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Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia, Canada

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Whale displacement by acoustic "pollution" has been difficult to document, even in cases where it is strongly suspected, because noise effects can rarely be separated from other stimuli. Two independent studies on the natural history of killer whales (*Orcinus orca*) monitored frequency of whale occurrence from January 1985 through December 2000 in two adjacent areas: Johnstone Strait and the Broughton Archipelago. Four high-amplitude, acoustic harassment devices (AHDs) were installed throughout 1993 on already existing salmon farms in the Broughton Archipelago, in attempts to deter predation on fish pens by harbour seals (*Phoca vitulina* Linnaeus). While whale occurrence was relatively stable in both areas until 1993, it then increased slightly in the Johnstone Strait area and declined significantly in the Broughton Archipelago while AHDs were in use. Both mammal-eating and fish-eating killer whales were similarly impacted. Acoustic harassment ended in the Broughton Archipelago in May 1999 and whale occurrence re-established to baseline levels. This study concludes that whale displacement resulted from the deliberate introduction of noise into their environment.

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Keywords: British Columbia, long-term change, noise, *Orcinus orca*.

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Introduction

Killer whales (*Orcinus orca*) commonly inhabit Johnstone Strait (Bigg *et al.*, 1990) and the adjacent waters of the Broughton Archipelago year-round (Morton, 1990). Both areas are located between northeast Vancouver Island and the mainland of British Columbia, Canada (Figure 1). Three distinct types of killer whales have been identified in this area and throughout British Columbia: resident, transient, and offshore (Bigg *et al.*, 1987; Hoelzel and Dover, 1990; Ford *et al.*, 1994). While transient and resident whales overlap geographically they differ genetically, socially, behaviorally, and morphologically (Bigg *et al.*, 1987; Morton, 1990; Hoelzel and Dover, 1990; Baird *et al.*, 1992; Barrett-Lennard *et al.*, 1996; Saulitis *et al.*, 2000). Most notably, all the available evidence indicates that transients are mammal-eaters, feeding exclusively on warm-blooded prey, while residents prey only on fish (Ford *et al.*, 1998). The terms (resident and transient) do not accurately reflect site fidelity. The offshore population has only recently been discovered and little is known of their natural history.

Although the northeast Pacific resident killer whale population has been growing since the 1960s (Olesiuk *et al.*, 1990; Ford *et al.*, 1994) they were listed as "threatened" by the federal Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 1999. Resident whales are fragmented into small, socially-isolated "communities" (Ford *et al.*, 1994) with small growth rate potential and thus are regarded as especially sensitive to human activities (Baird, 1998). Transient whales, which have a smaller and more widely dispersed population than residents, were listed of "special concern" due to exceptionally high bioaccumulation of persistent toxic chemicals resulting, most probably, from their diet high on the food chain (Ross *et al.*, 2000). In view of the various concerns regarding the welfare of these whales, studies which clarify their habitat needs, and the impact of human activities on them in

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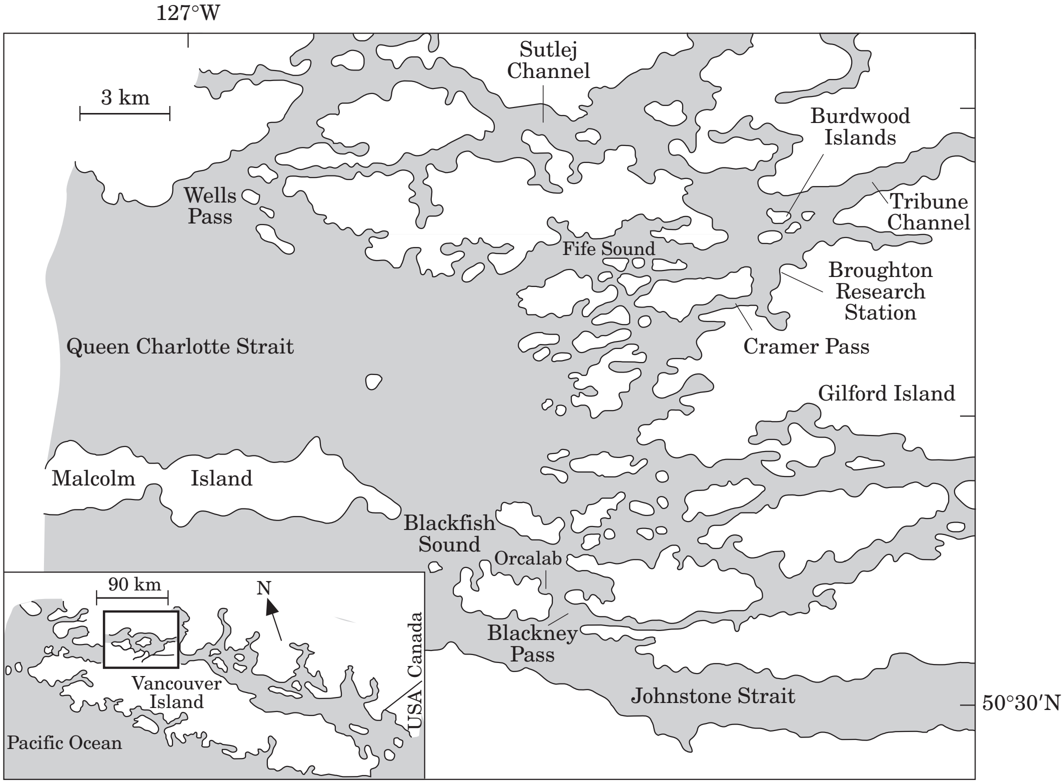

