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Geostatistical analyses of interactions between killer whales (*Orcinus orca*) and recreational whale-watching boats

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Abstract

Johnstone Strait in coastal British Columbia, Canada, is a core habitat for seasonal concentrations of killer whales (*Orcinus orca*), which have attracted considerable attention from commercial whale-watching operators and recreational boaters. Within the Strait lies the Robson Bight–Michael Bigg Ecological Reserve, a marine reserve set aside as critical habitat for killer whales and closed to recreational boat traffic. The geography of encounters between killer whales and seven types of whale-watching vessels (including kayaks, charter and pleasure craft) in and near this reserve was analysed with a suite of geostatistics in a geographic information system (GIS) vector environment. Reserve boundary violation was high among most user groups, with kayakers being the most frequent offenders. Motorized vessels had significantly longer contact times with whales compared to kayaks and sailboats. Motorized vessels showed the travel characteristic of deliberate tracking of whales. The movements of killer whales also appear to be affected by boats. These results have important implications for killer whale conservation and management in areas where they are subject to intensive whale-watching activities, and possible chronic disturbance.

Keywords: British Columbia; Geostatistics; Killer whales; Marine geography; Non-consumptive wildlife recreation; *Orcinus orca*; Spatial analysis; Whale-watching; Wildlife disturbance

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Introduction

Interest in non-consumptive wildlife recreation has grown substantially in recent years with attendant economic benefits. It involves observing wildlife in a natural setting without removing or destroying the focal species (Boyle & Samson, 1985). For example, 24 million Americans took trips for the specific purpose of observing, photographing or feeding wildlife in 1996, while 61 million enjoyed non-consumptive wildlife-related recreation around their homes. Total expenditure in support of these activities approximated $29 billion (US Department of the Interior, Fish and Wildlife Service and US Department of Commerce, Bureau of the Census, 1997). Another significant benefit is that wildlife-related recreation engenders positive attitudes towards wildlife in its natural environment, which can be instructive in terms of habitat protection and maintaining biodiversity. The notion of non-consumptive wildlife recreation is shrouded in the belief that wildlife viewing is relatively benign, with little or no impact on the species of interest (Wilkes, 1977; Gutzwiller, 1995). The term 'non-consumptive' may be quite misleading, however, because wildlife-viewing recreation can have serious negative impacts on wildlife (Wilkes, 1977; Boyle & Samson, 1985). The interactions between observer and wildlife often tend to be frequent and of long duration whenever possible (Boyle & Samson, 1985). Disturbance may lead to increased behavioural and physiological stress responses. These may include increased metabolic rates, disruption of movement patterns, making it more difficult for wildlife to locate reliable sources of food, forcing animals to occupy unfamiliar and often sometimes less suitable habitats and alter their predator avoidance tactics (Klein, 1971; Pomerantz, Decker, Goff, & Purdy, 1988; Gabrielson & Smith, 1995). The overall consequence may be reduced vigour and lower reproduction and survival rates (Knight & Cole, 1991). Boyle and Samson (1985) surveyed 166 articles with original data on non-consumptive recreational impacts on wildlife; 81% considered the effects to be negative.

Over the last two decades cetacean populations (i.e. whales, dolphins and porpoises) throughout the world have become major targets of a growing ecotourism industry centred on non-consumptive wildlife recreation (Duffus & Dearden, 1993; Blane & Jackson, 1994; Corkeron, 1995; Findlay, 2000). At its 1993 annual meeting in Kyoto, Japan, the International Whaling Commission (IWC) resolved to 'recognise whale watching as an expanding tourist industry which contributes significantly to the economies [of a number of countries]' and to recognize 'the contribution which whale watching makes to education and to further scientific knowledge'. The following year, an IWC resolution explicitly encouraged whale-watching as a sustainable use of cetacean resources (International Whaling Commission, 1994). Tilt's (1986) survey of knowledge and attitudes in relation to whale-watching in California (which included perceptual, attitude and knowledge statements) found that 86% of respondents judged that seeing a whale in the wild was one of their greatest outdoor experiences and 88% wanted to touch a whale. Clearly whales engender significant interest on the part of the general public, and a large industry has grown up around providing recreational whale-watching opportunities. Relatively little is known about the nature of the interactions between whale-watchers and whales, or the impact of whale-watching activities on cetacean behaviour and physiology (Corkeron, 1995; Au & Green, 2000; Erbe, 2002). The known behavioural responses of whales to the presence of whale-watching boats include boat avoidance, attraction to boats, shortened bouts of surface feeding and longer dives, and alteration of travelling behaviour (Watkins, 1986; Blane & Jackson, 1994).

