Fisheries and Oceans Canada Pêches et Océans Canada

Science Sciences

**Canadian Science Advisory Secretariat (CSAS)**

---

**Research Document 2014/088**

**Pacific Region**

# Offshore Killer Whales in Canadian Pacific Waters: Distribution, Seasonality, Foraging Ecology, Population Status and Potential for Recovery

John K.B. Ford[1], Eva H. Stredulinsky[1], Graeme M. Ellis[1], John W. Durban[2], and
James F. Pilkington[1]

[1]Fisheries and Oceans Canada, Pacific Biological Station
Cetacean Research Program, Conservation Biology Section
Nanaimo, BC V9T 6N7 Canada

[2]Marine Mammal and Turtle Division, Southwest Fisheries Science Center, National Oceanic and Atmospheric Administration
La Jolla, California 92037

---

October 2014

## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

**Published by:**

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON  K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

**Correct citation for this publication:**

Ford, J.K.B, Stredulinsky,E.H., Ellis, G.M., Durban, J.W., and Pilkington, J.F. 2014. Offshore Killer Whales in Canadian Pacific Waters: Distribution, Seasonality, Foraging Ecology, Population Status and Potential for Recovery. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/088. vii + 55 p.

## TABLE OF CONTENTS

ABSTRACT ..... VI
RÉSUMÉ ..... VII
INTRODUCTION ..... 1
BACKGROUND: LIFE HISTORY, SOCIAL STRUCTURE AND ECOLOGY OF KILLER WHALES ..... 1
OFFSHORE KILLER WHALE STATUS ..... 2
Data Sources ..... 2
Presence in Canadian Waters ..... 3
Distribution and Habitat Characterization ..... 4
Seasonal Occurrence ..... 5
Foraging Ecology ..... 6
Abundance and Population Dynamics ..... 8
Social Organization ..... 11
RECOVERY POTENTIAL ASSESSMENT ..... 12
ASSESS CURRENT/RECENT SPECIES/ STATUS ..... 12
ASSESS THE HABITAT USE ..... 13
Prey Availability ..... 14
Underwater Noise ..... 15
Chemical and Biological Contamination ..... 15
Oil Spills ..... 15
Disturbance ..... 16
SCOPE FOR MANAGEMENT TO FACILITATE RECOVERY ..... 17
SCENARIOS FOR MITIGATION AND ALTERNATIVES TO ACTIVITIES ..... 19
Prey Depletion ..... 19
Underwater Noise ..... 19
Toxic Spills ..... 20
Biological and Chemical Pollution ..... 20
Disturbance ..... 21
Fishery Interactions ..... 21
ALLOWABLE HARM ASSESSMENT ..... 22
ACKNOWLEDGEMENTS ..... 23
REFERENCES ..... 23
TABLES ..... 31
FIGURES ..... 36

## LIST OF TABLES

Table 1. Number of days with acoustic detections of OKWs by month, from autonomous underwater recording instruments and real-time listening stations in Canadian Pacific waters. ....31

Table 2. Euclidean distance to 200m, 500m and 1000m isobaths and water depth at locations of OKW encounters....32

Table 3. Summary of OKW predation events with prey species identification from published and unpublished sources. ....33

Table 4. Seasonal migration patterns, depth distribution, and estimated energetic value of the known prey species of Offshore Killer Whales. ....34

## LIST OF FIGURES

Figure 1. Map of locations of autonomous recording instruments and fixed real-time hydrophone networks used for passive acoustic monitoring of Offshore Killer Whales. .......................36

Figure 2. OKW encounters by year, separated by region .......................................................37

Figure 3. Vessel survey effort during Cetacean Research Program research cruises, 2002–2011, and locations of OKW sightings on those surveys .................................................38

Figure 4. Distribution of encounters with OKWs (red dots; 1988–2012) and numbers of days in which OKWs were detected acoustically at fixed monitoring sites...................................39

Figure 5. Frequency distribution of OKW encounters with respect to distance from the 200 m isobaths near the continental shelf break. ........................................................................40

Figure 6. Track of a satellite-tagged Offshore Killer Whale as it travelled northwards off Vancouver Island, 24 February to 2 March, 2013. ..........................................................41

Figure 7. Frequency of OKW encounters by month, for Alaska, BC, and California. N = 192 ....41

Figure 8. Latitude of OKW encounter locations by month. .......................................................42

Figure 9. Number of “visits” by OKWs per unit effort at acoustic monitoring stations by month in BC waters. ..........................................................................................................42

Figure 10. Seasonality of “visits” by OKWs at acoustic monitoring stations. .............................43

Figure 11. Locations of predation events by OKWs involving four confirmed prey species........44

Figure 12. Representative photographs of Killer Whale teeth: ..................................................45

Figure 13. Photos showing severely worn teeth in the mandible .............................................46

Figure 14. Discovery curve of cumulative distinct OKWs (N = 355; solid blue) encountered and proportion of distinct OKWs encountered that were new (dashed red), across annual May-September sampling periods between 1988 and 2012. ...................................................47

Figure 15. Estimates of the probability of identification ($p_t$), abundance of distinctive OKW individuals ($N_t$), survival rate ($\varphi_t$), per-capita recruitment rate ($N_t$) for each year 1989-2011$^*$. ..........................................................................................................48

Figure 16. Frequency distribution of OKW group sizes based on total count of identified individuals in each encounter. ..........................................................................49

Figure 17. Social network of 186 OKWs that were identified in 5 or more encounters. ..............50

Figure 18. Social network of 95 OKWs linking “preferred companions” – pairs of individuals with simple ratio indices greater than 0.6.....................................................................51

Figure 19. Distribution of fishery catches of Pacific Sleeper Sharks (top), Blue Sharks (middle) and Pacific Spiny Dogfish (bottom) in Canadian Pacific waters 1996–2012. ....................52

Figure 20. Catch per unit effort of Pacific Sleeper Sharks in longline (top; 2006–2012) and trawl fisheries (bottom; 1996–2012) off the BC coast. .............................................................53

Figure 21. Catch per unit effort of Blue Sharks in longline (top; 2006–2012)) and trawl fisheries (bottom; 1996–2012) off the BC coast..............................................................................54

Figure 22. Catch per unit effort of Pacific Spiny Dogfish in longline (top; 2006–2012) and trawl fisheries (bottom; 1996–2012) off the BC coast. .............................................................55

# ABSTRACT

In 2011, Offshore Killer Whales off Canada's Pacific coast were uplisted to Threatened from Special Concern under the *Species at Risk Act*. With this uplisting, it is required that a Recovery Strategy be prepared by DFO to facilitate recovery. Here, we present an assessment of the distribution, seasonality, foraging ecology and population status of Offshore Killer Whales (OKWs), as well as an assessment of the recovery potential of the population. This document is intended to support the development of goals and objectives in the future Recovery Strategy. For this assessment, we used an archive of observations and photo-identifications of individual OKWs collected during 137 encounters between 1988 and 2012, as well as detections of OKWs from a network of underwater acoustic stations during 2006–2012. The OKW population ranges widely in continental shelf waters from southern California to the eastern Aleutian Islands, and may occur in Canadian Pacific waters in any month of the year. Recent evidence suggests that this population feeds primarily on sharks, although some teleost fishes such as Chinook Salmon and Pacific Halibut are also consumed. To assess abundance and trends, we applied a 'mark-recapture' approach to the analysis of the photo-identification dataset using a Bayesian modeling framework. These analyses indicate that the OKW population is small, with an average annual abundance estimate of 300 (95% Highest Posterior Density Interval (HPDI) = 257–373). The population appears stable, with average annual survival rates of 0.98 (95% HPDI = 0.92–0.99) balanced by annual recruitment rates of 0.02 (95% HPDI = 0–0.07). A recovery potential assessment is provided that identifies threats to OKWs and their habitat, and measures to mitigate these threats. A Potential Biological Removal (PBR) of 0.55 animals per year suggests that the population could sustain very little human-caused mortality without declining.

# Épaulards hauturiers dans les eaux canadiennes du Pacifique : répartition, caractère saisonnier, écologie de l'alimentation, état de la population et potentiel de rétablissement

## RÉSUMÉ

En 2011, l'état de la population d'épaulards hauturiers dans les eaux canadiennes du Pacifique est passé de « menacé » à « préoccupant » en vertu de la *Loi sur les espèces en péril*. Ce reclassement exige que le MPO prépare un programme de rétablissement afin de faciliter le rétablissement de la population. Voici une évaluation de la répartition, du caractère saisonnier, de l'écologie de l'alimentation et de l'état de la population des épaulards hauturiers, ainsi qu'une évaluation du potentiel de rétablissement de la population. Le présent document vise à soutenir l'élaboration des buts et objectifs du futur programme de rétablissement. Aux fins de l'évaluation, nous avons consulté dans les archives les observations et identifications photographiques d'épaulards hauturiers recueillies au cours de 137 rencontres entre 1988 et 2012, ainsi que de détections d'épaulards hauturiers au moyen d'un réseau de stations acoustiques sous-marines de 2006 à 2012. La population d'épaulards hauturiers se déplace librement dans les eaux du plateau continental, du sud de la Californie jusqu'à l'est des îles Aléoutiennes, et elle peut se manifester dans les eaux canadiennes du Pacifique durant n'importe quel mois de l'année. Des données récentes laissent entendre que cette population se nourrit principalement de requins, même si elle consomme également certains poissons téléostéens comme le saumon quinnat et le flétan du Pacifique. Pour évaluer l'abondance et les tendances, nous avons utilisé une méthode de marquage-recapture lors de l'analyse de l'ensemble de données d'identification photographique à l'aide d'un cadre bayésien de modélisation. Ces analyses indiquent que la population d'épaulards hauturiers est faible, avec une abondance annuelle moyenne estimée à 300 individus (intervalle de densité postérieure le plus élevé [IDPE] à 95 % = de 257 à 373). La population semble stable avec des taux de survie annuels moyens de 0,98 (IDPE à 95 % = de 0,92 à 0,99) équilibrés par des taux de recrutement de 0,02 (IDPE à 95 % = de 0 à 0,07). L'évaluation du potentiel de rétablissement fournie définit les menaces pour l'épaulard hauturier et son habitat, et présente des mesures visant à atténuer ces menaces. Un prélèvement biologique potentiel (PBP) de 0,55 animal par an semble indiquer que la population ne pourrait soutenir que très peu de mortalités d'origine anthropique sans diminuer.

# INTRODUCTION

In 2001, the northeastern Pacific Offshore Killer Whale population was designated Special Concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). The status of this population was reassessed in 2008 and uplisted to Threatened. Reasons for this designation were the very small size of the population and its exposure to threats from "high levels of contaminants, acoustical and physical disturbance, and potential oil spills". This population became legally listed on Schedule 1 of the Species at Risk Act (SARA) in 2011.

As required by SARA for species of Special Concern, a Management Plan for Offshore Killer Whales in Canada was prepared by Fisheries and Oceans Canada (DFO) in December 2009 (Fisheries and Oceans Canada 2009). With the uplisting of Offshore Killer Whales (OKWs) under SARA in 2011, DFO is now required to develop a Recovery Strategy, which is a planning document that identifies what needs to be done to arrest or reverse the decline of a species. In order to provide an up-to-date assessment of the population's status and potential threats to recovery, DFO Science has been requested to prepare a Recovery Potential Assessment (RPA) that will serve as the scientific basis for the development of the Recovery Strategy. An RPA provides scientific background, identification of threats and probability of recovery of a population that is deemed to be at risk. Specifically, an RPA addresses the 17 tasks identified in the *Revised Protocol for Conducting Recovery Potential Assessments (*DFO 2009).

This document provides an assessment of the distribution, seasonality, foraging ecology and population status of OKWs based primarily on on-going studies by the Cetacean Research Program (CRP), Pacific Biological Station (Nanaimo, BC). This status assessment is followed by the RPA, which address the 17 tasks identified in DFO (2009), as well as 10 additional tasks related to the identification of important habitats and threats to those habitats.

## BACKGROUND: LIFE HISTORY, SOCIAL STRUCTURE AND ECOLOGY OF KILLER WHALES

The following provides broad background information on the life history and ecology of Killer Whales globally as well as in waters off Canada's Pacific coast. The Killer Whale is the largest member of the family Delphinidae and one of the most widely distributed mammals. It is currently considered a single wide-ranging species, *Orcinus orca*, with a cosmopolitan distribution in all the world's oceans and most seas. It is most commonly found in productive coastal waters in high latitude regions and is rare in most tropical regions. There is an estimated total abundance of at least 50,000 (Forney and Wade 2006), but this is likely far short of the true global abundance. The Killer Whale is the apex marine predator, capable of feeding on a great diversity of prey, from the largest whales to small schooling fish. It has no natural predators. Despite being a generalist predator as a species, different regional populations of Killer Whales are often distinct ecotypes with highly specialized foraging strategies and diets. These ecotypes are often sympatric, sharing the same waters but maintaining social isolation from each other. Recent molecular studies using mitogenomic techniques have shown that ecotypes in the North Pacific and Antarctic represent reciprocally monophyletic clades, or lineages, with divergence times ranging from 150,000 to 700,000 years. These lineages may represent distinct species or subspecies (Morin et al. 2010).

Three sympatric and genetically-distinct lineages of Killer Whales have been described in coastal waters of the northeastern Pacific Ocean. These lineages, named *Transient*, *Resident* and *Offshore*, differ in morphology, social structure, diet, foraging behaviour and acoustic behaviour. Despite having overlapping ranges, these lineages do not mix and are thus reproductively isolated from each other. Transient Killer Whales (also known as Bigg's Killer

Whales) specialize on marine mammal prey, though they occasionally kill and eat seabirds as well. There is no evidence from decades of field observations that they feed on fish. Resident Killer Whales prey mainly on fish, particularly salmon, and some squid. Offshore Killer Whales also feed on fish and may specialize in preying on sharks (Ford et al. 2011a). Neither Residents nor Offshores have been observed to prey on marine mammals. These foraging specializations appear to be fixed behavioural traits maintained by cultural transmission within populations. The Offshore Killer Whale and Resident Killer Whale lineages are estimated to have diverged from each other approximately 200,000 years ago (P. Morin, pers. comm.).

Killer whales are long-lived animals that have a low reproductive potential. Best known are Resident Killer Whales in British Columbia, and their life history parameters as presented in Olesiuk et al. (2005) may be generally representative of other lineages as well. Their survival patterns are typical of mammals, being U-shaped with highest mortality rates in very young (neonate) and very old age classes. Survival rates of juveniles and adults are high (0.97–0.99), particularly among mature females and during periods of population growth. During a period of growth in the Northern Resident Killer Whale population, females had a mean life expectancy of 46 years and a maximum longevity of about 80 years. Males had a mean life expectancy of 31 years, with maximum longevities of 60–70 years. Females give birth to their first viable calf at approximately 14 years, and produce an average of 4.7 calves over a 24-year reproductive lifespan. Gestation is 16–17 months and the minimum calving interval is about 3 years (mean = 4.9 years). Females give birth to their last calf at around 40 years, then become reproductively senescent for the remainder of their lives. Calving is diffusely seasonal, with a peak in fall and winter.

Killer whales tend to live in long-term matrilineal groups (Bigg et al. 1990; Ford et al. 2000). In Resident Killer Whales, social structure is extremely stable, as there is no dispersal from the natal group by either sex. Thus, the basic social unit, known as a matriline, can be composed of up to five generations of whales, generally a post-reproductive female matriarch and her living descendants. Transient Killer Whale society is also matrilineally based, but is considerably more dynamic than that of Residents with the regular dispersal of individuals from the natal matriline (Baird and Dill 1996; Ford and Ellis 1999). Little is known of the social structure of Offshore Killer Whales. They are frequently observed to travel in large groups of 50 or more individuals that may represent temporary aggregations of smaller social units.

## OFFSHORE KILLER WHALE STATUS

### Data Sources

Killer whales in Canadian Pacific coastal waters have been studied by means of photographic identification of individuals from natural markings for four decades. Field studies using this technique have been undertaken each year since the early 1970s (Bigg et al. 1987, 1990; Ford and Ellis 1999; Ford et al. 2007; Towers et al. 2012). This long-term effort has resulted in an archive of identification photographs collected from 10,580 encounters[1] (up to 2012) with Killer Whales by researchers based at the Pacific Biological Station (Fisheries and Oceans Canada, Nanaimo, B.C.) involving over 300 collaborators in waters from British Columbia, Alaska, Washington State, Oregon and California. Others contributing photo-identification data included independent researchers, whale watch operators, and natural history tour operators. The photo-identification archive is maintained by the Cetacean Research Program (CRP) at the Pacific

---

[1] An “encounter” is the interception and photographic identification of an individual (if alone) or group of killer whales at one location on a given day.

Biological Station (PBS). The great majority (85%) of encounters were made in Canadian waters, with 7% occurring in US waters to the south from Washington State to California and 8% occurring to the north in Alaska. Individual photo-identification data were used to estimate abundance, population dynamics and social organization. Of the 10,580 total encounters, 6529 (62%) involved Resident Killer Whales, 3914 (37%) involved Transient Killer Whales, and only 137 (1%) involved Offshore Killer Whales (OKWs). Of these 137 encounters, 103 took place in Canadian waters, 13 to the south as far as California and 21 in Alaska. An additional 20 photographic encounters with Offshore Killer Whales in California and Alaska are described in Black et al. (1997) and Dahlheim et al. (2008), and these are included in this analysis.

It is important to note that encounters with OKWs were opportunistic. Because of the unpredictable occurrence of OKWs, encounters were generally made while researchers were undertaking field studies focused on Resident Killer Whales and other cetacean species. Similarly, natural history tour and whale watch operators typically encountered and photographed OKWs during unrelated activities or while searching for other whale populations or species. The spatial and temporal distribution of encounters is thus biased by observer effort, which was concentrated in nearshore waters and in areas frequented by Resident Killer Whales, which were usually the focus of research surveys and whale watch operators. Unfortunately, the majority of observer effort outside of surveys by the Cetacean Research Program is unrecorded, thus encounter rates cannot be corrected quantitatively to account for this bias.

Passive acoustic monitoring was also used as a supplement to photo-identification data in the assessment of seasonal occurrence of OKWs. Distinctive stereotyped calls produced by Resident, Transient, and Offshore Killer Whales are readily distinguishable (Ford 1991; Deecke et al. 2005; Cetacean Research Program, unpubl. data). A network of 13 autonomous underwater recording moorings deployed off the coast of British Columbia during 2006–2012 collected long-term acoustic data that included detections of Killer Whale vocalizations (Figure 1). Recording instruments consisted of PATC, AURAL-M2 (Multi-Electronique Inc.), and SM2M (Wildlife Acoustics Inc.) submersible recorders (for further details, see Vagle et al. 2004, Ford et al. 2010 and Riera 2012). Other acoustic datasets that were examined included those recorded from cabled shore-based monitoring stations in the Caamano Sound area on the northern mainland coast (courtesy of Cetacealab) and in the Johnstone Strait and Blackfish Sound area off northeastern Vancouver Island (courtesy of OrcaLab). Offshore Killer Whales were detected acoustically on 69 days off the BC coast. Acoustic detections of OKWs on an additional 14 days from an autonomous recorder off the Washington coast (Oleson et al. 2009) are also included in this analysis.

## Presence in Canadian Waters

The annual distribution of encounters separated by region (BC, Alaska, and California) is depicted in Figure 2. Despite significant annual survey effort for Killer Whales in BC since 1973, no encounters with OKWs took place prior to 1988. This is likely due primarily to the restricted spatial distribution of survey effort in the first 15 years of the time series, which was focused mostly in nearshore waters off eastern and southern Vancouver Island. Very little effort took place in waters more than 10 km from shore off the west coast of Vancouver Island, or anywhere to the north of Vancouver Island or around Haida Gwaii. These waters are where the majority of encounters with OKWs have been documented. Little Killer Whale survey effort existed in California or Alaska waters prior to the mid 1980s (Black et al. 1997; Dahlheim et al 1997; Matkin et al. 1999), which likely also accounts for the lack of earlier encounters in those areas. There is no doubt that OKWs existed in west coast waters prior to 1988. Morin et al. (2006) used DNA to identify museum specimens of Killer Whales and documented eight OKW individuals that were stranded or collected in Baja California or California between the mid-1800s and 1985. Ford et al. (2011a) similarly showed by DNA analysis of skeletal remains that a mass stranding of 20 Killer Whales that took place in 1945 at Estevan Point, west coast of Vancouver Island, involved OKWs.

Despite their apparent long-term presence in Canadian waters, OKWs have been rarely encountered even with expanded observer effort in recent years. This is most likely because 1) their preferred range in outer coast waters over the continental shelf seldom brings them into contact with Killer Whale researchers and whale watch operators in nearshore waters, and 2) their low population abundance and large group sizes mean there are few groups to be encountered (these factors are discussed in the following sections). As an example of this rarity, OKWs were only encountered three times during over 44,600 linear km of cetacean survey effort from research ships and smaller vessels during 2002–2011, which covered both inner coast and continental shelf waters (Figure 3). As mentioned previously, OKWs only represented about 1% of over 10,000 Killer Whale encounters in the photo-identification database archived with the CRP.

## Distribution and Habitat Characterization

The locations of encounters with OKWs are shown in Figure 4. These are distributed from the coast of southern California (~33°30’ N) north to Prince William Sound, Alaska (~60° N) and west to the eastern Aleutian Islands (~160° W). These encounters comprise the known current range of the population. It is likely that OKWs occur further to the south in Mexican waters, but there are no recent encounters in that area; a Killer Whale stranded on the central west coast of Baja California in 1951 (~27°30’ N) was subsequently identified from DNA to be an OKW (Morin et al. 2006). OKWs have not been seen further west in the Aleutian Islands despite significant recent survey effort in those waters (Zerbini et al. 2007). The extent of potential occurrence in oceanic waters beyond the continental shelf is unknown.

Offshore Killer Whales were first encountered in the protected inside waters off eastern and southern Vancouver Island in 1992, 19 years after annual survey effort for Killer Whales began. It is doubtful that the whales visited these waters but were missed, at least during the summer months, since they typically occur in large groups that are quite conspicuous. Since 1992, they have entered these waters on at least 31 occasions in 13 of the last 21 years (1992–2012). These visits to inside waters lasted an average of 3 days (range 1–15 days) before the whales departed for outer coast areas. It is thus apparent that a change in distribution took place around 1992, with OKWs beginning to include periodic visits to inside waters, at least around Vancouver Island. It is unknown whether this change reflects a return to part of their historical range, an expansion of their current habitat, or a shift inshore and away from other habitats.

The numbers of acoustic detections of OKWs as well as locations of encounters in Canadian waters are illustrated in Figure 4. Encounters were scattered widely off the coast, although some concentrations are apparent. Clusters of encounters are located off southeastern and northeastern Vancouver Island, which is at least partly due to observer effort. These waters are frequented by numerous whale watch vessels over much of the year. A year-round network of hydrophones maintained by OrcaLab in Johnstone Strait and Blackfish Sound, northeastern Vancouver Island, has also resulted in many detections (Table 1). As mentioned above, these encounters and detections have all taken place since 1992.

Other areas with relatively numerous encounters with OKWs include the banks off the southwest coast of Vancouver Island, the nearshore waters off southeast Moresby Island, Haida Gwaii, and around Langara Island. The southeast Moresby Island and Langara Island areas have had relatively high levels of observer effort, but the ratio of encounters to effort seems qualitatively high relative to other areas. Encounters offshore of southwest Vancouver Island are similarly numerous relative to effort.

