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Technical Report

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Cover Image: Puget Sound Harbor Porpoise (Joseph Evenson, WDFW) with DHC-2 Beaver inset (Tom Cyra, WDFW).

RETURN OF HARBOR PORPOISE TO PUGET SOUND:
20 YEAR PATTERN REVEALED FROM WINTER AERIAL SURVEYS

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Summary

Harbor porpoise were a common year-round resident in the Puget Sound in the 1940s, but by the 1970s, they had disappeared from the Sound, and their numbers were greatly reduced in the Straits of Georgia and Juan de Fuca, and around the San Juan Islands. Some survey efforts were conducted to verify that there were no harbor porpoise within the Puget Sound, but prior to 2013, there were no dedicated small cetacean surveys providing complete coverage of Washington's inland waters, including the Puget Sound. Beginning in the early 2000s, there were increasing reports of harbor porpoise sightings by the public, and by researchers involved in other activities on the water. Unfortunately, there wasn't funding during this period for the National Marine Fisheries Service (NMFS) to conduct aerial surveys of the inland Washington harbor porpoise stock, leaving many questions about the increase in sighting reports unanswered.

Washington Department of Fish & Wildlife (WDFW) conducts annual winter aerial marine bird surveys that cover all of the Washington inner marine waters from southern Puget Sound to the Canadian border, out to the west entrance of the Strait of Juan de Fuca. These surveys have been conducted every year (except 2007) since 1994, and record all marine mammal observations in addition to the marine bird observations. While it is not designed as a dedicated marine mammal survey, because of the consistent survey methodology throughout the survey area, and that all marine mammal observations were recorded, this 20-year dataset provides a record of increasing harbor porpoise numbers in the northern portion of the survey area in the early years, followed by their expansion into the waters of the Puget Sound. The rate of increase exceeds the maximum potential local recruitment rate, not only within the Puget Sound, but throughout the inland marine waters, suggesting immigration from outside the study area is supplementing recruitment.

During this same period, reports of Dall's porpoise had been decreasing, concurrent to the increase in harbor porpoise sightings. These surveys confirmed a downward trend in Dall's porpoise numbers, with none sighted in 2014.

Acknowledgements

We would foremost like to thank Dave Nysewander for his efforts in establishing the survey and in seeing that the surveys continued while he was the project leader; it is thanks to Dave's leadership that this survey exists as it is today with the high regard it enjoys. We are grateful to Don Kraege for his continued support for the survey since its inception, and for his efforts in seeing that the survey maintained funding during the various cycles of budget cuts; it is because of the primary objective of the survey to monitor winter sea duck population trends to set hunting regulations, and the funding from the Pittman–Robertson Federal Aid in Wildlife Restoration Act to meet these objectives, that these surveys are even possible. We are also very grateful to Don for his constant support in the safety of the crew by supporting all of the trainings identified and requested, as well as the acquisition of all safety equipment identified to ensure the safety of the flight crew. We are greatly indebted to the many pilots who have flown these survey over the years. The primary pilots were Val Judkins and Jim Hodgson with WDFW, Mark Schoening with Sound Flight, and Chuck Perry with Kenmore Air. We are especially thankful to Kenmore Air and Chuck Perry for their enthusiasm, professionalism, focus on flight safety, and continued support in working with us as the survey has evolved to follow the current standardized transect lines; we are also grateful to the Kenmore mechanics for their superb detail regarding the maintenance of the survey aircraft. We thank Matt Nixon, Wendy Parsons, and Warren Michaellis for serving as observers during the early years of the survey. Finally, we are indebted to the many flight followers who have tracked our flights over the years, these include Kye Iris, Don Kraege, Ruth Milner, Debbie Moe, Mikal Moore, Dave Nysewander, Scott Pearson, Carol Powers, Celia Roberts, Jeff Skriletz, and Heather Tschaekofske; we apologize for those we may have left off this list.

Primary survey flight crew and aircraft (from left to right) B. Murphie, T. Cyra, J. Evenson, and C. Perry, in front of N900KA "Maggie", the last Beaver commercially manufactured by de Havilland.

Introduction

Harbor porpoise (*Phocoena phocoena*) were considered the most common cetacean in the inner marine waters of Washington State including Puget Sound in the 1940s, the most common cetacean in Washington state-wide, and seen year round in the Puget Sound (Scheffer & Slipp 1948). Research and observations from the 1970s through the 1990s, however, revealed harbor porpoise were virtually absent from PS (Everitt et al. 1980; Osborne et al. 1988; Osmek et al. 1996; Laake et al. 1997; Calambokidis & Baird 1994) so systematic aerial surveys to estimate abundance generally did not even include these waters. Reports of harbor porpoise within the Puget Sound began in the early 2000s, with regular sightings in southern Puget Sound starting in 2008. The return was monitored by NMFS, WDFW, Cascadia Research Collective (CRC) and the Marine Mammal Stranding Network. This included several stranded animals within the Puget Sound during the Unusual Mortality Event (UME) of 2006-2007 (Huggins et al. 2015).

Eastern Pacific harbor porpoise are distributed almost continuously along the west coast of the United States and Canada. They are considered non-migratory and relatively resident to specific areas with NMFS recognizing six different management stocks along the US West Coast based on genetic and contaminant research (Calambokidis & Barlow 1991; Chivers et al. 2002; Chivers et al. 2007; Sveegaard et al. 2012; Carretta et al. 2012).

Dall's porpoise (*Phocoenoides dalli*) also occur in Puget Sound but are considered to be a more pelagic species (Carretta et al. 2012). Though Scheffer and Slipp (1948) mention Dall's porpoise, it is unclear whether any of the sightings were in the inner marine waters, or if the animals were caught off the coastal waters by boats that returned to inland ports. Other records from the middle of the 20th century included sightings in inland waters in British Columbia during the summer and fall, but only in the wide straits and channels with fast currents, with no Dall's porpoise sighted in any of the narrow passages or bays frequented by harbor porpoise (Scheffer 1949; Cowan 1944). Cowen (1944) specifically noted that Dall's porpoise had not been recorded in the Strait of Juan de Fuca or the Gulf of Georgia (includes all marine waters east of SJF). Reports during the 1960s, 1970s and 1980s documented Dall's porpoise presence in the inland waters during all months of the year, with the center of abundance in the Strait of Juan de Fuca, including animals sighted as far east as Rosario Strait, and down into the central Puget Sound Basin, with occasional sightings into the south Puget Sound. Dall's porpoise were not reported in the Strait of Georgia, Whidbey Basin or the Hood Canal (Everitt et al. 1980; Pike & MacAskie 1969; Miller 1990). Abundance in inland waters appears to be seasonally dependent in other inland areas of the Dall's porpoise range, with greater numbers appearing in the summer than during other times of the year (Cowan 1944), and this is supported by the few studies published for the Strait of Juan de Fuca and the Puget Sound (Miller 1990). A photo-ID study conducted in the Central Puget Sound and Admiralty Inlet in 1987-1988 had few resightings, which combined with their changing seasonal abundance, suggest that their presence in the inland waters could be transitory in nature (Miller 1990).

The Washington Department of Fish and Wildlife has conducted winter aerial marine surveys since 1993. Beginning in 1995 all marine mammal sightings were recorded. While not designed to study marine mammals, these surveys provide the most comprehensive documentation of the changes in porpoise populations in Washington's inner marine waters.

A variety of factors undoubtedly lead to the near extirpation of harbor porpoise from the Puget Sound. It is beyond the scope of this paper to fully explore, yet the inner marine waters were subject to most of the commonly cited threats to harbor porpoise populations. Interactions with fisheries and pollution are two threats that were a known problem in the inner marine waters during the period of harbor porpoise decline. Changes have been made in recent decades that would reduce the impact of these threats, allowing the Washington Inland Waters Stock of harbor porpoise to increase to its current level.

Fisheries interactions, specifically gillnet and set-net fishing is commonly considered to be the greatest threat to most porpoise populations (Hammond et al. 2008), and likely were the major factor in the unsustainable reduction in the Washington inland harbor porpoise stock. Scheffer & Slipp (1948) mention many bycaught porpoise in many of the fisheries, including gillnets, deep nets for shark fisheries, fish traps, trawls and seines. Fisheries records show a dramatic increase in the number of commercial licenses issued in the post-WWII years. Commercial and tribal salmon fisheries are now managed to recover endangered salmonid runs, with a smaller fleet, few fishing days, exclusion zones and bycatch reduction efforts required (Washington Department of Fish and Wildlife 2015). Pressures on harbor porpoise from other net based fisheries are also greatly reduced, as dogfish and cod bottom set nets, most trawl fishing, are no longer legal within PS (WAC 220-48-015).