In coastal British Columbia, Canada, killer whales *(Orcinus orca)* can be found in highly sociable, stable family groups ('pods') organized on a matriarchal lineage. Pods usually consist of several mothers and their offspring, which generally travel together. They may include as many as 45 individuals, but an average size is 5–20. Killer whales generally swim at speeds of 2–8 km h^{-1}, sometimes travelling as a tightly knit group and at other times dispersed over a few square kilometres. The so-called Northern Resident Community of killer whales, which are the subject of this paper, have a geographic range extending from North Georgia Strait to Kitimat, British Columbia, and along the west coast of Vancouver Island (Bigg, Olesiuk, Ellis, Ford, & Balcomb, 1990). During the summer months, 17 matrifocal pods (approximately 180 whales) visit Johnstone Strait on a weekly (sometimes daily) basis, principally to take advantage of foraging opportunities and to use pebble beaches as rubbing areas, the latter possibly to remove ectoparasites. Salmon constitute their major prey item and Johnson Strait acts as a 'bottleneck' during the salmon journey to the Fraser River, up which they travel to spawn (Nichol & Shackleton, 1996). Whales frequent areas contiguous to the salmon runs. Killer whales have highly developed acoustics, which are used for communication, navigation and to echo-locate prey (Ford, 1991).

The propensity of killer whales to use Johnstone Strait attracts a large number of whale-watching kayakers and tourists on charter and private pleasure vessels (Duffus & Dearden, 1993). Commercial whale-watching in this area began in the early 1980s and has grown from one operator in 1980 to 27 in 1990 (Johnstone Strait Killer Whale Committee, 1991). An estimated 30 000 recreational whale-watchers visit Johnstone Strait each year. Whales are frequently followed by more than one vessel, with whale-watching bouts lasting from several minutes to three or more hours at a time. During the recreational boating season, it is typical for as many as five or more vessels to follow a group of whales (Duffus & Dearden, 1993). Clearly the potential for whale disturbance is high, particularly with increasing whale-watching traffic.

In Johnstone Strait, killer whales spend much of their time at the Robson Bight Michael Bigg Ecological Reserve (hereinafter referred to as the reserve), an area that has been designated as a legal sanctuary for killer whales by the provincial government (Duffus & Dearden, 1993) (Fig. 1). The reserve is a narrow marine refuge bounded to the south by the shoreline and to the north by Johnstone Strait, which carries substantial boat traffic, including kayaks, recreational sailboats, powerboats, commercial fishing boats and cargo carriers. At the time of this study, it included marine and terrestrial components of 1750 ha in area, was approximately 10 km in length and varied in width from 1 to 2 km from the shore. An unofficial code of conduct urges boat operators to keep a minimum distance of 100 m from

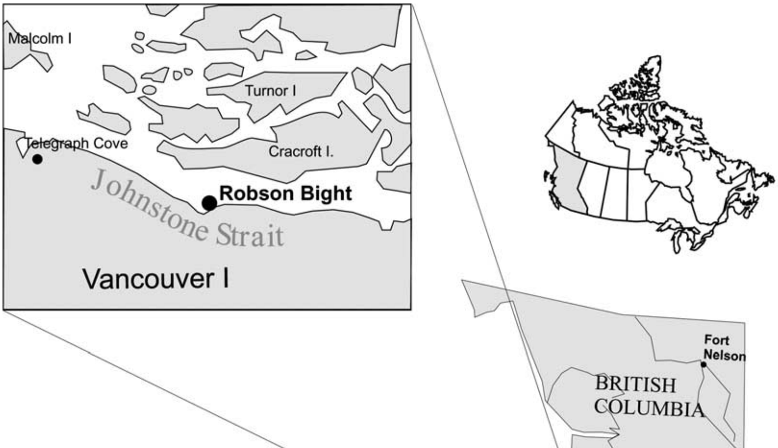

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Fig. 1. Location of the study site within Canada and the province of British Columbia.

whales in the strait, and the reserve itself is closed to recreational traffic (Johnstone Strait Killer Whale Committee, 1993). Despite these efforts, the reserve is frequented by whale-watching boats. Moreover, limited enforcement of guidelines challenges the reserve's effectiveness as a protective area for whales (Trites, Hochacka, & Carter, 1995). Protection, however, is a complex issue, both in terms of institutional jurisdiction, and because a legal description of harassment of marine mammals does not exist.

The most pressing management issue facing the whale-watching industry is disturbance of whales by recreational boat traffic and whale-watching activities (Duffus & Dearden, 1993; Trites et al., 1995). There has yet to be an analysis of user groups categorized by vessel type, either in terms of whether they respect the reserve boundary, or their effects on the spatial characteristics of whale movements. Moreover, there is virtually no information in the marine geography literature, or wildlife management and recreation literature, that makes such comparison. Better quantitative information is necessary as a first step in determining the degree to which killer whales may be facing undue pressure from whale-watching vessels. The aims of this study are to analyse (1) the spatial distribution of whale-watching vessels with respect to the reserve and (2) the relationship between boats and the distribution of whales. The hypothesis is that whale-watching encounters vary spatially in relation to the reserve, and that this spatial variation can be attributed to different characteristics of recreational whale-watching vessels.

We focus on two principal sets of questions. First, is there variation in the degree of boundary violation among different groups of whale-watchers according to vessel type (e.g. kayak, charter, pleasure craft)? We hypothesized that certain vessel types pursue whales for longer distances relative to others, owing in part to their variable ability to track whale movements precisely and quickly. A related question concerns whether there are differences in boundary violation when whale-watching vessels are grouped in terms of method of propulsion (e.g. motor, sail, paddling). The second series of questions relates to the spatial relationships that exist between patterns of movements of whale-watching vessels and killer whales. This serves as a first approximation of the effects of whale-watching vessels on killer whales.

