The effects of berleying on the distribution and behaviour of white sharks, *Carcharodon carcharias*, at the Neptune Islands, South Australia

FINAL REPORT

August 2011

B. D. Bruce ☐ R. W. Bradford

CSIRO Wealth from Oceans Flagship
Marine and Atmospheric Research, Hobart, Tasmania

Client: Department of Environment and Natural Resources
South Australia

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Introduction

Seal and sealion (pinniped) colonies are important feeding sites for white sharks across their global distribution. However, white sharks are only temporary residents to such colonies, as pinnipeds form only a component of their annual diet (Bruce 2008). The periods of residency of white sharks at pinniped colonies are regionally variable and can range from days to months. Individuals may return on an annual or more frequent basis after spending considerable intervening periods distant from these sites where they focus on other sources of prey (Bonfil *et al*. 2005, Bruce *et al*. 2006, Domeier and Nasby-Lucas 2007). White sharks commonly make extensive movements over distances of 1000s of kilometres between visits to pinniped colonies including travel from temperate to tropical waters and, in some areas, they can spend considerable periods in the open ocean (Boustany *et al*. 2002, Bruce *et al*. 2006, Weng *et al*. 2007, Domeier and Nasby-Lucas 2008, Bonfil *et al.* 2010).

The regularity with which white sharks visit some pinniped colonies and the often protected anchorages these provide, makes these sites ideal for shark-viewing tourism. White shark cage diving is now well established around certain pinniped colonies known to have significant white shark activity in areas such as South African, Mexico, California and southern Australia (Malcolm *et al*. 2001, Domeier and Nasby-Lucas 2007, Laroche *et al*. 2007). White shark cage diving requires that sharks are first attracted to the viewing vessel to increase the likelihood of visible contact time. The most common means of doing so is through the use of berley (chum) which is generally a mix of chopped or minced fish and fish oil, although other animal products are used in various areas of the world.

In Australian waters, white shark cage diving currently occurs exclusively at the Neptune Islands in South Australia, approximately 60-70 km south of Port Lincoln. The Neptune Islands support the largest aggregation of pinnipeds in Australia and is an active feeding area for white sharks (Shaughnessey and McKeown 2002, Bruce *et al*. 2006). The waters surrounding the Neptune Islands to a distance of two nautical miles from low water mark were incorporated into the Neptune Islands Conservation Park in 1997 and the area was gazetted as Marine Park in 2009. White shark cage diving has a long history in South Australia, first commencing in the 1960s and commercial tours have operated at various sites including Dangerous Reef, The Sir Joseph Banks Group, The Pages and the Neptune Islands since the late 1970s. The industry has involved up to eight operators, although this number declined to two by 2000. Since 2002, white shark cage diving has been restricted to waters surrounding the Neptune Islands and operators are required to hold a Commercial Tour Operator license pursuant to the National Parks and Wildlife Act 1972 and, if undertaking berleying, an exemption under the Fisheries Act 1982 to permit the use of berley for attracting white sharks which is otherwise prohibited in waters within two nautical miles of the coast. The composition of berley is restricted to fish-based products and the industry has worked under a Code of Practice since 2004 to ensure that the operations are consistent with shark conservation, minimising negative impacts on sharks and maintaining client safety and satisfaction.

The shark cage diving industry in South Australia has seen a recent expansion in activities with the number of days where berley occurs rising from an annual average of 128 days (2000-2007) to 270 days in 2009-2010 (Figure 1). This has corresponded with a change in 2007 from irregular multi-day trips with berleying at various times, to a more regimented, near to daily operation with berleying occurring over a more regular daily schedule.

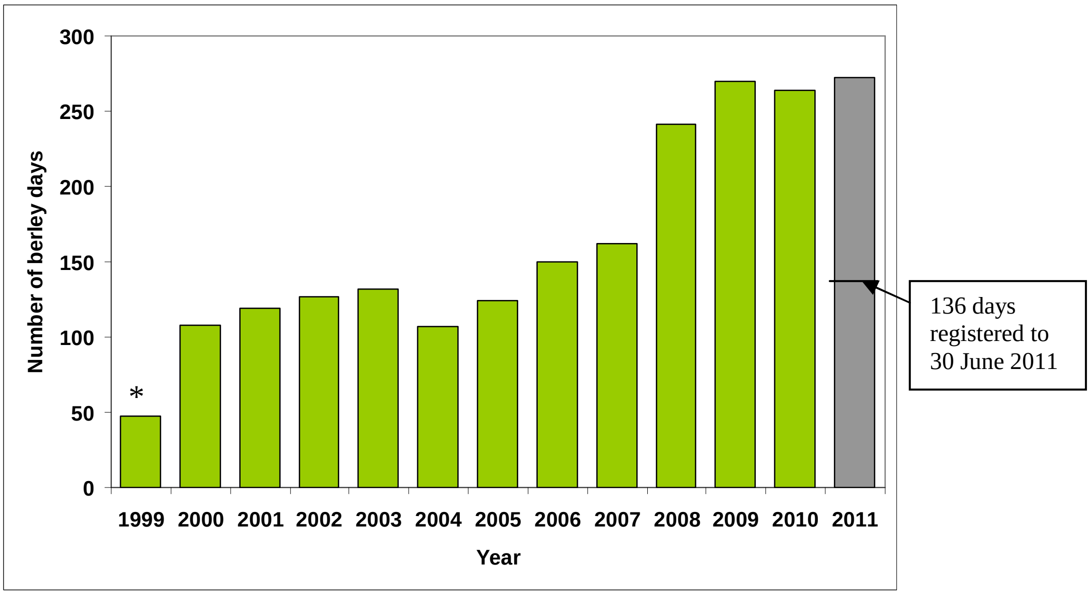

Figure 1: Number of days where berleying operations were undertaken at North Neptune Island in South Australia (1999-2011). Note that data for 1999* do not include a complete 12 month period (data includes only August - December) and thus underestimate the actual number of days. 2011 data in grey are projected (272 days) based on the 136 days registered from 1 January to 30 June 2011.

The prospect of additional active operators and the potential for further expansion of the industry has generated a number of issues for the two Government agencies that manage the industry (Department of Environment and Natural resources [DENR] and Primary Industries and Resources South Australia [PIRSA]) and a subsequent need to establish the underpinning science required to effectively manage the industry. Both agencies have identified a high priority need to investigate the impact of berleying on the behaviour of sharks at the Neptune Islands with the specific purpose of providing a rational management plan for the industry.

White sharks are protected in all Australian waters as a listed threatened species and are the subject of a national recovery plan (see DEWHA 2010). Evaluating the impact of cage-dive operations on shark behaviour is an identified priority action in the National White Shark Recovery Plan. The North Neptune Islands have been the site of significant research effort primarily in establishing white shark movement patterns, behaviour and habitat use. Sharks tagged with electronic tags (satellite, archival, acoustic) have been tracked from the Neptune Islands travelling across their Australasian range to offshore waters off Exmouth in northwest Western Australia, Rockhampton in central Queensland and across the Tasman Sea to New Zealand (Bruce *et al*. 2006). The movement of sharks from, and return to, the Neptune Islands from across their Australasian range suggests that this may represent a critical site for the species in Australian waters. This may have implications under the Environment

Protection and Biodiversity Conservation (EPBC) Act 1999 for activities at the site that have the potential to impact white sharks visiting the area.

The residency times and habitat use by white sharks at the Neptune Islands was the subject of study from 2001 to 2003 (Bruce *et al*. 2005). That study, using coded acoustic tags and bottom-moored acoustic receivers, concluded that berleying had a localised and short-term effect on the distribution and behaviour of sharks at the islands and that the effects were primarily concentrated within the bay of the main island where most berleying and shark cage diving activities occurred. The timing of that study during a period of comparatively lower berleying effort, provided an opportunity to examine if white shark behaviour had changed at the North Neptune Islands since the 2007 increase in berleying effort.

The purpose of this project was to examine the residency and movement patterns of sharks within the Neptune Islands system and to determine if there was evidence of changed behaviour in sharks visiting this site compared to the 2001-2003 data set. The primary data for comparisons to the 2001-2003 period came from an array of acoustic receivers that monitored the presence/absence of individual tagged sharks at both North and South Neptune Islands from 2010 to 2011. Additional data were obtained from a single acoustic receiver set inside the main bay at the North Neptune Islands since 2008 and from daily logbook data providing details of shark cage dive operator activities from 1999-2011. A series of three questions were posed for this study:

How do sharks currently use the Neptune Islands group?

What are the daily spatial patterns of habitat use at the North Neptune Islands and how do sharks respond to berleying operations?

How does the current pattern of habitat use compare to data collected in 2001-2003, prior to the 2007 increase in berleying effort?

Results of these data were integrated to assess the movements and patterns of residency of white sharks at the Neptune Islands and the effects of berleying on their behaviour.

Methods

Study area

The Neptune Islands (35^{o} 16.72’ S; 136^{o} 5.48’ E) are a series of granite formations rising steeply from waters of approximately 60-100 m depth. The islands comprise two groups, North and South Neptune Islands, which are approximately 12 km apart and are located 60-70 km south of Port Lincoln on the continental shelf. Each island group comprises two main islands and various small rock outcrops (Figure 2). Sub-tidal habitat includes areas of shallow sand and seagrass as well as shallow and deep reef systems (DENR 2010). Both island groups hold breeding colonies of New Zealand fur seals (*Arctocepalus forsteri*) and Australian sealions (*Neophoca cinerea*). Combined, the Neptune Islands group supports the largest aggregations of pinnipeds in Australian waters of which the majority reside on the North Neptune Islands (Shaughnessy and McKeown 2002). Both island groups are included within the Neptune Islands Marine Park. The marine park extends two nautical miles (3.7 km) from the coastline of each island group, covering an area of 146 km^2 (DENR 2010).

Field methods

Acoustic receivers

Arrays of acoustic receivers (VR2W and VR3-UWM - Vemco-Amirix Ltd, Halifax, NS Canada) were deployed at both North and South Neptune Island sites over two consecutive periods between December 2009 and April 2011. These deployments are herein referred to as the 2010-2011 study. Eight receivers were deployed at North Neptune Island and three at South Neptune Island, eleven in total (Figure 2). The array at North Neptune Island complemented an existing, iridium satellite-linked acoustic receiver (VR4-Global [VR4G]; Vemco-Amirix Ltd, Halifax, NS Canada) which has been maintained within the main island's bay since 1 April 2008 (Bradford *et al.* 2011). Acoustic receivers log and store the date, time and unique code identity of Vemco RCODE acoustic transmitters fitted to animals that swim within the detection range (typically a 300-500 m radius). Data retrieval from VR2W acoustic receivers requires that units are physically recovered and downloaded. Data retrieval from a VR3-UWM is possible via an acoustic communications modem incorporated within each unit which can be remotely activated from a vessel-based hydrophone and deck unit system without retrieving the units. The initial deployment of receivers in December 2009 included both VR2W and VR3-UWM units. VR3-UWM units were used to allow for opportunistic retrieval of data between full retrieval periods. However, this proved impractical and all VR3-UWM units were replaced with VR2W receivers for the second deployment period.