Figure 1. Broughton Archipelago spans from Wells Passage through Sutlej Channel, Fife Sound Tribune Channel, and Gilford Island.

British Columbia waters, are particularly critical at present.

Salmon farming has become a rapidly expanding industry in the study area in recent years. These open-net farms are sited in calm water: small bays in the protected archipelagos of the coast of British Columbia. Among concerns relating to the industry is its response to harbour seal predation on farm fish. In January 1993, a salmon farm in the Burdwood Island Group that is directly in front of the Broughton research station deployed an Airmar acoustic harassment device (AHD) to deter harbour seals. Over the next few months three more Airmar acoustic harassment devices were deployed throughout the Broughton Archipelago in passages less than 5 km in width (Figure 2). The AHDs were operated until May 1999.

Underwater noise devices have been used in attempts to resolve marine mammal-fishery conflicts in North America since the early 1980s. There are two basic categories of these sound production devices: low-powered and high-powered. The low-powered acoustic deterrent device is used to protect marine mammals from potential danger by alerting them to the presence of unnatural structures, such as monofilament net. The high-powered acoustic harassment device is designed to cause pain to a marine mammal (Johnston and Woodley, 1998). These devices are used on fishing gear, aquaculture pens and disturbed estuarine habitat to protect fish that have been made vulnerable to marine mammal predation (Johnston and Woodley, 1998). In general, the low-powered acoustic deterrent devices target cetaceans, in particular harbour porpoise (*Phocoena phocoena* Linnaeus), while the high-powered AHDs target pinnipeds (Olesiuk *et al*., 1995; Kraus *et al*., 1997). Experiments have been conducted on the efficacy of acoustic deterrent devices in preventing porpoise by-catch in gillnets (Koschinski and Culik, 1997; Kraus *et al*., 1997; Kastelein *et al*., 2000b; Culik *et al*., 2001) and the shortterm impact of acoustic harassment on harbour porpoise was tested for Canada's Department of Fisheries and Oceans (DFO) by Olesiuk *et al*. (1995). There have been no reports, however, on cetacean occurrence trends in areas affected by AHDs in the long term.

An Airmar AHD tested in the Broughton Archipelago for DFO by Haller and Lemon (1994) under calm conditions emitted a 10 kHz signal at 194 dB re 1 ΦPa @ 1 m underwater and was estimated to reach ambient noise levels 50 km from source. Since acoustic harassment devices work on the principle of causing sufficient