Methods

Field personnel were placed at the edge of the northern cliffs of Cracroft Island, overlooking Johnstone Strait, in June, July and August 1997. They were equipped with a theodolite and spotting scope to monitor whale-watching traffic entering the study area. Cartesian coordinate locations of vessels were recorded at various points during each vessel–whale encounter (defined as any vessel moving within 300 m of a whale). Distance measurements were corrected for tide using a theodolite and tide tables. A total of 314 vessel–whale encounters were recorded on weekdays between 09.30 and 17.30 PST. Data include encounter time and location, vessel type, vessel registry and behaviour (movement pattern), whale orientation, whale speed, whale spacing and whale identification.

Vessels were classified into seven types: charter motor, charter sail, kayak, large pleasure motor, large pleasure sail, small pleasure motor and small pleasure sail. Vessel movement behaviour relative to whales was classified following Tilt (1985) and included the following:

1. a side approach, indicating a vessel approaching from either side of a whale;
2. a rear approach, occurring when a vessel follows a whale;
3. a head-on approach, placing the vessel in the path of a whale, and
4. drifting, occurring when the engine is turned off, usually when observing a slow-moving whale.

Whale speed was categorized into three groups:

- ‘fast’ (whale speed estimated at 4 knots or greater);
- ‘slow’ (whale speed $<$4 knots), and
- ‘motionless’ (no movement).

Whale spacing was defined by the dispersal of whales comprising a pod:

- small-level dispersion (all whales of a pod within 5 m of one another);
- moderate-level dispersion (whales grouped within 5–19 m), and

- high-level dispersal (whales spaced 20 m or more apart).

Whale orientation was classified as directional or non-directional, directional movement being defined as movement from one area to another and non-directional movement as resting or milling within an area. Altogether 260 observations were transcribed and used for analysis. The ESRI ARC/INFO geographic information system (GIS) was used to display and analyse vessel–whale encounter data. Digital line coverages were generated from vessel coordinate locations, coastlines and the reserve boundary. Geographic coverages were linked to attribute tables consisting of encounter time and date, vessel type, and vessel and whale behaviour.

Vessel distribution relative to the reserve

The distribution of vessels was overlaid in a GIS with the coastline and the reserve boundary to analyse differences in vessel movement (Figs 2–8). Particular attention was focused on reserve violation. If a vessel–whale encounter moved into the reserve, it was considered a violation. The distribution of reserve violations was recorded and mapped for each vessel type using ARC/INFO. Variations in reserve violation were analysed using a two-sample χ^2 test.

The reserve is bounded on the west by a line extending from the information sign at Sir John Henry Creek 1 km offshore and on the east by a line extending from the information sign at Schmidt (Peel) Creek to 1 km offshore. In total, the reserve encompasses some 1248 ha of marine habitat (and 505 ha of upland habitat). Although there is considerable signage onshore drawing attention to the protected area, the precise location of the seaward boundary is not marked by buoys or other similar navigational devices. Thus boundary violation may occur that is not necessarily purposeful. Therefore, to determine if vessel operators were attempting to approximate the boundary location, the sensitivity of the boundary to violation was tested. Using ARC/INFO, a 200-m buffer was generated around the reserve and a

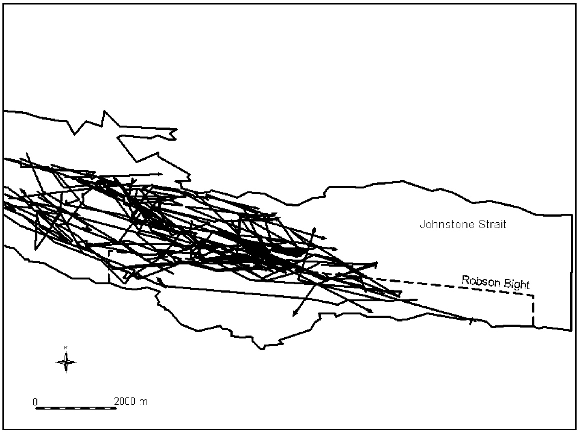

Fig. 2. Charter motor vessel whale encounters.

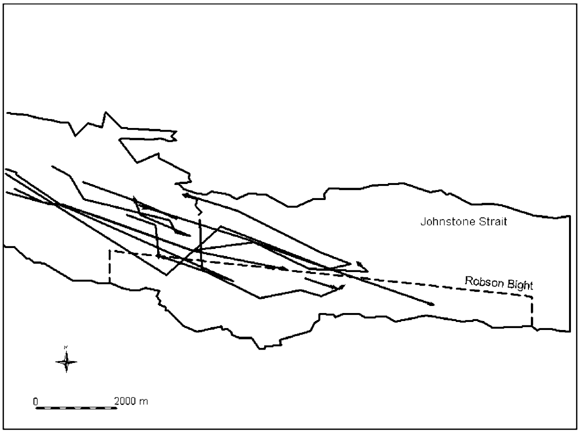

Fig. 3. Charter sail vessel whale encounters.

