991	78	Wulik 2012	Failed	—	—	—	—
107992	81	Wulik 2012	7/15/12	40	383	100	Russian Chukchi
107993*	86	Wulik 2012	7/4/12	29	138	99	Cape Espenberg
107994	82	Wulik 2012	Failed	—	—	—	—
107995	89	Wulik 2012	7/4/12	29	135	100	Kotzebue Sound
107996	82	Wulik 2012	7/12/12	37	306	100	Buckland River
107997	87	Wulik 2012	Failed	—	—	—	—
107998	86	Wulik 2012	6/24/12	19	0	100	Wulik River
107999	92	Wulik 2012	6/7/12	2	0	100	Wulik River
108000	82	Wulik 2012	8/15/12	71	381	98	Russian Chukchi
108001	79	Wulik 2012	N.A.F	—	—	—	—
108002	76	Wulik 2012	9/1/12	88	38	1	Wulik River
108003	85	Wulik 2012	8/15/12	71	359	97	Russian Chukchi
108004*	86	Wulik 2012	—	—	—	96	—
108005	79	Wulik 2012	6/18/12	13	45	100	Kivalina Lagoon
108006	83	Wulik 2012	N.A.F	—	—	—	—
108007*	82	Wulik 2012	—	—	—	54	—
108030	69	Kivalina 2013	N.A.F	—	—	—	—
108031	65	Kivalina 2013	Failed	—	—	—	—
108032*	64	Kivalina 2013	6/26/13	14	102	96	Cape Espenberg
108033	66	Kivalina 2013	6/22/13	9	120	100	Sheshalik Spit
108034*	62	Kivalina 2013	6/25/13	13	38	84	Coast
108035	71	Kivalina 2013	7/25/13	42	308	1	Noatak River
108036	67	Kivalina 2013	7/6/13	24	390	100	Russian Chukchi
108037	69	Kivalina 2013	6/27/13	14	140	99	Noatak Delta
108038	72	Kivalina 2013	7/15/13	33	40	7	Rabbit Creek
108039	65	Kivalina 2013	7/15/13	32	470	97	Russian Chukchi
108040	68	Kivalina 2013	7/10/13	27	365	100	Russian Chukchi
108041	83	Kivalina 2013	Failed	—	—	—	—
108042	79	Kivalina 2013	Failed	—	—	—	—
108043	79	Kivalina 2013	6/16/13	3	6	29	Wulik River
108044	67	Kivalina 2013	N.A.F	—	—	—	—
108045	70	Kivalina 2013	N.A.F	—	—	—	—
108046	79	Kivalina 2013	Failed	—	—	—	—
108047	76	Kivalina 2013	8/21/13	70	371	1	Noatak River
108048	73	Kivalina 2013	8/22/13	70	70	9	Omikviorok River
108223	72	Kivalina 2013	9/3/13	83	362	2	Noatak River
108224	71	Kivalina 2013	Failed	—	—	—	—
108225	78	Kivalina 2013	Failed	—	—	—	—
108226	80	Kivalina 2013	6/21/13	8	120	100	Sheshalik Spit
108227	72	Kivalina 2013	6/21/13	8	120	100	Sheshalik Spit
108228	74	Kivalina 2013	Failed	—	—	—	—
108229	79	Kivalina 2013	N.A.F	—	—	—	—
108230	83	Kivalina 2013	9/3/13	83	362	54	Noatak River
108231	68	Kivalina 2013	6/16/13	3	4	58	Wulik River
108232	76	Kivalina 2013	9/15/13	94	228	3	Noatak River
108233*	81	Kivalina 2013	—	—	—	82	—
108234	72	Kivalina 2013	10/17/13	127	45	4	Wulik River
129838	78	Kivalina 2013	7/27/13	44	191	17	Noatak River

<sup>1</sup> “N.A.F.” (not accounted for) refers to tags that never reported to satellites or were recaptured in fisheries, and “Failed” refers to tags that transmitted, but did not provide end location estimates.