Pollution can have both a direct impact on harbor porpoise, as well as leading to a reduction in prey. Harbor porpoise are high trophic level predators, with bioaccumulation of pollutants a concern (Bossart 2011); pollutants including heavy metals, organochlorides and PAHs have been implicated in weakened immune systems and reduced reproductive success (Bennett et al. 2001; Law et al. 1991; Law et al. 2002). Pollution has been, and continues to be a major problem within inshore marine waters (Dexter et al. 1985; Ecology & King County 2011). Studies of harbor seals have shown levels of many pollutants, including DDE and PCB, were concentrated at much higher levels in tissues of animals in the southern Puget Sound compared to the animals in the eastern Strait of Juan de Fuca and San Juan Islands (Calambokidis et al. 1984). Many sources of pollution have been eliminated or cleaned up in recent decades, including the elimination of a smelter near Tacoma, and several pulp mills, and tighter regulation of remaining point source polluters.

Several other factors have been suggested for the decline of harbor porpoise in the inside marine waters, including higher levels of vessel traffic, increasing noise pollution remain, which suggests that they are not the underlying factors of the decline, or to have hindered the recovery of the stock.

Methods

Study Area

The study was conducted in the inner marine waters of Washington State (Figure 1). These include the Strait of Juan de Fuca (SJF), the Puget Sound (PS) and Washington Sound/San Juan Archipelago to the Canadian border (WS) (Figure 1). The study area was divided into nine basins separated by prominent sills or other geographic features. These basins are commonly used to delineate both hydrographically and biologically distinct areas within the inland waters throughout a variety of studies. The Western Strait of Juan de Fuca (WSJF) basin runs from the Pacific Ocean to Ediz Hook, near Port Angeles, with the Eastern Strait of Juan de Fuca (ESJF)

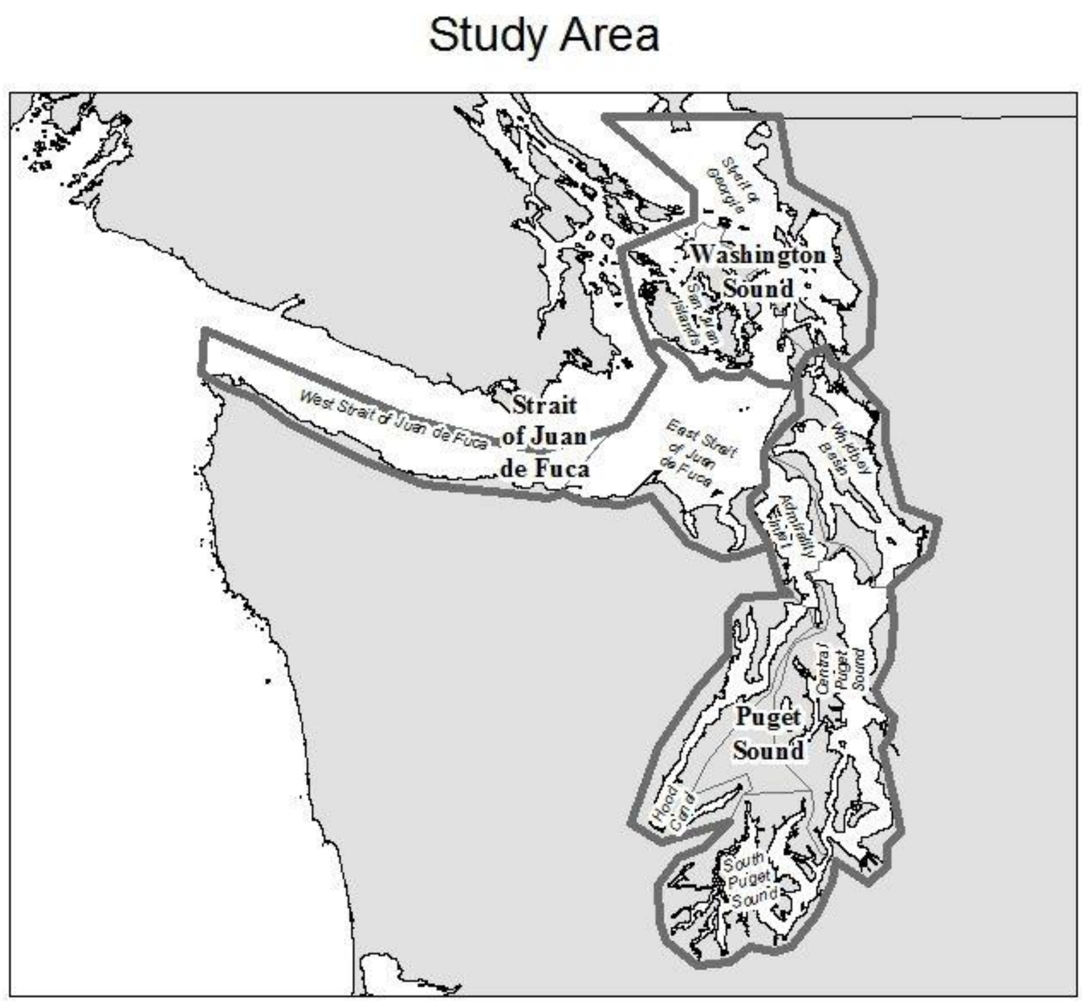

Figure 1. The inner marine waters of Washington State include 9 basins generally separated by sills; these were grouped into three larger regions, the Strait of Juan de Fuca, Washington Sound and Puget Sound.

extending from Ediz Hook to the western shore of Whidbey Island. The San Juan Islands (SJI) are situated between the mainland and Vancouver Island, to the north of ESJF. The Strait of Georgia (SG) is located to the east of SJI and continues up into Canadian waters. Admiralty Inlet (AI) is the primary connecting waterway into the Puget Sound from the northern waters, connecting with ESJF running down between the Olympic Peninsula and Whidbey Island. Hood Canal (HC) is a long, narrow, hook-shaped inlet off the west side of AI. Whidbey Basin (WB) is located to the East of Whidbey Island, including portions of Possession Sound, Port Susan, Saratoga Passage and Skagit Bay. Central Puget Sound (CPS) is the main basin of the Puget Sound, located to the south of AI and WB, extending to the Tacoma Narrows. South Puget Sound (SPS) is the area the furthest from the Pacific Ocean, and only connects with the other water bodies through the Tacoma Narrows where it joins up with the south end of CPS.

The basins were grouped into three geographic regions that showed similar trends in harbor porpoise abundance over the course of the study. The Strait of Juan de Fuca (SJF) includes WSJF and ESJF. Washington Sound (WS) includes SJI and SG. Puget Sound (PS) includes AI, HC, WB, CPS, and SPS.

Data collection

Figure 2. Biologists Cyra (right) and Murphie (left) viewing their respective transect strips through bubble windows.

Surveys were flown each year from early December until the survey was complete, usually by the end of January, but at times into early February (this timing was established to capture the mid-winter period when sea ducks and marine birds are least likely to be migrating). Flights were made at an altitude of 200 ft (61m) AGL at an airspeed of 85-90 kn. All surveys utilized piston de Havilland Canada DHC-2 Beavers on either strait or amphibious floats. Observations were made by two observers positioned in the center seats viewing through bubble windows on the left and right sides of the aircraft (Figure 2). To visibly delineate the transect boundary on each side of the aircraft a string was attached to the wing-strut (at 33^{o}) to delineate the outer boundary of the 50m transect strip, while the lower boundary was delineated by the float (58^{o}) (Figure 3 & 4). A 50m transect strip was used as it is possible to view the entire area of the strip abeam the aircraft within a single field of vision