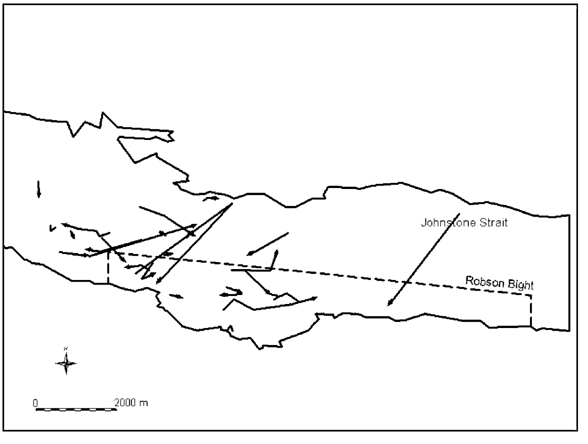

Fig. 4. Kayak whale encounters.

spatial query was used to detect encounters occurring within it (i.e. 100 m on either side of the boundary). The size of the buffer is somewhat arbitrary, though it is also based on the belief that boaters may have a difficult time judging more precisely the average 1-km distance from shore that delimits the seaward boundary of the reserve. Baird and Burkhart (2000) assert that humans underestimate distance on water. In effect, the buffer recreates the boundary as a zone, rather than as an area demarcated by sharp, cartographic-like lines. Reserve violation was then tested a second time by adding only those encounters occurring within the boundary and comparing the results to the original analysis.

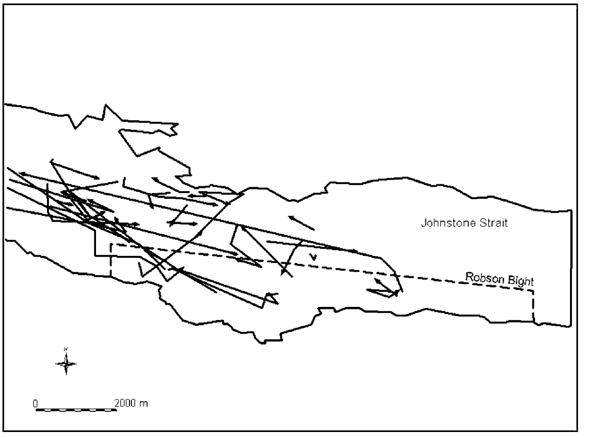

Fig. 5. Large pleasure motor vessel whale encounters.

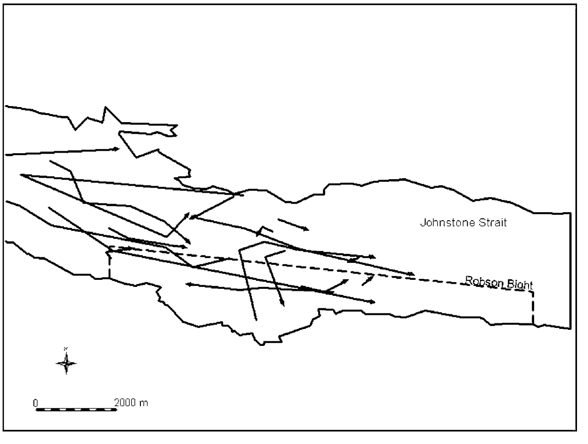

Fig. 6. Large pleasure sail vessel whale encounters.

Directional analysis of vessels

Directional movement of vessels was used to analyse vessel activity in the vicinity of the reserve. By examining patterns in vessel movement and the relationship between vessel orientation and alignment with the boundary, it is possible to determine if vessel operators appeared to avoid the boundary. Rayleigh's test (Davis, 1984) was used to evaluate the null hypothesis that vessel types do not vary in direction of travel with respect to the boundary. Rayleigh's test is based on the von Mises distribution (which is a circular equivalent to the normal distribution) to test for randomness in directional data according to the mean resultant length of the sample. Since directional data may be expressed as either of two opposite directions, data must be represented in a different manner to avoid over-inflating the dispersion

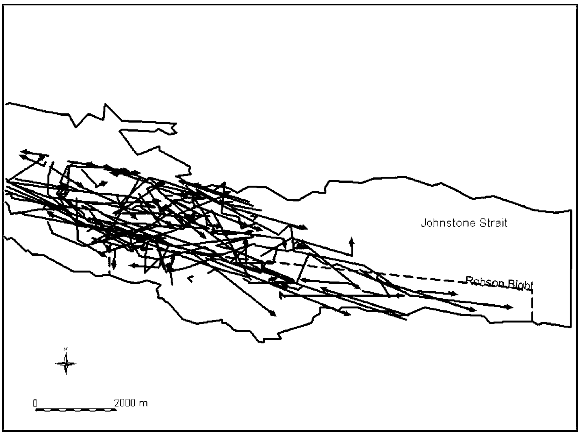

Fig. 7. Small pleasure motor vessel whale encounters.