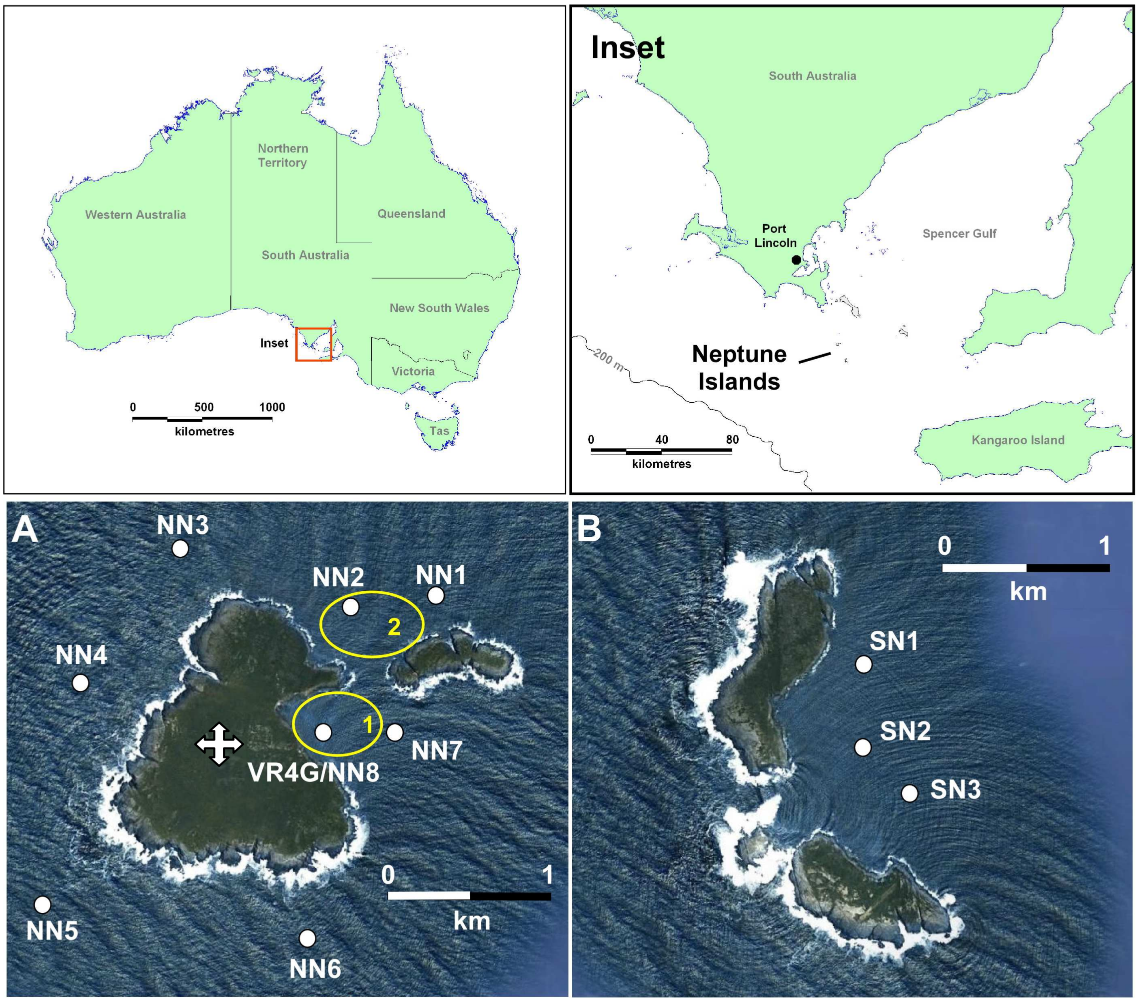

Figure 2. The location of the Neptune Islands, South Australia (insets). (A) North Neptune Islands; (B) South Neptune Islands. The locations of acoustic receivers are illustrated as white dots; berley regions are circled in yellow (1) Site 1; (2) Site 2. The reference point on North Neptune Island for centre of activity analyses is marked by the white cross. Receiver NN8 was positioned on the mooring line of the VR4G receiver.

Receiver moorings were anchored to the sea floor using either concrete filled truck tyres (approx 120 kg total mass) or 20 mm chain moorings each approximately 200 kg total mass, following protocols developed by the Australian Animal Tracking and Monitoring System (AATAMS - http://imos.org.au/aatams.html). Receivers were fixed to a 14 mm braided line attached to the mooring anchor and suspended under subsurface floats, with the receiver about 20 m below the surface. Moorings were located in bottom depths ranging between 23 and 93 m. Each mooring was fitted with a Sub Sea Sonics acoustic release mechanism and a rope canister which allowed receivers to surface on command and for the complete mooring system to be retrieved (Figure 3).

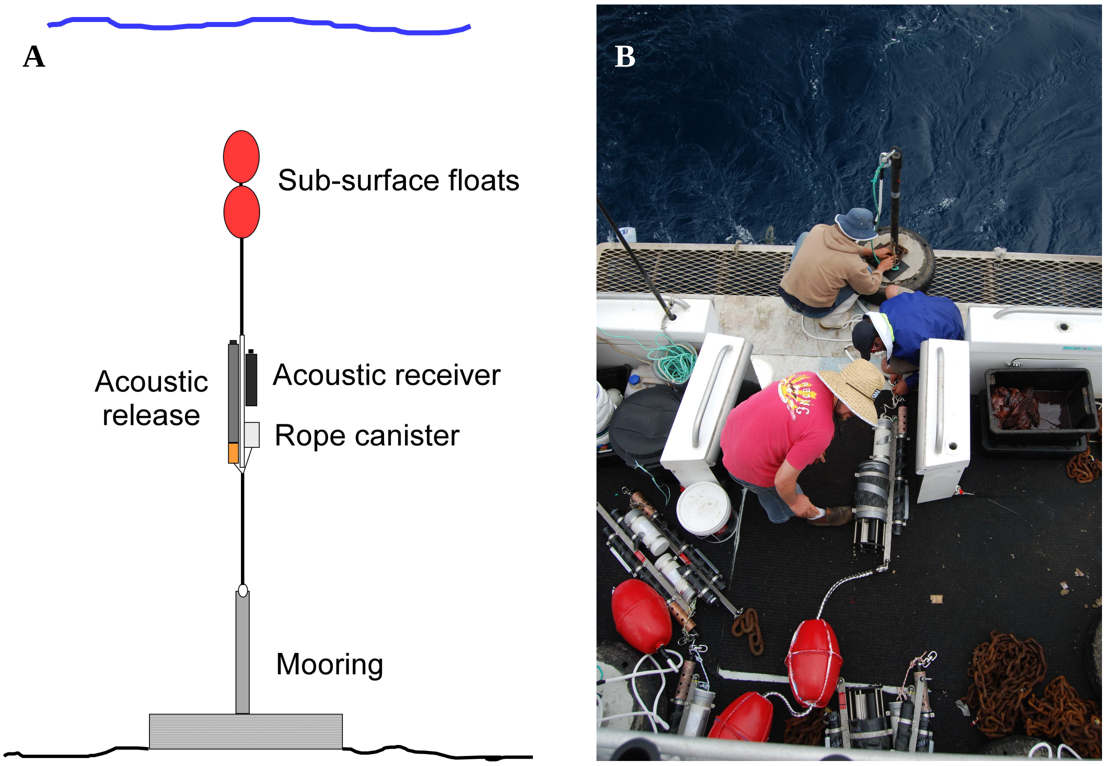

Figure 3: (A) Mooring design for acoustic receivers deployed at the Neptune Islands; (B) Preparing to deploy receivers at the Neptune Islands.

Acoustic tags

Sharks were tagged with Vemco V16 R64k coded acoustic transmitters (72 mm x 17 mm). Transmitters were each coded with a unique pulse series, operated on a frequency of 69 kHz and were rated for a battery life of approximately 6.5 years. Sharks were attracted to the vessel using fish-based berley and tags were attached externally to the dorsal musculature using a tagging pole following the procedures of Bruce *et al.* (2005) - Figure 4.