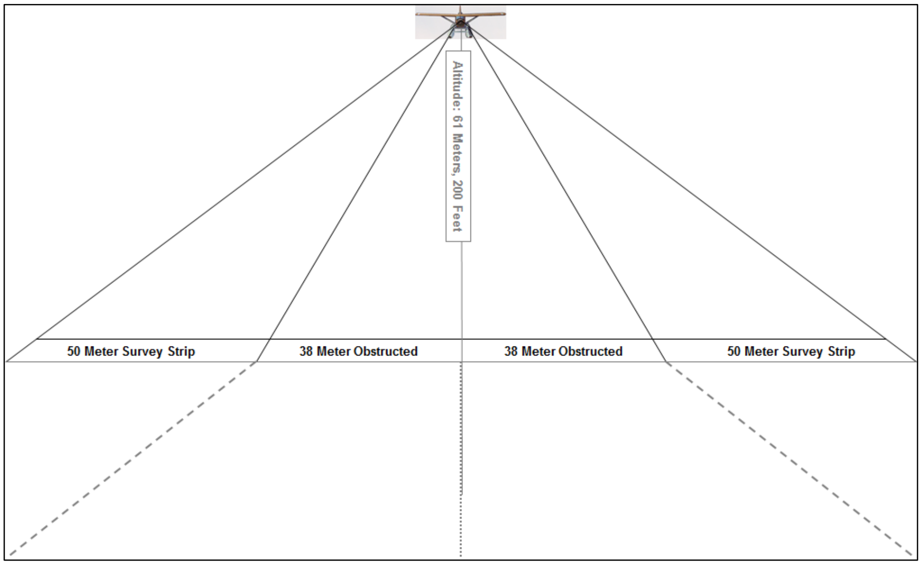

Figure 3. Diagram of left and right survey strips in relation to the transect line. An area 76 meters wide is obstructed from view directly below the aircraft due to the floats. A 50 meter transect strip is viewed from above the floats and out

Figure 4. View of transect strip delineated by float and string trailing off wing-strut.

without having to focus up and down the transect strip; this was done to increase the likelihood of not missing observations within the strip.

All observations were recorded into audio voice recorders noting species, count, behavior, and time (HH:MM:SS). All Surveys utilized a dedicated pilot and navigator sitting in the front seats of the aircraft (Figure 5). The navigator ran data logging software that automatically recorded continuous GPS coordinates as well as non-observational survey events.

While marine birds were the primary focus of the survey, all marine mammal observations were recorded beginning in 1995 as well. Prior to 1995, marine mammal observations were recorded but there may have been times when records were not consistent as they were not the primary subjects of the survey, thus pre-1995 surveys were omitted. All observations of marine birds and marine mammals were classified to species and count, and were noted if in or out of the transect strip. Viewing the transect strip was prioritized, however, some observations would be noted outside of the transect strip, or when off effort, when the observer thought the observation warranted note. These observations outside the transect strip and off effort were removed from the analysis.

Figure 5. View of the cockpit with computing devices showing navigation and event logging software used by navigator and transect navigation software used by pilot.

Surveys were only conducted during favorable conditions generally established for marine birds, these include Beaufort sea states ≤3, and during the hours with sufficient solar light availability. During winter months available sunlight is limited, with the shortest day of the year averaging ~8.3 hours between sunrise and sunset and the sun only reaching 18.3° above the horizon. In general, surveys were limited between 1000 – 1400 hours each day to restrict surveys from being conducted during low-light conditions. By limiting the survey between those hours, on most days, the angle of the sun above the horizon remains > 15°. There are some days during December that the Sun angle during surveys is as low as 12.5° above the horizon, but only for short durations during the morning hours. During the latter half of January and into early February the surveys hours may begin before 1000 and end after 1400 as long as the sun angle above the horizon was >15°, and the sun azimuth ranged between 136° and 215° from north. Surveys were not limited to cloud cover or rain factors as long as VFR flight conditions were maintained.

Transects were flown parallel to the shoreline, including all islands, islets and exposed rocks. Parallel transects were flown over submerged mudflats over the larger estuaries. In 1994-2010 saw-tooth transects were flown across inlets, bays and channels in an ad hoc manner that attempted to obtain even coverage (Figure 6). Beginning in 2011 these saw-tooth transects were split into two sets based on depth: <60m depth and >60m depth. Coverage in the <60m depth strata were increased while effort in the >60m depth strata were decreased from the pre-2011 levels (Figure 7). It is possible that this change in design might lead to some change in observations per unit effort. In addition, the post 2010 saw-tooth transects were repeatable between years. During some years transects were also flown over waters in British Columbia, Canada. All transect sections within Canadian waters were removed from this analysis to keep the dataset as consistent as possible from year to year.

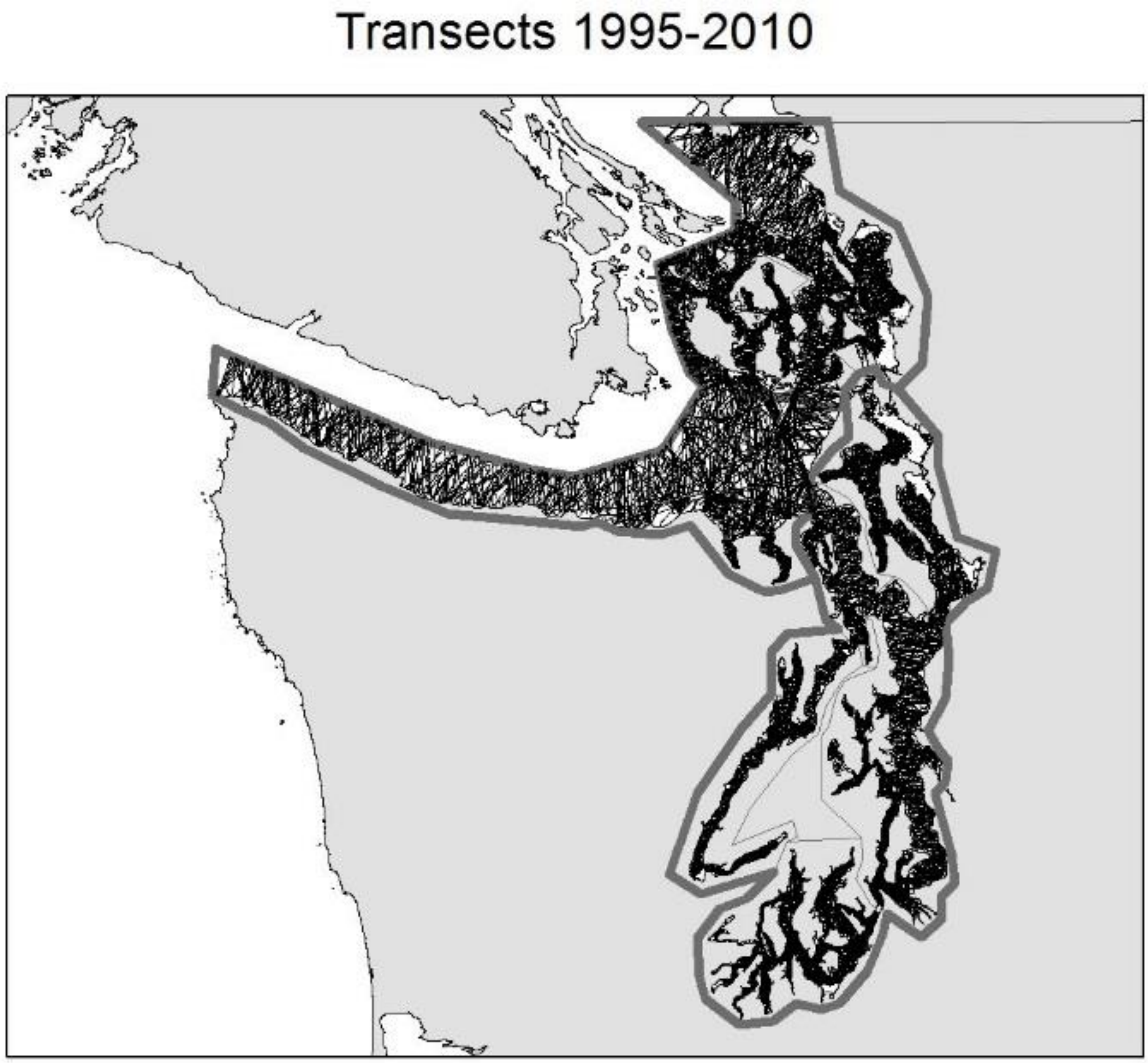

Figure 6. Transects flown during winter aerial surveys of marine birds and mammals from 1995 – 2010. Transects depicted are only the offshore transects used for analyses of harbor porpoise trends.