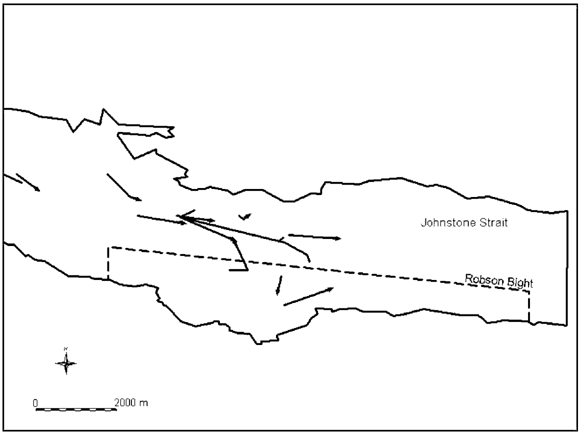

Fig. 8. Small pleasure sail vessel whale encounters.

of measurements. To correct this situation, angle measurements are doubled, since the same angle is recorded regardless of direction. The resultant length (R) is computed as

$$R = [(X_1)^2 + (Y_1)^2]^{1/2} \quad (1)$$

where X_1 = sum of the cosines of the vector angles
Y_1 = sum of the sines of the vector angles

The mean resultant length (R^*) was obtained by

$$R^* = R/n \quad (2)$$

To evaluate the null hypothesis that the directional observations are random (i.e. there is no preferred direction, or the probability of occurrence is the same for all directions), the mean resultant length of each vessel type was compared to a critical value for Rayleigh's test ($p < 0.05$). If the computed value of the mean resultant length exceeds the critical value, the null hypothesis is rejected and the vessel type must be exhibiting a 'preferred' (i.e. non-random) directional trend (Mardia, 1972).

To further investigate the spatial distribution of whale-watching vessels, a second null hypothesis was tested – that vessels classified by type are not aligned with the reserve boundary. First, mean angles of direction were calculated by vessel type. Cartesian coordinate pairs for encounter locations were determined using ARC/INFO, from which angles for each coordinate pair were generated based on the maximum and minimum coordinate points forming two adjacent lines completing a right-angled triangle.

To determine if a relationship existed between vessel type and boundary alignment, a confidence angle was calculated around the mean direction of observations for vessel types having preferred directional trends (Eq. 3). The standard error of the mean direction (Eq. 4) is determined with R equal to the mean vector length and k equal to the concentration parameter. The confidence angle was used to determine if it was large enough to include the reserve boundary. If the confidence angle contained the reserve boundary angle, then the direction of vessel travel was aligned with the reserve boundary. Since the confidence angle is based on the standard error of the estimate of the mean direction, the sample size (n) and dispersion are implicit in the formulation. The interval

$$\theta \pm Z_a s_e \tag{3}$$

contains the population mean (θ = mean angle of direction) 95% of the time. The approximate standard error of the mean direction, given in radians is

$$s_e = \frac{1}{(nRk)^{1/2}} \tag{4}$$

Vessel–whale interaction

Cumulative vessel speed was calculated by measuring the encounter distance divided by the total encounter time. Comparisons of vessel speed were made among vessel types in addition to comparisons of vessel behaviour were made. Chi-square tests of independence (Jelinski, 1991) were used to determine if statistical relationships existed between variables characteristic of whales (i.e. speed, spacing and orientation) and vessel variables (vessel type, method of propulsion and movement patterns). Directional and non-directional whale movements were analysed to determine their role in vessel–whale interactions.

Results and discussion

Vessel distribution

A total of 314 whale-watching boat encounters with killer whales were recorded. On average, vessel location and movement pattern (behaviour) were recorded 4.4

times per whale encounter. Vessel behaviour was recorded at least twice during each encounter, with a maximum of 14 observations. The encounter duration was not significant among vessel types ($p > 0.05$); however, when vessels were compared in terms of method of propulsion, motorized vessels exhibited longer encounter times compared to non-motorized vessels (Mann Whitney *U* Test, $Z = -2.51$, $p < 0.05$) (Fig. 2). Charter motor vessels had the longest encounter times (averaging 73 minutes), with kayaks tracking whales for the shortest times (2 minutes). The average time of contact for motorized vessels was 46 minutes compared to 34 minutes for non-motorized vessels. When the duration of encounters was combined into an aggregate time of viewing, charter vessels were found to have over 70 hours of documented encounters with whales during the two-month period.

Reserve violations occurred among all vessel types. An average of 39% of all vessels that were tracked violated the reserve boundary, varying from 48% of kayaks to 23% of small pleasure sail craft (Table 1). However, variation in reserve violation among vessel types was not statistically significant ($\chi^2 = 3.2$, df = 6, $p = 0.05$). Similarly, variation in reserve boundary violation when boats were classified by method of propulsion (motorized vs non-motorized) and vessel size (small and large) were not found to be statistically significant ($\chi^2 = 0.477$, df = 1, $p = 0.05$ and $\chi^2 = 0.276$, df = 1, $p = 0.05$, respectively). Thus, the ability of vessels to move in (and presumably out) of the reserve quickly, as can be done with motorized vessels, does not appear to be a motivating factor in terms of violating the reserve boundary.

To explore the effect of vessel type on boundary awareness, vessel–whale encounters that occurred in the 200-m buffer were analysed. The presence of vessels in the buffer may suggest attempts to remain outside the reserve and keep the required 100-m distance from whales. Less than a quarter of charter sail encounters (23%) and 15% of kayak encounters occurred in the buffer, yet these two vessel types most frequently violated the boundary, indicating a readiness to enter the reserve purposefully. Buffer encounters for each of the remaining vessel types – charter motor, large pleasure motor, large pleasure sail, small pleasure motor and small pleasure sail – were below 10%.