<sup>2</sup> Total number of individual depth and temperature readings received via Argos, divided by the number of readings that should have been transmitted and received by satellites.

their scheduled transmission date ( $n = 17$ ), we used the location of the first transmission (Argos location class 1, 2, or 3; positional error < 1.5 km). For tags that prematurely released from a tagged fish within 10 days before their scheduled transmission date ( $n = 3$ ), we back-calculated

end locations by estimating and subtracting the distance the tag traveled while drifting on the ocean surface between its premature release and the location of its first transmission to satellites (Chittenden et al., 2013a). For tags ( $n = 4$ ) that prematurely released in freshwater, we assumed (on the

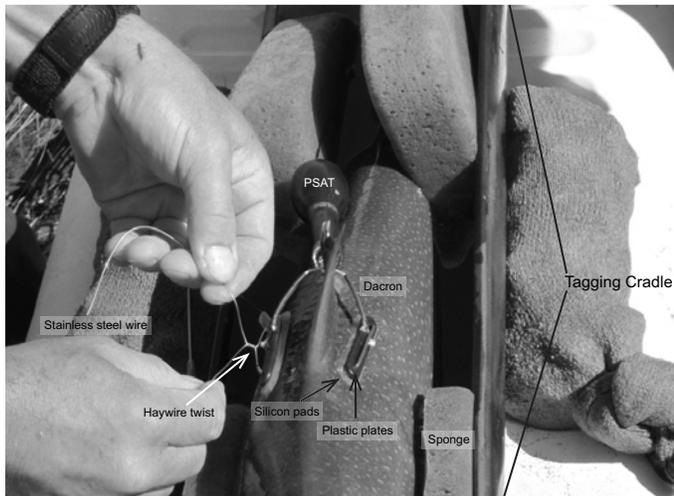


FIG. 2. An X-tag attached to a Dolly Varden with a wire harness “tag backpack” attachment system.

basis of a cyclic temperature range wider than that found in adjacent ambient water) that the tag had washed up on land near the release point (LaCroix, 2013); we assigned the position of the first transmission as the end location. Tagged fish recaptured in subsistence and sport fisheries ( $n = 9$ ) were assigned Global Positioning System (GPS) end locations (positional error  $< 0.2$  km) as reported by fishers.

Marine mortality of fish was assumed if tags had depth readings indicating that the fish had sunk to the bottom of the sea floor (15–50 m) and remained at that constant depth for at least three days ( $n = 6$ ). The first tag transmission with a Class 1–3 Argos location was considered the end location for fish presumed to be deceased if depth and temperature records indicated that tag drift (physical movement of the tag) before the tag reported to satellites was negligible (LaCroix, 2013). In all other cases (assumed tag-drift,  $n = 3$ ), end locations were excluded from dispersal analyses.

### Data Analyses

We analyzed the metrics examined as follows. The tag reporting rate was determined by tabulating the percentage of tags for which end locations could be determined (through reports to Argos or reports from fishers who recaptured tagged fish). The percentage of retrieved depth and temperature data was calculated as the total number of individual depth and temperature readings received via Argos, divided by the number of readings that should have been transmitted and received by satellites, assuming that depth and temperature data subsets (collected every 15 minutes) were transmitted. Additionally, the reporting rate and percent data retrieved from tags were qualitatively compared to time at liberty and end location habitat type (riverine, lagoon, or marine).