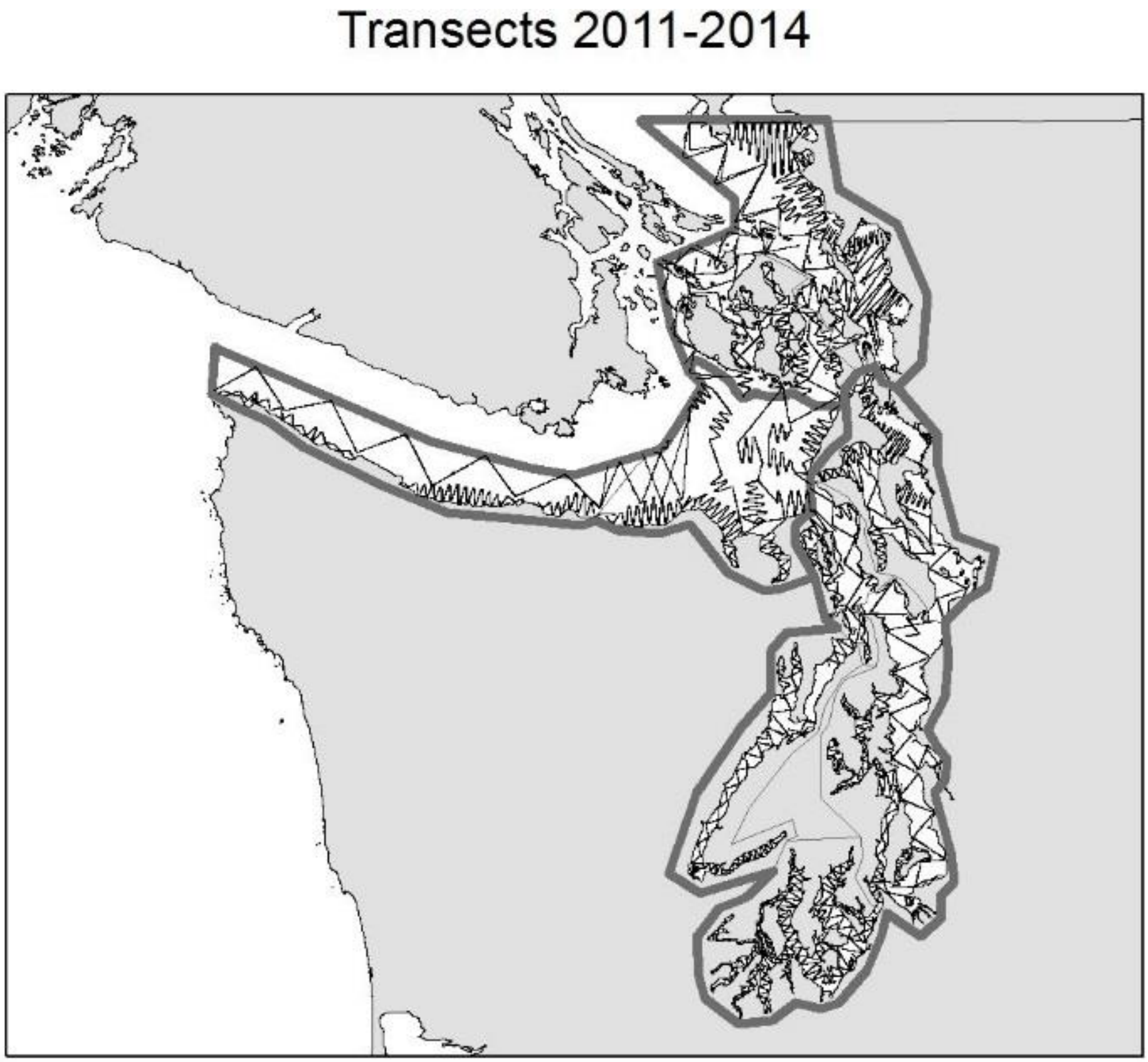

Figure 7. Transects flown during winter aerial surveys of marine birds and mammals from 2011 – 2014. Transects depicted are only the offshore transects used for analyses of harbor porpoise trends.

Data Analysis

As the study was designed for marine birds, certain sections of transects were removed from the analysis that would bias the results. These included the shoreline transects (those transects flying alongside and parallel to the shoreline) as only one observer was viewing offshore of the shoreline, and it would also bias survey effort to the shoreline habitats. In addition, areas above low-low water were also removed as these areas would not be suitable habitat throughout the tidal cycle. Transects that were in Canadian waters were also removed from analysis.

On effort transect GPS coordinates were translated into KML files using R 3.2.0 (R core team 2014), allowing shoreline sections of transect lines to be marked using Google Earth Pro

7.1.2.2041 (https://www.google.com/earth/). Corresponding GPS coordinates and sightings within the dataset were then marked as "shoreline", and considered to be off-effort during analysis. All observations and GPS coordinates were compared to the Washington State Department of Natural Resources aquatic land ownership parcels shapefile (https://fortress.wa.gov/dnr/adminsa/DataWeb/dmmatrix.html) retaining only the positions and observations that occurred over the marine baselands. In addition, only those observations that occurred within the transect strip were used.

Transect distance was calculated using the rgeos package in R to determine the distance between each recorded on effort GPS position. Transect distance was multiplied by 0.1 to convert the transect distance into km^2. The number of animals per km^2 was determined by dividing the on transect count by the km^2 of survey effort for each basin, region and for the complete survey area. Corrections for detection were not applied to these results.

Rate of Change in Density

The rate of change (annual growth rate = AGR) in harbor porpoise density was calculated to determine whether the increase in density could be attributed solely to local recruitment of the remaining animals, or if immigration from other areas would be necessary to account for the increase. The AGR in harbor porpoise density was determined overall for the inland waters, as well as in each of the regions (SJDF, WS and PS), using the RATE function in Microsoft Excel 2013. The overall AGR was calculated from 1995 through 2014 for the combined regions of the Strait of Juan de Fuca and Washington Sound as these had harbor porpoise present since the initial surveys in 1995. The AGR for Puget Sound was based on the density starting in 2000, as that is the point when harbor porpoise were observed on a consistent basis within the region. Rates of change were calculated for all year combinations to verify that the chosen years were not outliers.

Results

Transect Coverage

During the 20 years of surveys 123,015 km were flown on-effort, with 55,433 km along the shore and 5,218 km flown over mudflats and other shallow areas, with 62,364 km flown on-effort in the subtidal areas considered in this study (Table 1). Total annual effort from those areas used in this analyses ranged from 2,886 km to 3,593 km ($\bar{x}$ = 3,282 km).

Table 1. Survey effort by year from the 1995-2014 WDFW winter aerial surveys of marine birds and mammals. Transect lengths are only those offshore transects used for analyses of harbor porpoise trends. Observers: BM = Bryan Murphie; JE = Joseph Evenson; MN = Matt Nixon; TC = Tom Cyra; WM = Warren Michaelis; WP = Wendy Parsons.

					Total Offshore Transect Length (km) by Region & Basin									
					Strait of Juan de Fuca		Washington Sound		Puget Sound					
Year	Start Date	End Date	# Days	Observers	WSJF	ESJF	SG	SJI	AI	CPS	WB	SPS	HC	Total
1995	1994-Dec-15	1995-Feb-01	19	JE, WP	242	507	542	450	129	395	354	453	238	3310
1996	1995-Dec-06	1996-Jan-25	20	BM, JE, MN, WM	330	441	446	340	164	372	284	368	204	2951
1997	1996-Dec-10	1997-Jan-29	19	BM, JE, WM	161	424	441	357	143	438	260	518	238	2980
1998	1997-Dec-17	1998-Feb-19	24	BM, JE, TC	212	375	495	363	153	489	354	437	259	3137
1999	1998-Dec-09	1999-Feb-19	21	BM, JE, TC	181	433	503	351	139	405	270	366	238	2886
2000	1999-Dec-03	2000-Jan-26	20	BM, JE, TC	277	384	541	360	141	446	280	310	212	2952
2001	2000-Dec-04	2001-Jan-25	20	BM, TC	238	473	473	352	164	472	262	335	226	2995
2002	2001-Dec-03	2002-Jan-18	20	BM, TC	207	501	564	360	168	488	285	356	228	3157
2003	2002-Dec-03	2003-Jan-28	22	BM, JE, TC	244	518	638	412	181	531	335	373	256	3488
2004	2003-Dec-15	2004-Feb-10	19	BM, TC	212	424	507	353	150	491	277	337	206	2957
2005	2004-Dec-13	2005-Feb-08	21	BM, TC	236	541	592	414	163	521	330	379	221	3398
2006	2005-Dec-15	2006-Feb-12	22	BM, TC	308	562	681	431	166	508	308	350	222	3535
2008	2007-Dec-05	2008-Feb-04	18	BM, TC	285	454	557	357	187	566	317	378	220	3321
2009	2008-Dec-02	2009-Jan-29	17	BM, TC	312	500	617	416	210	545	381	346	217	3544
2010	2009-Dec-03	2010-Jan-26	16	BM, TC	275	513	610	443	192	523	363	379	229	3527
2011	2010-Dec-06	2011-Feb-01	19	BM, TC	324	594	770	330	187	392	334	349	187	3467
2012	2011-Dec-02	2012-Feb-03	21	BM, TC	347	628	786	342	183	396	343	360	196	3582
2013	2012-Dec-10	2013-Feb-01	17	BM, TC	335	631	789	342	193	399	345	360	197	3593
2014	2013-Dec-04	2014-Jan-28	20	BM, TC	334	629	789	343	191	397	343	364	196	3586
Mean	Dec-06	Feb-01	19.7		375	221	462	169	317	375	597	502	266	3282