OKWs are found in a variety of marine habitats off the BC coast, from deep oceanic waters beyond the shelf break to the heads of narrow inlets and bays. Judging from encounter rates relative to observer effort (which, as indicated above, is mostly unquantifiable), waters over the outer continental shelf waters and slope may be particularly important habitat for OKWs. Clusters of encounters near Langara Island, in western and eastern Hecate Strait, and off southwest Vancouver Island are all in relatively close proximity to the continental shelf margin or to Moresby Trough, a deep canyon that extends into Hecate Strait from the southwest.

To measure the distance between encounter locations and bathymetric contours, encounters were spatially joined to the contour, generating a distance attribute for each encounter. Depths were extracted from a mosaic raster composed of coastal digital elevation models compiled by the Geological Survey of Canada (GSC 2003), as well as coastal relief models from NOAA's National Geophysical Data Center (Lim et al. 2011; NOAA 2012). The proximity of OKW encounters to the 200 m, 500 m and 1000 m isobaths, representing the shelf break and slope, and encounter depths are summarized in Table 2. The frequency distribution of encounter locations inshore and offshore of the 200 m isobath are depicted in Figure 5. Encounters were in waters with a mean depth of 208 m (median = 122 m, range 8–2170) and were on average 38 km from the 200 m isobath. This mean depth and distance to the 200 m isobath are very similar to that of the outer coast subpopulation of West Coast Transient Killer Whales, which primarily frequent outer continental shelf waters (Ford et al. 2013). The tendency for OKWs to be associated with the outer continental shelf can also be seen in Figure 6, which illustrates the track of one of a group of OKWs that was fitted with a satellite tag as it travelled northward off the coast of Vancouver Island in February–March, 2013 (G. Schorr, Cascadia Research, pers. comm.).

Although the primary habitat of OKWs may be outer continental shelf waters, they do periodically enter protected nearshore locations and sometimes stay for a week or longer. Of the 31 occasions that OKWs have been documented in the inside waters off eastern Vancouver Island, about half involved single-day visits and half were for two or more days. Multiple day visits averaged six days duration (range = 2–15 days) before whales left the area. When in nearshore waters, OKWs are sometimes observed to spend significant time in confined waters at the heads of inlets such as Skincuttle Inlet, Haida Gwaii, and Saanich Inlet, southern Vancouver Island. On one occasion, a group of more than 50 OKWs was observed in Cowichan Bay over a 10-hr period, during which they made repeated forays into the river estuary. It is not clear why these whales enter such confined areas but it is likely related to foraging.

## Seasonal Occurrence

Offshore Killer Whales appear to exhibit a latitudinal shift in their distribution seasonally, although this shift is rather diffuse. Overall, OKW encounters are most frequent in California during the winter months and in Alaska during summer. In BC, encounters were documented in all months of the year, with peaks in March, August and September (Figure 7). The distribution of encounters by latitude and month is illustrated in Figure 8. This suggests more clearly a seasonal shift northward during spring and southward during late summer to fall. However, it is important to note that there is a seasonal bias in observer effort towards summer in BC and Alaska, when sea conditions are generally more favourable for finding whales, days are longer, and more boats are searching for whales. Presence of OKWs in these higher latitudes during winter may potentially be underestimated due to this bias. Effort in California waters is more consistent throughout the year.

To assess seasonal occurrence in Canadian waters with less temporally biased data, we examined the frequency of acoustic detections of OKWs from autonomous underwater recording instruments and fixed real-time hydrophone networks. Passive acoustic monitoring has the benefit of being equally effective day and night throughout the year and in all weather conditions. The locations of these monitoring stations are shown in Figure 1, and the number of days that OKWs were detected acoustically in each month of the year are tabulated in Table 1. Although acoustic effort is not consistent throughout the year for many stations, a peak in detections is evident in March, and lesser peaks in April, August, October and December. In some cases, particularly in the Hanson Island area (Johnstone Strait and Blackfish Sound), large numbers of detections reflect prolonged visits where OKWs were detected on multiple consecutive days. As these clusters of detections may distort the picture of actual seasonality in BC waters, we assessed detection rates by the number of "visits", defined as one or more detection days within a 7-day period, and adjusted these by the amount of monitoring effort per station in each month. This plot of visits per unit effort by month is illustrated in Figure 9. This shows peak months of visits detected at monitoring stations in BC waters as March, August and December.

There is no evidence of a clear pattern of seasonality in the occurrence of OKWs within BC waters. The seasonality of visits at each acoustic monitoring station is depicted graphically in Figure 10. Although sample sizes at some stations are small, no consistent seasonality is evident at stations with multiple visits.

In summary, there is some evidence of a broad seasonal shift in occurrence of OKWs within their extensive coastal range, but the pattern is by no means clear. In California waters, observer effort is reasonably consistent throughout the year and OKWs tend to be encountered mostly in winter. However, they are also encountered there in spring, summer and fall. In Alaska, encounters have been restricted to April–October, but observer effort outside this period is minimal. In British Columbia, OKWs have been encountered or detected acoustically in all months of the year, with some evidence of peaks in March, August and December.

## Foraging Ecology

The diet of OKWs has until recently been unknown. Aspects of the behaviour and acoustics of Offshore Killer Whales have been interpreted in the past to suggest that they do not routinely hunt marine mammals. They often travel in large groups of 50 or more individuals, and disperse widely in a manner similar to that of piscivorous Resident Killer Whales (Ford et al. 2000). As with similar sized aggregations of Residents, groups of Offshore Killer Whales tend to be highly vocal, producing a wide variety of pulsed calls and intense echolocation clicks (Ford et al. 1992, 2000). In contrast, mammal-eating Transient Killer Whales typically forage and travel in small groups and in near silence, as part of a hunting strategy based on stealth (Barrett-Lennard et al. 1996; Deecke et al. 2005). Offshore Killer Whales appear indifferent to the presence of potential marine mammal prey in their vicinity, and marine mammals generally do not react to their presence, implying that the whales do not represent a predatory threat to them (Dahlheim et al. 2008; CRP, unpubl. data).

Skin and blubber biopsy samples of Killer Whales revealed fatty acid, stable isotope and persistent organochlorine pollutant (POP) signatures suggesting that the OKWs' primary prey is different than that consumed by Resident and Transient Killer Whales, and likely consists of upper trophic-level marine fishes (Krahn et al. 2007). Documentation of diet composition of OKWs in the published literature is based on stomach contents of stranded or harpooned individuals and observations of predation at sea. The stomach of a female Killer Whale harpooned off the central California coast in 1964 (Rice 1968) and subsequently determined from DNA analysis to be an OKW (Morin et al. 2006) contained remains of two Opah (*Lampris guttatus*) and two sharks, most likely Blue Shark (*Prionace glauca*) but possibly Whitetip Shark (*Carcharhinus longimanus*). A mature male Killer Whale harpooned off the west coast of Vancouver Island in 1955 (Pike and MacAskie 1969) and recently determined from DNA to be an OKW (Ford et al. 2011a) was found to have remains of Pacific Halibut (*Hippoglossus stenolepis*) in its stomach. Heise et al. (2003) described the stomach contents of two OKWs, a female and male, found stranded in semi-tidal Barnes Lake, southeastern Alaska, in 1994. The stomach of the female contained salmonid bones, and that of the male contained bones of sculpin (family Cottidae) as well as some pieces of crab shell and eelgrass. As these whales had been entrapped within the lake for 6–10 weeks prior to death (Heise et al. 2003), these remains may not reflect normal feeding behaviour.

Several observations of possible or confirmed predation have been published previously. Jones (2006) reported an observation near Haida Gwaii, British Columbia, of an OKW feeding on what appeared to be a Pacific Halibut although species identification could not be confirmed. Dahlheim et al. (2008) observed OKWs interacting with Chinook Salmon (*Oncorhynchus tshawytscha*) and Blue Sharks off central California, but actual feeding was not seen. Predation on multiple Pacific Sleeper Sharks (*Somniosus pacificus*), identified from DNA analysis of tissue fragments collected from the water's surface, was observed on two occasions in Dixon Entrance, north of Haida Gwaii, and in Prince William Sound, Alaska, and was described by Ford et al. (2011a). Recent unpublished observations include seven additional cases of predation on Pacific Sleeper Sharks in Johnstone Strait, BC, and Resurrection Bay, Alaska, eight predation events involving Pacific Spiny Dogfish (*Squalus suckleyi*) and four involving Blue Sharks off the southwest coast of Vancouver Island. Also, three predation events involving Chinook Salmon were documented, two in Hecate Strait and one off southwest Vancouver Island. These published and unpublished predation events with confirmed prey species identification and prey identified from stomach contents are summarized in Table 3. Locations of predation events with confirmed prey species identification are shown in Figure 11.

Elasmobranchs are the predominant prey documented in observed predation events by OKWs. Of 40 prey items identified, 37 (93%) were sharks and only 3 (7%) were teleost fishes (Chinook Salmon). Of the elasmobranchs, Pacific Sleeper Shark was most common (68%), with Pacific Spiny Dogfish and Blue Shark together representing less than one-third of observed prey. Although neither Resident nor Transient Killer Whales are known to consume sharks (Ford and Ellis 2006; Ford et al. 1998, 2013), it is probable that OKWs preferentially focus on this prey type in their diet. Killer Whales are attracted to large prey with high lipid content – Resident Killer Whales, for example, prey selectively on adult Chinook Salmon, the largest salmonid in their habitat and the most lipid rich, and shun smaller species such as Pink and Sockeye Salmon (Ford and Ellis 2006). Sharks can have a very large liver relative to body size, and it is rich in lipids (up to 80% by wet weight in *Somniosus*). For example, a 3.93 m Pacific Sleeper Shark estimated to weigh ~900 kg had a liver of ~180 kg (Bright 1959), or ~20% of its total mass. Thus, a median sized 1.7 m sleeper shark (pre-caudal length, based on sizes in Alaska; Hulbert et al. 2006) having a mass of 75 kg would have a liver of ~15 kg (Ford et al. 2011a). Given the high lipid content of shark liver, this represents a substantial, high-energy food source for a Killer Whale. During sleeper shark predation by OKWs, large pieces (> 5 kg) were often observed to float to the surface from depth, where they were retrieved and consumed by the whales. It is not known if only the liver of the sharks was consumed, but this is possible. The musculature of the congeneric Greenland Sleeper Shark (*Somniosus microcephalus*) contains high levels of trimethylamine and is poisonous to humans and dogs (Bagnis et al. 1970; Anthoni et al. 1991). Pacific Sleeper Shark muscle may be similarly toxic, possibly to whales as well. It seems less likely that only the liver of smaller species of shark would be consumed. The pectoral and pelvic fins of two probable Blue Sharks were documented in the stomach contents of an OKW harpooned off California (Rice 1968). The seasonal migration patterns, depth distribution, and estimated energetic value of the known prey species of OKWs are summarized in Table 4.

A preponderance of sharks in Offshore Killer Whale diet has been hypothesized to be a cause of the severe tooth wear that is pervasive in the population (Ford et al. 2011a). Neither Resident nor Transient Killer Whales, which are not known to prey on sharks, typically exhibit significant wear on the crown of their teeth, even in old animals (Figure 12). However, the teeth of OKWs, particularly those in the mandible, are worn flat, often to the gum line, and many teeth may have exposed pulp cavities. Ford et al. (2011a) proposed that the hardened dermal denticles (placoid scales) embedded in the skin of sharks cause abrasion of the teeth during prey handling and consumption, leading to the pattern of tooth wear seen in Offshore Killer Whales. The dermal denticles of elasmobranchs vary widely in morphology and abrasiveness (Raschi and Tabit 1992), with deep-water sharks, including Pacific Sleeper Sharks, having particularly rough skin with placoid scales that have erect, narrow crowns and hooked cusps (Raschi and Tabit 1992; Yano et al. 2004).

Since the pulp cavity of Killer Whale teeth becomes increasingly occluded with maturity (Perrin and Myrick 1980), the presence of open pulp cavities in worn teeth in most Offshore Killer Whale specimens suggests that significant wear begins at an early age, well before physical maturity (Figure 13). In cases where most or all teeth are worn flat to the gum line, the large open pulp cavities of anterior teeth and the much smaller cavities of posterior teeth suggest that apical wear begins in anterior teeth and continues progressively over time towards the posterior teeth. This is likely due to prey being grasped mostly by the anterior teeth, which are then subjected to abrasion as the whale twists and shakes its head to tear and break apart the carcass.

It is not known if tooth wear in OKWs affects their foraging efficiency. Given the apparent ubiquity of tooth wear in all but the youngest age classes of OKWs (Figure 13; Ford et al. 2011a), it seems probable that sharp teeth are not needed to grasp and break apart sharks for consumption. Food sharing, which is common in fish-eating Resident Killer Whales (Ford and Ellis 2006), may provide for provisioning of individuals with particularly debilitated teeth. The exposed pulp cavities of worn teeth in OKWs are a possible source of infection due to food remains being compacted into the cavities (e.g., Loch and Simoes-Lopes 2013). However, there is no evidence available to suggest that this represents a serious health risk to OKWs.

## Abundance and Population Dynamics

To assess population abundance and dynamics of OKWs, we used data from photo-identifications of individual whales, a technique that has proved to be very effective in long-term studies of Resident and Transient Killer Whales. However, photo-identification of OKWs presents unusual challenges compared to the application of this technique with the other Killer Whale lineages. First, OKWs were usually encountered in exposed waters off the outer coast, where sea conditions often constrained photo-identification efforts from small vessels. Second, OKWs were often found in large groups of 50 to more than 100 individuals, and typically these groups were dispersed over many square kilometres. As a result, most encounters with large groups were incomplete in that some unknown proportion of the group was missed photographically. Third, encounters with OKWs were infrequent, so photo-identifications of many individuals were years apart. On average, there were only 6.3 encounters with OKWs per year during 1988–2012, compared to 157 per year for Transients and 206 with Northern Residents over the same period. OKWs can acquire small nicks and cuts on their dorsal fin at a high rate, so the distinguishing markings used for photo-identification can change markedly in a relatively short period, making it difficult to track individuals across time when there are long gaps in the photo-identification record. Finally, the associations of individuals within OKW groups are very dynamic within and between encounters, so close spatial grouping of related individuals such as that seen in Resident Killer Whale matrilines were uncommon. This made photo-identification of poorly marked OKW individuals even more difficult because travelling associations could not be used to assist in assigning identifications. A significant proportion of the population, mostly subadult animals, could not be reliably identified and named.

As a result of the difficulties in photo-identification of OKWs, it was not possible to conduct a true census as is done annually with Resident Killer Whales. Instead, we have relied on statistical modeling to provide insight into the abundance and population dynamics of OKWs. This model made use of a database of photo-identification histories that was designed specifically to reduce the possibility of including mis-assigned individuals and provided a means of incorporating unnamed animals into the analysis.

### Mark-recapture model

To assess population dynamics, we fit a Jolly-Seber mark-recapture model to the annual photo-identification histories (1988–2012) to estimate both additions and losses to the population (Seber 1982). Specifically, we used a Bayesian formulation of the model (Royle and Dorazio 2008; Fearnbach et al. 2012) to assess inherent uncertainty in the form of direct probability distributions and to simply allow for abundance estimation by selecting the number of unobserved individuals supported by the model. We augmented the data for the observed individuals with up to 200 candidate unobserved individuals (Royle and Dorazio 2008), and we assigned flat (Uniform) prior distributions between 0 and 1 to each of the annual probabilities of identification, survival and entry into the population. Key model parameters were the annual abundance Nt, probabilities of identification pt, survival ϕt, and per-capita recruitment rt (e.g., Fearnbach et al. 2012).

### Conforming to mark-recapture assumptions

To conform as closely as possible to the mark-recapture assumption of instantaneous sampling (Seber 1982), to ensure that annual probabilities had a consistent definition, we only used a subset of the full photo-identification dataset. Specifically, we constructed identification histories just for individuals encountered within an annual sampling period between May and September, but out-of-sample re-sightings of these individuals were used to input data on an individual's status (alive or not) even when it was not seen in some annual sampling periods (e.g., Fearnbach et al. 2012).

Similarly, to minimize bias due to mark-loss and incorrect recognition of marks (Seber 1982), we only constructed identification histories for whales deemed to possess distinctive markings readily apparent in high quality photographs. As a result, the annual abundance $N_t$ only referred to the distinctive proportion of the population, so we rescaled these estimates to the level of the full population using counts of the number of distinctive and non-distinctive whales identified from high quality photographs over a series of reference encounters (assuming all whales could be distinguished within an encounter from good photographs; e.g., Durban et al. 2010). These encounters were selected owing to their high photographic coverage, when there was good agreement between the group size visually estimated in the field and the total number of whales identified from photographs, to ensure that the photographic sample was representative. Counts of distinctive whales were treated as a binomial sample from the total whales in each of $k$=1 to 37 reference encounters, and we estimated the binomial proportions $\theta_k$ of whales that were deemed distinctive in each encounter. To fully describe the sampling variability, these proportions were assumed to be drawn from a hierarchical prior distribution, $\theta_k$~Beta ($a$, $b$), where $a = \mu/v$ and $b = (1-\mu)/v$. Flat Uniform(0,1) prior distributions were set on the hyper-parameters to learn about the mean, $\mu$, and sampling variability, $v$, over the set of encounters. These parameters were then used to predict a sampling distribution $\pi \sim$ Beta($a$, $b$) as an estimate of the proportion of the population that was distinctive, $\pi$, which as used to calculate overall population abundance $A$ =mean($N$)/$\pi$.

### Model fitting

The models for mark-recapture and distinctiveness rescaling were fit simultaneously using Markov Chain Monte Carlo (MCMC) sampling using WinBUGS software (Lunn et al. 2000), allowing uncertainty to be propagated across levels of this hierarchical model. Inference was based on 10,000 repeated draws from the posterior distribution of each model parameter conditional on the observed data, following MCMC convergence (Brooks and Gelman 1998). We employed the same MCMC simulation approach to generate predictive observations from the model to examine goodness-of-fit (Gelman et al. 1996). We calculated the summed absolute discrepancies to the model for both the predicted and observed data (e.g., Durban et al. 2010) and compared the distributions of these discrepancy measures to estimate the exceeding tail area probability, termed the posterior predictive p-value.

### Mark-recapture sample

Photographs were taken during 157 encounters with OKWs, resulting in 2229 individual identifications and 355 different distinct whales. Most (104 encounters, 1773 identifications) occurred within the May–September sampling period, comprising all 355 individual whales. These encounters spanned the known range of this population, with encounters in three broad coastal regions: the Gulf of Alaska / Aleutian Islands (GOA, $n$ = 14), Southeastern Alaska and British Columbia (SEAK/BC, $n$ = 85), and California (CA, $n$ = 5). However, there was little evidence for spatial segregation with almost all (350/355) individuals seen in SEAK/BC region; 157 whales were seen in GOA and 50 in CA. As a result, we pooled encounters across these regions to produce a single whale-by-year binary identification matrix.

After constraints for photographic quality were applied, this mark–recapture sample consisted of 1266 whale-by-year identifications. There were 125 additional identifications of these same individuals that were used from out-of-sample re-sightings and 2007 additional annual records that were imputed as ‘‘alive’’ for years when whales were not identified between years of repeated identifications. The number of these individuals identified in each annual sample varied across years (median = 35 individuals, range = 2–96), and individuals were identified in an average of three different years (median = 3 years, range 1–10). The cumulative number of distinct individuals increased throughout the study period (Figure 14), suggesting an open population with regular recruitment of new whales.

### Mark-recapture estimates

The mark-recapture model was a reasonable fit to the data, with a Bayesian p-value of 0.14 indicating that the data were not dissimilar to replications under the model (Gelman et al. 1996). However, identification probabilities were very low in some years, particularly due to relatively few encounters during the first half of the time series (Figure 15), limiting our power to precisely estimate abundance and demographic parameters in the early years of the study. This can be seen in the wider spans of the posterior distributions for early rates of survival, per capita recruitment and abundance (Figure 15), indicating greater uncertainty. However, higher identification probability allowed more precise inference in the last half of the time series (year 2000 onwards). During this time, survival rates were estimated to be high, with an average posterior median of 0.98 (95% Highest Posterior Density Interval [HPDI] = 0.92-0.99), with mortality balanced by per capita recruitment at an average rate of 0.02 (95% HPDI = 0-0.07). As a result, the abundance of distinctly marked whales alive in each year was estimated to be stable around an average estimate of 240 whales (95% HPDI = 223 to 258). Estimates of the proportion of whales that were distinctive in reference encounters had posterior medians ranging from 0.68 to 0.86, resulting in an overall sampling distribution for the average proportion centered on 0.80 (95% HPDI = 0.64 to 0.92). After rescaling to include both distinct and nondistinct whales, the average annual population abundance estimate, *A*, had a posterior median of 300 (95% HPDI = 257-373).

## Social Organization

The social organization of Offshore Killer Whales is poorly known. They are often observed in very large aggregations as well as occasionally in small groups of less than five individuals. Because of the difficulty in accurately estimating the size of large groups of animals that are dispersed widely in the open ocean, it is preferable to use counts of photo-identified individuals as a measure of group size. However, because not all individuals were photo-identified in many encounters, counts from photo-identifications are likely to under-represent the actual group size, especially for large groups. With this caveat, the mean group size based on counts of named animals was 32 (median = 25), with a range of 2–104 individuals. This is greater than the typical group sizes seen in Resident Killer Whales (10–25 individuals; Ford et al. 2000) and considerably greater than in Transient Killer Whales (3–6 individuals; Ford et al. 2013). The frequency distribution of OKW group sizes is shown in Figure 16.

Both Resident and Transient Killer Whales typically live in groups of individuals that are related by maternal descent. The matrilineal structure of Resident and Transient Killer Whales has been determined from long-term studies of association patterns of individuals during encounters, either by photo-identification or visual observation (e.g., Bigg et al. 1990). Newborn whales travel alongside of their mother for the first year and maintain close physical proximity as long as they remain in the matriline. The basic social unit is the matriline, which is composed of two or more generations of individuals of both sexes that have descended from a matriarch (Bigg et al. 1990; Ford et al. 2000). There is no permanent dispersal of individuals from the natal matriline in Residents, but individuals may leave the natal group in Transients.

To examine the social structure of Offshore Killer Whales, we used a similar approach as was done with Residents and Transients. To determine which individuals tend to travel together, we calculated pairwise associations between all OKW animals using the simple ratio index (SR; Ginsberg & Young 1992):

$$SR = \frac{x}{x + Y_A + Y_B}$$

where x = number of times A and B were sighted together, $Y_A$ = number of times A was seen without B, and $Y_B$ = number of times B was seen without A.

Animals recorded in fewer than five encounters were eliminated from this analysis in order to minimize inaccurate association values (Whitehead 2008). Animals were considered associated when they were seen in the same encounter. Taking into account the average gregariousness of the population, a critical association value was calculated, under which association values could be explained by a randomly associating society and above which pairings could be considered “preferred” (Whitehead 1995). Animals that were shown to have at least one preferred companion were then examined using social networking (NetDraw version 2.123; Borgatti 2002). This, in combination with observations of proximity of animal pairs/groupings during encounters and age estimates, allowed derivation of potential kin units. To examine larger-scale population structure, we conducted hierarchical cluster analysis of the preferred companion dataset using SOCPROG software (compiled version 2.4; Whitehead 2009).