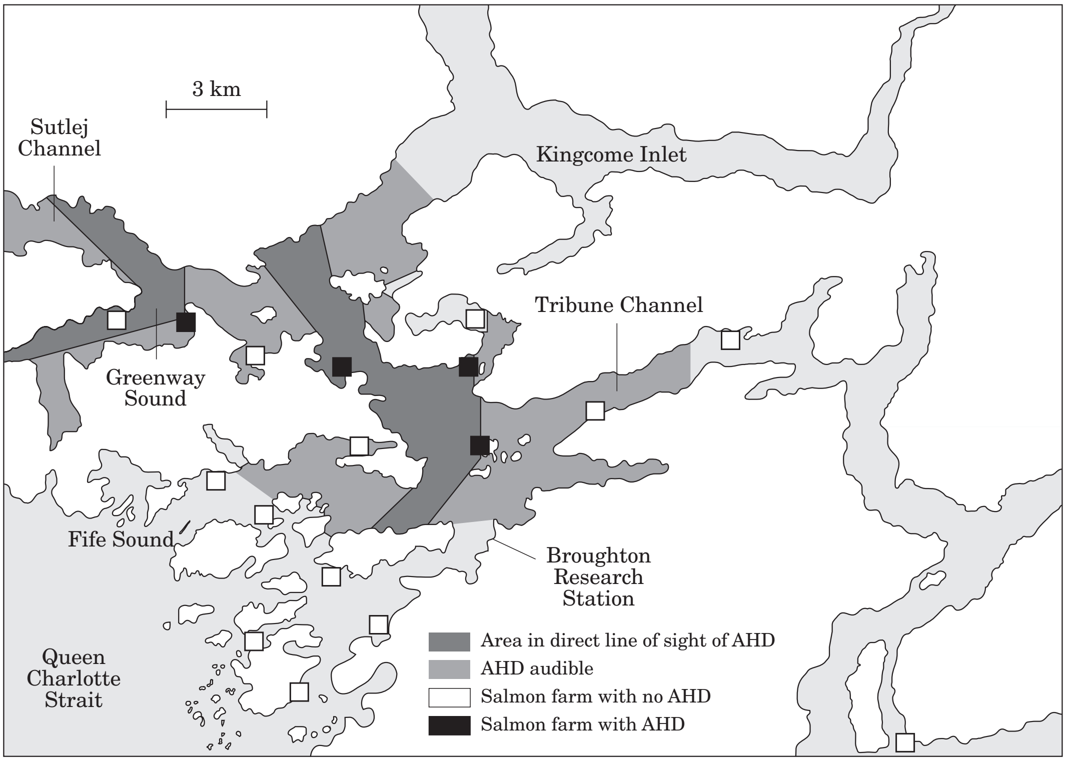

Figure 2. Approximate range of four AHDs in the Broughton Archipelago.

pain to turn pinnipeds away from the sound source, their impact on non-target, acoustically sensitive marine mammals should not be unexpected. Concern about the impact of man-made noise on cetaceans has been growing since the 1970s (Richardson *et al*., 1995). Long-term whale displacement by acoustic pollution has been difficult to document, though strongly suspected in several cases, because it has been associated with, and could not be separated from, other stimuli such as boats or oil drilling platforms. Additionally, there are often no baseline data collected prior to the introduction of the sound disturbance (Richardson *et al*., 1995). There are some examples of cetaceans being displaced by disturbance which included noise. For example gray whales (*Eschrichtius robustus* Lilljeborg) abandoned a calving lagoon in Baja California when vessel traffic increased and then returned after traffic diminished (Gard, 1974; Bryant *et al*., 1984) and humpback whale (*Megaptera novaeangliae* Borowski) mothers and calves have been shown to avoid some inshore waters of Hawaii where intense recreational vessel activities occur (Glockner-Ferrari and Ferrari, 1990; Salden, 1988). Humpback whales and Indo-Pacific humpbacked dolphins (*Sousa chinensis* Osbeck) have responded to loud noise from pile driving or seismic activity with avoidance, increased speed of travel or decreased abundance (McCauley *et al*., 2000; Würsig *et al*., 2000). Bowhead whale (*Balaena mysticetus* Linnaeus) occurrence declined in an approximately 10^4 km^2 area of intense offshore oil exploration in the Canadian Beaufort Sea (Richardson *et al*., 1985, 1987). Military testing of low frequency active sonar (SURTASS LFAS) systems was implicated in the stranding deaths of Cuvier's beaked whales (*Ziphius cavirostris* G. Cuvier) in the Mediterranean (Frantzis, 1998). More recently, military sonar has been implicated in the stranding deaths of numerous beaked whales in the Bahamas (Malakoff, 2001).