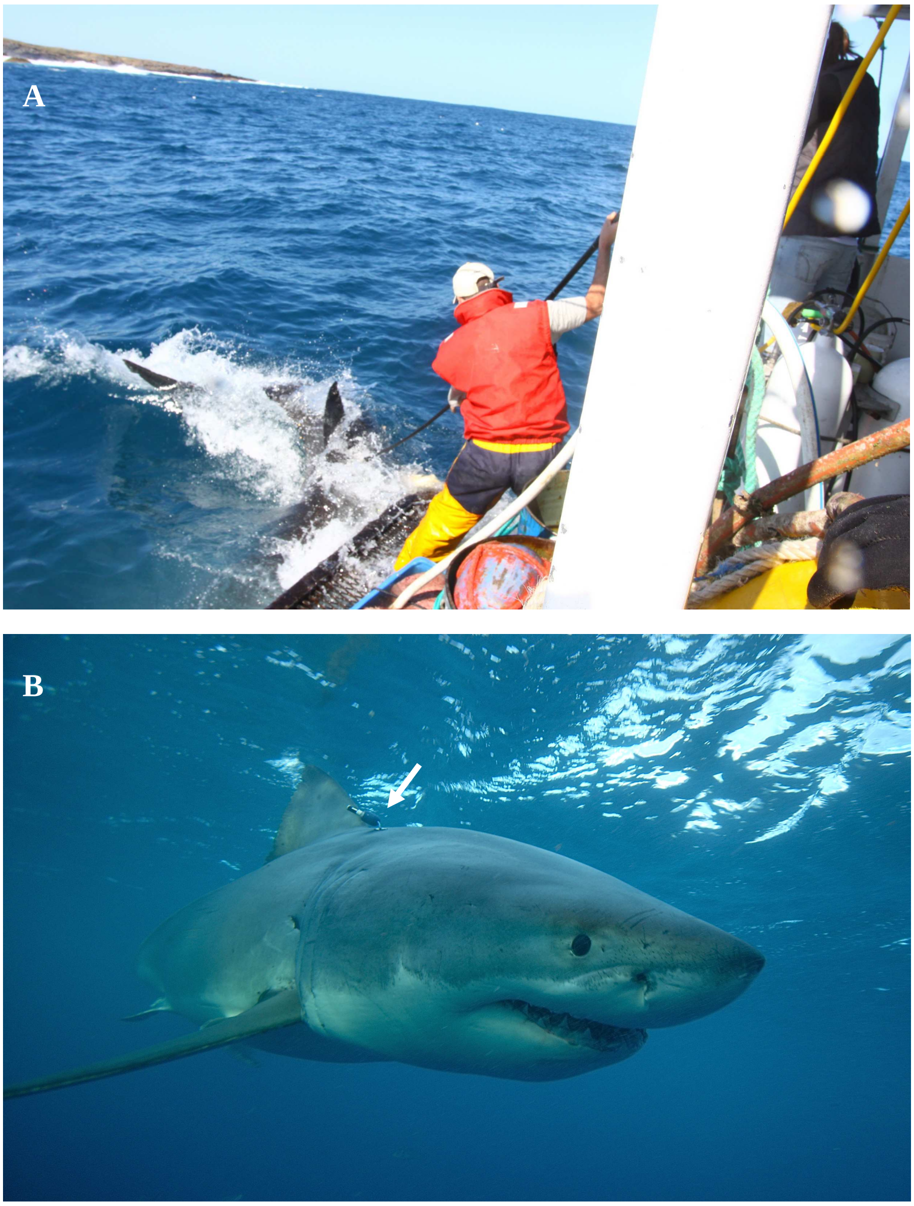

Figure 4: (A) Tagging a white shark with an acoustic tag at North Neptune Island; (B) A white shark tagged with an acoustic tag (arrowed). Photo courtesy of Andrew Fox.

Data Analyses.

Acoustic tag data

Detections recorded by receivers were used to examine the presence and behaviour of tagged sharks at North and South Neptune Islands as well as movements between the two island groups (the study area). Sharks were considered to be present at either North or South Neptune Islands if more than one detection was registered on any receiver on a given day. If a shark was not detected on a given day then it was assumed not to be present in the study area. Daily detection summaries were plotted to examine the pattern of overall presence of tagged sharks during the study period.

The number of consecutive days individuals were present was calculated each time they entered the study area. Two periods of site occupancy were defined by the daily summary data. '*Residency period*' was defined as the number of days between the first and last detection of a tagged shark provided gaps between consecutive days of detection did not exceed five days. A five day period was selected on the basis of transit times between the North and South Neptune Islands by individual sharks. The majority (89%) of transit times between the island groups were less than 100 h (= 4.2 days). A period of five days was deemed to allow for sharks remaining in the vicinity of the Neptune Islands but not registering a detection at either island. Where sharks were not detected over periods greater than five consecutive days, individuals were assumed to have left the Neptune Islands system and any subsequent return was considered to start a separate residency period. '*Visits*' were defined as the number of consecutive days with detections for any given shark during its residency period.

Data from the current 2010-2011 study were compared to similar acoustic tag data collected from North and South Neptune Islands during the 2001-2003 study of white shark residency patterns and habitat use (see Bruce *et al.* 2005 for details). The previous study was undertaken prior to the significant increase in berley activity beginning in 2007. The duration of visits between the two study periods were compared using a Mann-Whitney *U*-test (Conover 1999).

In addition to the 2001-2003 and the 2010-2011 acoustic array data sets, data from the VR4G acoustic receiver deployed in the bay at North Neptune Island was used to examine the frequency and nature of shark residency periods and the duration of visits over the 2008-2011 period using the same analytical techniques. Sharks were tagged at the Neptune Islands during the 2007-2009 period as part of a trial of the VR4G system (Bradford *et al*. 2011) and a separate, broad-scale study of the movement dynamics of the species in Australian waters utilising receivers deployed by AATAMS and affiliated agencies.

A third period of site occupancy was defined using acoustic data. '*Island contact time*' was defined as the total time period in consecutive 30 min blocks that sharks were detected by the North Neptune Island array. This time period measured the continuous, short temporal scale residency of sharks within the array and was specifically examined to determine if their activity close to the island changed over the duration of a visit. The duration of island contact may increase if sharks continue to be stimulated and respond to berleying vessels over time, or island contact time may decline if sharks gradually ignored the stimulus provided by berley. The latter case would suggest that sharks habituated to the presence of berley and slowly ignored its attraction. Habituation has been documented for white sharks exposed to berleying in South Africa (Laroche *et al.* 2007) and has been reported anecdotally for sharks at the Neptune Islands.

The centre of activity (COA) for each tagged shark at North Neptune Island was estimated from the 2010-2011 acoustic data every 30 minutes using a weighted mean position algorithm (Simpfendorfer *et al.* 2002) [Equation 1];

$$\text{COA}\ (X_{\text{Rad30}}) = \frac{\sum_{i}^{j} (w_i X_i + \ldots w_j X_j)}{\sum_{i}^{j} (w_i + \ldots w_j)} \qquad [1]$$

where X_{Rad30} is the mean weighted radian value identifying the centre of activity over each 30 minute period, w_i is the number of detections of an individual shark at receiver *i* during the monitored period (30 mins) and X_i is the radian value of the bearing from a central reference point on North Neptune Island to receiver *i*.

Thirty minute blocks were chosen to allow for movement to occur between the detection envelopes of adjacent receivers while minimizing movement between the reception envelopes of distant receivers. Because our array circled the North Neptune Islands, we converted the latitude and longitude of individual receivers to a bearing from a central reference point on North Neptune Island (see Figure 2) and then converted that value into radians. The radian value was used in the position algorithm in place of receiver location (latitude/longitude). The resultant value provided a weighted mean radian estimate identifying the centre of activity as a bearing from the central reference point on the island. COA bearings were binned into 30^o sectors to describe and compare the distribution of shark activity around the island during berleying and non-berleying periods.

A Watson-Williams test, analogous to a single-factor ANOVA for circular data (Berens 2009), was used to test for differences between the common mean bearing for individual shark's COAs between berley and non-berley days.

The daily patterns in the detections of sharks were examined at the North Neptune Islands berley Sites 1 and 2 and compared between 2001-2003 and 2010-2011. The number of detections of tagged sharks was summed in 30 minute bins and χ^2 goodness-of-fit tests were used to compare the frequency of detections to an even distribution. Significant departures from an even distribution were used to identify the presence of diel patterns in shark activity.

Daily logbook data

Data on the long-term number of sharks sighted per berley day, monthly means of these data and the total number of berley days at the Neptune Islands per year, were extracted from daily logbook data filed by shark cage dive operators (SCDO). A logbook system has been in place since 1999 and data are maintained on a database at CSIRO in Hobart. A berley day is defined as any day that berleying operations occur on site regardless of the number of operators present. Logbook data is also routinely used to monitor the North Neptune Island shark activity index (NNI shark index). The NNI index compares the monthly mean number of sharks sighted by operators per day of berleying to the long-term mean for that month. The resultant data provides a measure of the shark activity for any observed period and is designed to examine long-term patterns at North Neptune Island.

Data on shark activity and sightings were compared using logbook data over the entire 1999-2011 data set and between the two acoustic study periods (2001-2003 and 1999-2011). Data over 1999-2011 were also divided between pre-2007 and post-2007 periods to assess evidence for changed behaviours in sharks since the 2007 increase in berleying activity. Single factor ANOVA was used to compare the mean monthly number of sharks sighted per day between years, pre-2007 and post-2007. Monthly comparisons were made using a paired *t*-test.

Shark lengths are reported as total length (TL - see Wintner and Cliff 1999 for definition) unless otherwise stated. The TL for each tagged shark was visually estimated at the time of tagging based on reference to known length measures on the tagging vessel or the in-water dive cage.

Results

Acoustic receiver deployments.

Receiver arrays were successfully deployed around both North and South Neptune Islands in their planned positions over two separate deployment periods. This provided continuous coverage for approximately 485 days between 08 December 2009 and 13 April 2011 with retrieval-redeployment occurring on 6-8 October 2010 (Table 1).

All receivers were successfully recovered at the conclusion of deployment period one, although two VR3-UWM units (SN1 and NN1) had catastrophically failed, causing complete flooding and loss of all data. Data were successfully downloaded from all remaining receivers.

Just prior to the final recovery of the acoustic receivers in April 2011, the NN1 unit was found floating in the vicinity of Perforated Island, SA (34° 43.0 S, 135° 9.0 E) in the Whidbey Island group approximately 100 km northwest of North Neptune Island. The unit was still attached to its mooring line and float, in good condition and its data were successfully downloaded. The last detections of tagged sharks on this receiver suggests that it may have drifted off-site on 4 March 2011. Of the remaining 10 receivers in deployment period 2, one (NN4) failed to initiate communication during attempts to download and was sent back to Vemco-Amirix (Halifax, NS) where its data were successfully recovered and the unit repaired.

Table 1: Deployment details for acoustic receivers at Neptune Islands (see Figure 2 for station locations). Receiver NN8 was attached to the mooring line of the VR4G satellite-linked acoustic receiver moored in the bay at North Neptune Island.

Station	Deployment 1					Deployment 2				
	Deploy	**Recover**	**Type**	**Errors**	**No. of Sharks**	**Deploy**	**Recover**	**Type**	**Errors**	**No of Sharks**
NN1	09/12/2009	06/10/2010	VR3	Flooded	--	08/10/2010	13/04/2011	VR2W		14
NN2	09/12/2009	06/10/2010	VR2W		14	08/10/2010	13/04/2011	VR2W		16
NN3	09/12/2009	08/10/2010	VR2W		10	08/10/2010	13/04/2011	VR2W		14
NN4	09/12/2009	08/10/2010	VR2W		10	08/10/2010	13/04/2011	VR2W	comms	13
NN5	09/12/2009	08/10/2010	VR2W		10	09/10/2010	13/04/2011	VR2W		14
NN6	09/12/2009	08/10/2010	VR2W		13	09/10/2010	13/04/2011	VR2W		13
NN7	09/12/2009	06/10/2010	VR3		14	08/10/2010	13/04/2011	VR2W		16
NN8	09/12/2009	06/10/2010	VR2W		15	08/10/2010	13/04/2011	VR2W		15
SN1	08/12/2009	07/10/2010	VR3	Flooded	--	07/10/2010	13/04/2011	VR2W		6
SN2	08/12/2009	07/10/2010	VR3		6	07/10/2010	13/04/2011	VR2W		5
SN3	08/12/2009	07/10/2010	VR3		6	07/10/2010	13/04/2011	VR2W		5

Acoustic tag deployments

Following the initial deployment of receivers, there was an extended period of approximately seven months where shark sightings, based on daily log-book data, were well below the long-term average for North Neptune Island (Figure 5). The general absence of sharks during this period resulted in only a single shark being tagged prior to June 2010 and this therefore reduced the data collected by receivers between December 2009 and June 2010.