From the total dataset containing 355 named OKW individuals, we eliminated 169 individuals that were identified during five or fewer encounters. Associations among the remaining 186 animals were then analyzed using the SR index, which resulted in a social network depicted graphically in Figure 17. This suggests an extensive network of associations within the population, with widely varying strengths of association.

To better resolve potential structure within the social network, individuals without any associate having an SR index of 0.6 or greater were removed, which left 95 individuals that had at least one preferred companion. The resulting social network for this subset of the population is illustrated in Figure 18. This analysis reveals the existence of groupings that may be composed of kin-related individuals. However, because of the very dynamic nature of group composition and social associations within and between encounters and the difficulty in identifying young individuals, it is not clear whether any of these groupings represent matrilineal units as in Resident Killer Whales. It appears, however, that OKWs social organization lacks the stability seen in Resident and, to a lesser extent, Transient Killer Whales.

# RECOVERY POTENTIAL ASSESSMENT

The Terms of Reference for this Recovery Potential Assessment outlines 27 tasks to be addressed, given below (in italics). These are based largely on guidance provided in DFO (2007a and 2009). Unless otherwise specified, information provided in response to these tasks is drawn from the descriptions and analyses provided in the preceding sections of this document. The COSEWIC assessment and update status report for Killer Whales (COSEWIC 2008), DFO’s Management Plan for Offshore Killer Whales (Fisheries and Oceans Canada 2009), and relevant published literature are referenced as required. For additional details on threats to Killer Whales and their mitigation, the reader is referred to the Recovery Strategies for Resident Killer Whales (Fisheries and Oceans Canada 2011) and Transient Killer Whales (Fisheries and Oceans Canada 2007), as well as the Management Plan for OKWs (Fisheries and Oceans Canada 2009).

## ASSESS CURRENT/RECENT SPECIES/ STATUS

1. *Evaluate present status for* ***abundance and range and number of populations****.*

COSEWIC (2008) considered the Offshore Killer Whale population to comprise a single Designatable Unit (DU). The data used in our current assessment support this conclusion and indicate that the OKW population consists of a single network of socially-connected individuals that ranges over continental shelf and nearshore waters off the west coast of North America from southern California to the eastern Aleutian Islands, Alaska. The extent of potential movements outside of this range is unknown.

COSEWIC (2008) and the OKW Management Plan (Fisheries and Oceans Canada 2009) both used the CRP’s unpublished cumulative count of photo-identified individuals as a provisional estimate of population abundance. This estimate (288 unique individuals identified from encounters during 1988–2008) was crude as it did not take into account mortalities of named individuals over the time series or the proportion of animals that could not be reliably identified and named. In our current assessment, we have used a larger and improved photo-identification dataset incorporating data from numerous well-documented encounters with OKWs since 2008. We also have adopted a statistical modeling approach using a Bayesian mark-recapture framework to estimate abundance and population dynamics of OKWs from photo-identification data, which takes into account mortality and recruitment as well as the proportion of unnamed animals in the population. The current abundance of the OKW population is estimated to be 300 individuals (95% Highest Posterior Density Interval [HPDI] = 257-373).

2. *Evaluate* ***recent species trajectory*** *for abundance (i.e., numbers and biomass focusing on matures) and range and number of populations.*

Population modelling suggests that the OKW population is stable.

3. *Estimate, to the extent that information allows, the* ***current or recent life-history parameters*** *(total mortality, natural mortality, fecundity, maturity, recruitment, etc.) or reasonable surrogates; and associated uncertainties for all parameters.*

The recent annual survival rates are estimated to be 0.98 (95% HPDI = 0.92-0.99), with mortality balanced by per capita recruitment at an average rate of 0.02 (95% HPDI = 0-0.07). Life history parameters such as calving rate, age at maturity, longevity, etc., are not known for this population but may be similar to values determined for Resident Killer Whales (Olesiuk et al. 2005).

4. ***Estimate expected population and distribution targets for recovery****, according to DFO guidelines (DFO 2005).*

With no knowledge of historical population abundance or current carrying capacity of the habitats of Killer Whales, establishing quantitative recovery targets for the species in terms of abundance is difficult. Recovery Strategies for both Resident Killer Whale and Transient Killer Whales have recovery goals of ensuring their long-term viability through the maintenance of steady or increasing abundance and other population and distribution objectives (Fisheries and Oceans Canada 2007, 2011). As a result, the Management Plan for OKWs has as its goal:

> *To maintain a population level that is viable over the long-term within the known range for the northeastern Pacific Offshore Killer Whale population in Pacific waters of Canada*.

with the two main objectives over the 10 years after finalization of the plan being to:

> *Maintain the population at, or above its current level (averaged over 5 years)*

and

> *Maintain the population's current range of occupancy and distribution on the west coast of B.C.*

5. *Project* ***expected population trajectories*** *over three generations (or other biologically reasonable time), and trajectories over time to the recovery target (if possible to achieve), given current parameters for population dynamics and associated uncertainties using DFO guidelines on long-term projections.*

Given that the OKW population appears to have been stable over the time series covered by our photo-identification data, the expected population trajectory over three generations is the maintenance of its current abundance.

6. *Evaluate* ***residence requirements*** *for the species, if any.*

Cetaceans are highly mobile and generally do not have “residences” as defined in the Species at Risk Act. The OKW population ranges widely in both outer coast and inside waters off Canada’s west coast. There are no known residence requirements.

## ASSESS THE HABITAT USE

7. *Provide functional descriptions (as defined in DFO 2007a) of the* ***required properties of the aquatic habitat*** *for successful completion of all life-history stages.*

As with Resident and Transient Killer Whales, patterns of movement and habitat use of OKWs are expected to be driven by availability of prey. No specific habitats are likely to be used for particular life processes such as mating and calving.

It is reasonable to assume that the most important property of OKW habitat is the presence of sufficient prey resources to provide for profitable foraging. Although knowledge of the diet of OKWs in Canadian waters is limited, it appears to be dominated by elasmobranch fish, including Pacific Sleeper Shark, Blue Shark and Pacific Spiny Dogfish. Chinook Salmon and Pacific Halibut are also known to be consumed by OKWs, but the importance of these prey species is uncertain. The densities of prey species that are needed to meet the requirements of suitable habitat for OKWs are not known.

8. *Provide information on the **spatial extent of the areas that are likely to have these habitat properties**.*

The known prey species of OKWs are widely distributed in coastal and offshore waters off the Pacific coast of Canada. The Pacific Sleeper Shark is a relatively deep water species found mostly at depths of 150–450 m in continental shelf and slope waters (Hulbert et al. 2006; Courtney and Sigler 2007). Fishery bycatches off the BC coast indicate that the species occurs along the shelf break and in deep areas on the shelf such as Dixon Entrance and Moresby Trough in Hecate Strait (Figure 19). This species is also found in some inside passes and channels with particularly deep water. Blue Sharks are widely distributed throughout the North Pacific in coastal and epipelagic waters beyond the shelf slope. As with Sleeper Sharks, there is no directed fishery for Blue Sharks, but fishery bycatch in BC shows the species occurs in Hecate Strait, Dixon Entrance, along the continental shelf slope, and in oceanic waters (Figure 19). The Pacific Spiny Dogfish is found throughout nearshore and continental shelf waters off the BC coast, as well as in oceanic areas beyond the shelf (Figure 19).

9. *Identify the **activities most likely to threaten the habitat** properties that give the sites their value, and provide information on the extent and consequences of these activities.*

## Prey Availability

If high quality habitat is that which is used regularly for foraging (as is the case for Resident and Transient Killer Whales), reduction in availability of targeted prey species would reduce the value of such habitat. The primary means by which prey reduction could occur is through fisheries. Currently, there is no evidence that the abundance of the three shark species that dominate the known diet of OKWs has declined in recent years or is likely to in the foreseeable future. There is no directed fishery for either Pacific Sleeper Shark or Blue Shark in Canadian Pacific waters, but bycatch of these species does occur in trawl and longline fisheries and is monitored by DFO. Area-weighted CPUEs of Pacific Sleeper Sharks from bycatch monitoring in the Gulf of Alaska are either stable or increasing, depending on the area (Courtney and Sigler 2007). There are substantial fisheries bycatches for Blue Sharks in other regions of the North Pacific, but removals are estimated to be 74% of maximum sustainable yield (3.58 million sharks per year; Kleiber et al. 2009). Rates of removal through bycatch of Blue Sharks in Canadian Pacific waters are considered low at 20–40 tonnes per year (COSEWIC 2006). Recent stock assessments of the Pacific Spiny Dogfish in Canadian Pacific waters indicate that relative abundance is stable (King and McFarlane 2009; DFO 2010). In particular, the outside stock (continental shelf waters excluding the Strait of Georgia), which is likely to be consumed by OKWs, is healthy and fishing pressure is considered to be low relative to the estimated size of the population (Wallace et al. 2009).

## Underwater Noise

Given the apparent importance of underwater acoustics for communication and echolocation in Killer Whales, the acoustic environment is considered to be an important feature of critical habitat of Resident (Fisheries and Oceans Canada 2011) and potential critical habitat of Transient Killer Whales (Ford et al. 2013). Acoustics is no doubt an important feature of OKW habitat as well. The acoustic environment of OKW habitat can be affected by two main types of anthropogenic noise, acute and chronic, and these can affect habitats by masking vocalizations or natural ambient sounds that may be used for orientation, communication and echolocation, or by causing behavioural disturbance responses that result in disruption of life processes or avoidance of noisy areas. Acute noise sources include impulsive sounds generated in the mid to low frequency range, such as those produced during military tactical sonar use and seismic surveying, explosions, and construction-related activities such as pile driving. Chronic anthropogenic noise in the ocean is caused primarily by motorized vessels, but other sources such as offshore wind turbine arrays can also be significant in some regions. Mid-frequency tactical sonar used in navy operations has been observed to cause serious disturbance responses by Resident Killer Whales and the use of acoustic deterrent devices at aquaculture sites has been linked to displacement of Resident Killer Whales from their habitat (Fisheries and Oceans Canada 2009). Potential effects of chronic noise on Killer Whales are not well understood. Increased vessel noise has shown to be associated with the use of higher amplitude vocalizations in Resident Killer Whales, and there is some evidence of reduced foraging efficiency in high-noise habitats (Holt et al. 2012). Noise from increased shipping in the world's oceans has increased ambient noise levels by as much as 12 dB in recent decades (Hildebrand 2009). Shipping activity in some areas off the coast of British Columbia is significant and likely to increase. Noise levels are estimated to be particularly high off southwestern Vancouver Island due to cargo vessels transiting between the entrance to Juan de Fuca Strait and Asia (Erbe et al. 2012). This area is potentially important feeding habitat for OKWs. Underwater noise could also affect OKWs indirectly through effects on their prey. Sharks are sensitive to low frequency sounds (Myrberg 2001) and it is possible that changes in shark behaviour or distribution could result from loud anthropogenic noise

## Chemical and Biological Contamination

Degradation of water quality due to environmental contaminants poses a potentially significant threat to OKWs, their prey and habitat. The types of contaminants and the pathways by which they may enter Killer Whale habitat and prey, and the potential effects on the health and survival of Killer Whales are discussed in detail in Fisheries and Oceans Canada (2007, 2011). Potential contaminants include persistent organic pollutants (POPs) such as PCBs (polychlorinated biphenyls) and PBDEs (polybrominated diphenylethers), dioxins and furans, heavy metals, and DDT. Krahn et al. (2007) provided evidence that levels of PBDEs and DDT were particularly high in OKWs, and suggested that this may be attributable to the presence in coastal California waters, where these chemicals enter the marine environment through agricultural run-off. As high trophic level predators, sharks are particularly susceptible to bioaccumulation and biomagnification of pollutants due to the high lipid content of their liver and their long life span. Levels of POPs and heavy metals such as mercury in shark tissue can exceed recommended levels for human consumption (Walker 2011). No assessment has yet been made on heavy metal concentrations in OKWs.

## Oil Spills

Oil spills have the potential to cause direct mortality to Killer Whales (Matkin et al. 2008), and a large-scale catastrophic spill would have the potential to render OKWs habitat areas un-inhabitable for an extended period of time. Although the chance of a major spill in outer coast, continental shelf waters is remote, should a spill take place in confined waters such as the narrow inlets and channels occasionally used by OKWs, immediate and acute effects on individuals could occur and the habitat could be seriously degraded. Because OKWs tend to travel in large aggregations, a significant portion of the population could be affected by a single large-scale spill. Currently there are development proposals in environmental review that, if approved, could result in a significant increase in oil tanker traffic in nearshore waters.

### Disturbance

Disturbance from the close physical proximity of vessels, particularly those involved with whale watching activities, is a major concern for Resident and Transient Killer Whales in nearshore waters (Fisheries and Oceans 2007, 2011). OKWs are usually encountered in areas outside the current range of most whale watching excursions, but may be an attraction during their visits to inside waters off eastern and southern Vancouver Island. Given the rarity of such visits, targeted vessel disturbance is a negligible concern at present.

10. *Quantify how the **biological function(s) that specific habitat feature(s) provide** to the species varies with the state or amount of the habitat, including carrying capacity limits, if any.*

As indicated in Task 7, the importance of various prey species in the diet of OKWs are not well known due to the small sample size of identified prey, and the densities of identified prey species that may be needed to support effective foraging in OKW habitat are unknown. For these reasons, estimating carry capacities of OKW habitat in Canadian waters is not feasible at present.

It can be reasonably assumed that OKWs would concentrate in areas where the density of their preferred prey is greatest to provide for the most profitable foraging. If the Pacific Sleeper Shark is a key prey species that influences the movements of OKWs, then it would be expected that deeper continental shelf and slope waters would be important foraging habitat, as catches per unit effort (CPUE) are highest in these areas (Figure 20). CPUE for Blue Sharks also tends to be significant in shelf break areas (Figure 21). Pacific Spiny Dogfish are widespread over continental shelf waters, with particularly high densities evident off southwest Vancouver Island, an area with relatively high rates of OKW encounters (Figure 22). This is known to be an exceptionally productive fishery area (McFarlane et al. 1997).

Additional field studies to better understand patterns of habitat use and feeding ecology of OKWs are needed.

11. *Quantify the **presence and extent of spatial configuration constraints**, if any, such as connectivity, barriers to access, etc.*

OKWs are highly mobile and there is no evidence that their use of potential habitats is constrained in any way.

12. *Provide advice on **how much habitat of various qualities / properties exists** at present.*

As indicated in Task 8, too little is known of the relative importance of different prey species in the diet of OKWs to quantify the extent of available habitat of various qualities. However, given the widespread occurrence of sharks off the BC coast, it could be qualitatively stated that considerable potential habitat for this population exists in Canadian waters.

13. *Provide advice on the **degree to which supply of suitable habitat meets the demands of the species** both at present, and when the species reaches biologically based recovery targets for abundance and range and number of populations.*

There is no evidence that the OKW population is habitat- or prey-limited, either over its total range or within Canadian waters. With a population of only some 300 animals and a range that encompasses the continental shelf waters for more than 5000 km of coastline, habitat limitation seems highly unlikely. Although the total available biomass of their elasmobranch prey is not known, the three species known to be consumed by OKWs – Pacific Sleeper Shark, Blue Shark and Pacific Spiny Dogfish – are widespread and abundant, and there is no indication of any decline in the abundance of these species (see Task 9). However, no data are available on abundance trends for Pacific Sleeper Sharks and Blue Sharks in Canadian waters. These species may be of particular importance to OKWs. If OKWs forage preferentially for large elasmobranchs, it is possible that Basking Sharks (*Cetorhinus maximus*) represented an important food source in the past. Basking Sharks were once abundant in the range of OKWs including Canadian Pacific waters, but decades of exploitation, intentional culling and bycatch mortality in net fisheries almost extirpated them from the region and they remain extremely rare today (COSEWIC 2007).

14. *Provide advice on **feasibility of restoring habitat to higher values**, if supply may not meet demand by the time recovery targets would be reached, in the context of all available options for achieving recovery targets for population size and range.*

There is no evidence that habitat of OKWs has been reduced in quantity or quality by anthropogenic activities such as fisheries. Some habitat areas such as offshore of southwest Vancouver Island likely have higher levels of anthropogenic ambient noise due to shipping than was the case in past decades (Erbe et al. 2012), but it is not known if such levels are sufficient to cause functional habitat degradation. Hence, restoration of habitat does not appear to be required for recovery.

15. *Provide advice on **risks associated with habitat "allocation" decisions**, if any options would be available at the time when specific areas are designated as critical habitat.*

Potential critical habitat for OKWs in Canadian waters cannot yet be identified given the current lack of information on seasonal distribution in outer coast waters and the prey resources that may determine habitat quality. The data on seasonal distribution are currently seriously biased by temporal and spatial heterogeneity in effort, as are data on the spatial densities of known prey species. Further studies are needed to better define areas of potentially critical habitat and the functions, features and attributes that support them.

16. *Provide advice on the **extent to which various threats can alter the quality and/or quantity of habitat** that is available.*

Information relevant to this request is provided in Task 9, above.

## SCOPE FOR MANAGEMENT TO FACILITATE RECOVERY

17. *Assess the **probability that the recovery targets can be achieved** under current rates of parameters for population dynamics, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.*

The current goal of the Management Plan for OKWs is to "maintain a population level that is viable over the long-term", with a key objective being to "maintain the population at, or above its current level (averaged over 5 years)" (Fisheries and Oceans Canada 2009). The population abundance of OKWs appears to be stable, with mortalities and recruitment balancing each other over the last decade at least. Thus, a recovery target of a stable or increasing population is likely achievable in future years unless the population enters a period of decreased survival or recruitment. Factors affecting the population dynamics of OKWs are too poorly known to estimate the probability of such a change taking place. Killer Whales have no natural predators and their populations are likely to be regulated ultimately by bottom-up trophic forcing through food limitation unless they experience other sources of direct anthropogenic mortality. There is evidence from Resident Killer Whales that prolonged periods of reduced availability of important prey can be associated with significantly reduced survival and population decline (Ford et al. 2010).

Killer Whales have a long period of maturation before reaching reproductive age, have a long calving interval, and significant neonate mortality rates, thus, typically, they have a relatively low potential population growth rate of 2–3% (Olesiuk et al. 2005; Matkin et al., in press). Most Killer Whale populations in coastal waters of the eastern North Pacific are currently slowly increasing in abundance, including West Coast Transients (Ford et al. 2007, 2013), Northern Residents (Ellis et al. 2011), and southern Alaska Residents (Matkin et al., in press). There are several potential reasons for these increases, including recovery from historical depletion due to directed shooting and live captures, and increased food availability. It is not clear why the OKW population is remaining stable rather than showing an increasing trend. Food limitation is unlikely to be a factor since their apparently important prey species (sharks) are abundant in their range, and there are no known cases of direct anthropogenic mortality (see Task 18). However, potential biological removal (PBR) for this population is small (see Task 27), so even a few undetected mortalities could be limiting population growth.

18. *Quantify to the extent possible the **magnitude of each major potential source of mortality** identified in the pre-COSEWIC assessment, the COSEWIC Status Report, information from DFO sectors, and other sources.*

Potential natural limiting factors for OKWs are poorly known. As killer whales have no natural predators, populations are likely to be limited ultimately by food availability. The abundance of the OKW population is small enough so that inbreeding could potentially be an issue affecting fitness, but it is likely that OKWs have outbreeding mechanisms that mitigate this risk as in other killer whale populations (Barrett-Lennard 2000; M. Ford et al. 2011b). Severe tooth wear is ubiquitous among adult OKWs but it is not certain if this is a potential factor affecting survival or longevity. Mass strandings are a potential source of mortality for Offshore Killer Whales. A mass stranding of 20 OKWs took place at Estevan Point, west coast of Vancouver Island, in 1945 (Carl 1946; Ford et al. 2011a), and another involving 11 probable OKWs (based on photos of tooth wear) took place near Masset, Haida Gwaii, in 1941 (Cameron 1941; CRP unpubl. data). Mass strandings of Killer Whales are extremely rare and none are known to have involved Resident or Transient Killer Whales (Barbieri et al., 2013). The causes of these mass strandings are unknown but there is no evidence to implicate human activities.

Entrapment is another potential source of natural mortality for Offshore Killer Whales. In 1994, nine OKWs were trapped in semi-tidal Barnes Lake, southeastern Alaska, for at least six and possibly up to ten weeks, resulting in the mortality of two mature animals. The seven surviving individuals were driven out of the lake using devices that generated intense sounds to scare the whales (Bain 1995).

Potential sources of mortality from human causes to Killer Whales generally are described in COSEWIC (2008) and Fisheries and Oceans Canada (2007, 2011), and to OKWs specifically in Fisheries and Oceans Canada (2009). These include vessel strikes, interactions with fisheries (e.g., entanglement in fishing gear), oil spills, and direct killing. Of these potential sources, none have been shown to be the cause of any documented mortalities to OKWs. There is one case of a non-lethal injury to an OKW individual through a likely vessel propeller strike, which severed the dorsal fin (CRP unpubl. data).

19. *Quantify to the extent possible the **likelihood that the current quantity and quality of habitat is sufficient** to allow population increase, and would be sufficient to support a*

*population that has reached its recovery targets.*

Information relevant to this request is provided in Task 13, above.

20. *Assess to the extent possible the* ***magnitude by which current threats to habitats have reduced habitat quantity and quality****.*

As indicated in Task 14, above, there is no evidence that habitat of OKWs has been significantly reduced in quantity or quality by anthropogenic activities.

## SCENARIOS FOR MITIGATION AND ALTERNATIVES TO ACTIVITIES

21. *Using input from all DFO sectors and other sources as appropriate develop an* ***inventory of all feasible measures to minimize/mitigate the impacts of activities*** *that are threats to the species and its habitat (steps 18 and 20).*

### Prey Depletion

There is currently no directed fishery for two of the three shark species – Pacific Sleeper Shark and Blue Shark – that comprise the majority of known OKW prey. However, these two species are taken as bycatch in groundfish longline and trawl fisheries, although the numbers taken are considered low relative to their abundance (COSEWIC 2007; J. King, PBS, pers. comm.). The CPUE of bycatch is monitored but no analyses have been undertaken to determine whether trends in bycatch exist. Should such an analysis be undertaken and it shows a declining trend in CPUE, then management actions could be taken should a decline suggest depletion of these populations.

Historically, there have been major fisheries for Pacific Spiny Dogfish in Canadian Pacific waters to supply shark livers for Vitamin A production. Currently there is only a relatively small food fishery for this species. There is no immediate conservation concern for stocks of Pacific Spiny Dogfish in Canadian Pacific water based on current levels of removals (DFO 2010). The stock status of the species is regularly assessed by DFO Science to ensure management of fisheries at sustainable levels.

Two other OKW prey species documented in Canadian Pacific waters, Chinook Salmon and Pacific Halibut, are managed through DFO’s Integrated Fisheries Management Plans for these species.

### Underwater Noise

#### Military sonar

The Department of National Defence (DND) has established protocols to protect marine mammals from disturbance and/or harm from the use of military active sonar and deployment of ordnance. Maritime Command Order 46-13, for marine mammal mitigation, is to avoid transmission of sonar any time a marine mammal is observed within the defined mitigation avoidance zone, which is established specific to each type of sonar. Ship’s personnel receive training in marine mammal identification and detection. All foreign vessels are subject to Canadian regulations while in Canadian waters (D. Freeman, DND, pers. comm.). There remains some concern regarding compliance by foreign vessels with Canadian regulations and the effectiveness of these mitigation protocols.