Harbor Porpoise

Inner Marine Waters of Washington State, and by Region

Table 2. Heat map of winter mean densities of harbor porpoise from the inner marine waters of Washington State, 1995 – 2014, by region. AGR = Annual Growth Rate. *AGR for PS was calculated from 2000-2014.

	Region			
Year	SJF	WS	PS	All Regions
1995	0.174	0.071	0.038	0.079
1996	0.091	0.127	0.000	0.058
1997	0.154	0.276	0.000	0.104
1998	0.239	0.373	0.000	0.147
1999	0.228	0.293	0.000	0.135
2000	0.227	0.477	0.007	0.200
2001	0.380	0.340	0.055	0.210
2002	0.170	0.368	0.066	0.177
2003	0.485	0.447	0.024	0.252
2004	0.393	0.500	0.027	0.243
2005	0.193	0.308	0.012	0.141
2006	0.689	0.261	0.006	0.255
2008	0.460	0.328	0.126	0.256
2009	0.357	0.600	0.206	0.356
2010	0.419	0.428	0.142	0.289
2011	0.545	0.209	0.200	0.294
2012	0.626	0.275	0.304	0.383
2013	0.797	0.380	0.221	0.426
2014	0.768	0.415	0.423	0.513
AGR	0.081	0.098	0.368*	0.104

Harbor porpoise density increased throughout the inner marine waters of Washington state at a rate of 10.4% year^{-1} from 1995-2014 (Table 2). In 1995 the mean density across the study area was 0.079 porpoise/km^2 (26 porpoise observed on transect) and by 2014 the mean density increased to 0.513 porpoise/km^2 (184 porpoise observed on transect) (Figure 8).

Harbor porpoise were present in the SJF and WS during all years, while in the PS they were present during the first year (observed in AI only), and then were absent until 2000; harbor porpoise were present in PS and steadily increased beginning in 2000.

The regional annual growth rate (AGR) of harbor porpoise (1995-2014) was 8.1% and 9.8% year^{-1} in the SJF and WS respectively. The AGR during in SPS from 2000 – 2014 (2000 being the first year porpoise were regularly documented in the region) was 36.8%. During this same period the AGR in SJF increased to 9.1% year^{-1} while WS remained relatively stable, dropping slightly to -1.0% year^{-1}(Table 2, Figure 9).

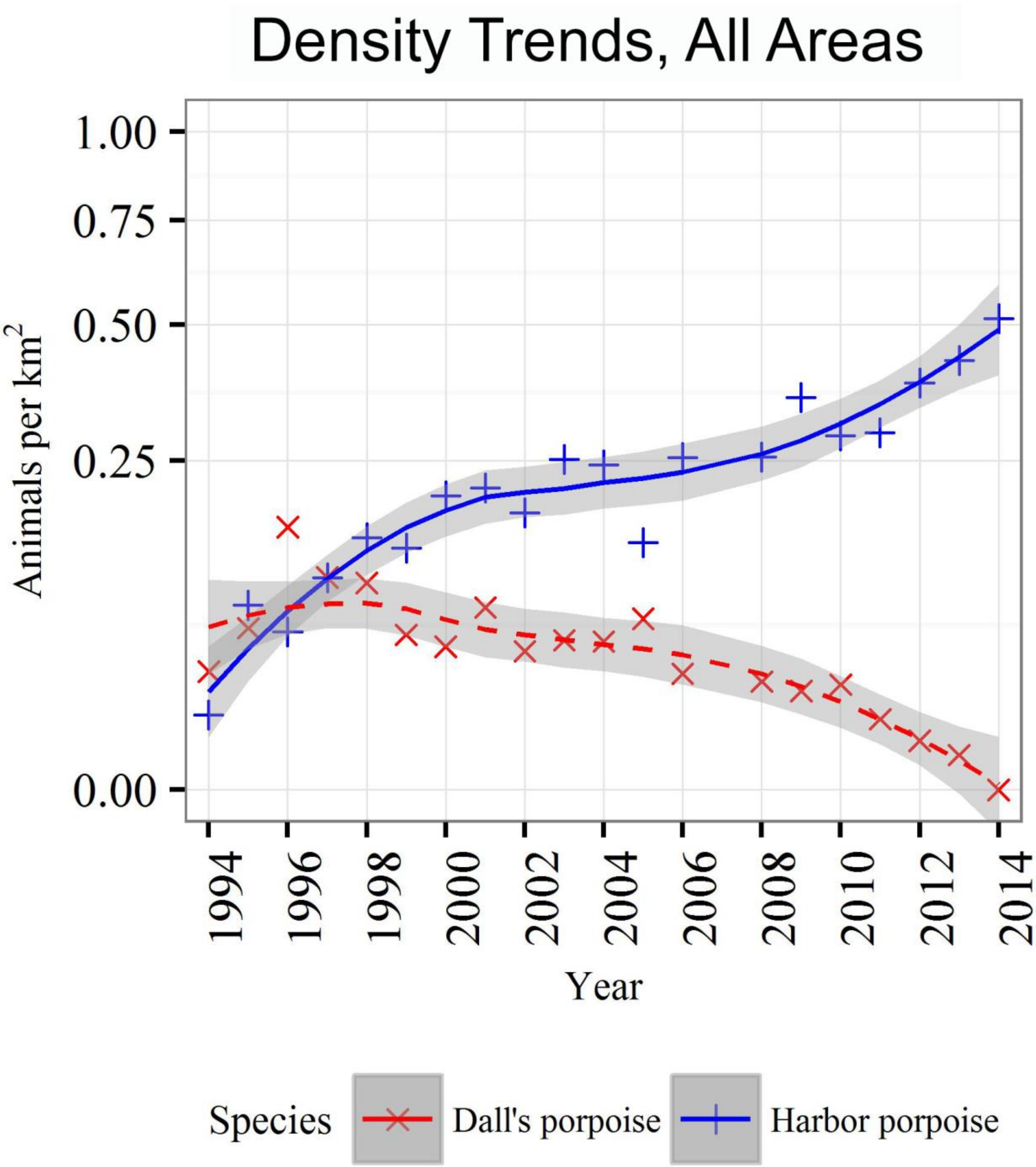

Figure 8. Winter density trends of harbor porpoise and Dall's porpoise from the inner marine waters of Washington State, 1995-2015.