Sharks sightings returned to average or above average levels in June 2010, facilitating the commencement of further tagging for the project. Six sharks were tagged in June/July 2010, and a further 14 were tagged over the remaining study period, providing a total of 21 sharks tagged for the study. Twenty sharks (2.8-4.8 m TL) were tagged at North Neptune Island; one shark (4.8 m TL) was tagged at South Neptune Island during the study period (Table 2). Tagged sharks were routinely re-sighted by SCDO and detected by the receiver arrays from June 2010 onwards.

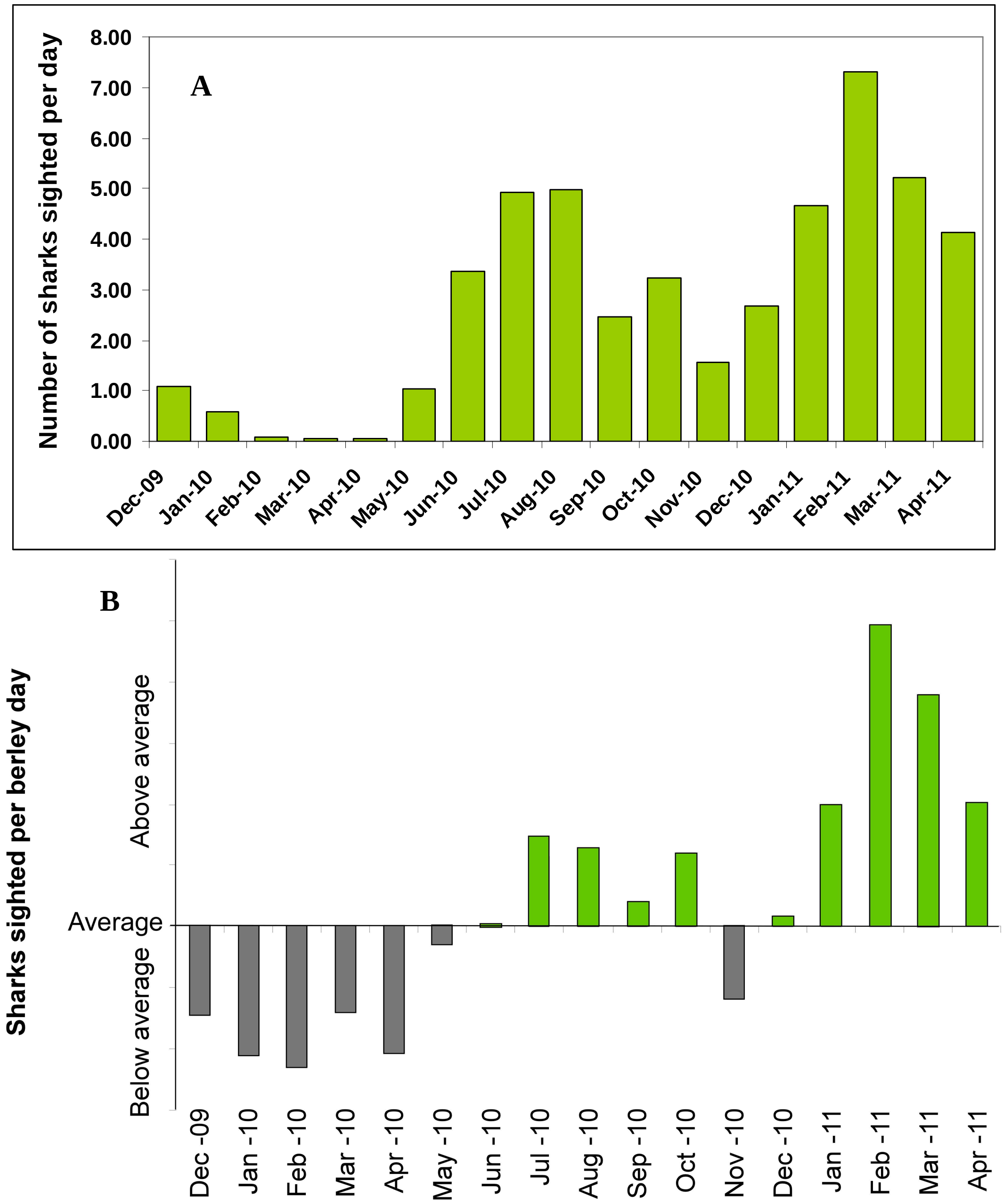

Figure 5: (A) Mean monthly numbers of sharks sighted per day at the North Neptune Islands from December 2009 to April 2011. (B) Differences between the mean numbers of sharks sighted from the long-term (1999-2011) monthly average. Grey bars indicate below average levels of shark sightings; green bars - above average.

Table 2: Acoustic tag deployment details for the Neptune Islands, South Australia. Location refers to the Site where sharks were tagged. NN-Site 1 is within the bay at North Neptune Island (Berley Site 1); NN-Site 2 is on the northern side of the North Neptune Island (Berley Site 2); SN = South Neptune Island. See Figure 2 for site location details.

Tag ID	Date	Length (m)	Sex	Location
8561	05/07/2010	3.2	Male	NN-Site 2
8562	19/08/2010	4.2	Male	NN-Site 1
32561	27/10/2010	3.5	Male	NN-Site 1
32562	17/02/2011	4.7	Male	NN-Site 1
32563	09/10/2010	4.3	Male	NN-Site 1
32565	16/01/2011	4.0	Male	NN-Site 1
58068	04/08/2010	3.2	Male	NN-Site 1
58069	08/10/2010	3.5	Male	NN-Site 1
58070	08/08/2010	4.2	Female	NN-Site 1
58071	4/03/2011	4.8	Male	NN-Site 1
62342	24/10/2010	NR*	NR	NN**
62343	15/12/2010	4.4	Male	NN-Site 1
62344	08/10/2010	4.5	Male	NN-Site 1
62345	08/10/2010	3.5	Male	NN-Site 1
62346	11/06/2010	3.5	Male	NN-Site 2
62347	11/12/2009	4.2	Male	NN-Site 2
62349	19/07/2010	3.5	Female	NN-Site 1
62350	21/06/2010	4.8	Female	SN
62351	27/06/2010	2.8	Female	NN-Site 1
62352	16/06/2010	4.0	Male	NN-Site 1
62353	13/06/2010	4.7	Male	NN-Site 2

* NR - data not recorded

** North Neptune; site not recorded

Acoustic tag detection patterns 2010-2011.

A total of 99,957 detections were recorded from all 21 different tagged sharks during the study period across North and South Neptune Island receiver arrays combined.

Detections were registered on all receivers indicating sharks, at times, utilized the entire area of the arrays including all waters surrounding North Neptune Island. However, not all sharks were detected on all stations and the frequency of detections was not even between stations.

All 21 sharks were detected at North Neptune Island. The frequency of detections was lowest at stations on the western side of the island (NN3, NN4 and NN5). The highest number of detections were recorded by stations on the eastern side of the Island and from within the bay (NN8). Detections at NN1 were disrupted during both deployment periods due to technical issues (see ‘Errors’ in Table 1) and this reduced the total number of detections recorded by that station.

Nine tagged sharks were detected at South Neptune Island. Tagged sharks were detected on all South Neptune Island stations although technical difficulties reduced the data set for SN1 due to the unit flooding during the first deployment.

Presence/absence summary

With the exception of Shark 62347 (tagged and recorded in December 2009), tagged sharks were detected over the period from 11 June 2010-12 April 2011 with up to six sharks present (NNI - late October 2010) on site at any one time (Figure 6). Residency periods within the Neptunes Island system ranged from 1 to 92 days (mean 21.0 d, SD 24.2); Figure 7. The number of residency periods ranged from one to five for individual sharks with the majority (12 out of 21 [57%]) recording multiple residency periods. Most periods (79%) were separated by 6-10 days and it is thus possible that the residency parameter under-estimated actual periods of residency if sharks patrolled areas outside of detection range while still present within the vicinity of the Neptune Islands system.

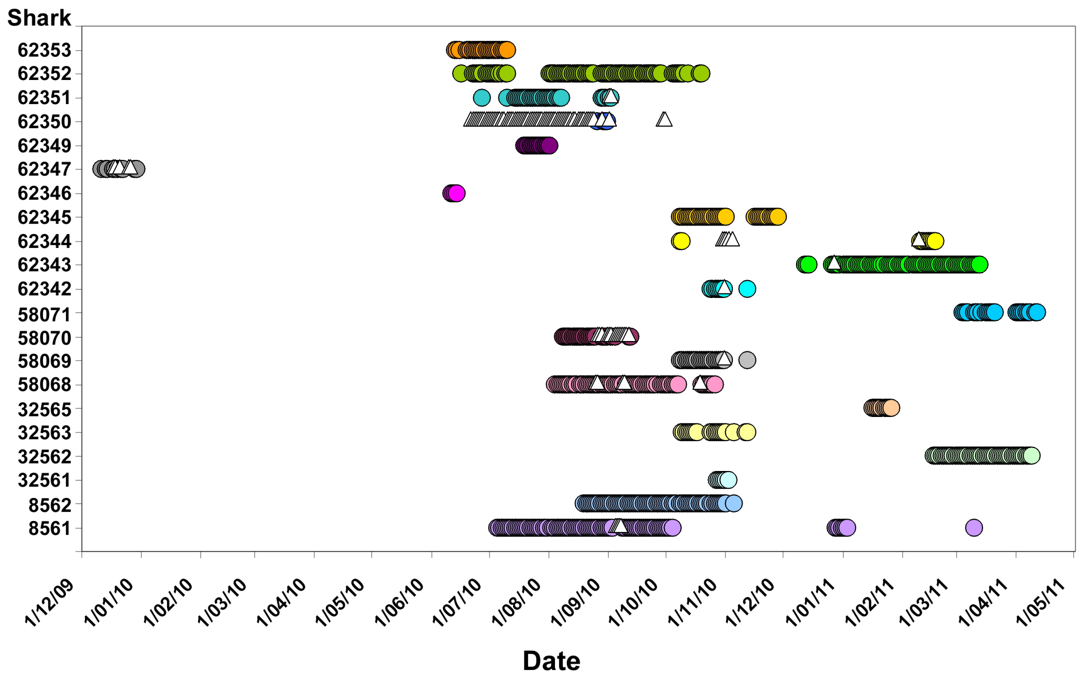

Figure 6: Daily presence-absence of acoustically tagged white sharks at the Neptune Islands. Shark numbers refer to unique acoustic tag codes for each shark. Filled circles indicate that the shark was detected on that day at the North Neptune Islands. White triangles indicate days when sharks were detected at the South Neptune Islands.