#### Seismic testing

There are currently few industrial or scientific seismic surveys conducted in western Canadian waters. Some projects involving seismic surveying trigger screening under the Canadian Environmental Assessment Act (CEAA), while others are reviewed regionally by DFO. In 2005, DFO developed a draft Statement of Canadian Practice on the Mitigation of Seismic Noise in the Marine Environment (DFO 2007b), to address concerns regarding the potential impact of seismic use on marine mammals and other marine life. In the Pacific Region, each proposed seismic survey is reviewed by DFO marine mammal experts and mitigation measures are developed based on the species of concern in the area of the survey for each project. Seismic mitigation protocols recommended by DFO Pacific Region are designed to prevent exposure of cetaceans to received sound pressure levels in excess of 160 dB re 1 µPa, which is generally the level at which behavioural disturbance can be anticipated. A slow ramp-up of air gun pressure, or a 'soft start', is utilized to allow cetaceans to leave the area ensonified with intense sound. A safety zone corresponding to the estimated 160 dB re 1 µPa isopleth is established around the sound source, and a marine mammal observer monitors this zone while air guns are operating. If a cetacean enters the safety zone, air gun use is suspended until it has left the zone.

While many seismic projects are screened prior to commencement, it is not clear that all projects are assessed for impacts to marine mammals prior to initiation of seismic activity. Also, even with a sound exposure mitigation protocol, OKWs may be difficult to detect by observers in high sea states, at night or in fog, and thus may be unknowingly exposed to intense sound.

#### Construction noise

Mitigation protocols to prevent exposure of cetaceans to noise associated with construction activities such as dredging and pile driving in the Pacific Region are similar to those for seismic air guns.

#### Chronic noise

There is currently no mitigation of chronic noise in the marine environment that originates from shipping and other marine vessel traffic.

### Toxic Spills

The Transportation of Dangerous Goods Act regulates handling and transport of toxic substances within Canada, and numerous international, federal and provincial measures are in place for the prevention and management of toxic spills (e.g. Canadian/U.S. spill response plans for trans-boundary waters, Oil and Gas Operations Act, BC EMA). Despite such regulation and preventative measures, spills are frequent along the coast of British Columbia, but most are very small and localized and do not present a major risk to OKW habitat.

### Biological and Chemical Pollution

There are numerous national and international regulations and agreements that govern the manufacturing and application of many kinds of Persistent Bioaccumulating Toxins (PBTs), particularly the so-called legacy PBTs such as PCBs. The Stockholm Convention on persistent organic pollutants (POPs) and other UN Protocols aim to reduce global levels of legacy PBTs. Manufacture and availability of toxic chemicals in Canada are managed via listing under Schedule 1 of the CEPA and the BC Environmental Management Act (EMA) has regulations in place for management of contaminants in industrial and municipal effluents and outflows. The Fisheries Act (S. 36) prevents discharge of toxic substances into fish habitat(s), mitigating toxic threats to killer whale prey. In 2010, Environment Canada published a Final Revised Risk Management Strategy for Polybrominated Diphenyl Ethers, under the Canadian Environmental Protection Act (CEPA) (Environment Canada 2010). This strategy has provisions for controls of the forms of PBDEs that are known to bioaccumulate in killer whales.

Regulations on manufacture of chemicals and vectors of contamination (e.g. sewage outflows) manage toxins in runoff in British Columbia. The BC Ministry of Environment's storm-water planning, as well as non-governmental programs are in place for education on toxic runoff. For agriculture, the Fertilizers Act manages chemicals and the BC EMA Agricultural Waste Control regulation and Best Agricultural Waste Management Plans (BAWMPs) specifically manage industry practices.

### Disturbance

Disturbance from the proximity of vessels such as those engaged in whale watching is a minor concern for OKWs at present due to the rare and unpredictable occurrence in nearshore waters. The Fisheries Act Marine Mammal Regulations legally protects all marine mammals from disturbance and recently drafted amendments will establish legal approach distance thresholds to improve protection once implemented. The Species at Risk Act also legally protects listed species including OKWs from disturbance. The ‘Be Whale Wise: Marine Wildlife Guidelines for Boaters, Paddlers and Viewers’ guidance has a range of recommendations to mitigate potential impacts from small vessels.

### Fishery Interactions

Fishery interactions such as entanglement in gear or depredation of catches has not been documented in OKWs. Amendments to the Marine Mammal Regulations under the Fisheries Act will require mandatory reporting of fishery interactions by commercial fishers, including bycatch, entanglement and depredation.

22. *Using input from all DFO sectors and other sources as appropriate develop an **inventory of all reasonable alternatives to the activities** that are threats to the species and its habitat (steps 18 and 20).*

It is unlikely that there are feasible alternatives to the main activities that potentially threaten OKWs and their habitat.

23. *Using input from all DFO sectors and other sources as appropriate develop an **inventory of activities that could increase the productivity or survivorship parameters** (steps 3 and 17).*

There are no anthropogenic factors known to be affecting the productivity or survivorship of OKWs.

24. *Estimate, to the extent possible, the **reduction in mortality rate expected by each of the mitigation measures** in step 21 or alternatives in step 22 and the increase in productivity or survivorship associated with each measure in step 23.*

Due to the lack of documented anthropogenic mortality to OKWs, this task is not applicable.

25. *Project **expected population trajectory (and uncertainties) over three generations** (or other biologically reasonable time), and to the time of reaching recovery targets when recovery is feasible; given mortality rates and productivities associated with specific scenarios identified for exploration (as above). Include scenarios which provide as high a probability of survivorship and recovery as possible for biologically realistic parameter values.*

Given the stable population trajectory of OKWs at present, projections into the future are not warranted.

26. *Recommend **parameter values for population productivity and starting mortality rates**, and where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts of listing the species.*

Not applicable.

## ALLOWABLE HARM ASSESSMENT

*27. Evaluate **maximum human-induced mortality** which the species can sustain and not jeopardize survival or recovery of the species.*

Due to the small population size of OKWs, any human-induced mortality would be a cause for concern. In order to estimate the level of human-caused mortality that may be allowable without causing serious population-level consequences or prevent recovery, the U.S. National Marine Fisheries Service has devised a means of calculating the Potential Biological Removal (PBR) for marine mammal populations. PBR estimates the maximum number of animals, excluding natural mortality, that may be removed per year while still allowing the population to reach or sustain its 'optimum sustainable population' (Wade 1998). PBR is calculated as:

$$PBR = N_{\min} \times \frac{1}{2} R_{\max} \times F_R$$

where:

$N_{\min}$ = minimum population estimate (20th percentile of estimated population size; see formula below for its derivation)

$R_{\max}$ = maximum theoretical or estimated net productivity of the stock at a small population size (0.04 as recommended for cetaceans [Wade 1998] and suggested by recent growth rates of Alaskan Resident Killer Whales [Matkin et al. in press])

$F_R$ = recovery factor (0.1, based on population abundance, trend and vulnerability [Taylor et al. 2003])

To determine $N_{\min}$, we used the following formula from Wade (1998):

$$N_{\min} = \frac{\hat{N}}{\exp(z\sqrt{\ln(1 + CV(N)^2)})}$$

where:

$\hat{N}$ = point estimate of population size (300 individuals)

$z$ = standard normal variate (0.842 for the $20^{th}$ percentile)

$CV(N)$ = coefficient of variation for population estimate (0.1)

The minimum population estimate ($N_{\min}$) for the OKW population was calculated to be 276 animals. The recovery factor used in the PBR calculation was determined by the population's abundance, trend, and vulnerability to extinction as recommended by Taylor et al. (2003). Abundance is naturally low in killer whale populations and the estimated population size for OKWs appears to be larger than that of Northern Resident Killer Whales, suggesting that the population abundance is consistent with healthy killer whale populations in the region. However with no knowledge of the population's historical abundance or exploitation, as well as the large confidence interval of the population estimate and trend, caution must be applied when assessing this population's status. Due to the small population size, trend uncertainty and large gaps in time between sightings of the population, it is likely that a decline in population size below a critical level could occur before the decline is detected. Regarding the population’s vulnerability to extinction, there seems to be high genetic variability in the population (Morin et al. 2010). However the small population size and tendency for the population to travel in large groups means that potentially up to one-third of the entire population could be present in one location at a given time, making the population vulnerable to stochastic, catastrophic events such as a major oil spill. For these reasons, the recovery factor chosen was 0.1, resulting in a PBR of 0.55 animals. It is clear that the small OKW population could not sustain any human-induced mortality without endangering the stability of the population size and preventing recovery.

## ACKNOWLEDGEMENTS

We thank the many contributors of sightings, observations, recordings and identification photographs that have helped provide insight into the life history and ecology of Offshore Killer Whales. In particular, we are grateful for the efforts of Robin Abernethy, Ken Balcomb, Lance Barrett-Lennard, Nancy Black, Jim Borrowman, Randy Burke, John Calambokidis, Dave Ellifrit, Jason Feaver, Brian Gisborne, Kathy Heise, John Hildebrand, Mark Malleson, Bill Mackay, Craig Matkin, Hermann Meuter, Linda Nichol, Dan Olson, Eva Saulitis, Alisa Schulman-Janiger, Amalis Riera, Peter Schulze, Paul Spong, Helena Symonds, Jared Towers, and Janie Wray. We thank Jackie King, PBS, for providing data on shark bycatch off the west coast. Mike Wetklo and Ruth Withler of the Genetics Lab at PBS identified shark species from tissue samples, and Shayne MacLellan and colleagues with the Sclerochronology Lab at PBS identified salmonid samples. Robin Abernethy assisted with map production. We also thank Greg Schorr, Cascadia Research, for allowing us to use their data from satellite tracking of an OKW individual off the BC coast, and to Moe Flannery, California Academy of Sciences, for providing the photos of O319. This report benefitted from constructive comments by Lance Barrett-Lennard, Steve Ferguson, Jack Lawson and Sean MacConnachie.

## REFERENCES

Anthoni, U., C. Christophersen, L. Gram, N.H. Nielsen, and P. Nielsen. 1991. Poisonings from the flesh of the Greenland shark *Somniosus microcephalus* may be due to trimethylamine. Toxicon 29: 1205–1212.

Armstrong, R.H. 1996. Alaska's Fish: a guide to selected species. Alaska Northwest Books. 94 p.

Bagnis, R., F. Berglund, P.S. Elias, P.J. van Esch, B.W. Halstead, B.W., and K. Kojima. 1970. Problems of toxicants in marine food products. 1. Marine Biotoxins. Bull. WHO 42: 69–88.

Bain, D.E. 1995. The use of sound to guide killer whales (*Orcinus orca*) entrapped in Barnes Lake, Alaska, to open water. In 11th Biennial Conf. Biol. Mar. Mamm., 14–18 December 1995, Orlando, FL, 6 p.

Baird, R.W., and L.M. Dill. 1996. Ecological and social determinants of group size in transient killer whales. Behav. Ecol. 7: 408-416.

Bane, G.W. 1968. The great blue shark. California Currents. 1(1): 3-4.

Barbieri, M.M., S. Raverty, M.B. Hanson, S. Venn-Watson, J.K.B. Ford, and J.K. Gaydos. 2013. Spatial and temporal analysis of killer whale (*Orcinus orca*) strandings in the North Pacific Ocean and the benefits of a coordinated stranding response protocol. Mar. Mamm. Sci. 29(4): E448-E462.

Barrett-Lennard, L. G. 2000. Population structure and mating patterns of killer whales (*Orcinus orca*) as revealed by DNA analysis. Ph.D. dissertation, University of British Columbia, agVancouver, British Columbia, Canada. 97 p.

Barrett-Lennard, L.G., J.K.B. Ford, and K.A. Heise. 1996. The mixed blessing of echolocation: differences in sonar use by fish-eating and mammal-eating killer whales. Anim. Behav. 51: 553-565.

Beamish, R. J., G. A. McFarlane, K. R. Weir, M. S. Smith, J. R. Scarsbrook, A. J. Cass, and C.C. Wood. 1982. Observations on the biology of Pacific Hake, Walleye Pollock and Spiny Dogfish in the Strait of Georgia, Juan de Fuca Strait and off the west coast of Vancouver Island and United States, July 13-24, 1976. Can. Man. Rep. Fish. Aquat. Sci.1651: 150 p.

Bigg, M.A., G.M. Ellis, J.K.B. Ford, and K.C. Balcomb. 1987. Killer whales:  a study of their identification, genealogy, and natural history in British Columbia and Washington State. Phantom Press, Nanaimo, British Columbia.

Bigg, M.A., P.F. Olesiuk, G.M. Ellis, J.K.B. Ford, and K.C. Balcomb III. 1990. Social organization and genealogy of resident killer whales (*Orcinus orca*) in the coastal waters of British Columbia and Washington State. Rep. Int. Whal. Commn. Special Issue 12: 383-405.

Black, N.A., A. Schulman-Janiger, R.L. Ternullo, and M. Guerrero-Ruiz. 1997. Killer whales of California and western Mexico: a catalog of photo-identified individuals. NOAA-TM-NMFS-SWFSC-247.

Borgatti, S.P. 2002. NetDraw: Graph Visualization Software. Harvard: Analytic Technologies.

Bright, D.B. 1959. The occurrence and food of the sleeper shark, *Somniosus pacificus*, in a central Alaska bay. Copeia 1959: 76–77.

Brooks, S. P., and A. Gelman. 1998. General methods for monitoring convergence of iterative simulations. J. Comp. and Graphical Stat. 7: 434–455.

Carl, G.C. 1946. A school of killer whales stranded at Estevan Point, Vancouver Island. Rep. Prov. Mus. Nat. Hist. Anthropol. 1945: B21 – B28.

Coad, B.W., and J.D. Reist. 2004. An annotated list of the arctic marine fishes of Canada. Can. Man. Rep. Fish. Aquat. Sci. 2674: iv + 112 p.

Compagno, L.J.V. 1984. FAO Species Catalogue. Vol. 4. Sharks of the World. An annotated and illustrated catalogue of shark species known to date. Part 1 - Hexanchiformes to Lamniformes. FAO Fish. Synop. 125(4/1): 1-249. FAO, Rome.

Compagno, L.J.V., F. Krupp, and W. Schneider. 1995. Tiburones. p. 647-744. In W. Fischer, F. Krupp, W. Schneider, C. Sommer, K.E. Carpenter, and V. Niem (eds.). Guia FAO para Identificación de Especies para los Fines de la Pesca. Pacifico Centro-Oriental. 3 Vols. FAO, Rome.

COSEWIC  2006. COSEWIC assessment and status report on the blue shark *Prionace glauca* (Atlantic and Pacific populations) in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vii + 46 p. (Accessed 16 June, 2014).

COSEWIC  2007. COSEWIC assessment and status report on the basking shark *Cetorhinus maximus* (Pacific population ) in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vii + 34 p. (Accessed 16 June, 2014).

COSEWIC 2008. COSEWIC assessment and update status report on the Killer Whale *Orcinus orca,* Southern Resident population, Northern Resident population, West Coast Transient population, Offshore population and Northwest Atlantic / Eastern Arctic population, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. viii + 65 p. (Accessed 16 June, 2014).

Courtney, D.L., and M.F. Sigler. 2007. Trends in area-weighted CPUE of Pacific Sleeper Sharks *Somniosus pacificus* in the northeast Pacific Ocean determined from Sablefish longline surveys. Alaska Fish. Res. Bull. 12: 292-316.

Cox, G., and M. Francis. 1997. Sharks and Rays of New Zealand. Canterbury Univ. Press, Univ. of Canterbury. 68 p.

Dahlheim, M.E., D.K. Ellifrit and J. D. Swenson. 1997. Killer whales of southeast Alaska: A catalogue of photo-identified individuals. Day Moon Press, Seattle, WA.

Dahlheim, M.E., A. Schulman-Janiger, N. Black, R. Ternullo, D. Ellifrit and K.C. Balcomb. 2008. Eastern temperate North Pacific offshore killer whales (*Orcinus orca*): occurrence, movements, and insights into feeding ecology. Mar. Mamm. Sci 24: 719-729.

Deecke, V.B., J.K.B. Ford and P. Slater. 2005. The vocal behaviour of mammal-eating killer whales: communicating with costly calls. Anim. Behav. 69: 395-405.

DFO. 2007a. Documenting habitat use of species at risk and quantifying habitat quality. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/038.

DFO. 2007b. Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment. (Accessed 16 June, 2014).

DFO. 2009. Revised protocol for conducting recovery potential assessments. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/039.

DFO. 2010. Assessment of Spiny Dogfish (*Squalus acanthias*) in British Columbia in 2010. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/057.

Durban, J., D. Ellifrit, M. Dahlheim, J. Waite, C. Matkin, L. Barrett-Lennard, G. Ellis, R. Pitman, R. LeDuc, and P. Wade. 2010. Photographic mark-recapture analysis of clustered mammal-eating killer whales around the Aleutian Islands and Gulf of Alaska. Mar. Biol. 157: 1591-1604.

Ellis, G.M., J.R. Towers, and J.K.B Ford. 2011. Northern resident killer whales of British Columbia: Photo-identification catalogue and population status to 2010. Can. Tech. Rep. Fish. Aquat. Sci. 2942: v + 71 p.

Environment Canada 2010. Risk Management Strategy for Polybrominated Diphenyl Ethers (PBDEs). (Accessed 16 June, 2014).

Erbe, C., A. MacGillivray, and R. Williams. 2012. Mapping cumulative noise from shipping to inform marine spatial planning. J. Acoust. Soc. Am. 132(5): EL423-EL428.

Fargo, J., A.V. Tyler, and R.P. Foucher. 1990. Distribution of demersal fishes in Hecate Strait, British Columbia, based on systematic trawl surveys conducted from 1984-1987. Can. Tech. Rep. Fish. Aquat. Sci.1745: 115 p.

Fearnbach, H., J.W. Durban, K.M. Parsons, and D. Claridge. 2012 Photographic mark-recapture analysis of local dynamics within an open population of dolphins. Ecol. Appl. 22(5): 1689–1700.

Fedorov, V.V., I.A. Chereshnev, M.V. Nazarkin, A.V. Shestakov, and V.V. Volobuev. 2003. Catalog of marine and freshwater fishes of the northern part of the Sea of Okhotsk. Vladivostok: Dalnauka, 2003. 204 p.

Fisheries and Oceans Canada. 2007. Recovery Strategy for the Transient Killer Whale (*Orcinus orca*) in Canada. *Species at Risk Act* Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa: vi + 46 p.

Fisheries and Oceans Canada. 2009. Management Plan for the Offshore Killer Whale (*Orcinus orca*) in Canada. *Species at Risk Act* Management Plan Series. Fisheries and Oceans Canada, Ottawa: v + 49 p.

Fisheries and Oceans Canada. 2011. Recovery Strategy for the Northern and Southern Resident Killer Whales (*Orcinus orca*) in Canada. *Species at Risk Act* Recovery Strategy Series, Fisheries & Oceans Canada, Ottawa: ix + 80 p.

Ford, J.K.B. 1991. Vocal traditions among resident killer whales (*Orcinus orca*) in coastal waters of British Columbia. Can. J. Zool. 69: 1454-1483.

Ford, J.K.B., and G.M. Ellis. 1999. Transients: Mammal-Hunting Killer Whales. UBC Press, Vancouver, British Columbia. 96 p.

Ford, J.K.B., and G.M. Ellis. 2006. Selective foraging by fish-eating killer whales *Orcinus orca* in British Columbia. Mar. Ecol. Prog. Ser. 316: 185-199.

Ford, J.K.B., G.M. Ellis, and K.C. Balcomb. 2000. Killer Whales: The natural history and genealogy of *Orcinus orca* in British Columbia and Washington, Second edition. UBC Press and University of Washington Press, Vancouver, BC and Seattle, WA. 104 p.

Ford, J.K.B., G.M. Ellis, and J.W. Durban. 2007. An assessment of the potential for recovery of West Coast transient killer whales using coastal waters of British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/088. iv + 34 p.

Ford, J.K.B, G.M. Ellis, P.F. Olesiuk, and K.C. Balcomb. 2010. Linking killer whale survival and prey abundance: food limitation in the oceans' apex predator? Biol. Lett. 6: 139-142. Published on-line before print September 15, 2009.

Ford, J.K.B., G.M. Ellis, C.O. Matkin, M.H. Wetklo, L.G. Barrett-Lennard, and R.E. Withler. 2011a. Shark predation and tooth wear in a population of northeastern Pacific killer whales. Aquat. Biol. 11: 213-224.

Ford, J.K.B., G.M. Ellis, and L.M. Nichol. 1992. Killer whales of the Queen Charlotte Islands: a preliminary study of the abundance, distribution and population identity of *Orcinus orca* in the waters of Haida Gwaii. Prep. for: South Moresby/Gwaii Haanas National Park Reserve, Canadian Parks Service, by the Vancouver Aquarium. 69 p.

Ford, J.K.B., B. Koot, S. Vagle, N. Hall-Patch, and G. Kamitakahara. 2010. Passive acoustic monitoring of large whales in offshore waters of British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2898: v + 30 p.

Ford, J.K.B, E.H. Stredulinsky, J.R. Towers and G.M. Ellis. 2013. Information in Support of the Identification of Critical Habitat for Transient Killer Whales (*Orcinus orca*) off the West Coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/155: v + 46 p.

Ford, M. J., M. B. Hanson, J. A. Hempelmann, K. L. Ayres, C. K. Emmons, G. S. Schorr, R. W. Baird, K. C. Balcomb, S. K. Wasser, K. M. Parsons, and K. Balcomb-Bartok. 2011b. Inferred paternity and male reproductive success in a killer whale (*Orcinus orca*) population. Journal of Heredity 102(5): 537-553.

Forney, K. A., and P. Wade. 2006. Worldwide distribution and abundance of killer whales. Pages 145-162 *in* J. A. Estes, R. L. Brownell, Jr., D. P. DeMaster, D. F. Doak, and T. M. Williams (eds.). Whales, whaling and ocean ecosystems. University of California Press, Berkeley, California.

Gelman, A., X. Meng, and H. Stern. 1996. Posterior predictive assessment of model fitness via realized discrepancies. Statistica Sinica 6: 733-759.

Hart, J.L. 1973. Pacific Fishes of Canada. Bull. Fish. Res. Board Can. 180: 740 p.

Hayashi, K. 1983. Component glyceryl ethers in liver lipids of Spiny Dogfish and Japanese Cat Shark. Bull. Fac. Fish. Hokkaido Univ. 34(3): 250-259.

Health Canada. 2010. The Canadian Nutrient File Database. (Accessed 25 June, 2014).

Heise, K., L.G. Barrett-Lennard, E. Saulitis, C. Matkin and D. Bain. 2003. Examining the evidence for killer whale predation on Steller sea lions in British Columbia and Alaska. Aquat. Mamm. 29: 325-334.

Hildebrand, J.A. 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser. 395: 5-20.

Holt, M.M., D.P. Noren and C.K. Emmons. 2012. Does vessel noise affect the use of sound by foraging Orcinus orca (killer whales)? Pages 327-330 *in* N. Popper and A. Hawkins (eds.), The Effects of Noise on Aquatic Life, Adv. in Exp. Med. and Biol. 730, DOI 10.1007/978-1-4419-7311-5_73

Hulbert, L.B., M.F. Sigler, and C.R. Lunsford. 2006. Depth and movement behaviour of the Pacific sleeper shark in the north-east Pacific Ocean. J. Fish. Biol. 69: 406-425.

IPHC (International Pacific Halibut Commission). 1998. The Pacific Halibut: Biology, Fishery and Management. IPHC Technical Report No. 40. 64 p.