We determined the summer distribution and dispersal patterns of tagged Dolly Varden by examining minimum dispersal distance, end locations, and daily geolocation estimates. Minimum dispersal distance traveled was

calculated by measuring the great arc circle distance of a non-meandering route that did not pass over land between tagging and end locations. We used minimum distance traveled to examine dispersal distance because the uncertainty of individual fish tracks prevented calculation of the actual or maximum distance traveled (see Results). Distribution and dispersal patterns were qualitatively described by examining end locations for each two-week period in a geographical information system (GIS) framework. In addition, we assessed the efficacy of light-based geolocation by tabulating the number of tags and the total number of days for which sunrise and sunset could be calculated to subsequently produce daily geolocation estimates. However, given the failure of most tags to provide daily geolocation estimates (see Results), the relatively large errors associated with light-based geolocation, and the short time at liberty ( $< 90$  days), we did not use alternative models based on light-based geolocations, (e.g., State-space Kalman filters; Sibert et al., 2003; Lam et al., 2008) to produce the most probable tracks of tagged fish. Instead, we developed a simple filtering method to examine the plausibility of daily locations. We defined plausible daily geolocations as locations within a body of water (i.e., not on land) where daily tag-recorded sea-surface temperatures (SSTs; i.e., tag-recorded temperature  $< 2$  m) were within  $\pm 1^\circ\text{C}$  of satellite-derived SSTs (National Oceanic and Atmospheric Administration, Geo-Polar Blended SST Analysis  $0.05^\circ \times 0.05^\circ$ ). We used the plausibility of daily locations to examine the utility of light-based geolocation qualitatively.

Two analyses were conducted to examine dispersal distance and survivorship of tagged Dolly Varden. First, we compared the size of fish who died, fish that were alive on the pop-up date, fish that failed to provide an end location, and fish that were not accounted for (never reported to satellites or recaptured in fisheries), using means and bootstrapped (1000 replications) 95% confidence intervals. Second, we used a linear model ( $\alpha = 0.05$ ) to examine the relationship between fork length and the square root of minimum dispersal distance (km). A transformation (square root) was used on the response variable in order to meet the statistical assumptions of linear regression (i.e., that errors are normally and identically distributed). All statistical tests were performed with the statistical software R (R Core Team, 2014).

## RESULTS

### Reporting Rates

Tagged Dolly Varden ranged from 62 to 92 cm in length ( $77 \pm 7$  cm, mean  $\pm$  SD) and were at liberty for 2 to 127 days (Table 1). Of the 52 tags deployed, 33 (63%) provided end locations used in the dispersal analyses. Specifically, 24 (46%) provided end locations calculated by Argos satellites, and nine tags (17%) recovered while still attached to fish in subsistence and recreational fisheries provided GPS

TABLE 2. Summary of annual deployment of pop-up satellite archival tags attached to Dolly Varden in the Wulik River and Kivalina Lagoon, Alaska.

Year	Tagged <sup>1</sup>	Recaptured <sup>2</sup>	Argos end locations <sup>3</sup>	Failed end locations <sup>4</sup>	Not accounted for <sup>5</sup>	Mortality <sup>6</sup>
2012	20	6 (30%)	7 (35%)	3 (15%)	2 (10%)	3 (15%)
2013	32	3 (9.4%)	17 (53%)	7 (22%)	4 (13%)	3 (9.4%)
Total	52	9 (17%)	24 (46%)	10 (19%)	6 (12%)	6 (12%)

<sup>1</sup> Number of fish tagged.

<sup>2</sup> Tagged fish recaptured in sport and subsistence fisheries.

<sup>3</sup> Tags that provided end locations determined by Argos satellites.

<sup>4</sup> Tags that reported to satellites, but failed to provide end locations.

<sup>5</sup> Tags that neither transmitted nor were recaptured.

<sup>6</sup> Fish that presumably died before the tag's scheduled pop-up date.

end locations (Table 2). The fates of the remaining 19 tags (37%) were as follows: 10 tags (19%) transmitted, but failed to provide any end locations; three tags (6%) prematurely released after death of the fish and drifted for 1–2 months; therefore, their subsequent end locations were not used; and six tags (12%) never reported and could not be accounted for (Table 2).