The exact mechanism by which sound can displace marine mammals is poorly understood, but impacts range from physical injury to interference. The noise generated by underwater explosions can kill or injure marine mammals (Trasky, 1976; Zhou and Zhang, 1991; Ketten *et al*., 1993; Baird *et al*., 1994; Ketten, 1995). However, man-made underwater sound can also affect marine mammals without causing physical damage. Impact through interference with the detection of acoustic signals, or "masking" has also been shown (Erbe and Farmer, 1998). There is also evidence that odontocetes will shift their acoustic output in frequency and volume to avoid excessive background noise levels (Au *et al*., 1974, 1985; Thomas and Turl, 1990; Romanenko and Kitain, 1992; Lesage *et al*., 1999; Miller *et al*., 2000). Loss of directional hearing capabilities may also occur (Richardson *et al*., 1995). While no data exist on noise levels causing permanent hearing impairment in marine mammals, temporary threshold shifts (TTS) have recently been measured in marine mammals (Au *et al.*, 1999; Schlundt *et al.*, 2000) and repeated exposure to TTS-causing noise is thought to cause permanent hearing damage. We can expect man-made noise pollution of the marine environment to increase from vessel traffic, research, aquaculture, resource extraction, military, and other sources as there is no evidence of these activities diminishing.

Our study presents data collected from 1 January 1985 through 31 December 2000 by two independent research projects on the daily presence of killer whales in both western Johnstone Strait through Blackfish Sound (hereafter called the Johnstone Strait area) and the waters of the adjacent Broughton Archipelago (Figure 1). Throughout the 15-year period, the Johnstone Strait area was not exposed to acoustic harassment devices whereas the Broughton Archipelago area was exposed to them for five years. The observations collected throughout the three time periods: before-, during- and after-AHD exposure form a natural experiment where whales in one region (Johnstone Strait) were unaffected by AHDs while whales in an adjacent area (Broughton Archipelago) were affected.

Materials and methods

Whale detection was accomplished by combining passive underwater acoustic monitoring, visual observation from strategically positioned platforms and VHF radio reports from reliable observers on vessels. Orcalab, located at the eastern end of Hanson Island where Blackney Pass joins Johnstone Strait and Blackfish Sound (Figure 1), monitored acoustically approximately 50 km^2 of that area via seven remote hydrophones year-round throughout the study except in 1985. In 1985, only a key 10 km^2 of Blackney Pass and the area of Johnstone Strait immediately adjacent was monitored, with coverage being increased in 1986 and becoming stable by 1987. At each listening point, a hydrophone (Sonobouy, 15 kHz bandwidth) was connected via cable to a radio transmitter. The signal was broadcast continuously and monitored on a receiver at the research station. During the peak season, June through October, the laboratory was manned by volunteers 24 hours a day. The signals from all hydrophones were ''mixed'', enabling continuous monitoring of all hydrophones during the rest of the year when the facility was manned, but without a 24 hour a day dedicated listener.

Monitoring effort of the Johnstone Strait area was continuous, except for the period 28 November–15 December 1986. Whenever killer whales were heard, they were recorded, producing an average of 1000 hours of recordings each year. The whales were identified on a daily basis by their calls using the methods described by Ford (1984). Supplementing the acoustic detection and identification were visual sightings of killer whales as they passed the year-round Johnstone Strait area research facility, as well as land-based summer observation sites staffed by Orcalab volunteers. The land observation sites overlooked many of the hydrophone listening points. The acoustic and visual data were reconciled daily at Orcalab to produce an accurate list of which pods were present in the Johnstone Strait area each day of the year.

Whale detection in the Broughton Archipelago was modelled after the Orcalab system. Underwater acoustic monitoring of 32 km^2 from Fife Sound (126E 35′W) to Viner Sound (126E 15′W) was conducted with a hydrophone (Offshore Acoustics model # 96b) feed into a second year-round research station. The intersection of four major passages at this site (Cramer Pass, Fife Sound, Sutlej Channel, and Tribune Channel), make it an ideal location to detect whales in the Broughton Archipelago (Figure 2). A single hydrophone was monitored 24 hours a day throughout the study with gaps from 1 July through 16 August 1989 and 1990, the month of December 1995 and occasional gaps totaling three to four weeks annually in the period 1986–1993, when the research facility was not manned. From 1993–2001 it was manned continuously. The visual field from the research facility was scanned 50–75 times a day from an elevation of 40 m. Boat-searches totalling 10 372 h were also conducted two to seven times a week with each search lasting two to eight hours (Morton, 2000).