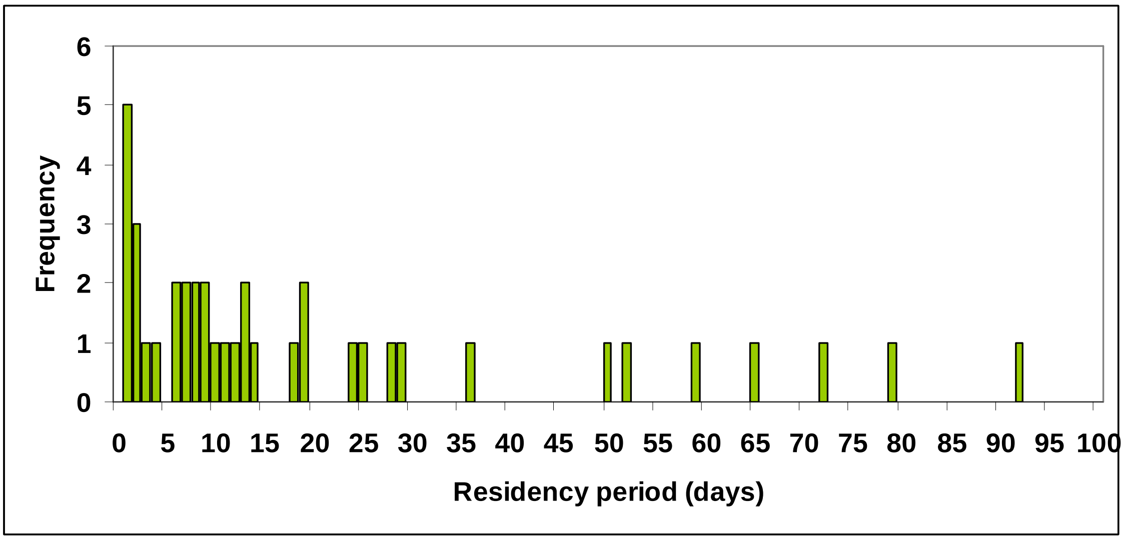

Figure 7: The frequency and duration of residency periods at the Neptune Islands (all tagged sharks combined).

Within their overall periods of residency, the presence of each shark was recorded in separate visits of consecutive days to the each island group. The duration of visits at the North Neptune Islands ranged from 1 to 52 consecutive days (mean = 11.0; SD = 11.69); Figure 8.

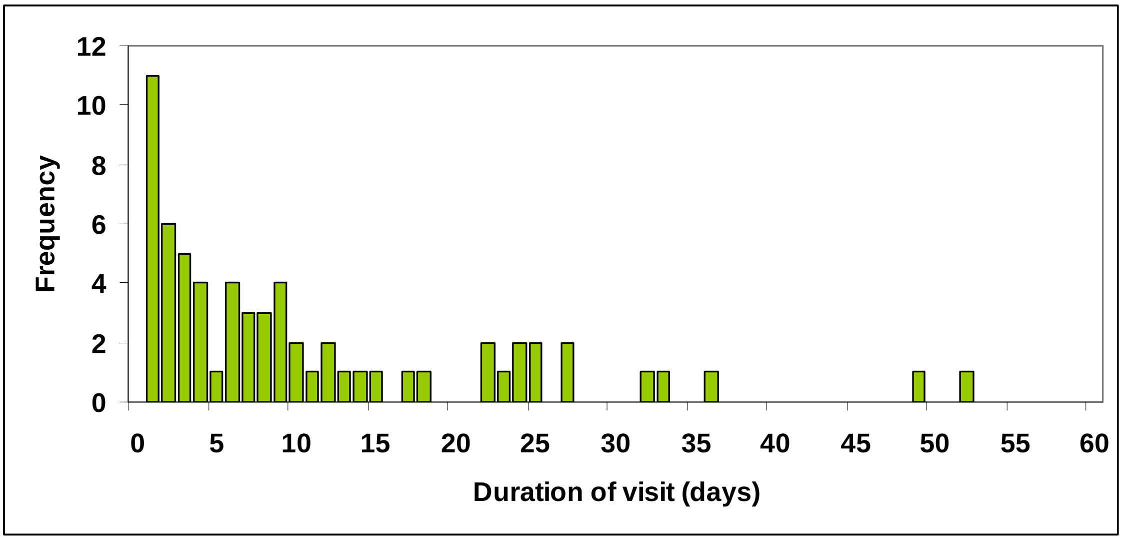

Figure 8: The frequency and duration of visits at North Neptune Island (all tagged sharks combined).

The duration of visits at South Neptune Island ranged from 1 to 34 consecutive days (mean = 4.5; SD = 7.48).

Exchange of sharks between the North and South Neptune Islands

All 21 sharks were detected at North Neptune Island (including the single shark tagged at the South Neptune Islands). Nine of the 21 sharks were detected at the South Neptune Islands indicating an exchange rate of approximately 43% between the two island systems. Sharks made a total of 37 transits between North and South Neptune Islands, representing 18 journeys where they returned to their island group of origin. Only one transit resulted in a shark not returning to its island group of origin. Shark 62351 made the transit from North Neptune Island to South Neptune Island in late September 2010 where it remained for 31 hours before again departing. This shark was not detected again on any receiver during the remaining period of the study and was assumed to have departed the region.

Movements between North and South Neptune Islands were, in general, relatively rapid indicating directed travel between the two systems. Most transit periods were less than 20 hrs duration (Figure 9) but ranged from 2.23 hrs to 504.4 hrs. The shortest duration for travel indicated a minimum sustained rate of movement (ROM) between the two island systems of 5.4 km per hour which is one of the highest recorded for white sharks (see Bruce and Bradford *in press*). The longer travel periods (> 50 hrs) suggest that not all travel was direct between the islands, although the incidence of these lengthy transits were relatively few.

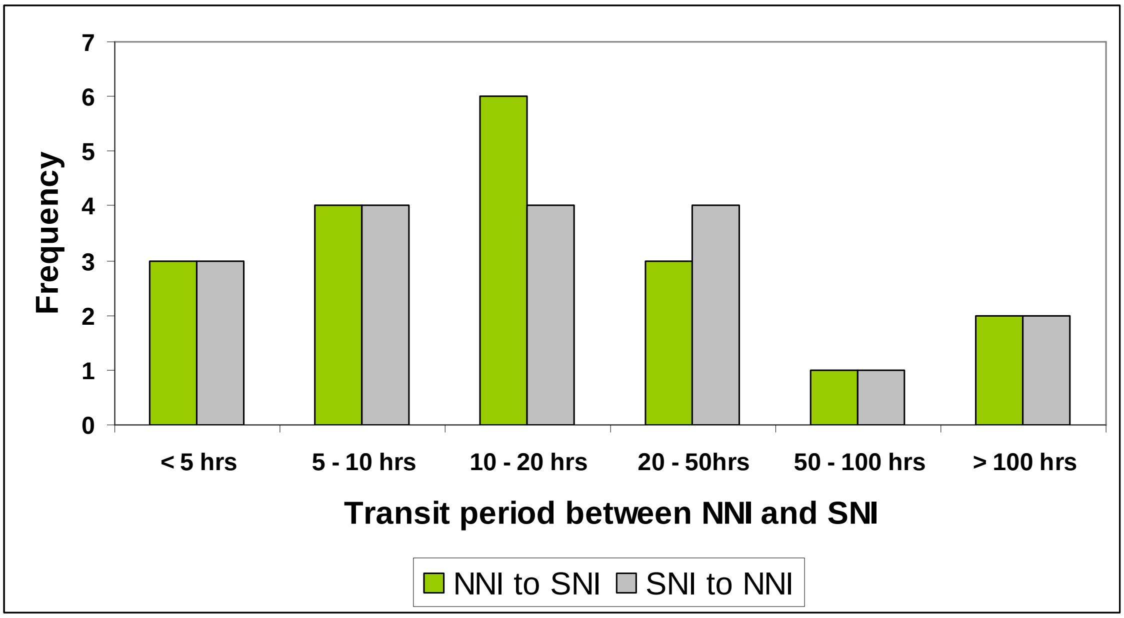

Figure 9: Transit periods for sharks moving between the North Neptune Islands (NNI) and South Neptune Islands (SNI).

Movement patterns away from the Neptune Islands

White sharks tagged previously at the Neptune Islands have been tracked moving primarily west into the Great Australian Bight and Western Australian waters, in some cases as distant as Exmouth in northwest Western Australia (Bruce *et al*. 2006). A number of acoustic receiver arrays maintained by AATAMS and various other collaborating organizations exist across this region (see http://imos.org.au/aatams.html for details of receiver locations) and data from these receivers were interrogated for detections of sharks tagged at the Neptune Islands.

Three sharks tagged at the Neptune Islands (Sharks 62342, 62346, and 62349) were recorded on receivers near Chatham Island, Western Australia (35^{o} 2.25’ S 116^{o} 29.45’ E). These detections occurred respectively on 18 April 2011 (Shark 62342), 8 March 2011 (Shark 62346) and 19 December 2010 (Shark 62349). Chatham Island is approximately 1800 km west of the Neptune Islands (approximately 2000 km following a typical on-shelf track). The last detections for each shark at the Neptune Islands were respectively 12 November 2010 (Shark 62342), 28 November 2010 (Shark 62346) and 31 July (Shark 62349). No intervening detections of these sharks were registered on other receiver arrays and these sharks were not re-detected at the Neptune Islands after the above departure dates.

Sharks 8561, 32562, 58068, and 58071 were detected on the VR4G receiver at North Neptune Island after the final recovery of the project VR2W array in April 2011, indicating that these sharks continued to revisit the region after the end of the study period.

Spatial and diel patterns in detections

Detections of tagged sharks varied both spatially and temporally around North Neptune Island (Figure 10). Detections were highest at receivers located on the northern and eastern areas of the island (NN1, NN2, NN7 and NN8) with these receivers accounting for 92.4% of all detections. A clear diel pattern in detections was apparent for each of these receivers with detections generally increasing from 0700 to a peak (1100-1300) followed by a decline to low levels after 1800-1900. This diel pattern was not evident at other receivers located to the west and south of the island although there were comparatively fewer data at these locations.