#### Percentage of Retrieved Data

The percentage of archived temperature and depth data received from tags that transmitted to satellites varied from 0% to 100% (Table 1; Fig. 3). Most tags attached to fish that reported from freshwater provided end locations, but failed to provide any substantial archived temperature and depth data (0%–1%); the exceptions were tags of four fish that presumably washed up on land, reported from freshwater rivers, and provided 17%–58% of their archived data (Table 1; Fig. 3). In contrast, fish tags that reported from the ocean provided 84%–100% of the subset of archived data recorded at 15-minute intervals, and tags that were recaptured provided 100% of archived data recorded at two-minute intervals (Table 1; Fig. 3). While tags reporting from freshwater and from saltwater differed greatly in the percentage of data retrieved, little correlation was observed between time at liberty and the percentage of data retrieved (Fig. 3).

#### Summer Distribution and Dispersal Patterns

Tagged Dolly Varden had end locations in both marine ( $n = 15$ ) and freshwater ( $n = 18$ ) habitats and dispersed a mean minimum distance ( $\pm$  SD) of  $206 \pm 162$  km (range 0–470 km; Table 1). Of the tags with end locations in marine habitats, seven reported from the Russian Chukchi Sea approximately 100–200 km north of the Chukotka Peninsula, exhibiting minimum travel distances from the tagging locations of 319–470 km (Table 1; Fig. 4). Eight other tags had end locations in nearshore marine waters adjacent to Kotzebue Sound, 40–135 km southwest of the tagging locations (Table 1; Fig. 4). Of the tags with freshwater end locations, nine reported

from locations in other river drainages, including the Omikviorok, Rabbit, Buckland, and Noatak drainages in northwestern Alaska, 40–362 km distant from the tagging sites (Table 1; Fig. 4). The other tagged fish with freshwater end locations showed less extensive dispersal, and their tags had end locations in Kivalina Lagoon ( $n = 2$ ) and in the lower and upper reaches of the Wulik River, near known overwintering and spawning areas ( $n = 7$ ) (Table 1; Fig. 4). We examined end locations in two-week intervals. In early to late June, fish were located near the tagging sites (mouth and lower reaches of the Wulik River) and in near-shore areas within or adjacent to Kotzebue Sound (Fig. 5). From early July to September, some fish still occupied the Wulik River; however, tagged fish were more widely distributed, with locations in the Chukchi Sea north of Russia, near Kotzebue Sound, and in other rivers (Fig. 5).

In addition to end locations, 10 PSATs (19%) provided limited daily light-based geolocation estimates. Daily geolocation estimates were calculated for a total of 30 days: 14 days in June, one day in July, and 15 days in August. The geolocation estimates provided in June and July (15 days from 10 PSATs) varied widely. None of these locations were validated as plausible, since 14 were on land and one had a daily corresponding sea surface temperature that was  $1^\circ\text{C}$  or more higher than the satellite-derived SST in the same location. In August, two tags provided daily geolocation estimates ( $n = 15$  d, 6–14 August 2012) and reported just days later (on 15 August 2012) in the Russian Chukchi Sea. Of these daily estimates, two were on land; however, the other 13 had daily corresponding SSTs that were within  $\pm 1^\circ\text{C}$  of satellite-derived SST and thus were considered plausible. All 13 were broadly distributed in the Chukchi Sea in the vicinity ( $106 \pm 55$  km, mean  $\pm$  SD) of their respective end locations. For the remaining tags ( $n = 42$ ), the light sensor was unable to distinguish any diel differences in light intensity, which precluded identification of sunrise and sunset events and subsequent calculation of daily geolocation estimates.