Table 1
Distribution of whale-watching boats by location and type in Johnstone Strait and the Robson Bight–Michael Bigg Ecological Reserve, British Columbia

Vessel type	Total number of encounters (%)		
	Reserve	Strait	200-m buffer
Charter motor	25 (39.1)	39 (60.9)	0 (0.0)
Charter sail	6 (46.2)	7 (53.8)	3 (23.1)
Kayak	13 (48.1)	14 (51.9)	4 (14.8)
Large pleasure motor	12 (38.7)	19 (61.3)	2 (6.5)
Large pleasure sail	8 (44.4)	10 (55.5)	1 (5.6)
Small pleasure motor	34 (36.2)	60 (63.8)	10 (10.6)
Small pleasure sail	3 (23.1)	10 (76.9)	1 (7.7)

When buffer encounters were included with reserve encounters, the proportions of reserve violation by vessel type remained similar to reserve-only encounters. As with the previous analyses, no significant variation was found in vessel distribution within the reserve when the buffer observations were included ($\chi^2 = 7.7$, df = 6, $p > 0.05$). In summary, there were no significant differences in reserve violation by vessel type. Motorized vessels did not have lower reserve violation rates than non-motorized vessels, despite their greater size and manoeuvrability, which would permit them to be more responsive to whale movements as well as increase their ability to move in and out of the reserve.

Directional analysis of vessels

The majority of vessels generally travelled from either west to east or east to west. Although the maps of vessel– whale encounters illustrate the overall complexity of directional vessel movement in the Strait (Figs 2–8), clear patterns of vessel movement do emerge when vessels are categorized by vessel type. Analysing boat movements in the vicinity of the reserve using Raleigh's test (Eq. 2) revealed directional trends with respect to the reserve boundary for five of seven vessel types (Table 2: charter motor, charter sail, large pleasure motor, large pleasure sail and small pleasure motor vessels). These showed significant mean resultant lengths ($p < 0.05$), indicating a deliberate mean direction of travel relative to the reserve. Kayaks and small pleasure sailing craft had unidirectional paths, leading to the conclusion that for them whale-watching is mostly opportunistic; they did not show regular changes in course direction in response to changing directions by killer whales (beyond following whales into the reserve).

Secondly, a confidence angle 'envelope' around the mean direction of observations was calculated for each of the five vessel types having a preferred directional trend (Eq. 3). Angles of travel direction varied slightly among five vessel types, with the highest mean angle occurring in charter sail vessels and the lowest in small pleasure motor vessels. The angle of the reserve boundary was compared to each vessel type's 95% confidence angle. The reserve boundary is located at an angle of 186.8° and none of the confidence angles were within the confidence limits at a 95% probability

Table 2
Directional trends among types of whale-watching boats in Johnstone Strait and the Robson Bight–Michael Bigg Ecological Reserve, British Columbia[a]

Vessel type	Mean angle of movement (°)	Confidence limits (°)
Charter motor	226.3	214.7–238.0
Charter sail	243.1	223.9–262.3
Large pleasure motor	226.1	198.7–253.5
Large pleasure sail	225.6	199.4–251.8
Small pleasure motor	220.2	202.9–237.6

[a] For the five types of boats that exhibited statistically significant directional trends

level. Thus the null hypothesis that vessel types are not aligned with the reserve boundary is rejected. Similarly, the results of Raleigh's test for randomness in directional data do not support the null hypothesis that vessel types are not aligned with the boundary. For none of the vessel types was direction of travel aligned with the reserve boundary. Thus vessels do not align themselves on a track parallel to the reserve boundary from which they would observe whales inside the reserve.

Vessel approaches to the reserve boundary varied only slightly among the five vessel types that exhibited directional trends, with the difference between the boundary's alignment and the angle of vessel movement ranging from 34 to 57°. The calculated angles exhibit a predominant northwest to southeast movement. Clearly, these represent a narrow margin of approach positioned towards the reserve (i.e. as vessels approach the reserve, they fall in a range of 23° off the reserve angle). Small angles or parallel movement suggest reserve avoidance, while large angles or perpendicular movement indicate a higher potential for reserve violation. Travelling at or near an angle of 45° allows for a close viewing opportunity while remaining outside the reserve.

Motorized vessels (both large and small) exhibited the most frequent zigzag-like changes in direction while in seeming pursuit of whales. It is assumed that this behaviour mirrored the whale movements, indicating possible evasive tactic on the part of killer whales. This is consistent with theory concerning predator avoidance and evasion tactics (Weihs & Webb, 1984).

In summary, analysis of vessel travel allows for first-order determinations of boundary awareness, with travel on a line parallel to and outside the reserve suggesting whale-watchers intent on not violating the reserve boundary. Our findings, however, do not support a high degree of avoidance of the reserve boundary. It is possible that the precise location of the reserve boundary is not well known to vessel operators, particularly since it is difficult to accurately estimate distance over water (Baird & Burkhart, 2000). Even when this contingency is accounted for by the construction of a liberal buffer zone around the boundary, our findings still support the conclusion that the reserve boundary does not influence or restrict directional movement of vessels.