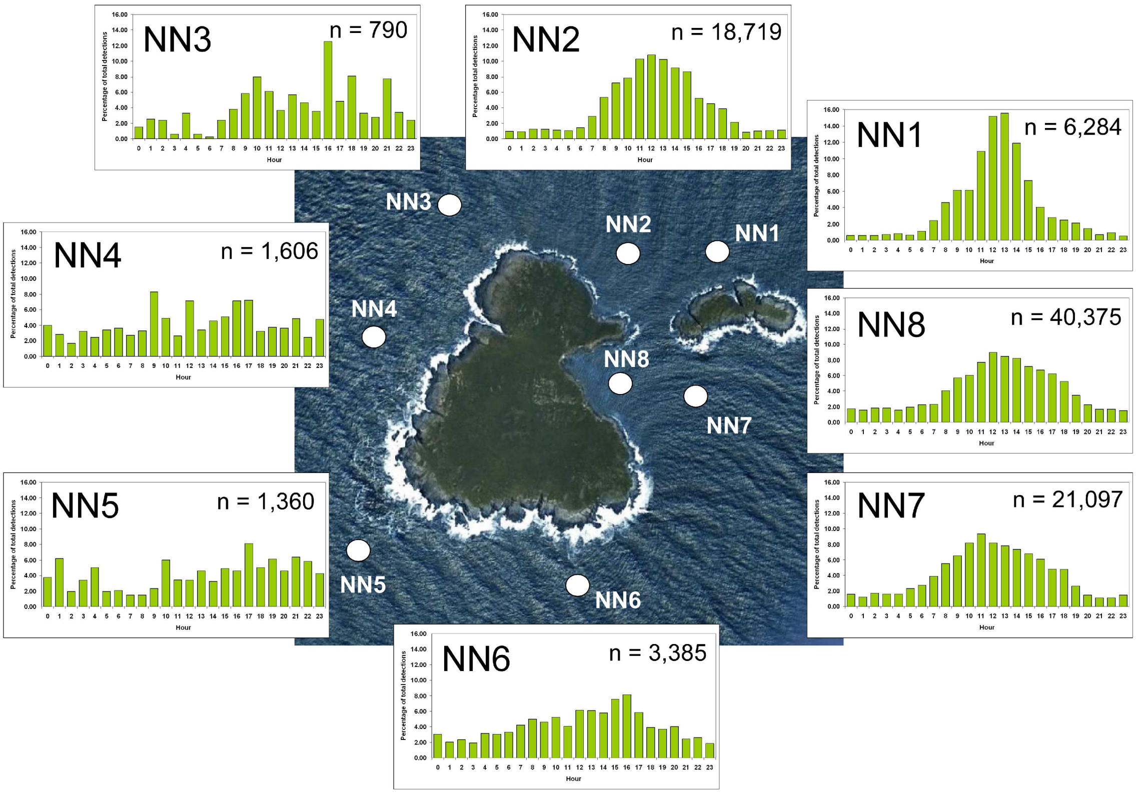

Figure 10: Hourly detections of tagged sharks at receiver locations around North Neptune Island (December 2009-April 2011). Data are percentage of total detections by hour for each site; n = total detections registered.

The largest number of detections of tagged sharks (75.8% of all detections) was recorded inside the Bay at North Neptune Island.

Detections of tagged sharks also indicated a diel pattern at South Neptune Island although the pattern differed slightly to North Neptune Island receivers (Figure 11). Detections generally increased from 1000 to a peak (1300-1600) followed by a decline to stable levels by 1900-2000. Data were few for SN1 due to flooding of the receiver during deployment period 1 and thus a pattern was less reliably portrayed.

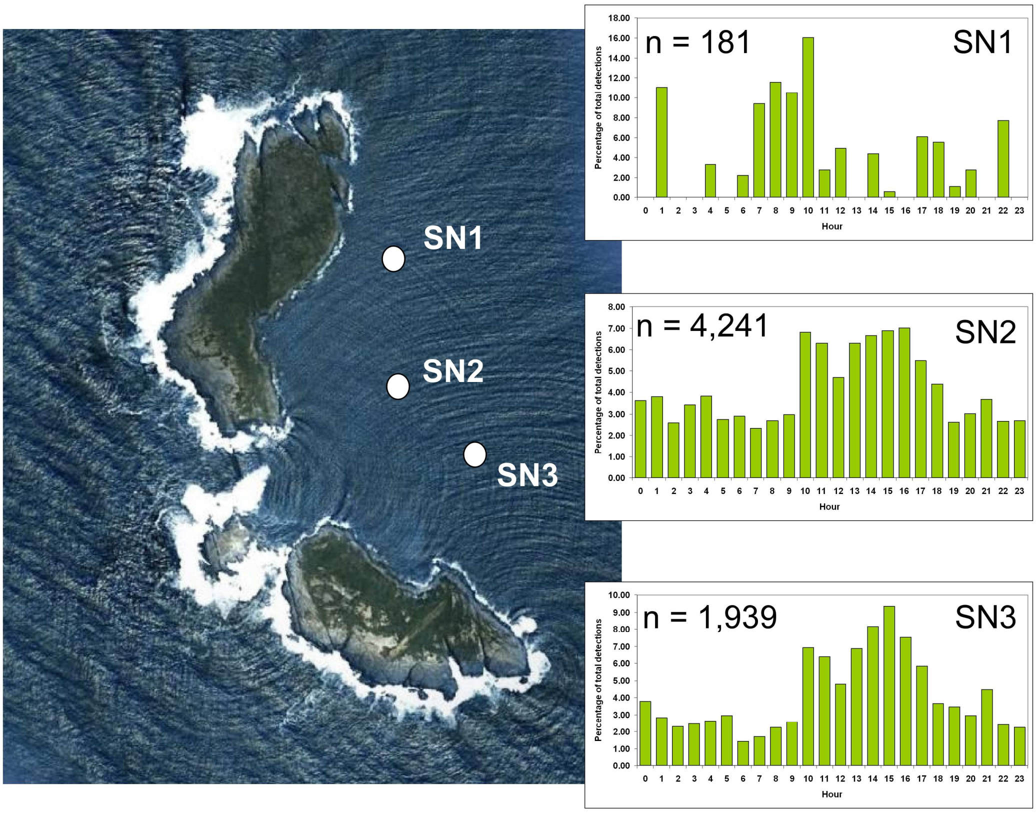

Figure 11: Hourly detections of tagged sharks at receiver locations around South Neptune Island (December 2009-April 2011). Data are percentage of total detections by hour for each site; n = total detections registered

Effects of berleying on the distribution and behaviour of tagged sharks

Distribution of shark activity at North Neptune Island

The calculated half-hourly centres of activity for each shark were assigned to 30^o sectors around the island for comparative analyses. All sharks showed a higher level of occupancy in the areas off the east and northeast sectors of the island (Figure 12). The distribution of shark activity by sector was highly significantly different between berley and non-berley days - both sites combined (Watson-Williams test, F_1=44.15, p >0.0001) and indicated that the centre of activity of shark activity was shifted towards those areas when berleying occurred. This was particularly apparent comparing the distribution of shark activity on days when berleying occurred inside North Neptune Bay (Site 1) to those when berleying operations occurred to the north of the bay, Site 2, (Watson-Williams test, F_1=1280.93, p >0.0001).

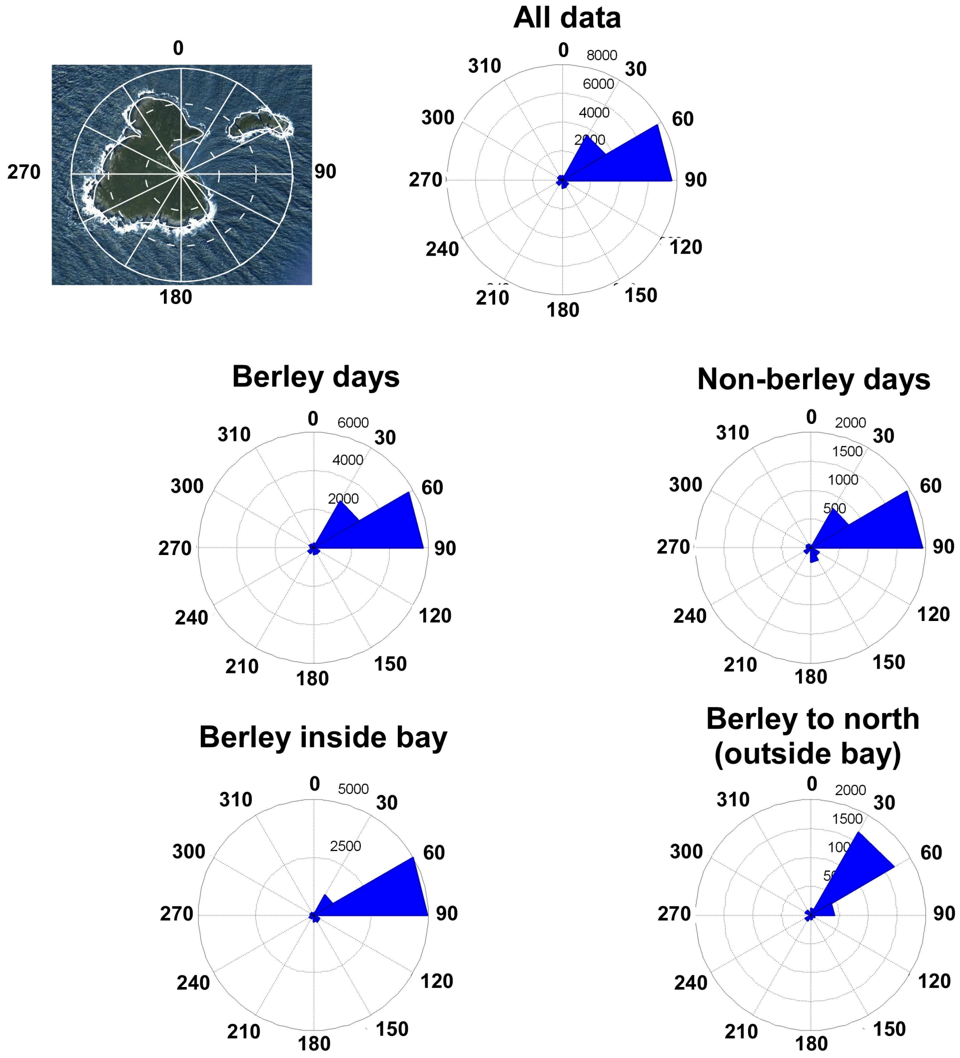

Figure 12: Distribution of tagged white sharks within the acoustic receiver array at North Neptune Island, South Australia.

These data support that the distribution of sharks is influenced by the presence of berley on at least the local (spatial) and short-term (temporal) scales.

Comparisons between pre-2007 and post-2007 data.