#### Trends in Dispersal Distance and Survivorship

Mortality was observed in fish ranging in length from 62 to 86 cm, which spanned nearly the entire range of fish

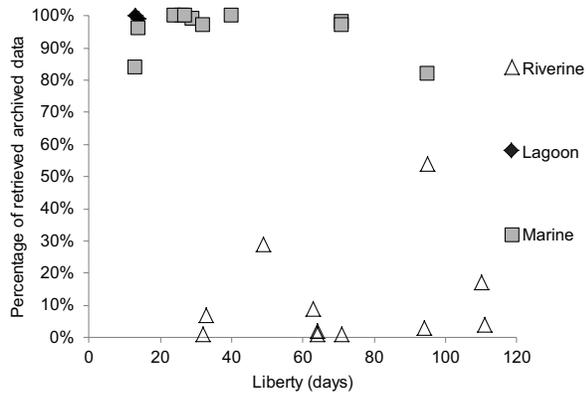


FIG. 3. Percentage of retrieved data (total number of individual depth and temperature readings received via Argos divided by the number of readings that should have been transmitted and received) compared to time at liberty (days) for fish with tags that reported to Argos satellites from three habitat types.

tagged in this study ( $n = 6$ ; Tables 1 and 2). Fish size did not appear to relate to whether a fish was alive or dead on its pop-up date, as mean sizes of live and deceased fish differed only slightly (Fig. 6). A similar lack of relationship was found between mean length and minimum distance traveled ( $p > 0.05$ ).

## DISCUSSION

PSATs offer an effective alternative method with which to study several aspects of large adult Dolly Varden behavior and habitat occupancy in locations where it is not economically or logistically practical or even feasible to recapture fish, such as coastal and offshore regions of the Arctic. While attached to Dolly Varden, PSATs provided unprecedented information about their dispersal patterns in Arctic Alaska, including the first evidence of offshore habitat occupation in the Arctic Ocean.

The overall reporting rate of 63% (from Argos and recaptures) in this study was lower than reporting rates analyzed in a review of other PSAT tagging studies (grand mean 79%; 95% CI = 76% to 82%), in which 731 tags were deployed on 19 species of marine animals (Musyl et al., 2011). This relatively low reporting rate is most likely attributable to the location of tagged Dolly Varden in freshwater on their pop-up dates. Given that the PSATs used in this study require 5 psu of salinity for the release mechanism to function properly, occupation of freshwater likely led to some failure of the release mechanism. Some tags did report from freshwater, but it is likely that instead of releasing from the fish, the tags were still attached to the fish. We surmise that while tags were attached to the fish, the antennae periodically protruded above the surface of the water and intermittently transmitted to satellites, thus providing sporadic transmissions that resulted in relatively few end locations and low data recovery rates. This claim is supported by the tags that presumably washed up on shore near

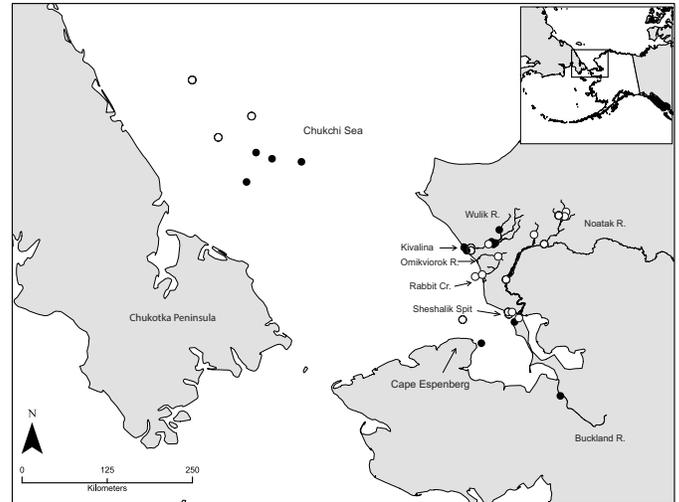


FIG. 4. End locations of Dolly Varden with pop-up satellite archival tags deployed in the Wulik River, Alaska, in 2012 (black dots) and in Kivalina Lagoon in 2013 (white dots). End locations indicate where the tag transmitted to satellites or the fish was physically recaptured.

freshwater. While these tags still had lower data retrieval rates compared to tags that reported from marine waters, they provided substantially more data (17%–58% of their archived data) than the tags that reported from freshwater rivers. While the reasons that tags washed up on shore and reported from land adjacent to freshwater are unknown, possible explanations include predation by birds and mammals or tag shedding.