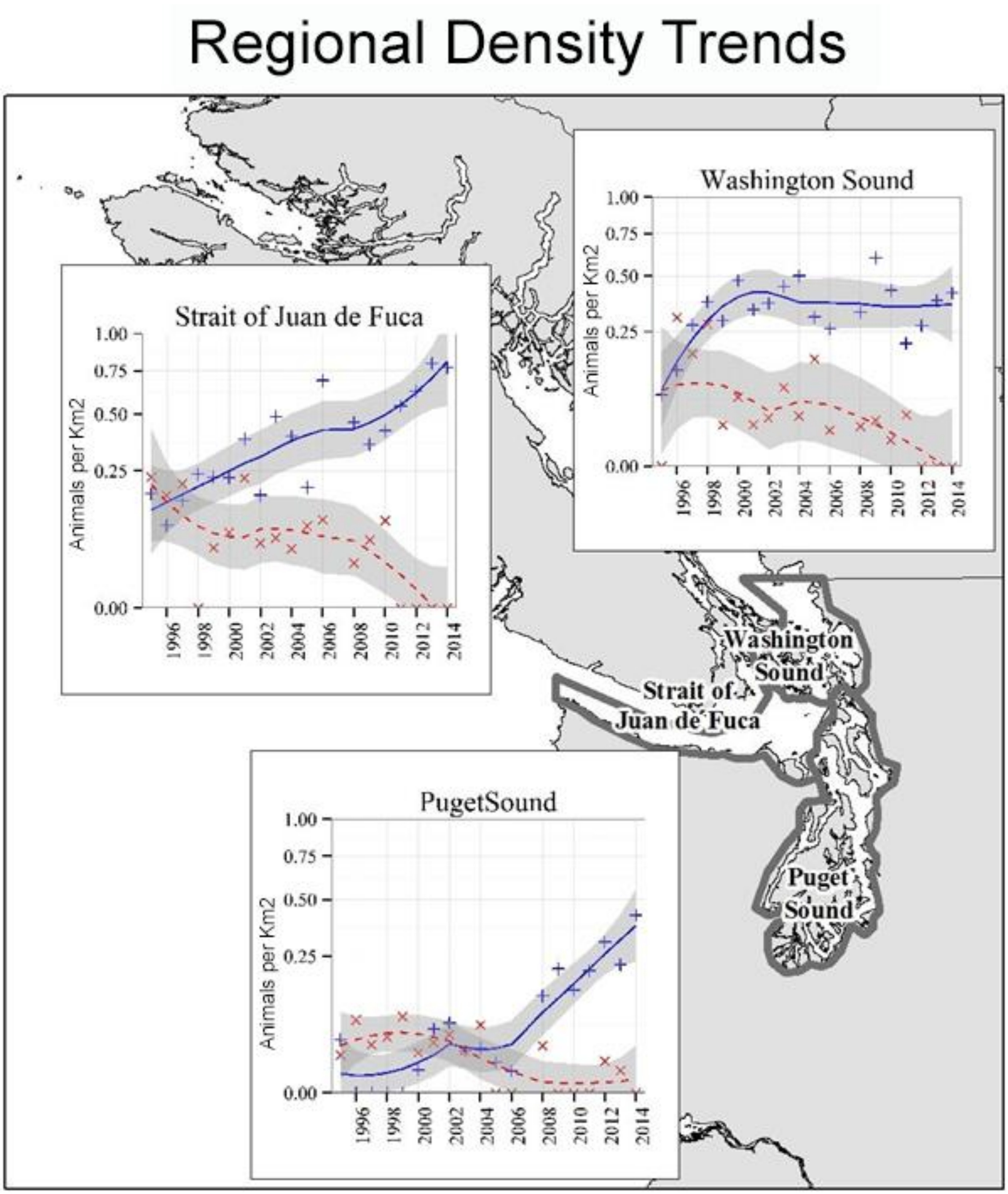

Figure 9. Winter density trends of harbor porpoise and Dall's porpoise from the inner marine waters of Washington State, 1995-2015, by region.

By Basin

Table 3 is organized across the study area from the north and west (WSJF through SJI) to east and south (AI through HC). With the exception being SG and SJI (the WS region), the densities reported temporally by basin show a progressive increasing trend across the basins and an expansion east and south. This same trend is also apparent in figures 11, 12, 13 and 14 where harbor porpoise observations, shown in 5-year increments, show a clear increase in numbers over time, as well as the expansion into all basins within the PS. The basins within WS did not follow this trend, but harbor porpoise steadily increased there up through the early 2000's, then generally stabilized through 2014.

The AGR from WSJF (1994-2014) was 10% year^{-1} with densities starting at 0.17 and then averaging 1.04 animals/km^2 from 2011-2014. This basin had the highest average annual densities across the study area. The trend in this basin has continued to increase through 2014 (Figure 10).

The AGR from ESJF (1994-2014) was 6.9% year^{-1}. This low AGR is influenced by a moderate density of 0.18 animals/km^2 in 1995 (the first year of the study). Densities there dropped for

Table 3. Heat map of winter mean densities of harbor porpoise from the inner marine waters of Washington State, 1995 – 2014, by basin. AGR = Annual Growth Rate. *AGR calculated from 2001 – 2014; ** AGR calculated from 2011 – 2014; AGR calculate from 2008 – 2014.

Region	Strait of Juan de Fuca		Washington Sound		Puget Sound				
Year/Basin	WSJF	ESJF	SG	SJI	AI	CPS	WB	SPS	HC
1995	0.17	0.18	0.07	0.07	0.47	0.00	0.00	0.00	0.00
1996	0.18	0.02	0.13	0.12	0.00	0.00	0.00	0.00	0.00
1997	0.25	0.12	0.16	0.42	0.00	0.00	0.00	0.00	0.00
1998	0.57	0.05	0.24	0.55	0.00	0.00	0.00	0.00	0.00
1999	0.66	0.05	0.26	0.34	0.00	0.00	0.00	0.00	0.00
2000	0.29	0.18	0.39	0.61	0.07	0.00	0.00	0.00	0.00
2001	0.04	0.55	0.30	0.40	0.30	0.06	0.00	0.00	0.00
2002	0.34	0.10	0.34	0.42	0.54	0.02	0.00	0.00	0.00
2003	0.90	0.29	0.56	0.27	0.22	0.00	0.00	0.00	0.00
2004	0.38	0.40	0.51	0.48	0.27	0.00	0.00	0.00	0.00
2005	0.13	0.22	0.20	0.46	0.12	0.00	0.00	0.00	0.00
2006	1.39	0.30	0.32	0.16	0.00	0.02	0.00	0.00	0.00
2008	0.88	0.20	0.29	0.39	0.70	0.09	0.00	0.08	0.00
2009	0.45	0.30	0.68	0.48	0.76	0.29	0.00	0.09	0.00
2010	0.25	0.51	0.25	0.68	0.31	0.34	0.00	0.00	0.00
2011	0.93	0.34	0.30	0.00	0.70	0.15	0.06	0.14	0.16
2012	1.12	0.35	0.25	0.32	0.38	0.58	0.35	0.08	0.00
2013	1.07	0.65	0.34	0.47	0.00	0.45	0.26	0.11	0.10
2014	1.02	0.64	0.43	0.38	1.26	0.15	0.79	0.14	0.05
AGR	0.100	0.069	0.097	0.096	0.054	0.075*	1.36**	0.096***	-0.317**

the next four years (1996 – 1999) with an average of 0.06 animals/km^2 during that period. Since 1999 the densities there have steadily increased to 0.64 animals/km^2 in 2014 (Table 3, Figure 10). From 1999 – 2014 the AGR in this basin has been 20.6% $year^{-1}$.

The AGR from SG and SJI (1995-2014) were 9.7% and 9.6% $year^{-1}$, respectively. This high AGR is influenced by the low densities documented in both basins during 1995. Harbor porpoise densities in these two basins have been generally stable since the early 2000's (Table 3, Figure 10).

No harbor porpoise were observed in CPS until 2001. Harbor porpoise were recorded in low densities during 2001 and 2002, then were again absent between 2003 and 2005. Since 2006 harbor porpoise have been recorded each year. The AGR from this basin (2001 – 2014) was 7.5% $year^{-1}$. This was influenced by a low density of 0.15 animals/km^2 during 2014; the two previous years, 2012 and 2013, had densities of 0.58 and 0.45 animals/km^2, respectively.

Harbor porpoise were absent from WB until 2011 when a density of 0.06 animals/km^2 was recorded. Since that harbor porpoise have been observed each year with steadily increasing densities. The AGR from this basin from 2011 – 2014 was 136% $year^{-1}$ with a high density of 0.79 animals/km^2 recorded.

Harbor porpoise were not observed in SPS until 2008 when a density of 0.08 animals/km^2 was recorded. With the exception of 2010, harbor porpoise have been observed in this basin each year since 2008 with an AGR of 9.6% $year^{-1}$ through 2014 (Table 3, Figure 10).

HC has had the lowest densities of harbor porpoise of all the basins. Harbor porpoise were not observed there until 2011, and have been present in low densities in three of the last four years of the study. The harbor porpoise that were observed in HC were at the north end near the entrance where it joins with AI.