Numbers of sharks sighted

Logbook data recording the numbers of sharks sighted per day by each of the two active shark cage dive operators were not significantly different over the period 1999-2011 (ANOVA, F = 1.066059, *p* = 0.3019) and thus both data sets were pooled for analyses. Mean shark activity (sharks sighted per day) was compared between years prior to 2007 and post-2007 using the combined logbook data (Figure 13). The mean number of sharks sighted per day was significantly higher in the post-2007 period (ANOVA F = 547.0, *p* < 0.0001).

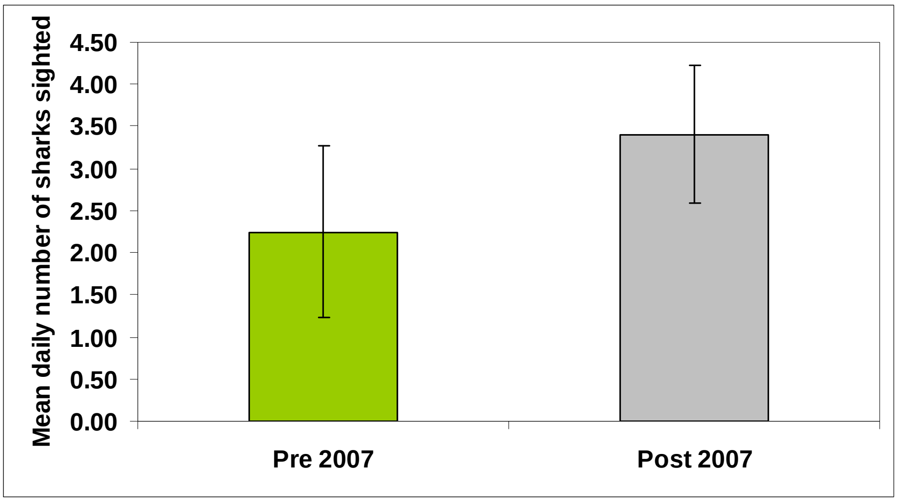

Figure 13: Comparison of mean daily number of sharks sighted between 1999-2006 and 2007-2011. Bars indicate one standard deviation.

The 2011 period was, however, particularly strong for increased shark numbers (Figure 14) and this coincided with much of the acoustic monitoring period for the current study.

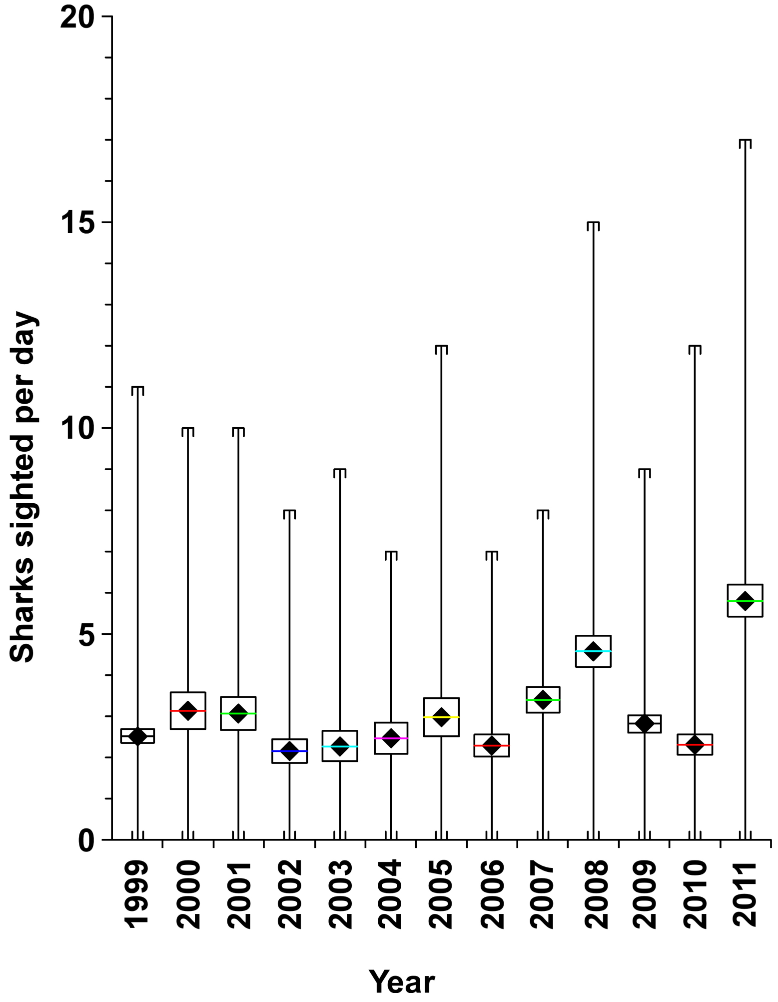

Figure 14: Mean annual number of sharks sighted per day 1999-2011 from SCDO logbook data. Annual means are given by the black diamond and horizontal line; surrounding boxes provide the 95% confidence interval about the mean; vertical bars provide range (minimum and maximum values).

Data also indicated a significant increase post-2007 in the number of sharks sighted for each month (paired *t*-test, $p = 0.038$; mean difference pre-2007 to post-2007 = 1.13, 95% CI = 0.45 to 1.81) suggesting that this increase in shark numbers was spread over the entire annual period (Figure 15).

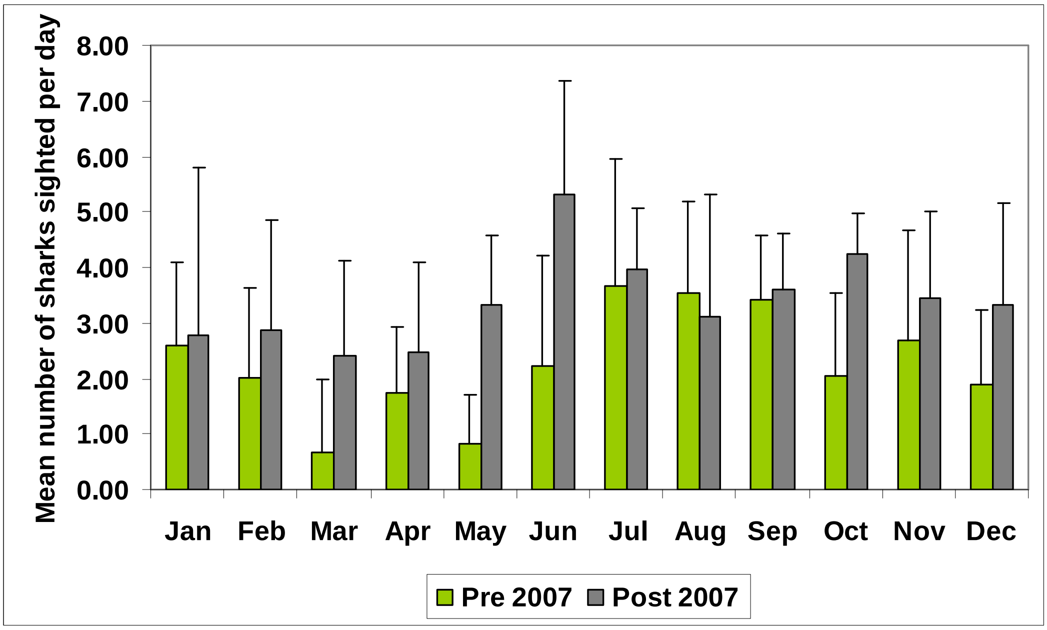

Figure 15: Comparison of the mean monthly number of sharks sighted per day from SCDO logbook data for pre-2007 and post-2007 periods. Bars indicate one standard deviation.

Duration of visits

The duration of visits by sharks to North Neptune Island during the study were compared to equivalent data from the 2001-2003 period. The duration of visits during the 2010-2011 study were significantly higher than during the 2001-2003 period (Mann Whitney *U*-test, median 2010-2011 = 6.5 days; median 2001-2003 = 2 days; p <0.0001). The 2010-2011 data, however, were based on both a larger number and a different configuration of receivers, with eight receivers surrounding North Neptune Island (2010-2011) as apposed to three receiver deployments within and immediately north of the bay in 2001-2003 (see Bruce *et al*. 2005 for details of the latter). To ensure that these results were not a product of differences in receiver location and coverage, analyses were repeated using only data from the VR4G receiver. The VR4G receiver was deployed near to the 2001-2003 location of receivers in the bay and thus data were less likely to be biased by such effects. The VR4G receiver was deployed continuously from 2008 and this also provided data over a longer period than the full 2010-2011 array. Differences between the duration of visits were again highly significant between the two periods with the 2008-2011 VR4G data set recording significantly longer visit durations than those recorded during the 2001-2003 period (Mann Whitney *U*-test, median 2008-2011 = 3 days; median 2001-2003 = 2 days; p = 0.0005).

It is possible that the number of sharks present may influence the duration of visits as a result of competitive interference (Case and Gilpin 1974, Krause and Ruston 2002). This may occur if sharks naturally compete for resources, in this case, access to seals or access to the most reliable zones around the Neptune Islands for successfully intercepting such prey. Such competition may result in sharks increasing their duration of visits to ensure they capture sufficient prey during periods of increased shark abundance when competition between sharks is highest. The 2010-2011 period (after June 2010) was notable for the extended period of above average shark sightings (see Figure 5) whereas data from 2009-2010 was more comparable to average shark activity at the Neptunes (based on operator logbook data - Figure 14). To remove possible confounding effects of increased shark numbers on comparisons between periods, analyses were repeated separately removing first, the 2011 data and, second the 2010+2011 data from the VR4G data series. Both subsequent analyses also supported highly significant increases in the duration of visits compared to the 2001-2003 period (Mann-Whitney *U*-test, 2008-2010 visits > 2001-2003 visits, p<0.0001; 2008-2009 visits > 2001-2003 visits, p = 0.0001).

The duration of visits by sharks to the South Neptune Islands were also compared between 2001-2003 and 2010-2011 periods. Receivers were deployed in nearly the same locations between the study periods (see Bruce *et al*. 2005 for details of the 2001-2003 deployments) and thus were readily comparable. In this case, the duration of visits was not significantly different between the two periods (Mann-Whitney *U*-test, median 2001-2004 = 1.5 days; median 2010-2011 = 2.0 days; *p* = 0.709). This combined with the above analyses suggest that the increased duration of visits by sharks was an effect restricted to the North Neptune Islands only.

Island contact time

Island contact time was plotted for both the 2001-2003 and 2010-2011 periods to provide a visually interpretable relationship with the duration of visits. Island contact time gradually declined with increasing visit duration during both periods (Figures 16 and 17) suggesting a possible habituation response over time.