Krahn M.M., D.P. Herman, C.O. Matkin, J.W. Durban, L. Barrett-Lennard, D.G. Burrows, M.E. Dahlheim, N. Black, R.G. LeDuc and P.R. Wade. 2007. Use of chemical tracers in assessing the diet and foraging regions of eastern North Pacific killer whales. Mar. Env. Res. 63(2): 91-114.

Lim, E., B.W. Eakins, and R. Wigley. 2011. Coastal Relief Model of Southern Alaska: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-43. 22 p.

Loch, C., and P.C. Simoes-Lopes. 2013. Dental wear in dolphins (*Cetacea: Delphinidae*) from southern Brazil. Arch. Oral Biol. 58: 134-141.

Jones, I.M. 2006. A northeast Pacific offshore killer whale (*Orcinus orca*) feeding on a Pacific halibut (*Hippoglossus stenolepis*). Mar. Mamm. Sci 22: 198-200.

Ketchen, K.S. 1986. The Spiny Dogfish (*Squalus acanthias*) in the northeast Pacific and a history of its utilization. Canadian Special Publication of Fisheries and Aquatic Sciences. 88: 78 p.

King, J.R., and G.A. McFarlane. 2009. Trends in abundance of spiny dogfish in the Strait of Georgia, 1980–2005. Pages 89–100 *in* V.F. Gallucci, G.A. McFarlane, and G.G. Bargmann (eds.). Biology and management of spiny dogfish sharks. American Fisheries Society, Bethesda, Maryland.

Kleiber, P., S. Clarke, K. Bigelow, H. Nakano, M. McAllister, and Y. Takeuchi. 2009. North Pacific blue shark stock assessment. U.S. Dep. Commer., NOAA Tech. Memo., NOAA-TM-NMFS-PIFSC-17, 74 p.

Matkin, C.O., G.M. Ellis, E.L. Saulitis, L.G. Barrett-Lennard, and D.R. Matkin. 1999. Killer Whales of Southern Alaska. North Gulf Oceanic Society, Homer, Alaska.

Lunn, D. J., A. Thomas, N. Best, and D. Spiegelhalter. 2000. WinBUGS—a Bayesian modelling framework: concepts, structure and extensibility. Stati. and Comput. 10: 325–337.

Matkin, C.O., E.L. Saulitis, G.M. Ellis, P. Olesiuk, and S.D. Rice. 2008. Ongoing population-level impacts on killer whales *Orcinus orca* following the 'Exxon Valdez' oil spill in Prince William Sound, Alaska. Mar. Ecol. Prog. Ser. 356: 269-281.

Matkin, C.O., J.W. Testa, G.M. Ellis, and E.L. Saulitis. 2013.. Life history and population dynamics of southern Alaska resident killer whales (*Orcinus orca*). Mar. Mamm. Sci. 30: 460-479.

McFarlane, G.A., D.M. Ware, R.E. Thomson, D.L. Mackas, and C.L.K. Robinson. 1997. Physical, biological and fisheries oceanography of a large ecosystem (west coast of Vancouver Island) and implications for management. Oceanologica Acta 20: 191-200.

McMillan, P.J., M.P. Francis, G.D. James, L.J. Paul, P.J Marriott, E. Mackay, B.A. Wood, L.H. Griggs, H. Sui, and F. Wei. 2011. New Zealand Fishes. Volume 1: A field guide to common species caught by bottom and midwater fishing. New Zealand Aquatic Environment and Biodiversity Report No. 68. 329 p.

Morin, P.A., R.G. LeDuc, K.M. Robertson, N.M. Hedrick, W.F. Perrin, M. Etnier, P. Wade and B.L. Taylor. 2006. Genetic analysis of killer whale (*Orcinus orca*) historical bone and tooth samples to identify western U.S. ecotypes. Mar. Mamm. Sci. 22: 897-909.

Morin P.A., F.I. Archer, A.D. Foote, J. Vilstrup, E.E. Allen, P. Wade, J. Durban, K.L. Parsons, R.L. Pitman, L. Li, P. Bouffard, S.C. Abel Nielsen, M. Rasmussen, E. Willerslev, M.T.P. Gilbert, and T. Harkins. 2010. Complete mitochondrial genome phylogeographic analysis of killer whales (*Orcinus orca*) indicates multiple species. Genome Res. 20: 908-916.

Myrberg, Jr. A.A. 2001. The acoustical biology of elasmobranchs. Environmental Biology of Fishes, 60:31-45.

NOAA National Geophysical Data Center. U.S. Coastal Relief Model. (Accessed 16 June, 2014).

Oleson, E.M., J. Calambokidis, E. Falcone, G. Schorr, and J.A. Hildebrand. 2009. Acoustic and visual monitoring for cetaceans along the outer Washington coast. NPS-OC-09-001, Naval Postgraduate School, Monterey, CA.

Olesiuk, P.F., G.M. Ellis, and J.K.B. Ford. 2005. Life history and population dynamics of northern resident killer whales (*Orcinus orca*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2005/045: iv + 75 p.

Oliveira, A.C.M., P.J. Bechtel, A. Morey, K. Brenner, and T.J. Lapis. 2012. Chemical composition of Spiny Dogfish (*Squalus suckleyi*) harvested in Alaska. Journal of Food Processing and Preservation. DOI: 10.1111/jfpp.12008. 7 p.

Orlov, A.M. 1999. Capture of especially large sleeper shark *Somniosus pacificus* (Squalidae) with some notes on its ecology in northwestern Pacific. Journal of Ichthyology 39: 548-553.

Orsi, J.A., and A.C. Wertheimer. 1995. Marine vertical distribution of juvenile Chinook and coho salmon in southeastern Alaska. Trans. Am. Fish. Soc. 124: 159-169.

Perrin, W.F., and A.C.J. Myrick. 1980. Age determination of toothed whales and sirenians. Rep. Int. Whal. Commn. Spec. Issue. 3.

Pike, G.C., and I.B. MacAskie. 1969. Marine mammals of British Columbia. Bull. Fish. Res. Board Can. 71: 1–54.

Raschi, W., and C. Tabit. 1992. Functional aspects of placoid scales: a review and update. Aust. J. Mar. Freshw. Res. 43: 123–147.

Rice, D.W. 1968. Stomach contents and feeding behaviour of killer whales in the eastern North Pacific. Norsk Hvalfangst-Tidende 57: 35–38.

Riera, A. 2012. Patterns of seasonal occurrence of sympatric killer whale lineages in transboundary waters off Southern Vancouver Island and Washington state, as determined by passive acoustic monitoring. MSc thesis: School of Earth and Ocean Sciences, University of Victoria, BC.

Royle, J. A., and R. M. Dorazio. 2008. Hierarchical modeling and inference in ecology: the analysis of data from populations, metapopulations and communities. Academic Press, New York, NY.

Seber, G.A.F. 1982. The estimation of animal abundance and related parameters. 2nd Ed. Charles Griffin and Company Ltd., London.

Smith, C.L. 1997. National Audubon Society field guide to tropical marine fishes of the Caribbean, the Gulf of Mexico, Florida, the Bahamas, and Bermuda. Alfred A. Knopf, Inc., New York, NY. 720 p.

Taylor, B.L., M. Scott, J.E. Heyning, and J. Barlow. 2003. Suggested Guidelines for Recovery Factors for Endangered Marine Mammals under the Marine Mammal Protection Act. U.S. Dept. Commer., NOAA Tech. Memo. NMFS SWFSC-354, 6 p.

Terranova, R.J., C. Stillwell, and F.W. Steimle, Jr. 1980. Suggested Guidelines for Recovery Factors for Endangered Marine Mammals under the Marine Mammal Protection Act.. NOAA Rep. No. SHL 80-19. 9 p.

Towers, J.R., G.M. Ellis, and J.K.B. Ford. 2012. Photo-identification catalogue of Bigg's (Transient) killer whales form coastal waters of British Columbia, northern Washington, and southeastern Alaska. Can. Data Rep. of Fish. and Aquat. Sci. 1241: v + 127 p.

Tricas, T.C. 1977. Food habits, movements, and seasonal abundance of the blue shark, *Prionace glauca* (Carcharhinidae), in southern California waters. M.A. thesis: California State University, USA.

Vagle, S., J.K.B. Ford, N. Erickson, N. Hall-Patch, and G. Kamitakahara. 2004. Acoustic recording systems for baleen whales and killer whales on the west coast of Canada. Can. Acoustics. 32: 23-32.

Wade, P.R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. Mar. Mamm. Sci. 14: 1-37.

Walker, C.J. 2011. Assessing the effects of pollutant exposure on sharks: a biomarker approach. MSc thesis: University of Northern Florida, FL. Available: http://digitalcommons.unf.edu/etd/141

Wallace, S., G. McFarlane, S. Campana, and J.R. King. 2009. Status of spiny dogfish in Atlantic and Pacific Canada. Pages 313-334 *in* V.F. Gallucci, G.A. McFarlane, and G.G. Bargmann (eds.). Biology and management of spiny dogfish sharks. American Fisheries Society, Bethesda, Maryland.

Whitehead, H. 1995. Investigating structure and temporal scale in social organizations using identified individuals. Behav. Ecol. 6: 199–208.

Whitehead, H. 2008. Analyzing Animal Societies: Quantitative Methods for Vertebrate Social Analysis. University of Chicago Press, Chicago. 336 p.

Whitehead, H. 2009. SOCPROG programs: analyzing animal social structures. Behav. Ecol. and Sociobiol. 63: 765-778.

Yano, K., J.D. Stevens, and L.J.V. Compagno. 2004. A review of the systematics of the sleeper shark genus Somniosus with redescriptions of *Somniosus* (*Somniosus*) *antarcticus* and *Somniosus* (*Rhinoscymnus*) *longus* (Squaliformes: Somniosidae). Ichthyol. Res. 51: 360–373.

Zerbini, A.N., J.M. Waite, J.W. Durban, R. LeDuc, M.E. Dahlheim, and P.R. Wade. 2007. Estimating abundance of killer whales in the nearshore waters of the Gulf of Alaska and Aleutian Islands using line-transect sampling. Mar. Biol. 150: 1033-1045.

# TABLES

*Table 1. Number of days with acoustic detections of OKWs by month, from autonomous underwater recording instruments and real-time listening stations in Canadian Pacific waters. Autonomous instruments were deployed for durations of 6–12 months between 2006 and 2012. Locations of stations are shown in Figure 1. Monitoring effort, expressed by the number of times a given month has been monitored or recorded and analyzed, is shown by colour shades according to the legend below the table.*

| *Station* | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | *Total* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Langara Island AURAL | 1 |  | 6 | 2 |  | 1 | 1 |  |  | 1 |  | 1 | *13* |
| Langara Island OrcaBox |  |  | 1 |  |  |  |  |  |  | 1 |  |  | *2* |
| Hecate Strait WFG Stn[1] |  |  |  | 1 |  |  |  |  |  |  |  |  | *1* |
| Hecate Strait SC Stn[1] |  |  |  |  |  | 1 |  | 1 |  |  |  |  | *2* |
| Cape St. James AURAL |  |  |  |  |  |  |  |  |  |  |  | 1 | *1* |
| Gil Island area RTLS*[2] |  | 1 |  | 1 |  |  |  |  |  | 1 |  |  | *3* |
| Caamano Sound SM2M |  |  |  | 1 | 1 |  |  |  |  |  |  |  | *2* |
| Triangle Island AURAL |  |  |  |  |  |  |  | 2 |  |  |  |  | *2* |
| Union Seamount PATC2 |  |  |  |  |  |  |  |  |  |  |  |  | *0* |
| Hanson Island area RTLS[3] | 1 | 4 | 17 | 2 |  |  |  | 3 | 2 | 4 | 1 | 5 | *39* |
| Brooks Penin. AURAL |  |  | 2 |  |  |  |  |  |  |  |  | 1 | *3* |
| La Pérouse Bank PATC2 |  |  |  |  |  |  |  |  |  |  |  |  | *0* |
| Swiftsure Bank AURAL |  |  |  |  |  |  |  | 1 |  |  |  |  | *1* |
|  | *2* | *5* | *26* | *7* | *1* | *2* | *1* | *7* | *2* | *7* | *1* | *8* | *69* |

* RTLS = real-time listening stations. All other hydrophones listed are remote and analyzed after their recovery.

[1] Data courtesy of JASCO Naikun Project

[2] Data courtesy of NCCS/CetaceaLab

[3] Data courtesy of OrcaLab

Effort scale:

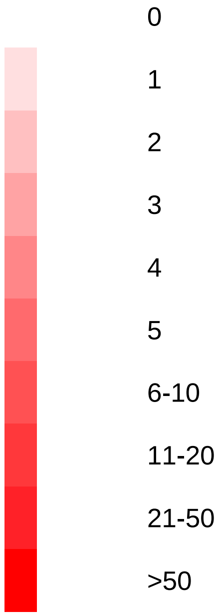

*Table 2. Euclidean distance to 200m, 500m and 1000m isobaths and water depth at locations of OKW encounters (N = 157 photographed encounters).*

| Encounter | Distance (km) to isobaths: | | | Depth (m) |
|---|---|---|---|---|
| | 1000m | 500m | 200m | |
| n | 157 | 157 | 157 | 157 |
| mean | 74 | 65 | 38 | 208 |
| min | 0.22 | 0.1 | 0.02 | 8 |
| max | 221 | 212 | 174 | 2170 |
| median | 69 | 53 | 22 | 122 |
| SD | 50 | 51 | 38 | 259 |
| SE | 5.8 | 6.3 | 6.2 | 18 |

*Table 3. Summary of OKW predation events with prey species identification from published and unpublished sources. No. is the number of individual prey items of each species documented in each stomach or encounter, and Method is the means by which the prey species was identified.*

| **Date** | **Location** | **Species** | **No.** | **Method** | **Source** |
|---|---|---|---|---|---|
| 19 May 1955 | West coast Vancouver I. | Pacific halibut | n/a | Stomach contents | Pike and MacAskie 1969; Ford et al. 2011a |
| 9 Jan 1964 | S California | Opah<br>Blue shark? | 2<br>2 | Stomach contents | Rice 1967; Morin et al. 2006 |
| 13 Oct 1994 | Barnes Lk, SEAK | Sculpin<br>Unid. salmonid | n/a<br>n/a | Stomach contents | Heise et al. 2003 |
| 11 Mar 1996 | Johnstone Strait | Pacific sleeper shark | 1 | Tissue (DNA) | CRP unpubl. |
| 30 May 2008 | Dixon Entrance | Pacific sleeper shark | 11 | Tissue (DNA) | Ford et al. 2011a |
| 13 Jun 2009 | Prince William Sd., AK | Pacific sleeper shark | 7 | Tissue (DNA) | Ford et al. 2011a |
| 22 Aug 2010 | La Perouse Bk, WCVI | Chinook salmon<br>Blue shark | 1<br>1 | Scales<br>Photo | CRP unpubl. |
| 30 Mar 2011 | Johnstone Strait | Pacific sleeper shark | 1 | Tissue (DNA) | CRP unpubl. |
| 8 Aug 2011 | Hecate Strait | Chinook salmon | 1 | Scales | CRP unpubl. |
| 18 Aug 2011 | SW Vancouver I. | Blue shark | 3 | Tissue (DNA) | CRP unpubl. |
| 5 Sep 2011 | SW Vancouver I. | Pacific Spiny dogfish | 1 | Tissue (DNA) | CRP unpubl. |
| 29 Jun 2012 | Resurrection Bay, AK | Pacific sleeper shark | 5 | Tissue (DNA) | CRP unpubl. |
| 7 Sep 2012 | SW Vancouver I. | Pacific Spiny dogfish | 7 | Tissue (DNA) | CRP unpubl. |
| 3 Mar 2013 | Hecate Strait | Chinook salmon | 1 | Scales | CRP unpubl. |

*Table 4. Seasonal migration patterns, depth distribution, and estimated energetic value of the known prey species of Offshore Killer Whales.*

| Prey species | Seasonal migration | Depth distribution | Tissue consumed | Estimated energetic value (kcal)[1] |
|---|---|---|---|---|
| Pacific sleeper shark | ▪ Unknown | ▪ Depth range: 0-2000m (Cox & Francis 1997); usually found between 150-450m (Hulbert et al. 2006)<br>▪ Found on continental shelves and slopes<br>▪ At high latitudes, occur in littoral and even intertidal areas; in lower latitudes it may never come to the surface and ranges down to at least 2000m (Compagno 1984; Orlov 1999)<br>▪ No consistent seasonal pattern for depth range; extensive diel vertical movements (Hulbert et al. 2006) | Liver<br>Due to size of animal & liver, probable toxicity of flesh, and field observations, it appears that only the liver is targeted.<br>Liver is approximately 20% of animal's body weight (Bright 1959) | 75200 [2] |
| Blue shark | ▪ Common off southern California most of the year, but during warm water periods occurs much further north.<br>▪ Immature sharks may exhibit seasonal migration, moving inshore each spring/summer (Tricas 1977)<br>▪ Females move northward in early summer (Bane 1968; Tricas 1977) | ▪ Depth range: 1-1000m (McMillan et al. 2011); usually between 80-220m (FMNH 2005); usually found to at least 150m (Smith 1997)<br>▪ Widespread in oceanic waters and over continental shelf; concentrations along shelf break (Last & Stevens 1994; Mundy 2005; COSEWIC 2006) | Whole<br>Uncertain as to whether the whole animal or just liver is consumed. Photographic evidence and stomach contents suggest that at least on some occasions the entire animal is consumed. | 67600 [3] |
| | | | Liver<br>Liver approximately 5% of total body weight (Terranova et al. 1980) | 15000 [4] |
| Pacific Spiny dogfish | ▪ Migrate seasonally as temperatures change.<br>▪ Most dogfish in Canadian waters move inshore in summer and offshore in winter (Fargo et al. 1990; Ketchen 1986)<br>▪ Some individuals may make latitudinal migration between Oregon in winter and northern BC in summer (Ketchen 1986)<br>▪ During summer & fall, preference for warmer, shallower shelf waters. | ▪ Usually near bottom, but also in midwater and at surface (Cox & Francis 1997)<br>▪ Depth range: 0-1460m (Cox & Francis 1997); occurs mainly between 10-200m depth (Compagno et al. 1995)<br>▪ Daily movements in water column from bottom during the day to the surface at night.<br>▪ Males generally found in shallower water than females, except for pregnant females that enter shallow bays to pup. Immature juveniles live near surface. Found in increasing depths with age (Beamish et al. 1982) | Whole<br>Due to small size of fish and low nutritional yield from liver, it seems too costly for OKWs to solely target dogfish liver. It is most likely that the entire animal is consumed. | 4600 [5] |
| | | | Liver | 1000 [6] |

| **Prey species** | **Seasonal migration** | **Depth distribution** | **Tissue consumed** | **Estimated energetic value (kcal)[1]** |
|---|---|---|---|---|
| Chinook salmon | ▪ Stream-type migrate to high seas returning only to spawn at age 4-5; ocean-type remain on continental shelf year-round. | ▪ Depth range: 0-375m (Coad & Reist 2004)<br>▪ Size significantly increases with depth – for juveniles (Orsi & Wertheimer 1995) | Whole | 14000 [7] |
| Pacific halibut | ▪ From November to March, mature halibut concentrate annually on spawning grounds along edge of continental shelf at depths from 600 to 1500 ft. (IPHC 1998)<br>▪ Older individuals typically move from deeper water along the edge of the continental shelf in winter, to shallow coastal water (30-275m) in summer (Armstrong 1996) | ▪ Depth range: 0-1200m (Fedorov et al. 2003)<br>▪ Juveniles found near shore and move out to deeper waters as they grow older (Hart 1973) | Whole | 8500 [8] |

[1] Approximate average weight of consumed tissue and nutritional value (kcal/kg) of the tissue

[2] Approximate liver weight of median sized Pacific sleeper shark (Hulbert et al. 2006; Bright 1959). As no caloric data exist for Pacific sleeper shark liver, the value of blue shark liver was used for this calculation.

[3] Average body weight from Terranova et al. (1980). No caloric data available, therefore dogfish caloric data used.

[4] Average caloric values and liver weights from Terranova et al. (1980).

[5] Ketchen (1986) liver to body weight conversion, as well as caloric data from Canadian Nutrient File (Health Canada 2010).

[6] Weights from Hayashi (1983) and caloric data from Oliveira et al. (2012) and Smith (2011).

[7] Using O'Neill et al. (cited in Ford et al. 2010) fork length-caloric regression and age-structure breakdown of Resident Killer Whale prey samples

[8] IHPC length/weight regression and length derived from the only OKW halibut predation event where there is indication of length (Jones 2006). Nutritional data from Canadian Nutrient File (Health Canada 2010).