While occupation of freshwater lowered the tag reporting and data recovery rates, PSATs that reported from marine waters provided informative end locations. Some of the tagged fish in this study demonstrated movement patterns similar to those previously described for Dolly Varden in northwestern Alaska (reviewed in DeCicco, 1997), including movements to other rivers and southerly marine nearshore movements. However, several PSATs in this study provided the first documentation of a northwesterly offshore dispersal in the Russian Chukchi Sea. It is likely that previous studies did not document offshore dispersal in the Arctic Ocean because there were no fisheries in that region and therefore no feasible method for recovering tagged fish. Our new data underscore the importance of using technology that does not rely on the physical recapture of tagged fish.

The dearth of geolocation estimates in this study is likely due to the inability of the X-tag to detect changes in ambient irradiance during the Arctic summer, when the sun does not set in our study area from mid-May to mid-July, thus preventing the calculation of light-based geolocation estimates on most days. Even when tags provided limited daily geolocation estimates, most derived location estimates were not plausible until the middle of August, when there were approximately seven hours between sunset and sunrise events. Given that Dolly Varden spend only a short time (up to three months) in the ocean each summer before returning to freshwater, the method of light-based geolocation used in

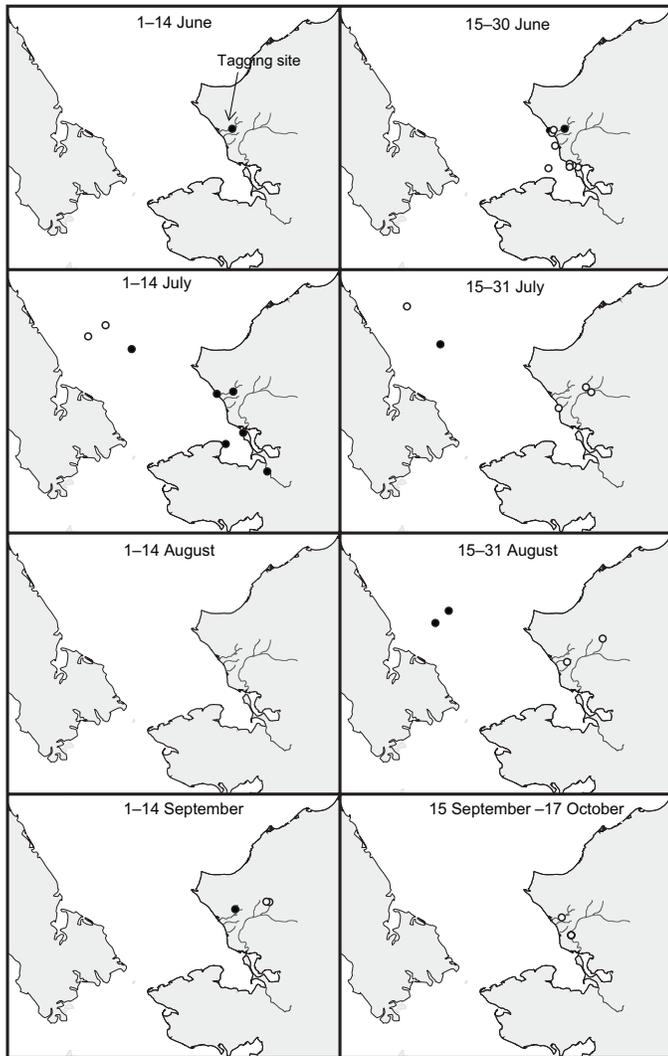


FIG. 5. End locations of Dolly Varden with pop-up satellite archival tags throughout the summers of 2012 (black dots) and 2013 (white dots). End locations indicate where the tag transmitted to satellites or the fish was physically recaptured.

this study does not appear to be effective for understanding the most probable tracks of fish occupying the Arctic Ocean during the summer. However, alternative location estimation models based on tag-recorded depth and temperatures may have the potential to provide valuable insights into the spatial and temporal distribution of Dolly Varden during the summer (Hayes et al., 2011; Chittenden et al., 2013a, b; Courtney et al., 2015).