A network of local residents, fishermen, sea planes, commercial vessels, whale-watch vessels, visiting scientists and recreational boaters reported whale sightings to both research facilities via VHF radio. The vessel-based sightings in the Johnstone Strait area were typically confirmed by the Orcalab land observation sites and hydrophone array. In the Broughton Archipelago, recreational boaters and fishing lodges became increasingly diligent in reporting whale sightings which were confirmed by taking a boat to the location. During the last six years of this study we believe killer whales rarely entered the archipelago without eliciting more than one VHF radio call to the research station. Each day of observation was categorized based on either the presence or the absence of orca in the study areas.

The output from the Airmar acoustic harassment devices was detected via a portable hydrophone deployed from a 7.3-m research vessel used by the Broughton research station. Recordings were made on a Sony TC-D5M cassette tape recorder. The minimum range of audibility for the AHDs was determined by moving the research vessel throughout the Broughton Archipelago, deploying the hydrophone and listening for the presence or absence of a signal (Figure 2). As a

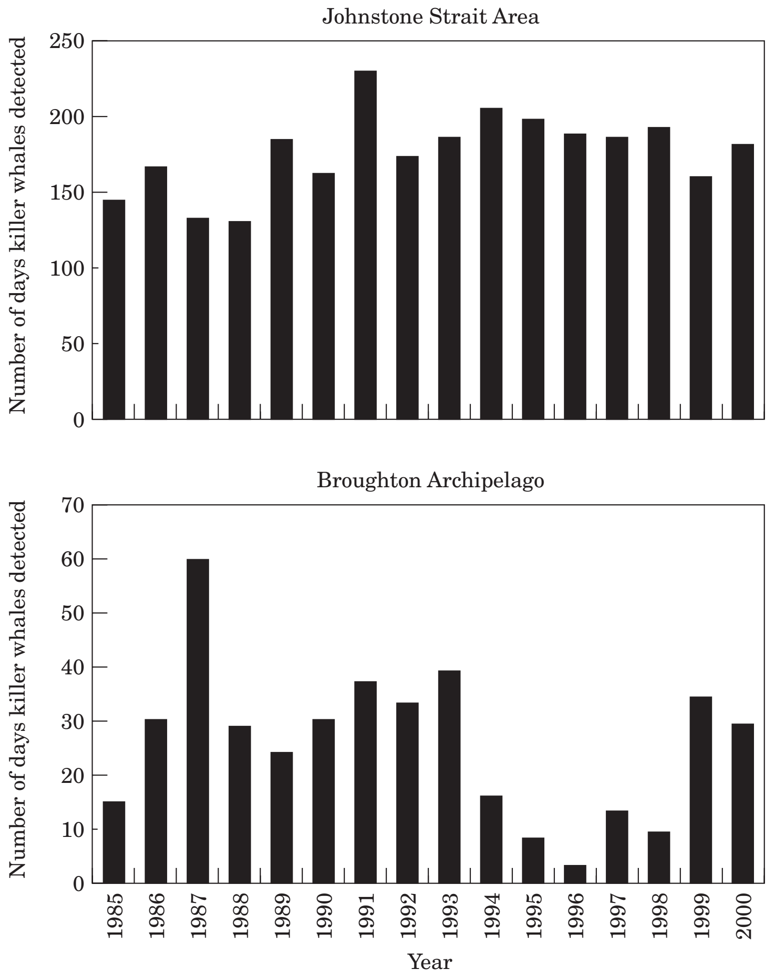

Figure 3. Number of days killer whales detected in the Johnstone Strait area and Broughton Archipelago from 1 January 1985 to 31 December 2000.

result of the geographic confines of the waterways, it was not possible to move in a linear course to the point where the signal was no longer audible or even much diminished. Echoes from the AHDs were also detected in areas not in direct line of sight of fish farms as indicated in Figure 2.

Results

Killer whale presence in the Johnstone Strait area remained relatively stable throughout the study but underwent dramatic change in the Broughton Archipelago (Figures 3–5). In statistical terms whale sightings in Johnstone Strait were not significantly different during the years of AHD activity (mean=192.40, s.d.=8.26, n=5) to those of both pre-exposure (mean=166.78, s.d.=30.85, n=9) and post-exposure (mean=169.00, s.d.=15.56, n=2) periods (one-way ANOVA: $F_{2,13}=1.75$, $p=0.211$). In contrast whale sightings in the Broughton Archipelago were significantly lower in number during the years of AHD activity (mean=9.80, s.d.=4.97, n=5), than those of both the pre-exposure (mean=33.00, s.d.=12.35, n=9) or post-exposure (mean=31.50, s.d.=3.54, n=2) periods (one-way ANOVA: $F_{2.13}=8.84$, $p=0.004$) (Figure 4; Stewart-Oaten, 1995). Figure 5 shows changes in the occurrence of resident, fish-eating killer whales were most dramatic coinciding exactly with use of the acoustic harassment devices.