# FIGURES

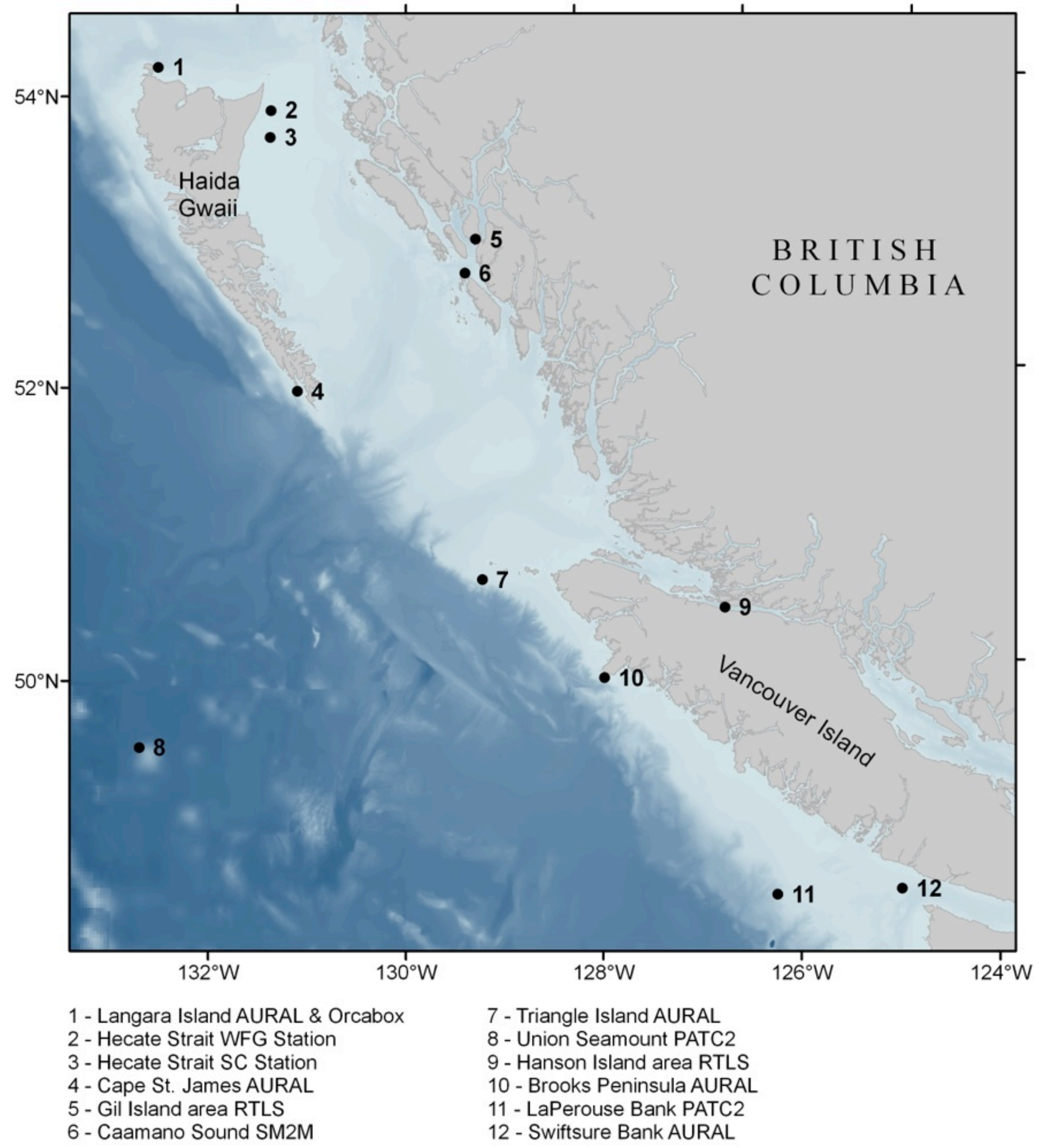

*Figure 1. Map of locations of autonomous recording instruments and fixed real-time hydrophone networks used for passive acoustic monitoring of Offshore Killer Whales. (see Table 1).*

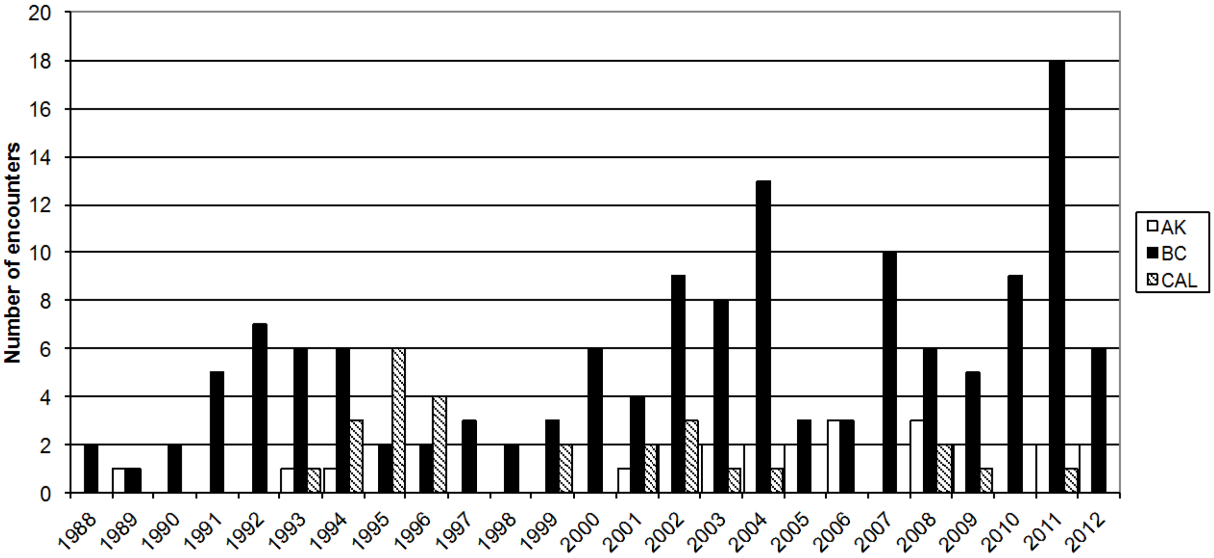

*Figure 2. OKW encounters by year, separated by region (AK = Alaska, BC = British Columbia, and CAL = California). N = 192 (121 photo, 40 acoustic and 31 photo/acoustic).*

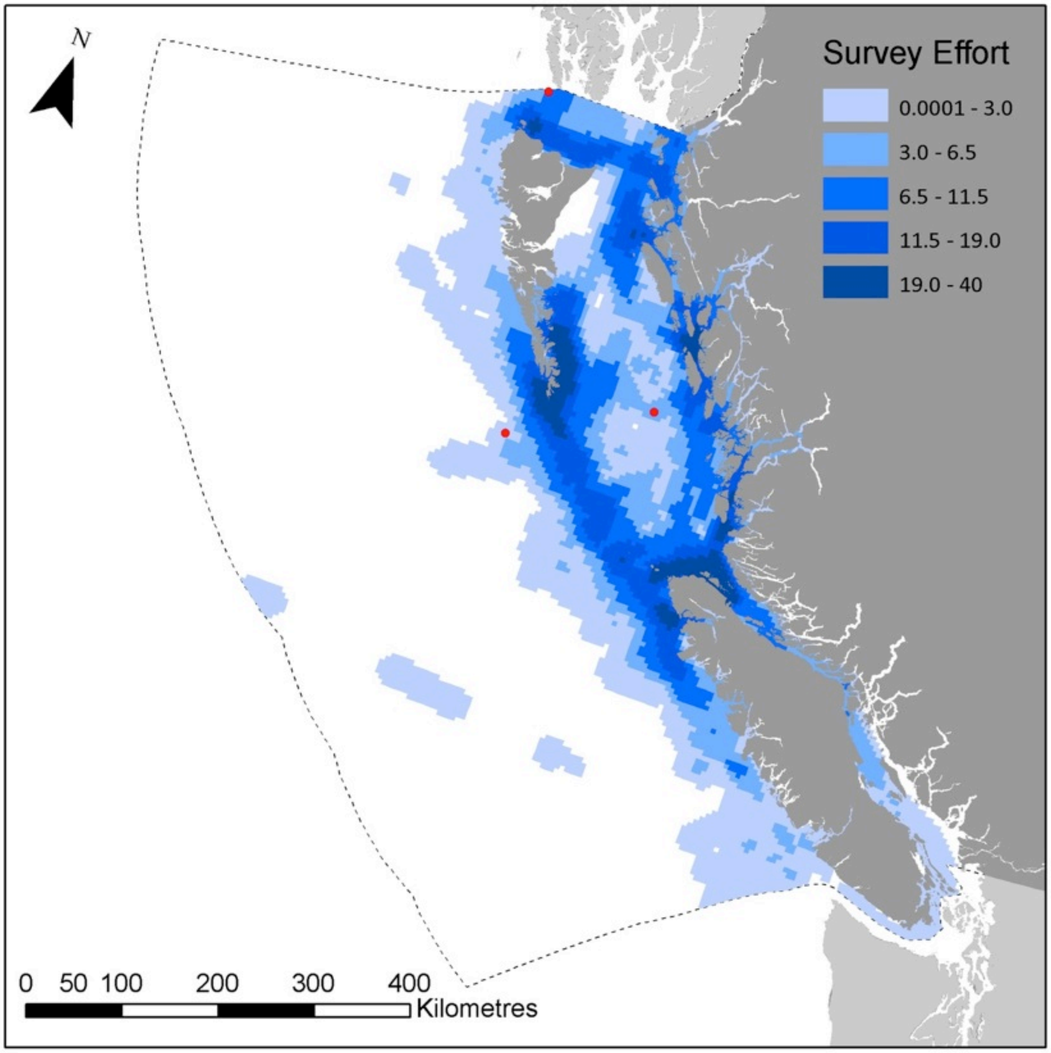

*Figure 3. Vessel survey effort during Cetacean Research Program research cruises, 2002–2011, and locations of OKW sightings on those surveys (red dots; n = 3). Effort is shown according to a grid of 25 km² cells (5 x 5 km), with blue shading representing an index based on the number of times each cell was surveyed.*

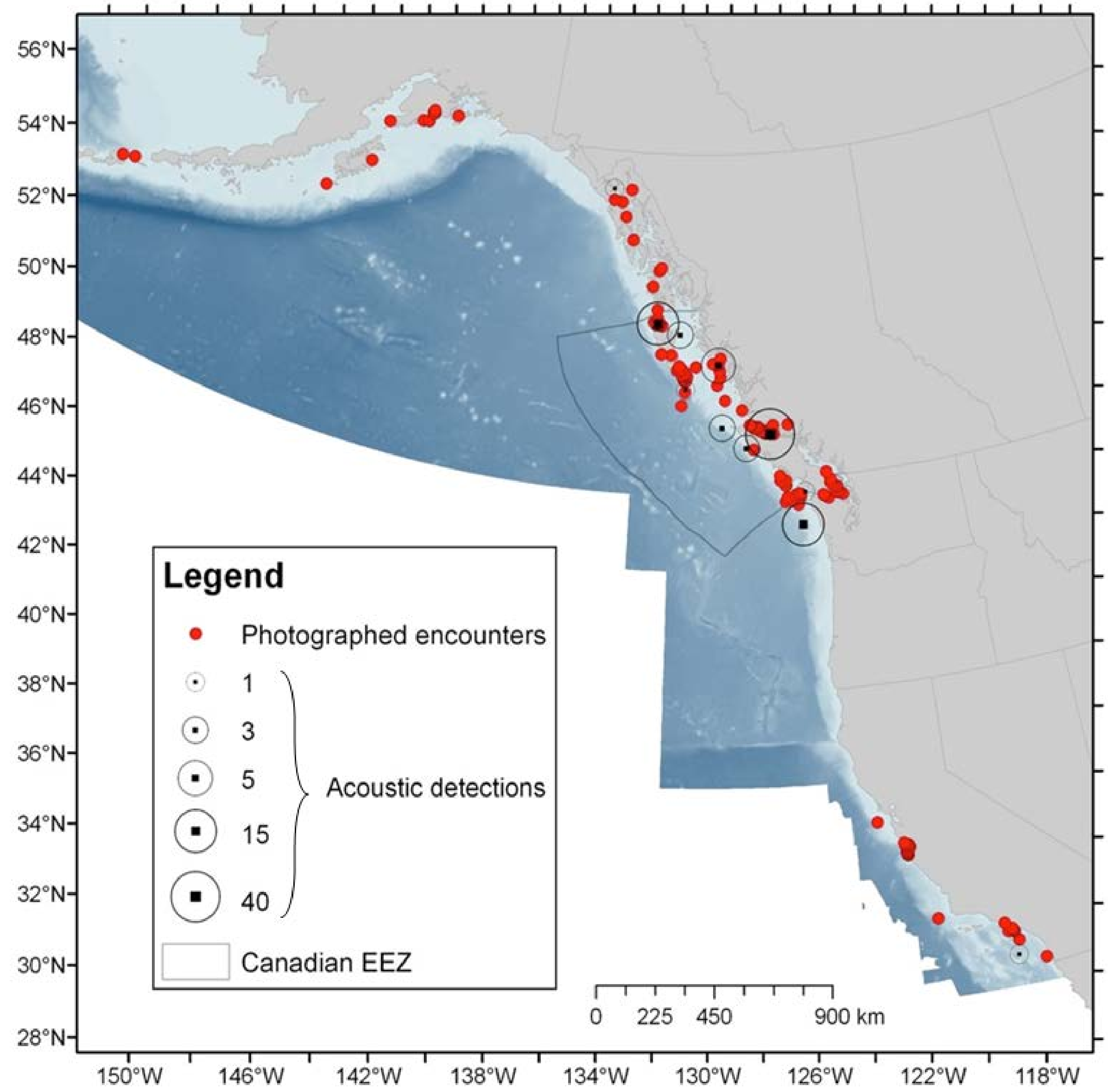

*Figure 4. Distribution of encounters with OKWs (red dots; 1988–2012) and numbers of days in which OKWs were detected acoustically at fixed monitoring sites (open circles; 2006–2012). Relative water depths are shown with shades of blue with the continental shelf and sea mounts being the lightest. N = 157 photographed encounters and 83 acoustic detections.*

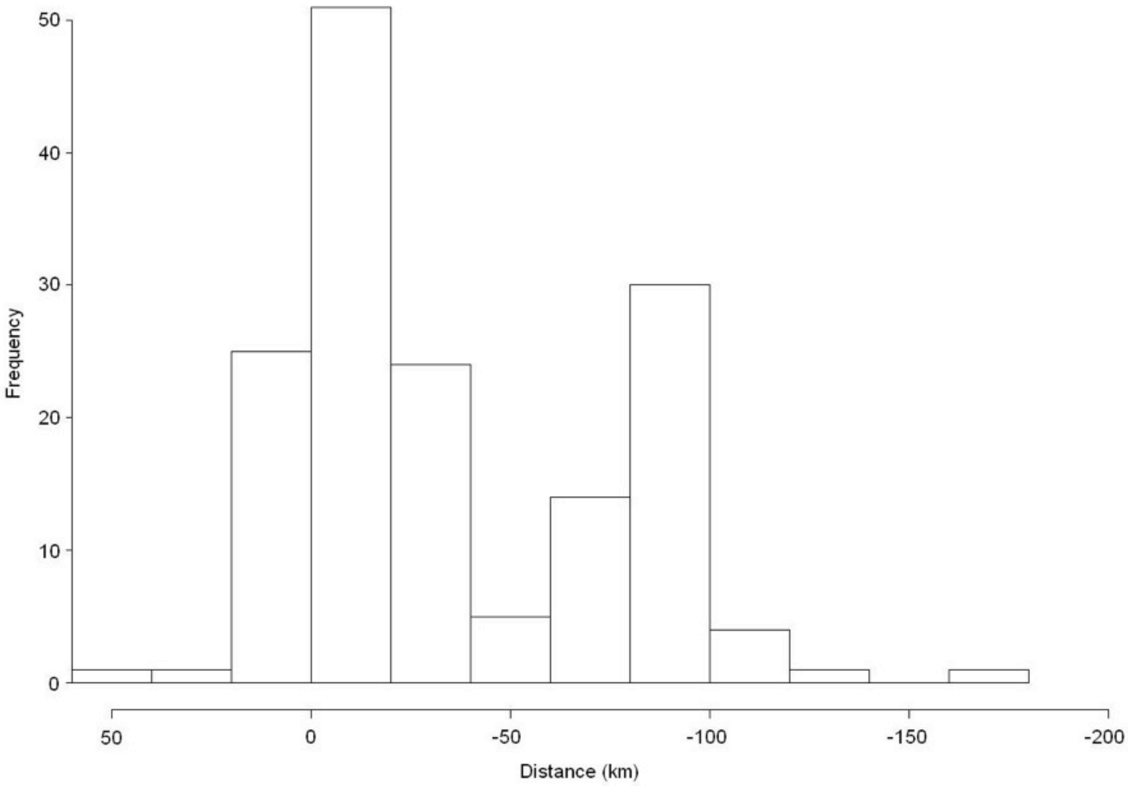

*Figure 5. Frequency distribution of OKW encounters with respect to distance from the 200 m isobaths near the continental shelf break. Negative values indicate distance inshore of isobath. Positive values indicate distance offshore of isobath. N = 157 photographed encounters.*

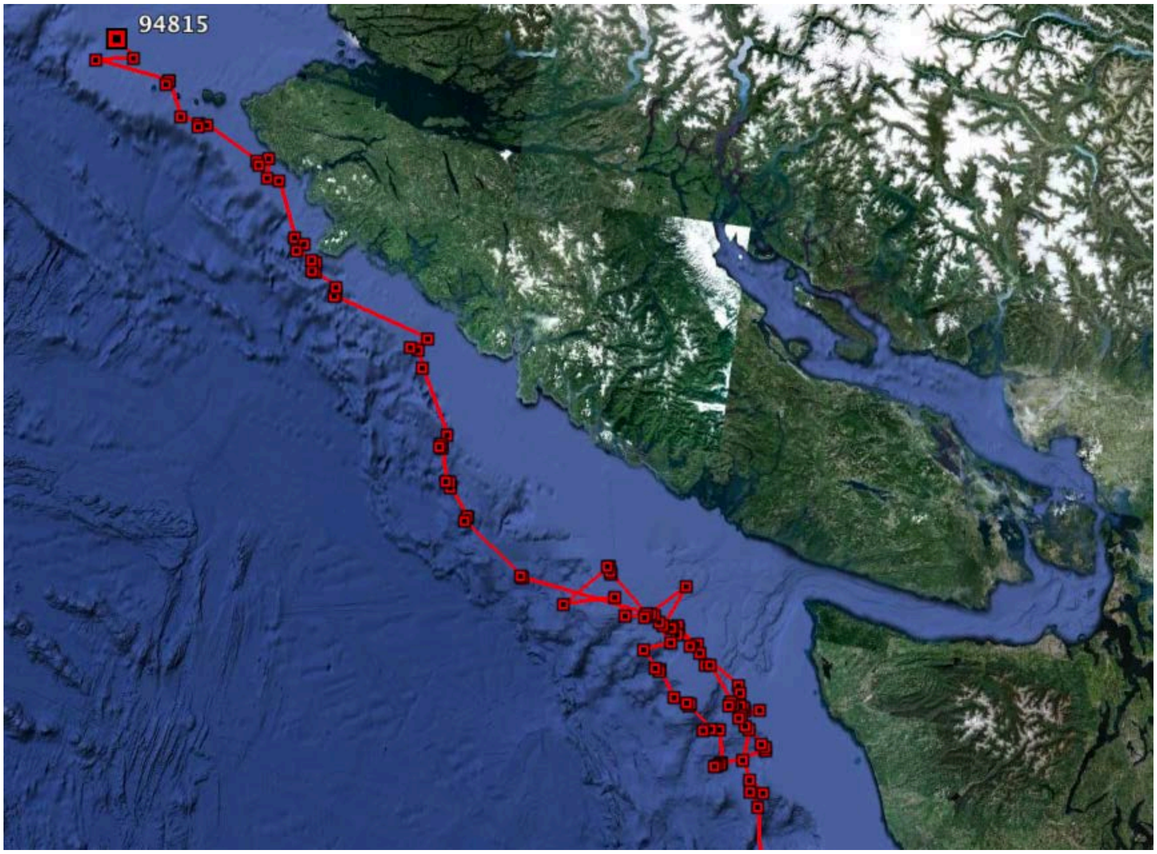

*Figure 6. Track of a satellite-tagged Offshore Killer Whale as it travelled northwards off Vancouver Island, 24 February to 2 March, 2013. This individual was encountered in a group of more than 50 OKWs on 3 March in Hecate Strait by a CRP research survey. Data provided courtesy of G. Schorr, Cascadia Research (Olympia, WA).*

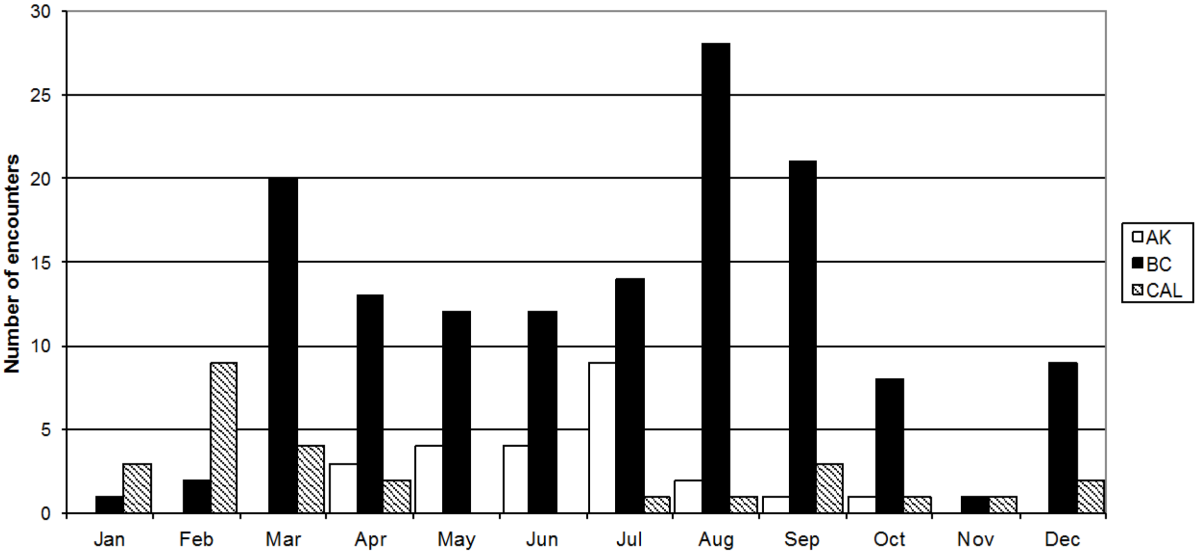

*Figure 7. Frequency of OKW encounters by month, for Alaska, BC, and California. N = 192 (121 photo, 40 acoustic and 31 photo/acoustic).*

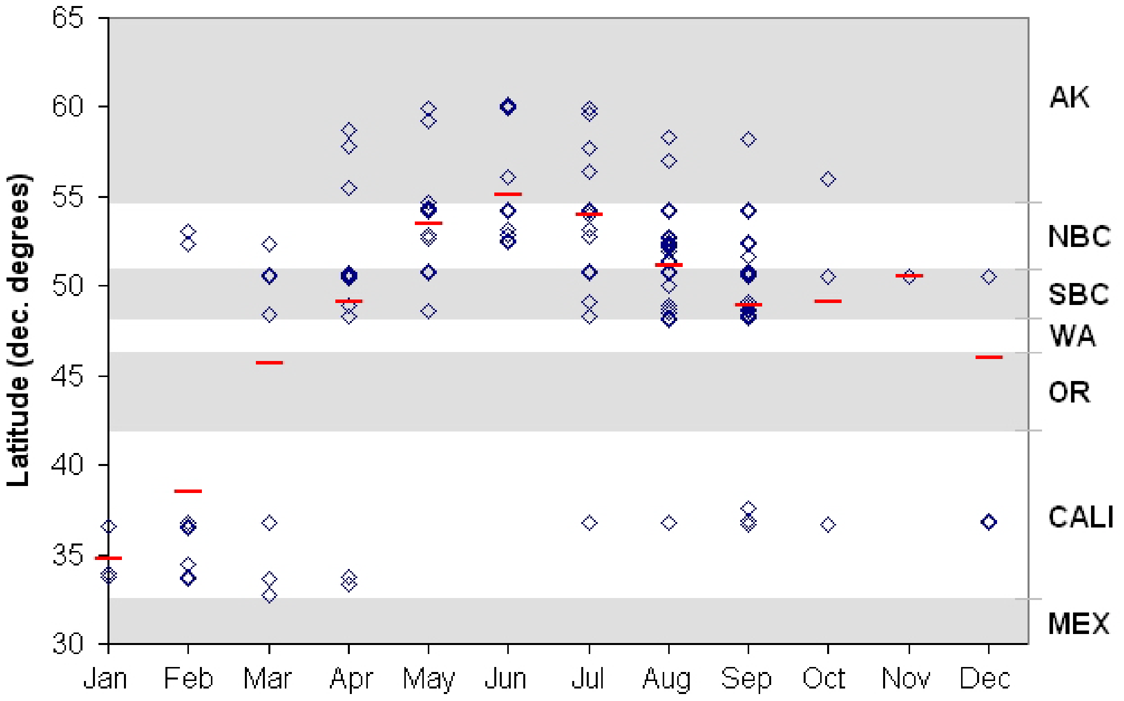

*Figure 8. Latitude of OKW encounter locations by month. The red bar indicates the mean latitude for each month. N = 157 photographed encounters.*