Vessel movement patterns

Vessel movement patterns varied significantly according to vessel type ($\chi^2 = 30.2$, df = 18, $p < 0.05$). and method of propulsion ($\chi^2 = 10.8$, df = 3, $p < 0.05$). Certain movement patterns could be considered inherent to a vessel type, thereby explaining some variation. For example, head-on approaches are easy for motorized vessels that can quickly respond to whale movements. Side approaches may be more suitable for non-motorized vessels, as they constrain forward motion of the vessel. Drifting and side approaches accounted for approximately 80% of all vessel movements. Drifting was the predominant behaviour in charter motor, kayak, large pleasure motor, small pleasure motor and small pleasure sail vessels. Side approaches occurred most frequently among charter sail and large pleasure sail vessels. Head-on approaches (11%) and those from the rear (8%) were less common, with head-on approaches being slightly higher among motorized vessels. From an acoustics point of view, head-on approaches are most disturbing to whales; side or rear approaches are less disruptive to whale communication (Erbe, 2002).

Whale movements and vessel behaviour

Directional movement is defined as movement from one area to another, and non-directional movement as resting or milling within an area. Whale movement was associated with patterns of movement in whale-watching vessels ($\chi^2 = 16.98$, df = 3, $p < 0.05$); however, there was no significant relationship between whale orientation and vessel type when categorized by method of propulsion ($\chi^2 = 0.375$, df = 1, $p = 0.05$) nor vessel size ($\chi^2 = 0.427$, df = 1, $p = 0.05$). When vessels were present, killer whales often moved toward the open waters of Queen Charlotte Strait. This finding is in agreement with suggestions that killer whales in the Strait alter their direction of travel when approached by vessels (Johnstone Strait Killer Whale Committee, 1991).

Vessels and whale speed

There was no association between whale speed in relation to vessel movement patterns ($\chi^2 = 9.837$, df = 6, $p = 0.05$), method of propulsion ($\chi^2 = 0.634$, df = 2, $p = 0.05$) or vessel size ($\chi^2 = 5.03$, df = 2, $p = 0.05$). By comparison, Richardson, Fraker, Wursig and Wells (1985) reported a strong increase in swimming speed in bowhead whales *(Balaena mysticetus*) in response to approaching vessels. Similarly Baker, Herman, Bays and Bauer, 1983 claimed that humpback whales (*Megaptera novaeangliae*) swim faster in the presence of vessels. Blane (1990) found that beluga whale (*Delphinapterus leucas*) response increased as the number of vessels increase. While there was no statistically significant relationship between whale speed and the number of vessels in the present study, some whales did exhibit increased speeds when more than two vessels were present, a tendency noted by Kruse (1991) for a similar-sized whale population. Kruse also found that killer whales did not respond differently (in terms of whale speed) to varied boat sizes, nor did whales respond differently to outboard motors or inboard engines. The methods for recording whale speed are somewhat coarse, however, as they were simply grouped into three categories. More importantly, there could be gender-based sampling bias in that males and females may respond differently to various boat craft in terms of speed or directional movements. Our data do not permit distinguishing whales on the basis of sex.

Whale spacing

Whale spacing did not vary significantly with vessel behaviour (i.e. its course trajectory) ($\chi^2 = 11.96$, df = 6, $p = 0.05$) or size ($\chi^2 = 3.96$, df = 2, $p = 0.05$), but it was clearly associated with method of propulsion ($\chi^2 = 10.96$, df = 2,

$p = 0.05$). The acoustical abilities of marine mammals is a highly developed sensory receptor compared to vision and chemoreception. Acoustics are used by marine mammals for a variety of purposes and vary from species to species. For toothed whales such as killer whales (i.e. odontocetes), underwater noise can mask the animal's abilities to navigate and locate food (Erbe & Farmer, 2000 and references therein; Erbe, 2002). Given that killer whales frequent Johnstone Strait because it is a rich source of salmon, the potential for finding food is compromised by boat noise. Further, killer whales have highly developed social systems, and underwater noise may mask communication signals that relate to social cohesion, group activities, mating, warning or individual identification (Erbe & Farmer, 2000). The possible consequences of ocean noise include short- and long-term changes in behaviour, with possible profound physiological consequences (see review in Richardson, Greene, Malme, & Thomson, 1995).

Frequent and extensive boat noise has been present in Johnstone Strait since the early 20th century, yet killer whales continue to use areas of high underwater noise. It may be that they have become habituated to the presence of boat noise. This does not negate the possibility, however, that boat noises may have an impact on them. Bain and Dahlheim (1994) assert that boat noise may reduce the distance over which killer whales can effectively search for and identify sources of food by masking the low-frequency components of echo-location click trains (other calls include burst-pulse sounds and whistles (Ford, 1991)). Erbe (2002) showed that boat noise can interfere with killer whale communication, though its effects on their navigational or prey searching remains poorly known. Cavitating propellers exhibit pure tones at low frequencies, with the lowest tones corresponding to the rotational speed of the propeller (Erbe, 2002). At low speeds, propeller cavitation is reduced (Erbe, 2002) and thus the masking of prey-searching echo-location sounds may well be reduced.