Discussion

The number of killer whale sightings remained high during 1993, the first year of AHD activity, for two reasons. First the whale population did not simultaneously encounter the noise devices. The AHDs were

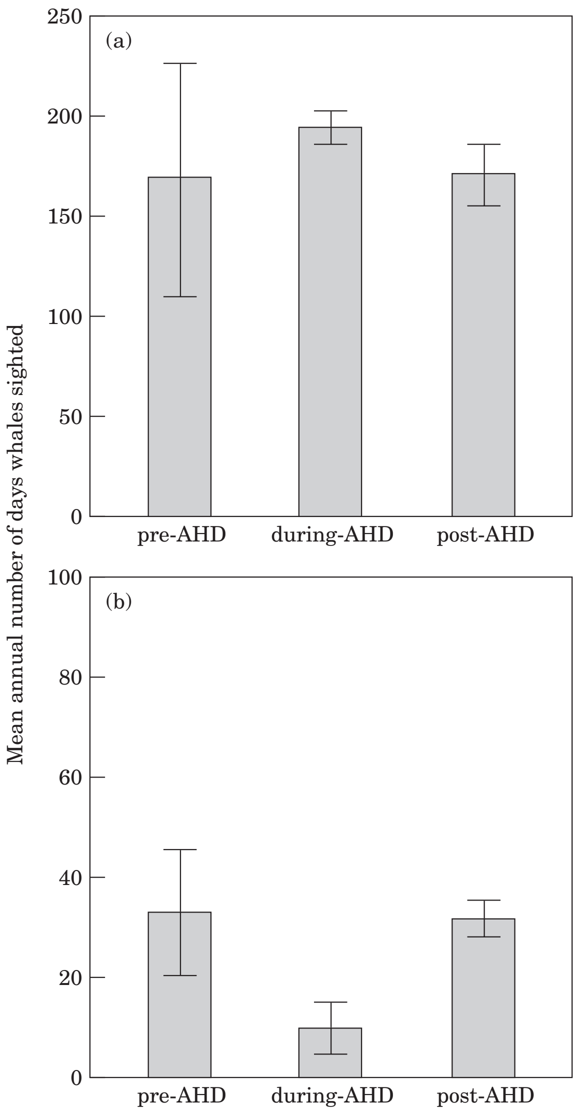

Figure 4. Means and standard errors for killer whale occurrence in the (a) Johnstone Strait and (b) Broughton Archipelago areas for pre-, during-, and post-acoustic harassment periods.

not audible from beyond the archipelago and so each pod of whales was not exposed until it entered the archipelago over the course of the year. Second, one route, Sutlej Channel through Kingcome Inlet, remained free of AHDs for a few months of 1993 and the whales continued to frequent that area until AHD activity was initiated there as well.

We were concerned that the particularly high number of sightings in 1987 could have exerted undue influence on our pre-AHD sighting rates. In fact the difference between the mean number of sighting days pre-AHD and during-AHD was still highly significantly different after removal of this observation. We decided to retain data from all years, since it offers a fairer description of pre-AHD variability in sighting rates.

There is always a concern about violating model assumptions when dealing with small sample size. We present two-way ANOVA results only, since this test allowed us to model within- and between-period variability simultaneously, using the fewest tests, and because we have no *a priori* reason for suspecting that our response variable should follow a non-normal distribution. However, we did explore alternative analyses to see how robust our results were to the violation of assumptions of non-normality and heterogeneity in sample variance. The non-parametric Mann-Whitney U-test and a two-sample t-test assuming unequal variance both yielded results that were significant at $p<0.05$.

The increase in whale sightings in 1999 did not occur immediately after the AHDs were deactivated in May. All the 1999 sightings were in November, six months later.