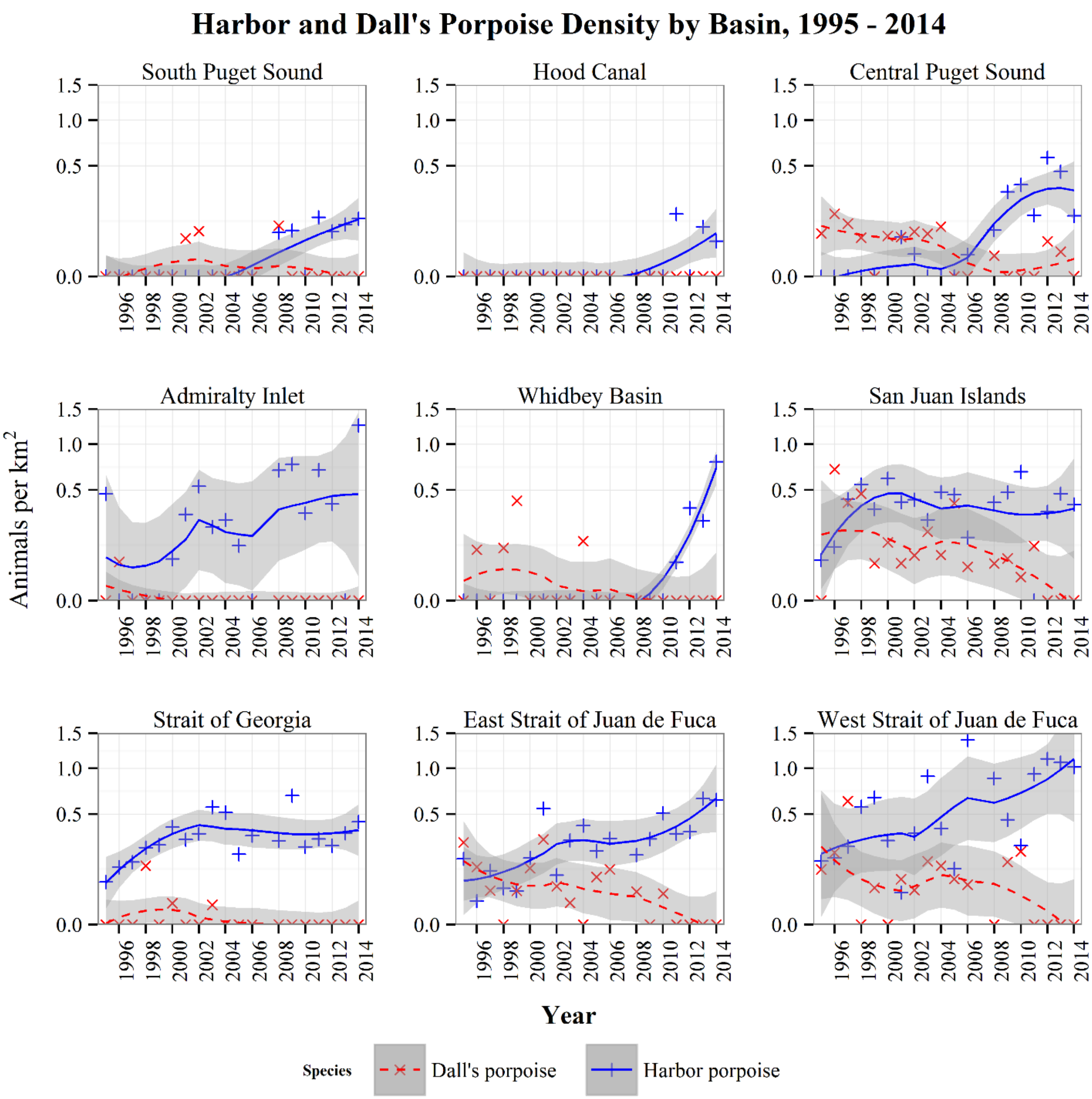

Figure 10. Winter density trends of harbor porpoise and Dall's porpoise from the inner marine waters of Washington State, 1995-2015, by basin.

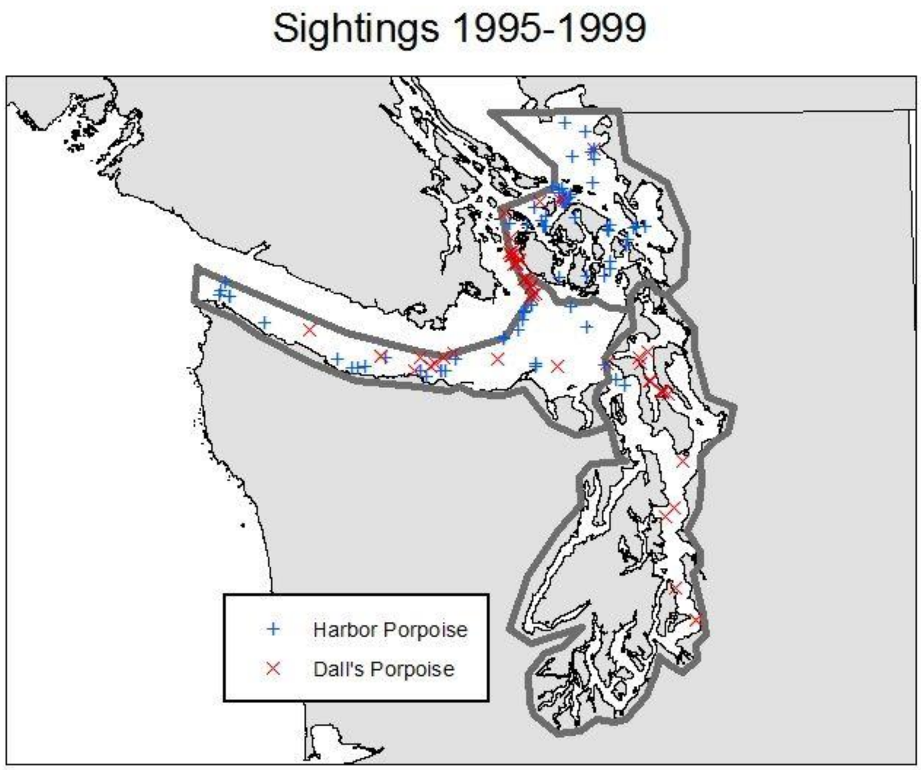

Figure 11. Winter harbor and Dall's porpoise observation locations within the inner marine waters of Washington State, 1995-1999.

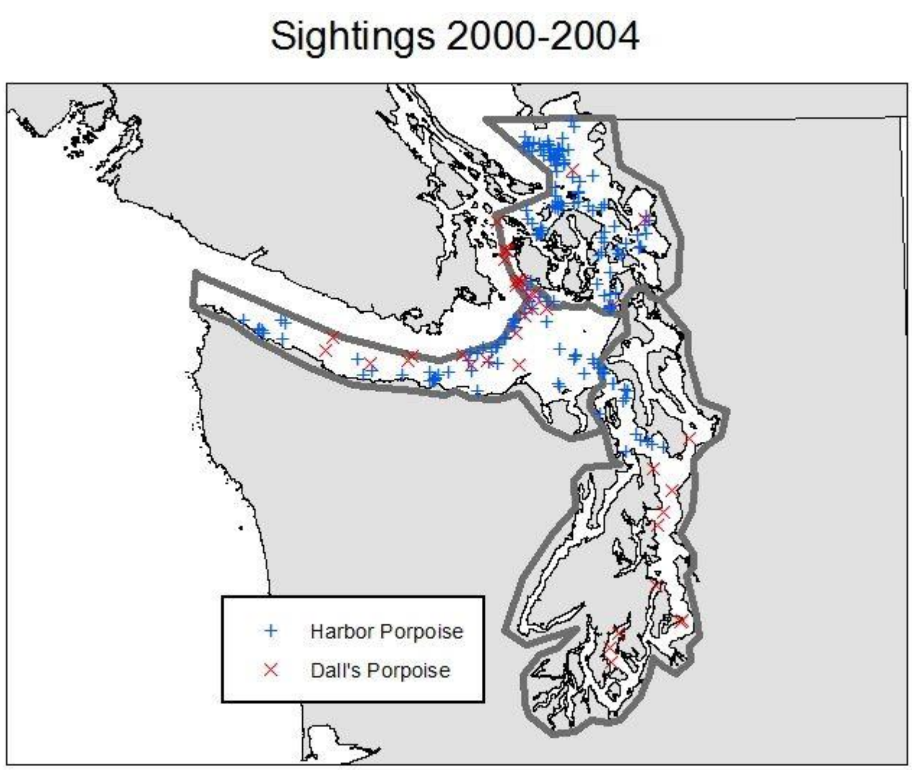

Figure 12. Winter harbor and Dall's porpoise observation locations within the inner marine waters of Washington State, 2000-2004.