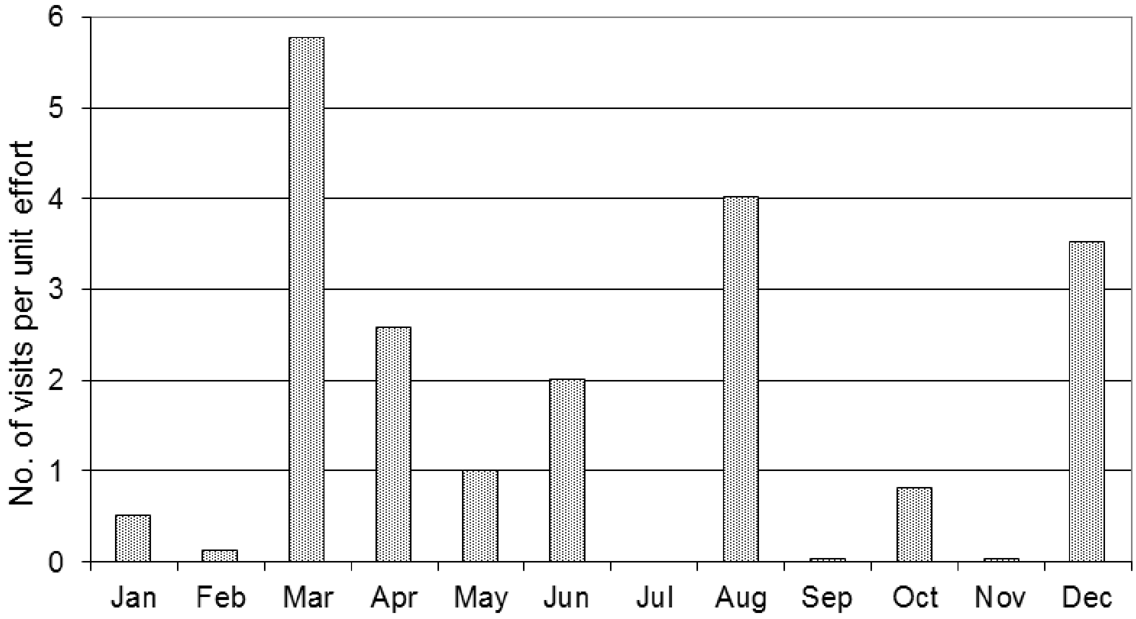

*Figure 9. Number of "visits" by OKWs per unit effort at acoustic monitoring stations by month in BC waters. A "visit" includes all detections at a station within a 7-day period and effort is the total number of times each month was monitored.*

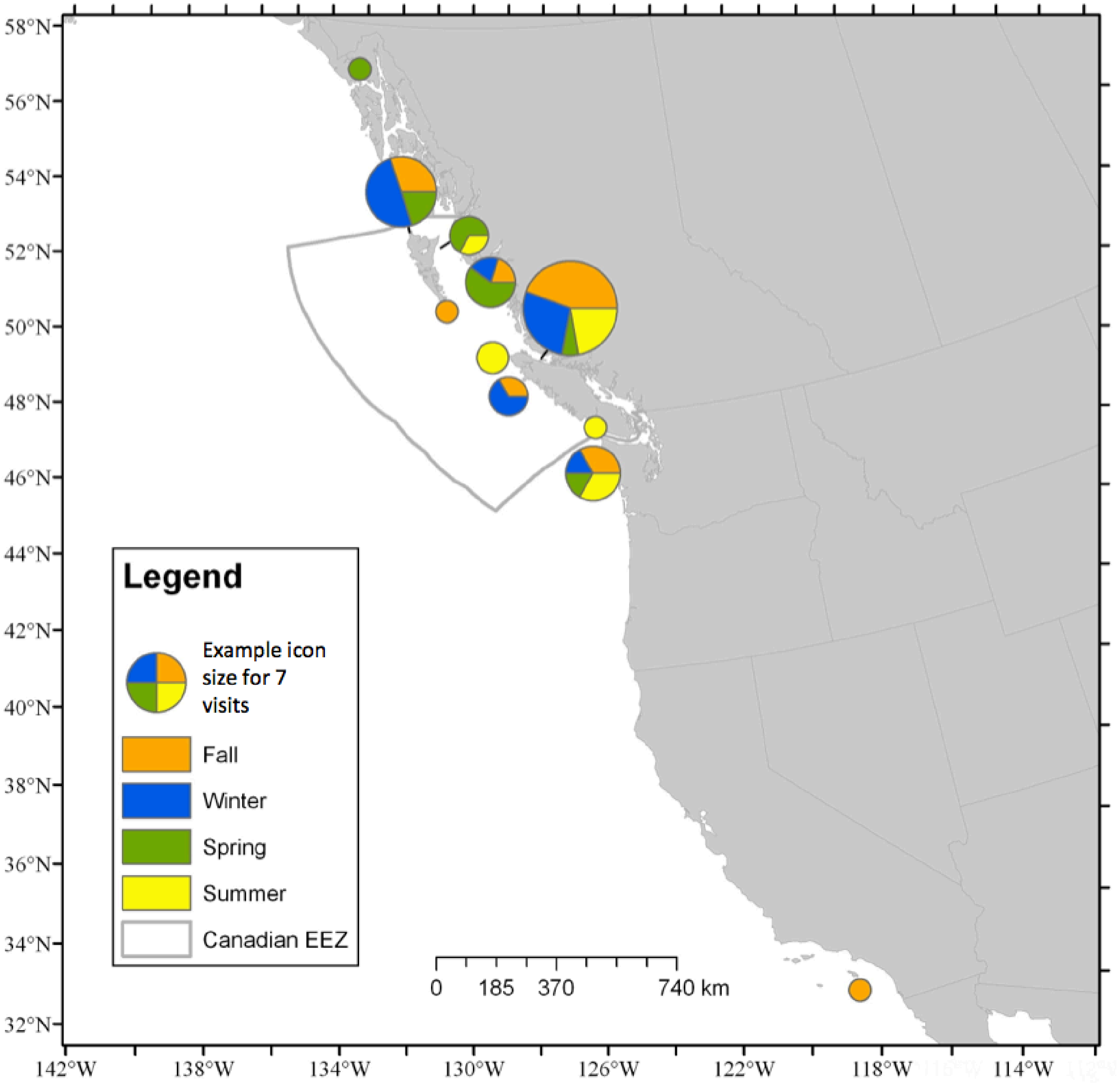

*Figure 10. Seasonality of “visits” by OKWs at acoustic monitoring stations. Icon size is relative to number of visits (range = 1–18, N = 51).*

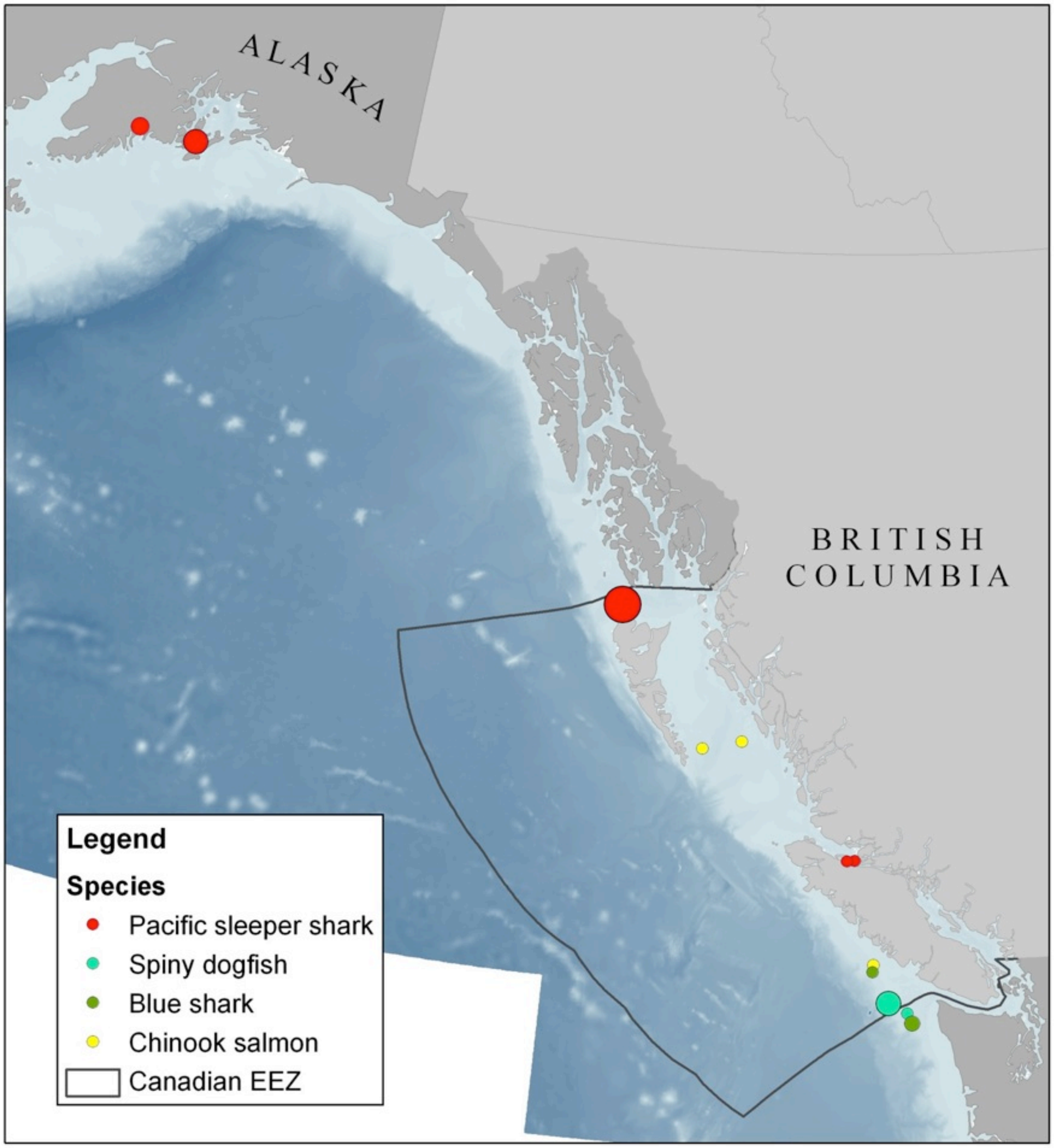

*Figure 11. Locations of predation events by OKWs involving four confirmed prey species. Size of icon reflects number of prey items consumed at each location (range = 1–11).*

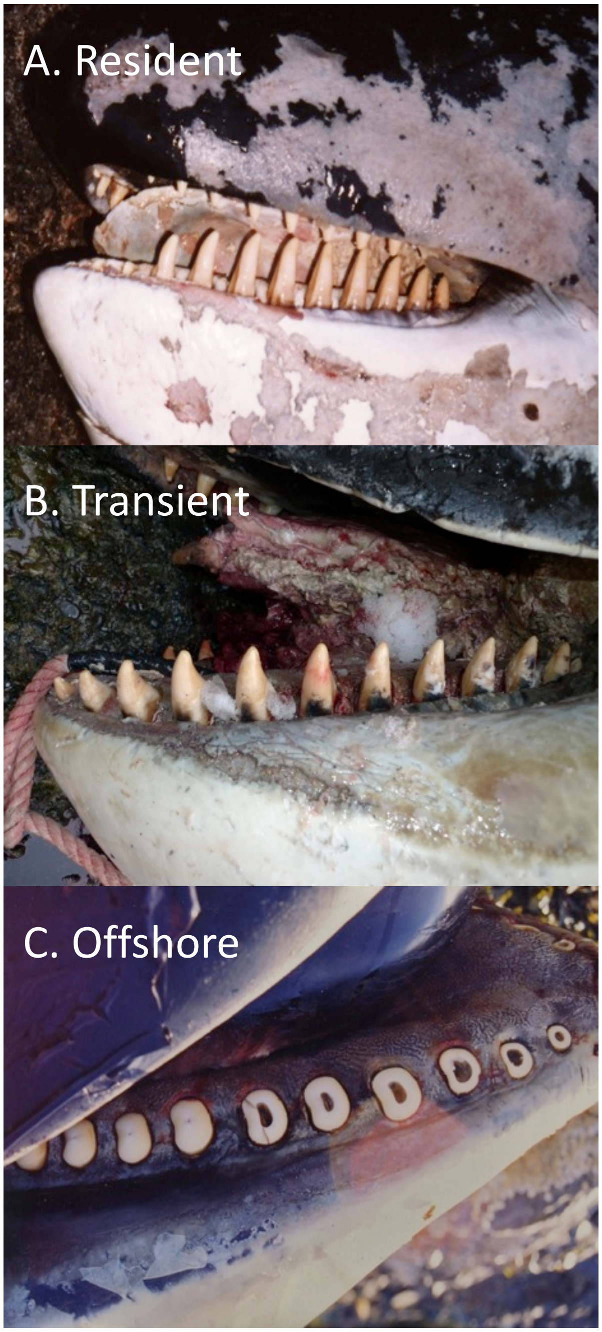

*Figure 12. Representative photographs of Killer Whale teeth: (A) Resident female A9, (B) Transient male T44 and (C) Offshore female O120 (all adults). (Illustration from Ford et al. 2011a).*

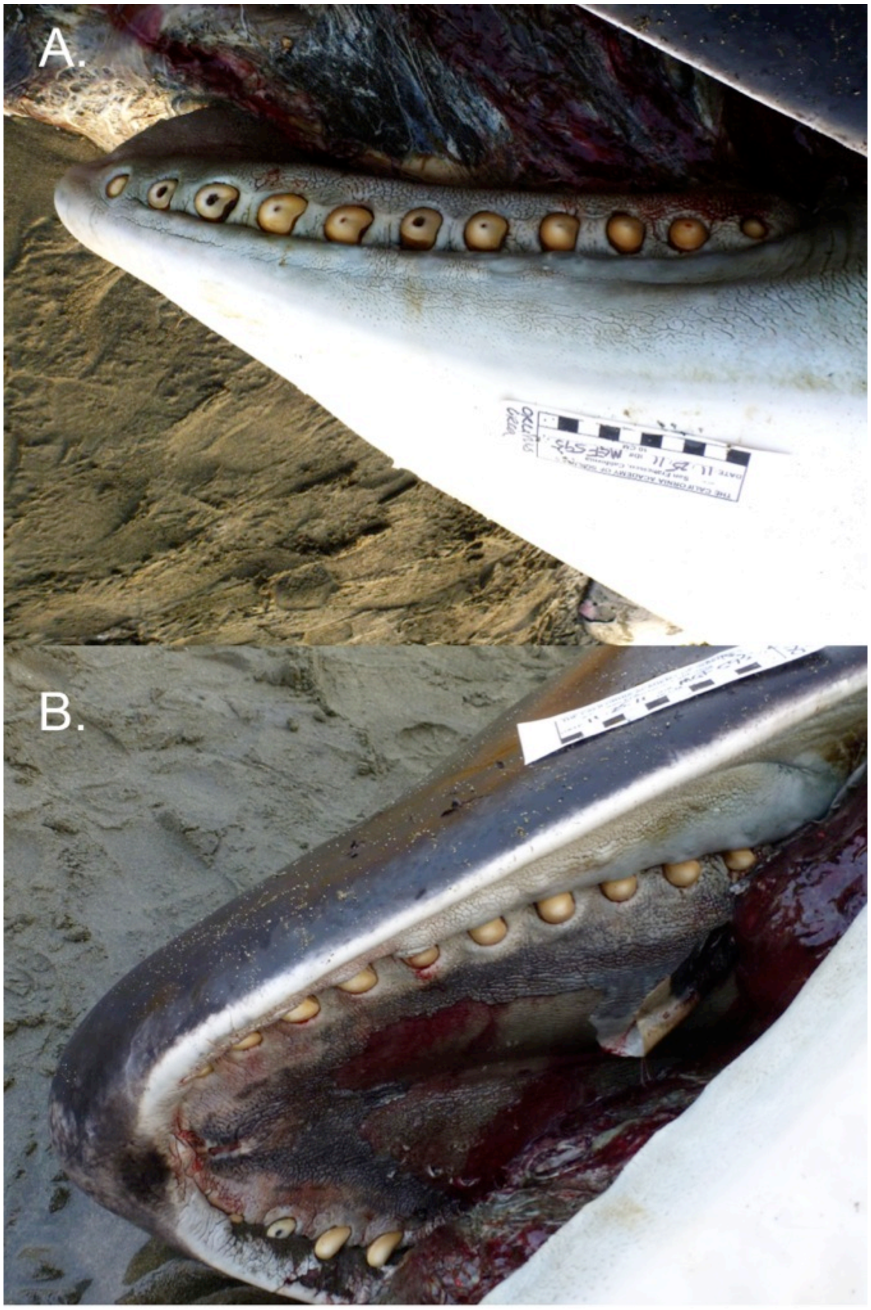

*Figure 13. Photos showing severely worn teeth in the mandible (A) and maxilla (B) of stranded OKW individual O319, a subadult male estimated to be about 15 years of age. Photos by Moe Flannery, California Academy of Sciences.*

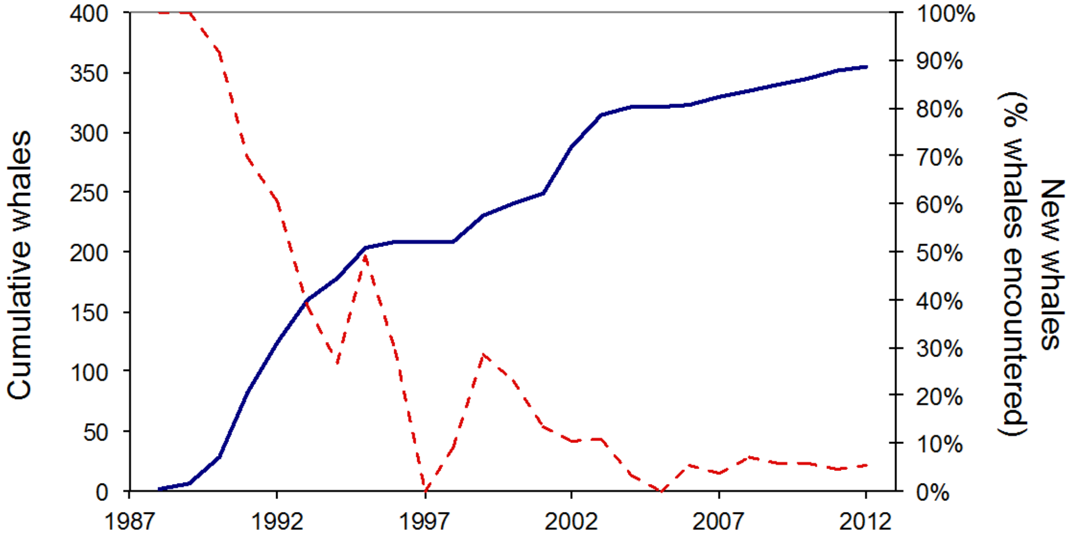

*Figure 14. Discovery curve of cumulative distinct OKWs (N = 355; solid blue) encountered and proportion of distinct OKWs encountered that were new (dashed red), across annual May-September sampling periods between 1988 and 2012.*

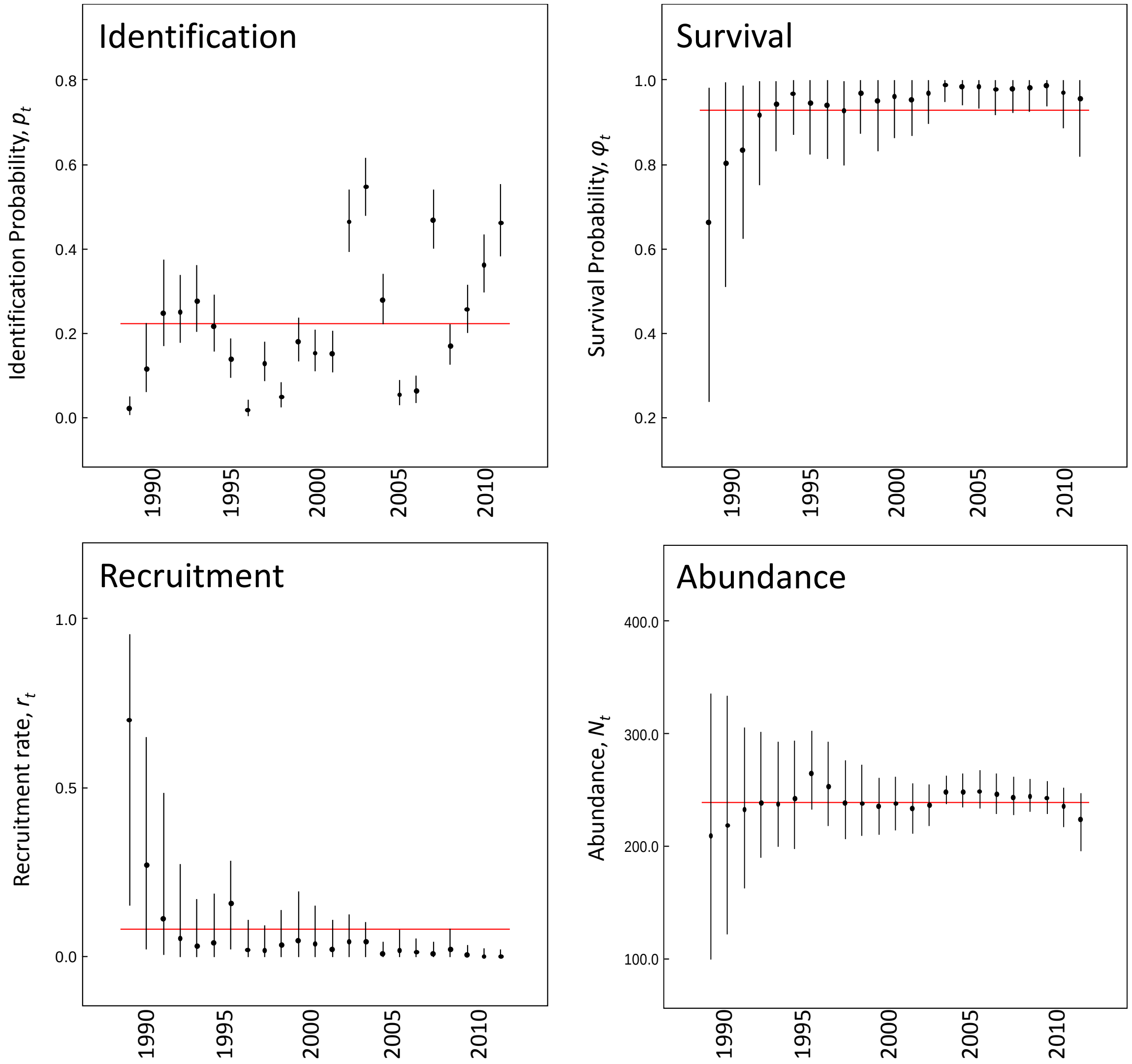

*Figure 15. Estimates of the probability of identification ($p_t$), abundance of distinctive OKW individuals ($N_t$), survival rate ($\varphi_t$), per-capita recruitment rate ($N_t$) for each year 1989-2011*. Vertical lines represent the full range of the posterior distribution for each parameter, circles represent the posterior median and horizontal lines represent the average levels over the time series. *Estimates from years 1988 and 2012 were omitted because identification probability was fixed in the model to ensure parameter identifiability (e.g. Fearnbach et al. 2012).*