The deployment of Airmar acoustic harassment devices is seen as the probable cause of killer whale decline in the Broughton Archipelago. The mechanism by which the acoustic harassment devices repelled the killer whales is beyond the scope of this study but it may not be a simple response to pain. It is not unreasonable to expect various zones of acoustic harassment influence, ranging from non-responsiveness through to physical damage, since we know that at extremely close range acoustic harassment devices could cause physical damage (Richardson *et al.*, 1995). High amplitude noise may have sufficient masking effect on the 10 kHz pulsed calls, whistles and echo-location made by these whales (Ford, 1989, 1991; Wood and Evans, 1980) to cause them to move out of range.

While the 10 kHz Airmar acoustic harassment device was designed specifically to cause physical pain to seals, the nature of killer-whale hearing makes this species vulnerable to impact by this type of sound source as well. Hall and Johnson (1972) and Szymanski *et al.* (1999) found that a killer whale's peak auditory response is 20 kHz, the lowest for any odontocete tested. Szymanski *et al.* (1999) also found that these whales have the most sensitive hearing reported for any odontocete, +36 dB re 1 ΦPa @ 20 kHz, which agrees with Hall and Johnson (1972), who reported detection of a 15 kHz signal of ~30 dB re 1 ΦPa @ 1 m in killer whales, 10 dB less than recognized for most other marine mammals (Richardson *et al.*, 1995). Given this acoustic sensitivity the response of killer whales to AHD deployment seems unsurprising. Indeed if an operator activated an Airmar acoustic harassment device (194 dB re ΦPa @ 1 m) in response to a pod of killer whales surfacing beside a fish farm to protect the substantial economic investment represented by 1 000 000 Atlantic

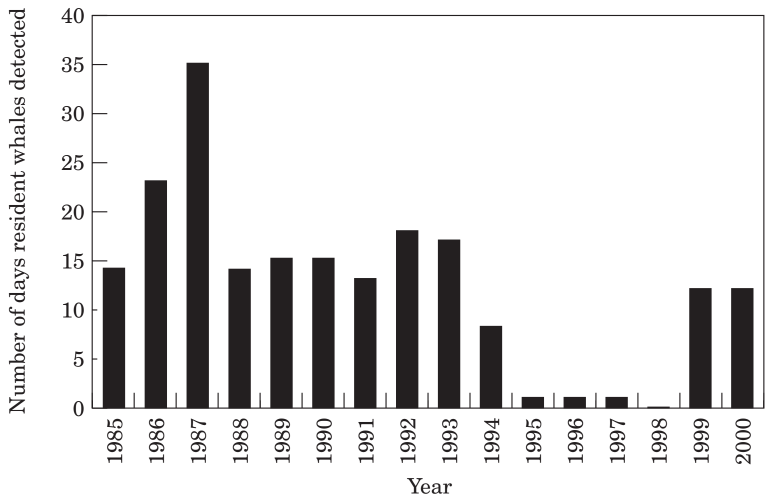

Figure 5. Number of days resident killer whales detected in Broughton Archipelago from 1 January 1985 to 31 December 2000.

salmon (*Salmo salar* Linnaeus), then the exceptionally responsive hearing of the whales could be irreversibly damaged (Richardson *et al.*, 1995).

Odontocetes with much higher peak-hearing sensitivities also appear to have been repelled by the Airmar acoustic harassment devices in the Broughton Archipelago and elsewhere. Although Anderson (1970) found harbour-porpoise hearing was most sensitive at 130 kHz, a DFO experiment in the Broughton Archipelago found that harbour-porpoise abundance ‘‘declined precipitously’’ when exposed to the Airmar AHDs and returned to normal when the devices were turned off (Olesiuk *et al.*, 1995). Johnston and Woodley (1998) suggest that harbour porpoises in the Bay of Fundy may also be displaced by acoustic harassment devices on salmon farms. Kraus *et al.* (1997) found the by-catch of harbour porpoise declined dramatically when 10 kHz alarms with a source level of 132 dB re 1 ΦPa @ 1 m were placed on gillnets.

We considered whether changes in prey abundance could offer an alternative explanation for the period of decline in Broughton Archipelago killer-whale presence. The diets of resident and transient killer whales differ dramatically (Morton, 1990; Baird *et al.*, 1992; Ford *et al.*, 1998), but there was no evidence that the two most important prey species; the resident's chinook salmon (*Oncorhynchus tshawytscha* Walbaum) (Ford *et al.*, 1998) and the transient's harbour seals (Baird and Stacey, 1988; Felleman *et al.*, 1991; Heimlich-Boran, 1998) fluctuated in a pattern corresponding to whale occurrence.