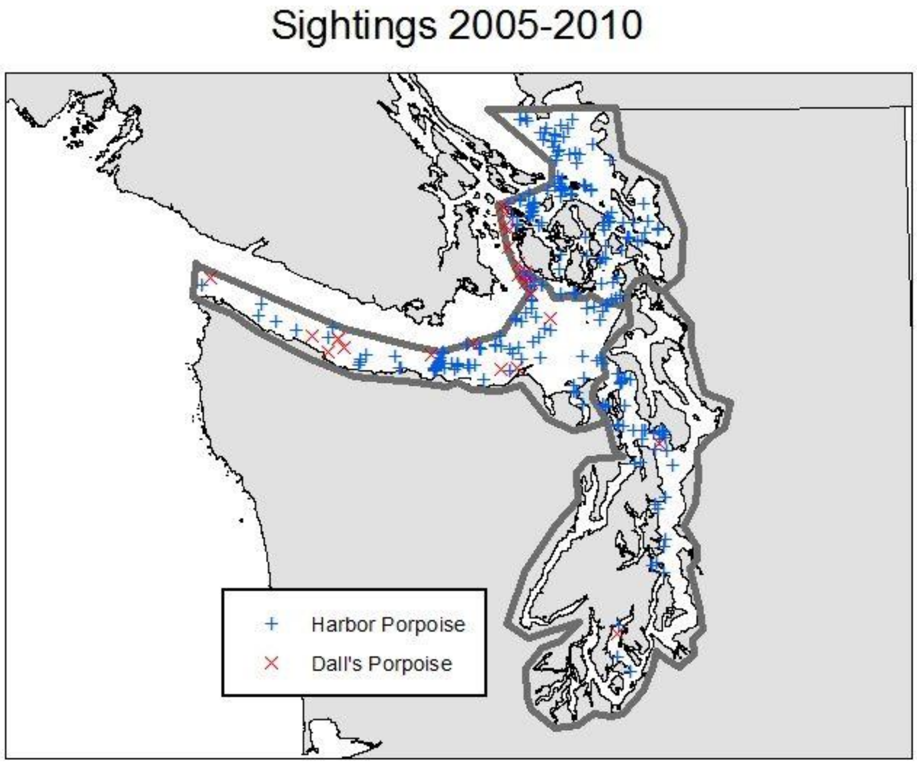

Figure 13. Winter harbor and Dall's porpoise observation locations within the inner marine waters of Washington State, 2005-2010.

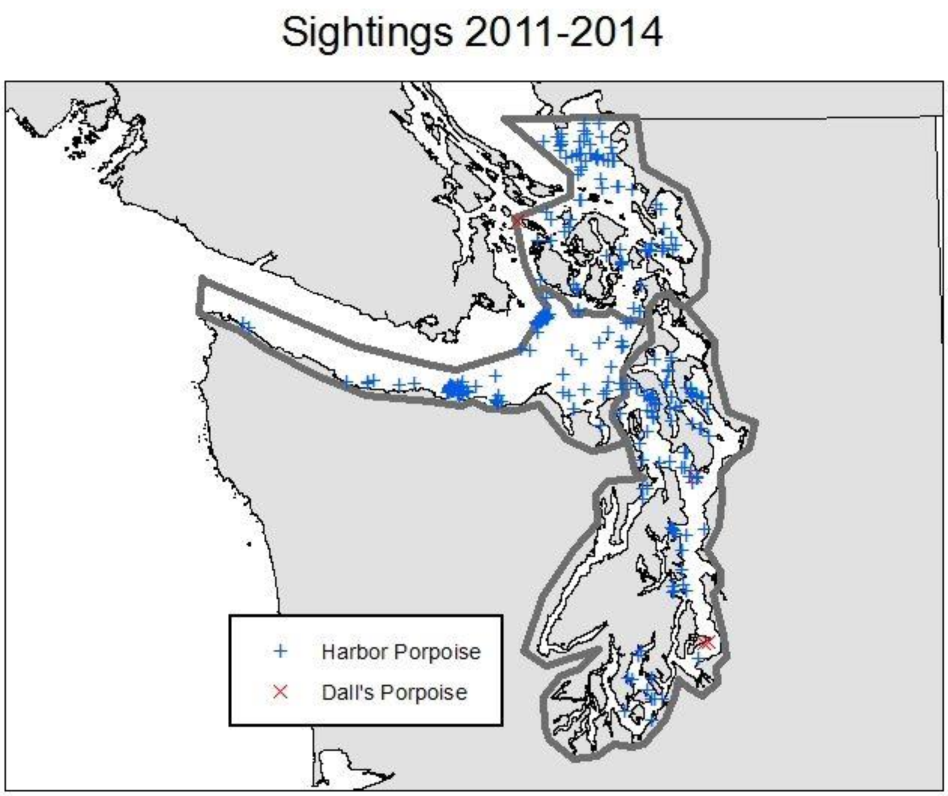

Figure 14. Winter harbor and Dall's porpoise observation locations within the inner marine waters of Washington State, 2011-2014.

Dall's Porpoise

When the study began, Dall's porpoise were commonly sighted in all three regions, though at much lower densities than current harbor porpoise. Over the course of the study, Dall's porpoise sightings steadily decreased (Figures 10, 11, 12, 13, and 14), until they were completely absent from the 2014 survey. The highest densities were in both ESJF, WSJF, SJI and CPS. They were only sighted sporadically in SPS (3 years), WB (4 years), AI (1 year) and SG (3 years). No Dall's porpoise were sighted in HC during any year.

Discussion

The results of these aerial surveys, over a period of two decades, document both increasing trends followed by stabilization of the harbor porpoise in the waters of the Strait of Juan de Fuca and Washington Sound, and their expansion into the previously abandoned waters of the Puget Sound and the waters of the Eastern Strait of Georgia, along with the concurrent decline of Dall's porpoise over the same time period.

As the surveys suggest, it is likely that harbor porpoise populations increased in the northern inland waters through the late 1990s, then expanded into the southern waters as competition for resources increased. The population may have approached carrying capacity in both the Strait of Georgia and the San Juan Islands beginning in 2000 to 2002, while continuing to increase in the Strait of Juan de Fuca through the most recent years. Given the population leveling off in Washington Sound at around the same time as incursions into the Puget Sound, it is possible that the move into Puget Sound was a consequence of resource limitations in the northeastern areas.

Little is known about actual harbor porpoise maximum net productivity (R_{MAX}), though most models suggest an R_{MAX} of 4%-10% based on their life parameters, with 4% the recommended rate to use for the Washington Inland Waters Stock (Carretta et al. 2012; Lockyer 2003). The growth rate throughout the study area was around 10%, though the late-1990s saw growth rates that were around twice that rate, suggesting that there was immigration of animals from outside the study area. It is possible that immigrants could have come from inland British Columbia waters, or from the coastal region of Washington and/or British Columbia. Within Puget Sound, the growth rate was 33.8%, which was calculated from 2000-2014, as this was the period where they were observed every year, which is far higher than even the highest estimates for R_{MAX}. If there was a remnant of the original Puget Sound population subunit, they only accounted for a small part of the reoccupation of the waters south of Admiralty Inlet, with most of the animals coming from the Strait of Juan de Fuca, Washington Sound, Canadian or coastal waters.

Dall's porpoise are believed to be more abundant in the inland waters during the summer months (Cowan 1944), so the annual winter aerial surveys may not be the best method to assess their overall abundance. Even so, the population trend during the winter months suggest a clear decline in abundance during this time of the year. This pattern has been supported by anecdotal evidence provided by whale watching industry reports and sighting reports provided to Cascadia Research and the National Marine Fisheries Service. Aerial surveys for the U.S. Navy (Smultea et al. 2015), providing seasonal observations over several years, should document whether this decline is occurring year round.

The increase in harbor porpoise abundance in the inland waters is likely to be the reason for the decrease in Dall's porpoise sightings. Since papers published prior to the 1960s suggest that Dall's porpoise were rarely, if ever, seen in Washington's inner marine waters before the decline of the harbor porpoise, Dall's porpoise were likely filling a niche vacated by the harbor porpoise. If this is the case, the occurrence of Dall's porpoise would be expected to decrease as harbor porpoise recovered within their historic range.

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Aerial view of harbor porpoise cow and calf near Waldron Island in the San Juan Islands, Washington.
– Joseph Evenson, WDFW.