The effect of underwater noise from whale-watching boats on killer whales has been studied by Erbe (2002), who measured boat noise and modelled its acoustic impacts. She considered four potential impacts:

1. the zone of audibility predicts the ranges and depths over which noise is audible to killer whales;
2. the zone of masking predicts over what ranges and depths boat noise might obscure communication sounds of killer whales;
3. the zone of responsiveness predicts over what ranges killer whales are likely to react to boat noise, and
4. the zone of hearing damage predicts over what ranges and depths a temporary or permanent hearing loss can occur.

Erbe showed, for example, that an inflatable boat (zodiac) with twin 150-hp outboard motors travelling at 51 km h^{-1} can be audible to killer whales over ranges of about 16 km, can mask killer whale calls over 14 km, can elicit a behavioural response over 200 m, and can cause a temporary threshold shift (TTS) in hearing of 5 dB after 30–50 minutes within 450 m. If boats such as a zodiac with twin 225-hp outboard motors slow to 10 km h^{-1}; however audibility and masking are reduced to 1 km, behavioural responses reduced to 50 m and TTS to 20 m. Masking is strongest when the noise and signal come from the same direction (Erbe, 2002). Unfortunately, no studies have assessed the long-term possible impacts on reproductive rates, mortality, or habitat avoidance; principally because of the difficulty in isolating whale-watching effects from other environmental factors such as changes in food resource availability or climate/oceanographic effects such as El Niño (Erbe, 2002).

The effects of boats and method of propulsion have been confirmed in other studies of cetaceans. Irvine, Scott, Wells and Kaufmann (1981) found bottlenose dolphins *(Tursiops truncatus)* left an area when a motorized vessel was present. Stewart, Evans and Awbrey (1982) stated that beluga whales may react differently to outboard motors than diesel engines and Baker et al. (1983) reported that humpback whales appeared to respond to vessel size. On the other hand, there is no evidence that grey whales, which are well known to interact closely with humans in Baja, respond to the noise of boat engines. Au and Green (2000) measured the underwater acoustic noise of three representative humpback-whale-watching boats in the waters of Hawaii (inflatables with outboard engines, coastal boats with twin inboard diesel engines, and a small water-plane twin-hull ship). They found boats with inboard engines produce less-intense sounds with fewer tonal bands, and inflatables produced complex sounds with many bands of tonal-like components. Erbe (2002) also found that inflatables were slightly louder than motorboats when controlling for speed. Overall, however, Au and Green (2000) concluded that it is unlikely the levels of sounds produced by the boats would have 'grave effects' on the auditory system of humpback whales. In order to substantiate a link between whale spacing, movements and vessel characteristics, more testing involving the presence and absence of vessel characteristics is necessary. Even after doing this, however, one would need to be careful about drawing conclusions, since other factors, such as bubbles and flashing of propellers, may be involved, plus confounding effects of environmental sounds such as surf.

Summary and conclusions

Concern that unregulated and increased whale-watching may harm or displace whales is escalating (Beach & Weinrich, 1989; Corkeron, 1995; IFAW, 1995). A primary objective of a whale-protection area should be to provide a safe environment free from harassment and disturbance while, ideally, allowing humans to enjoy a wildlife-watching experience. Identifying acceptable levels of human whale interactions is critical for establishing regulations that minimize impacts on whales. Until there is compelling evidence that only specific types of recreational behaviour significantly impact killer whales, the potential for whale disturbance will continue to be based on general activity classifications (e.g. consumptive) rather than on impact-based activities that clearly demonstrate the relationship between the wildlife viewers and the focal species.

In this study, significant differences were revealed between vessel types in encounter direction and whale-watching boat behaviour. All vessel types, except kayaks and small pleasure sail vessels, demonstrated a preferred, deliberate direction of travel in Johnstone Strait, suggesting behaviour characteristic of tracking whales. The vessel patterns indicate, however, that the reserve boundary does not influence or restrict directional movement of vessels. Furthermore, reserve violation is high among all user groups, as there is minimal evidence of vessels actively avoiding the sanctuary and its boundaries. This is an important finding, because reserve violation not only challenges the effectiveness of the reserve, it also illustrates the potentially aggressive nature of wildlife viewing. Upon contact with whales, vessel movement patterns were dominated by drifting and side approaches, with head-on approaches occurring slightly more often in motorized groups than non-motorized groups. Vessel behaviour was also associated with vessel size and method of propulsion. Analyses of vessel whale interaction showed a statistically significant relationship between whale orientation and vessel behaviour, as well as a relationship between whale spacing and method of vessel propulsion. These results indicate possible short-term changes in killer whale movement, although studies are needed to ascertain more definitively the short- and long-term physiological and behavioural consequences of exposure to whale-watching boats. We support the recommendations of Erbe (2002) for killer whale-watching, which were based on acoustic analysis of whale-watching and suggest that slow cruising boats should approach no closer than 50 m to avoid hearing loss and changes in behaviour, and that a cruising speed of about 10 km h^{-1} is recommended within a few hundred metres of killer whales. Where possible, motors should be turned off rather than left to idle. Finally, when there are a number of boats (e.g. five or more), superimposed noise levels may cause permanent hearing damage over prolonged exposure, though this can be avoided if boats stay at a minimum distance of 400 m.

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