We examined chinook salmon escapement records kept by the DFO for the five largest salmon rivers in the Broughton Archipelago (Kingcome, Wakeman, Kakweikan, Klinaklini, and Ahnuhati) during the study time-period. There was no apparent relationship between fluctuations in chinook salmon escapement (Figure 6) and annual killer whale presence. There was also no conclusive evidence of decline in the number of seals in the study area despite the use of acoustic harassment devices. The DFO counted seals in the Broughton Archipelago in 1989 and 1996. While they counted 296 in 1989 and 360 in 1996, corrections for unborn pups, proportion of area covered and ‘‘estimated proportion hauled out’’ produced an estimated abundance of 777 in 1989 and 666 in 1996 (Olesiuk, 1999). Olesiuk *et al.* (1995) suggest the Airmar acoustic harassment device elicited a ‘‘dinner-bell effect’’ in seals because their numbers actually increased in some sessions, despite a lack of fish at the study site. Ultimately, we rejected the hypothesis that reduced forage opportunity had lowered the annual killer whale presence in the Broughton Archipelago.

The decline of all killer whales in this study, regardless of diet, corresponds in time and space, with the use of AHDs on the salmon farms. The Johnstone Strait area provides data from an acoustic harassment device-free portion of the whales' range showing no significant change in occurrence of the same whales during the same time period. Because these whales have been individually identified (Bigg *et al.*, 1987; Ford *et al.*, 1994; Ford and Ellis, 1999) and their presence monitored in the Johnstone Strait area we were able to confirm that the pods which were not observed in the Broughton Archipelago were present in Johnstone Strait. We are able to report, therefore, that the absence of killer whales in the Broughton was not due to unrelated death or large-scale abandonment of habitat but rather to the abandonment of a specific portion of their habitat. We conclude that it appears likely that killer whales were driven from the Broughton Archipelago by the high amplitude Airmar AHDs.

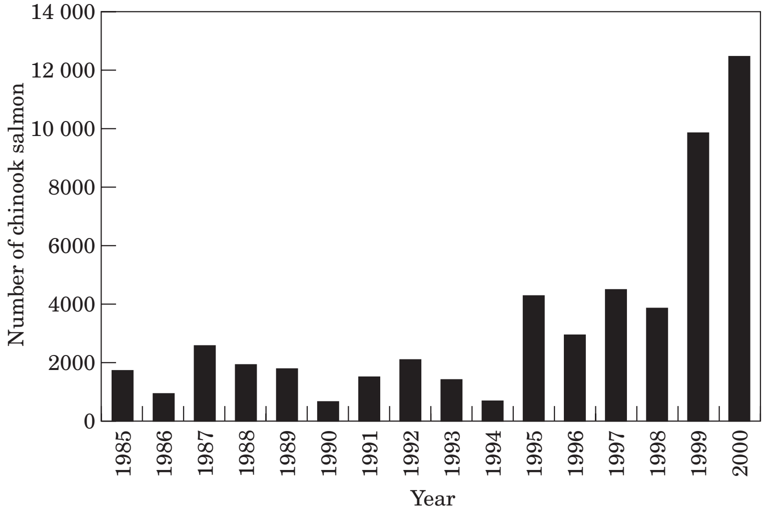

Figure 6. Chinook salmon escapement in the five major salmon producing rivers of the Broughton Archipelago.

Our findings have wide implications. If the use of AHDs continues to increase throughout the oceans of the world, as the net-pen fish aquaculture industry continues its expansion then significant negative impacts on whale habitats can be expected. As Richardson *et al.* (1995) point out, it cannot be assumed that displaced cetacean populations will fare as well in some other part of their range. Globally we can expect man-made noise pollution of the marine environment from vessel traffic, resource extraction, aquaculture, scientific research, military, and other sources to increase. Government agencies in the USA and Canada have begun to address the concern for potential negative impacts on marine mammals from noise pollution. The US National Oceanic and Atmospheric Administration advises that possible effects of sound on non-target species should be of primary concern. The Canadian Fisheries and Oceans (previously the Department of Fisheries and Oceans) consolidated marine mammal protection under its "Marine Mammal Regulations" in 1993. These regulations state that "no person should disturb a marine mammal". Clearly "disturbance" needs to include the acoustic mode, as well as other impacts. We think there is a pressing need for the international community at large to address the issue of oceanic noise pollution.

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