Because there were no observed relationships between fish size, mortality, and dispersal patterns, PSATs appeared to have relatively little effect on the health and swimming ability of tagged Dolly Varden at least 60 cm long. Specifically, while at liberty for up to 126 days, tagged Dolly Varden traveled up to 470 km and transited at speeds up to 60 km·day<sup>-1</sup> (Courtney et al., 2015), suggesting that the tag did not adversely affect the swimming ability of tagged fish. These results suggest that 60 cm is likely an appropriate guideline for minimum PSAT tagging size of Dolly Varden. This guideline is similar to that for another salmonid

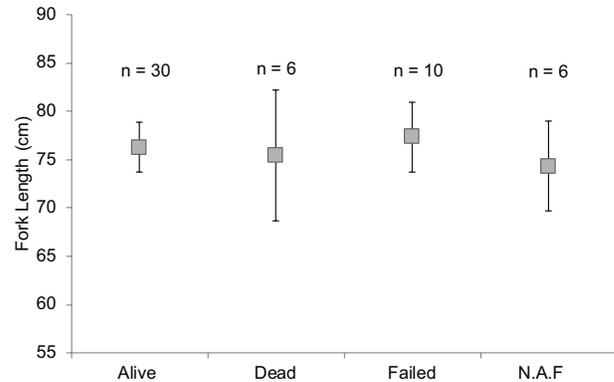


FIG. 6. Relation of fish length to fate of the fish and tag (based on archived data). Mean fork lengths (bootstrapped 95% confidence intervals) for Dolly Varden that were alive on the scheduled pop-up date, those dead on that date, those whose tags failed to transmit an end location, and those that were not accounted for.

species, the Atlantic salmon; individuals as small as 52 cm have been tagged and tracked with the same PSAT (Lacroix, 2013). However, because our study used a small sample and a design lacking control groups, a precise minimum size guideline is not known. Future laboratory studies of the physiological effects of PSAT tagging on salmonids would help to define this guideline.

Interpreting mortality events in this study is difficult because it is challenging to distinguish natural mortality from tag-induced mortality. While little is known about its causes and rates, natural mortality of Dolly Varden from Arctic Alaska is thought to be highly variable and dependent on environmental conditions (Arvey, 1991). Past research has suggested that birds and marine mammals, particularly spotted seals *Phoca largha*, may cause significant mortality of Dolly Varden in northwestern Alaska in some years (DeCicco, 1985, 1996). Although the specific cause of fish mortality in this study is unknown, most of the identified mortality events (five out of six) occurred in nearshore areas where marine mammals are common, suggesting that predation is the cause, as has been documented for Atlantic salmon (Lacroix, 2014).

The pop-up schedule used in this study, while successful for ensuring that some fish would be in marine waters on the pop-up date and thus properly release and transmit data, could be refined in future studies. The results from this study suggest that scheduling pop-up dates between 15 July and 15 August will likely maximize the probability of retrieving data in future experiments on Dolly Varden in northwestern Alaska. Therefore, future PSAT tagging studies on Dolly Varden and other anadromous species should take into account the population-specific knowledge about the biology, ecology, and life history of the study species, to maximize data retrieved. Additionally, an alternative technology that does not rely on a galvanic corrosion release mechanism (and thus would allow for freshwater release) would be invaluable for studying anadromous fishes and would allow researchers to obtain more data during the entire ice-free season.

Natural resource development, which is currently occurring in both offshore and nearshore areas of the Arctic Ocean, may present challenges for fish communities, including Dolly Varden. In the future, monitoring and understanding interactions between fish and these anthropogenic activities will be directly pertinent to assessing a species' vulnerability. PSATs could offer an effective alternative method for expanding our knowledge of a species' distribution and habitat use, as well as its potential interactions with current and future anthropogenic activities.

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