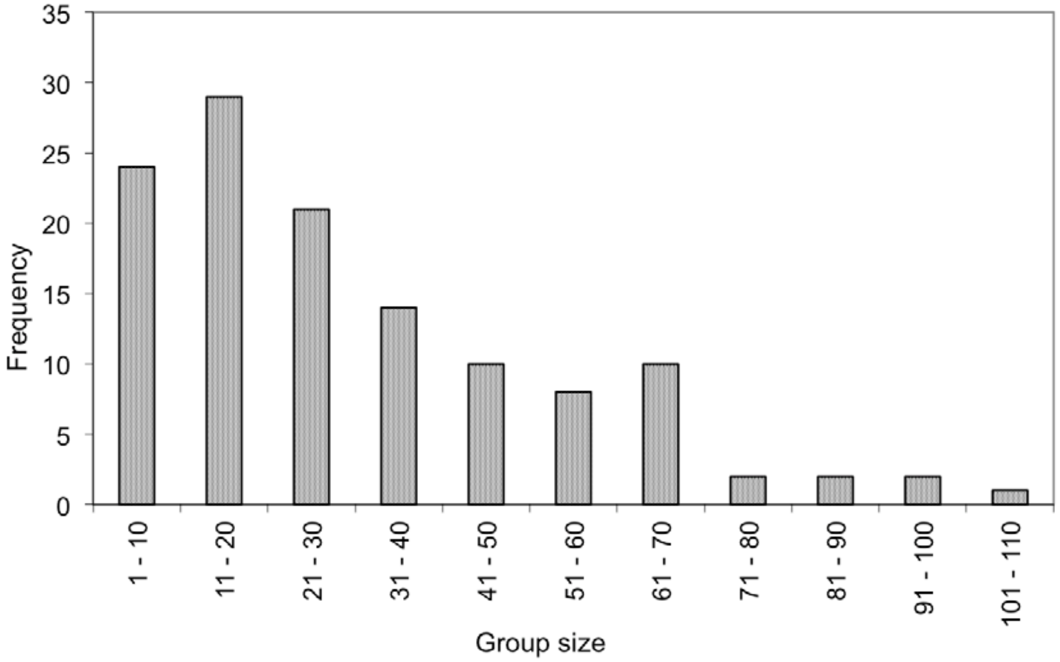

*Figure 16. Frequency distribution of OKW group sizes based on total count of identified individuals in each encounter. Group sizes are underestimates, particularly for large groups, because not all individuals were photo-identified in many encounters.*

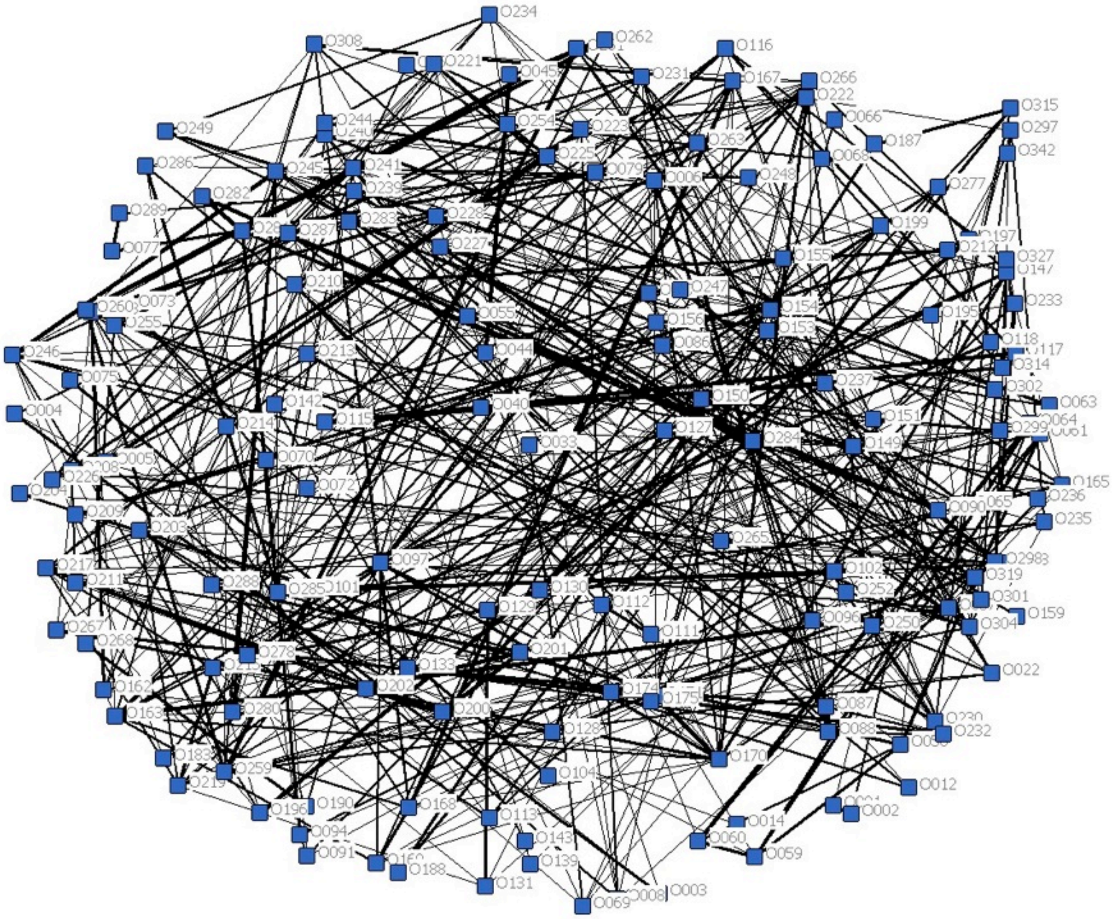

*Figure 17. Social network of 186 OKWs that were identified in 5 or more encounters. Thickness of lines connecting pairs of individuals reflects the strength of association according to the simple ratio index.*

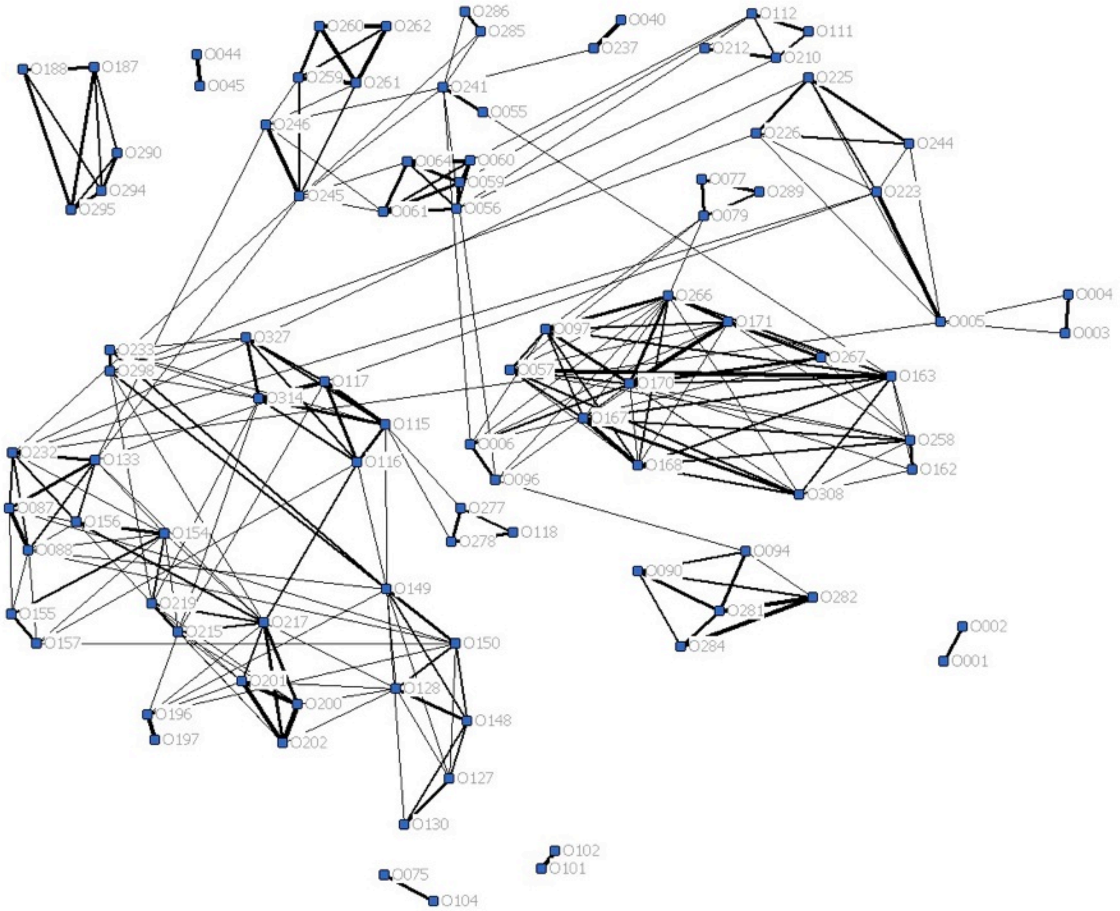

*Figure 18. Social network of 95 OKWs linking "preferred companions" – pairs of individuals with simple ratio indices greater than 0.6. Thickness of lines connecting pairs of individuals reflects the strength of association according to the simple ratio index.*

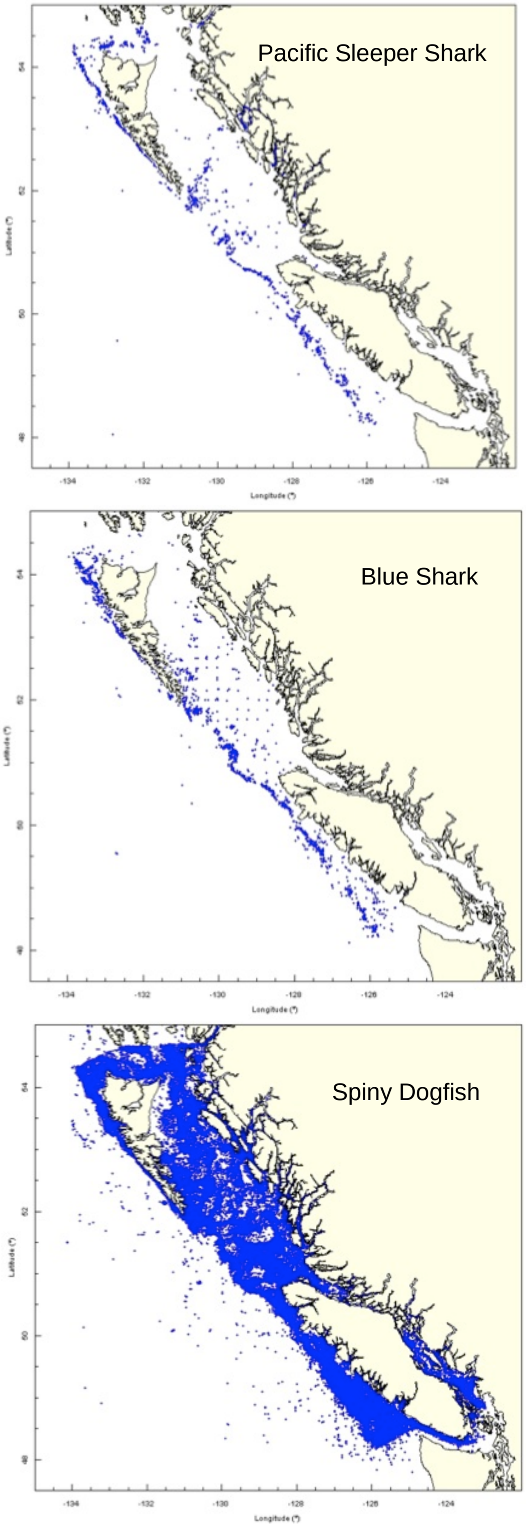

*Figure 19. Distribution of fishery catches of Pacific Sleeper Sharks (top), Blue Sharks (middle) and Pacific Spiny Dogfish (bottom) in Canadian Pacific waters 1996–2012. Unpubl. data courtesy of J. King, PBS.*

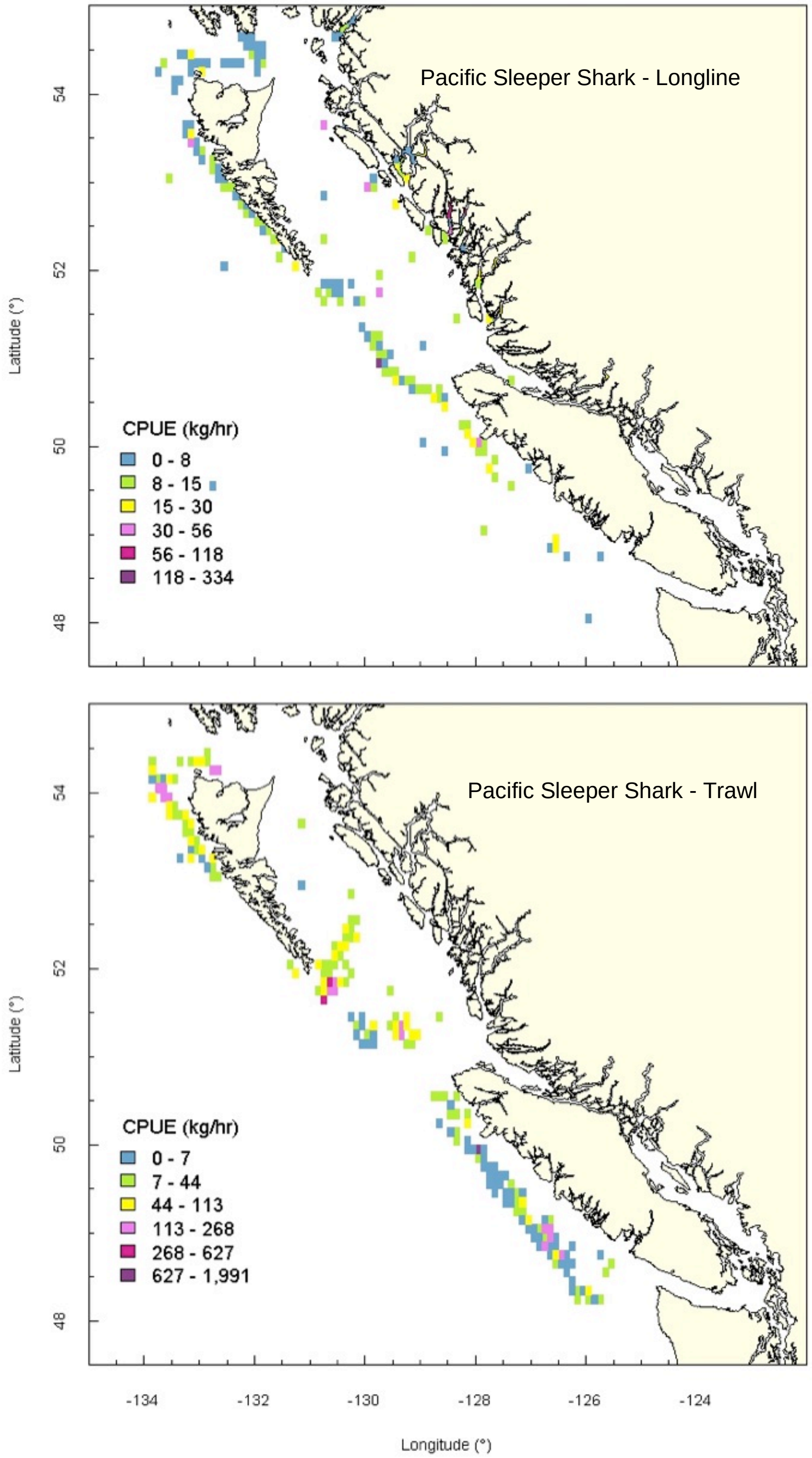

*Figure 20. Catch per unit effort of Pacific Sleeper Sharks in longline (top; 2006–2012) and trawl fisheries (bottom; 1996–2012) off the BC coast. Unpubl. data courtesy of J. King, PBS.*

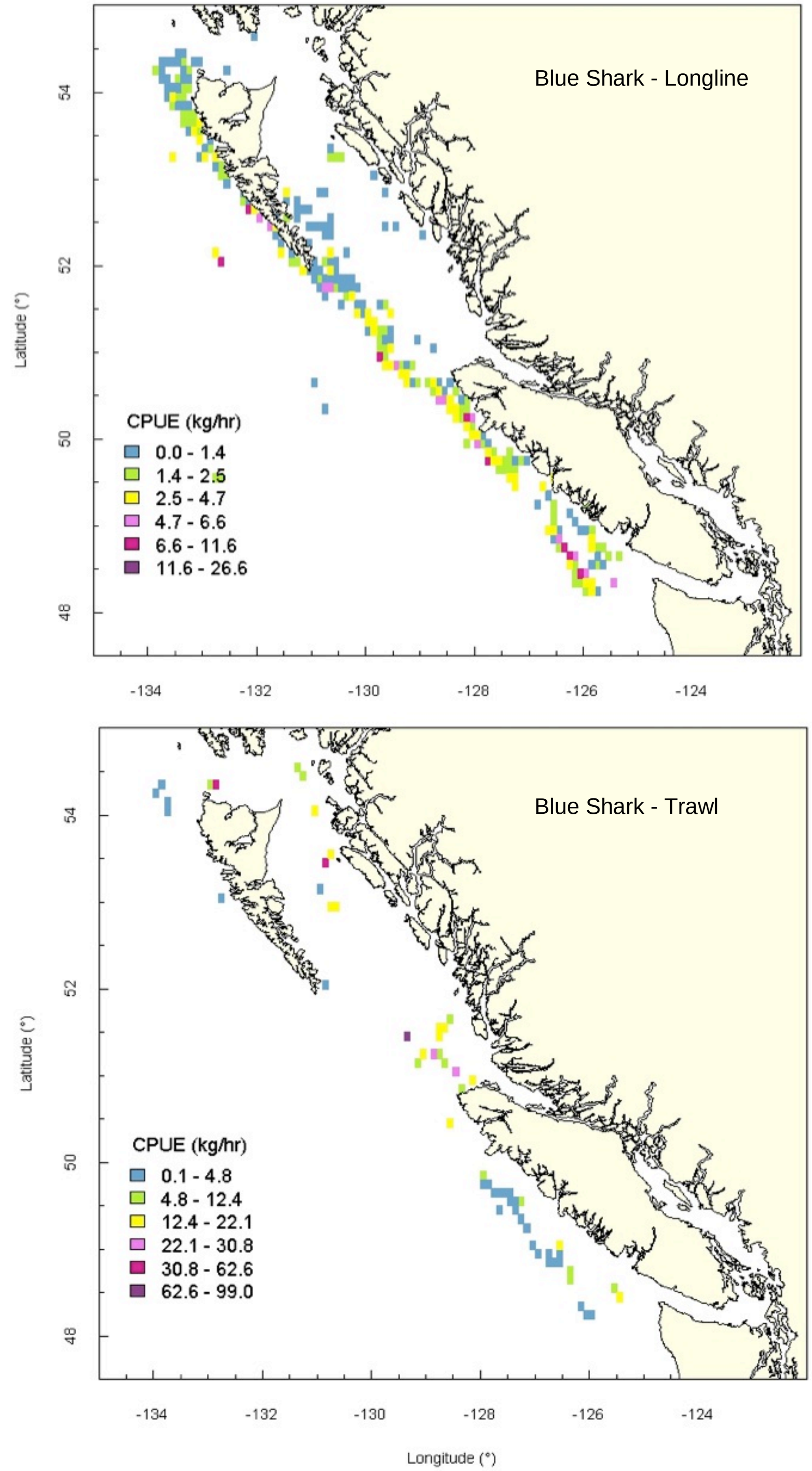

*Figure 21. Catch per unit effort of Blue Sharks in longline (top; 2006–2012)) and trawl fisheries (bottom; 1996–2012) off the BC coast. Unpubl. data courtesy of J. King, PBS.*

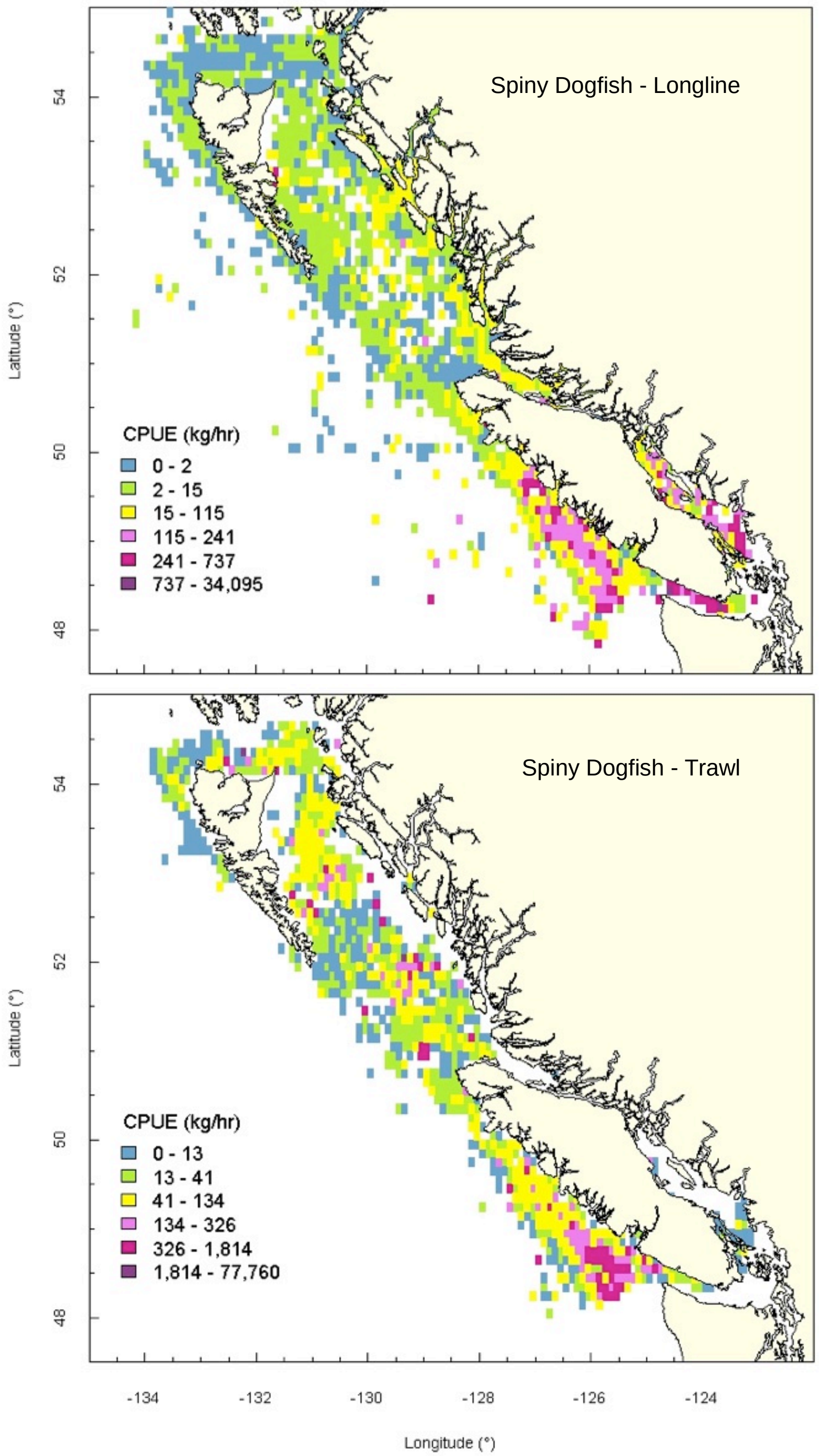

*Figure 22. Catch per unit effort of Pacific Spiny Dogfish in longline (top; 2006–2012) and trawl fisheries (bottom; 1996–2012) off the BC coast. Unpubl. data courtesy of J. King, PBS.*