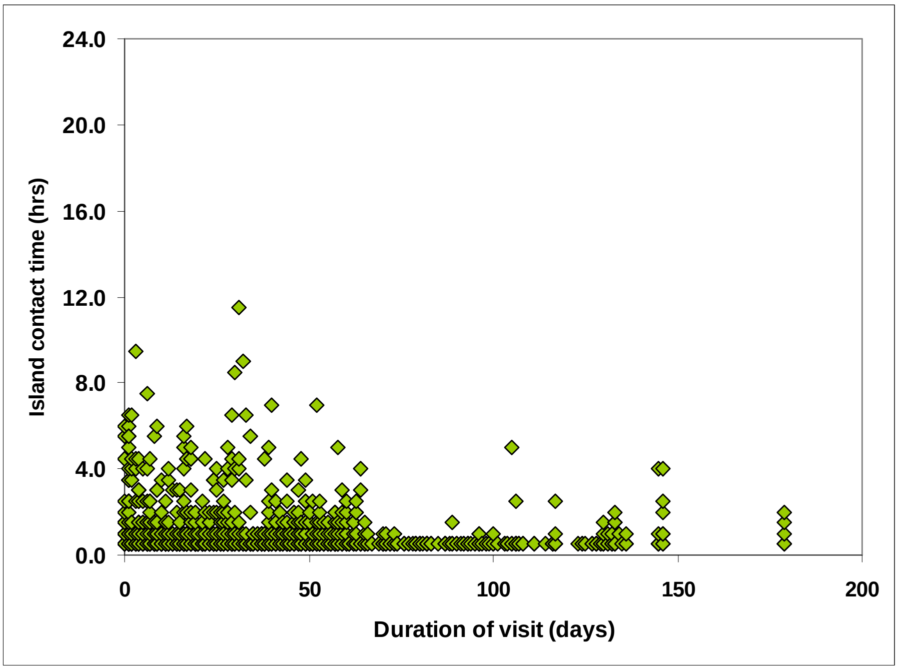

Figure 16: Island contact time as a function of visit duration (2001-2003).

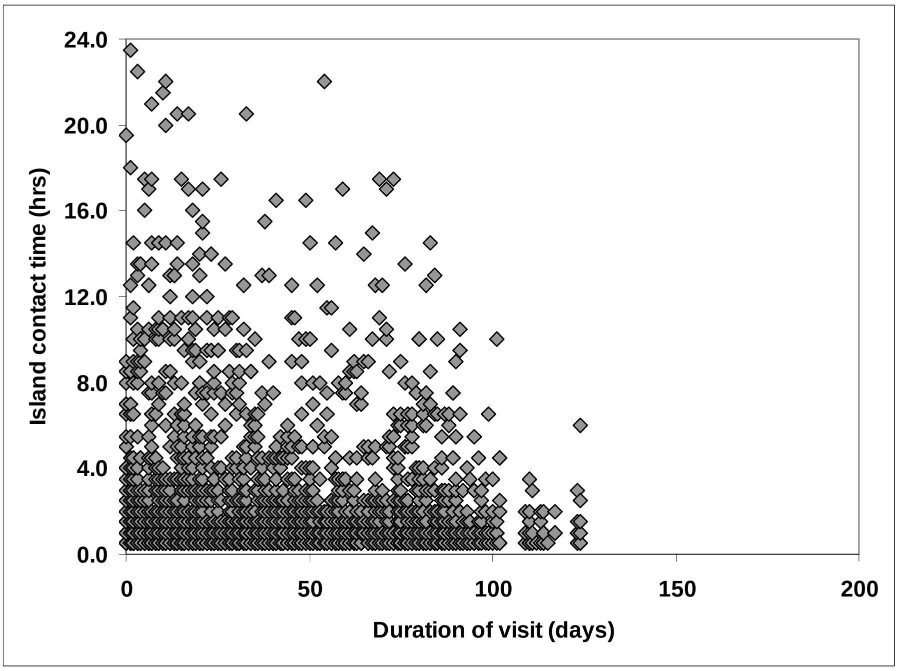

Figure 17: Island contact time as a function of visit duration (2010-2011).

Diel Pattern of shark activity at North Neptune Island berley sites

Current study (2010-2011)

A clear diel pattern of detections was apparent at both the North Neptune Island berley sites (Figures 18 and 19), with detections increasing in frequency from 0700-0800, rising to a peak during the day and then declining to a low and stable level after 2000-2100. However, there was some evidence of slight differences between berley and non-berley days. The diel pattern on days when berleying occurred was a more evenly distributed rise and fall in the detection frequency of tagged sharks over the period 0700-2000 with a peak around 1300. On days when berleying did not occur, detections of tagged sharks tended to peak earlier in the day (1030-1200) and drop off more substantially during the afternoon (1400-1700). The amount of data (detections) during non-berley periods was significantly less than during berley periods (due to the lower frequency of non-berley days at both sites), so these patterns may be biased by the differences in the amount of data. However, patterns were consistent between sites which support an effect during berley periods.

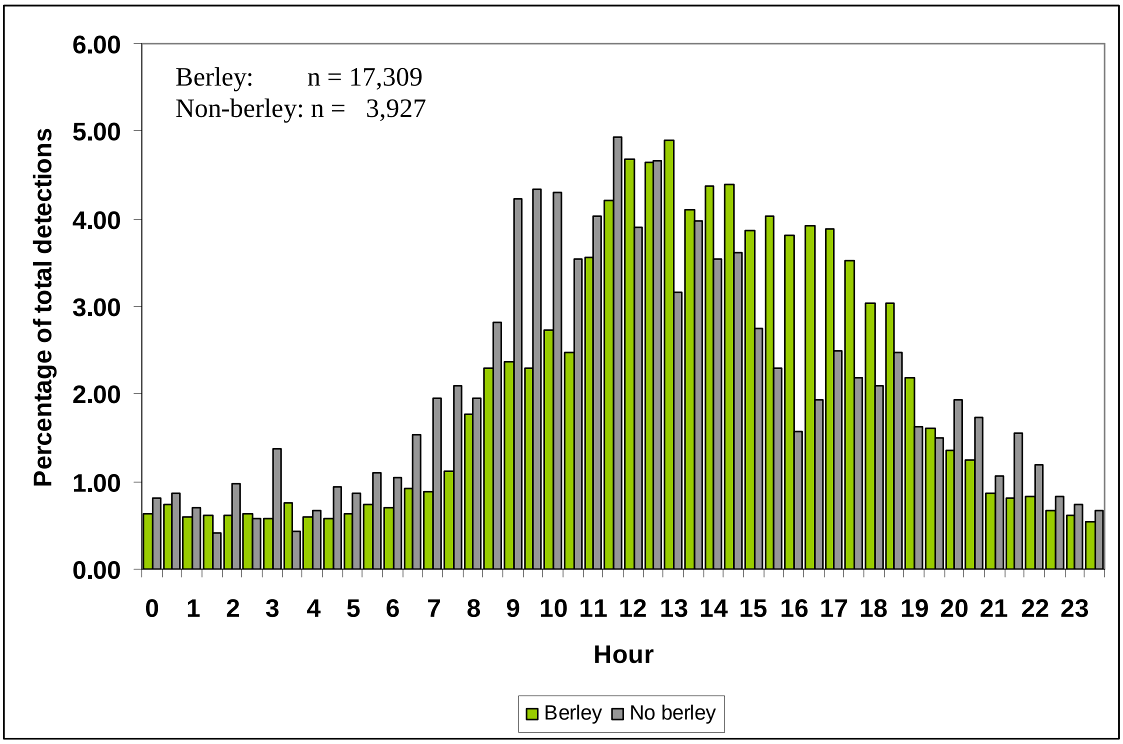

Figure 18: Diel pattern of detections (30 min blocks) of tagged sharks at North Neptune Island 2010-2011 during berley and non-berley periods at the berley site inside the bay (Site 1); n = number of detections of tagged sharks.

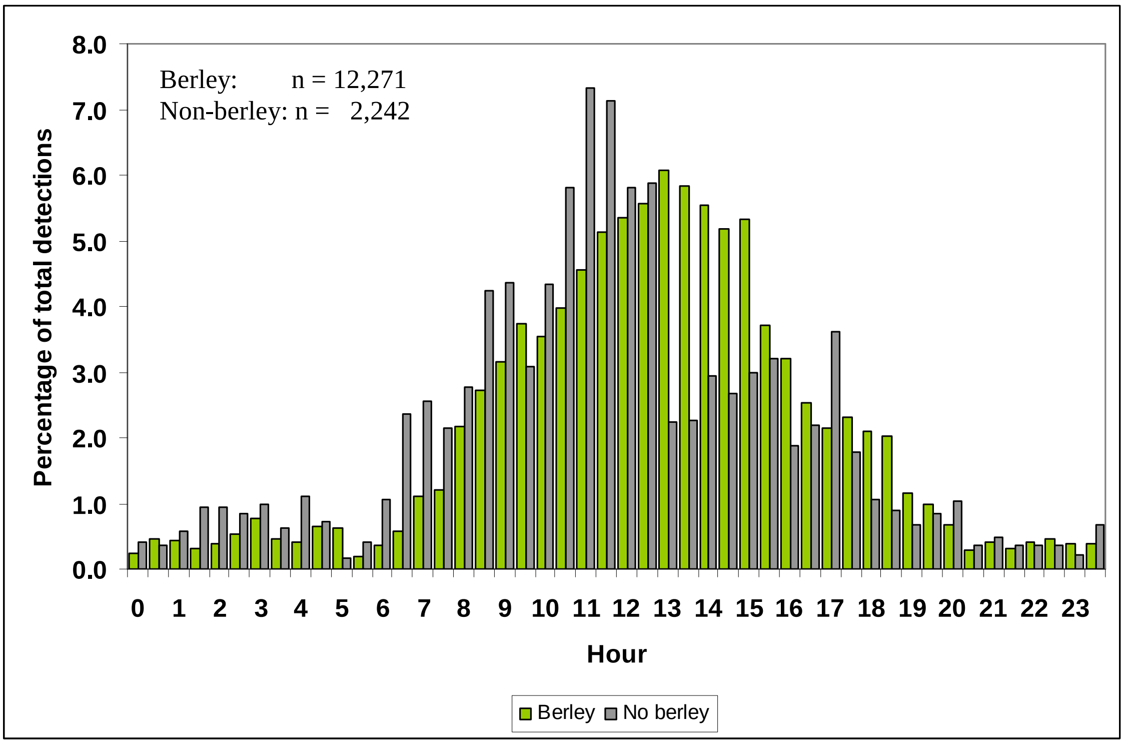

Figure 19: Diel pattern of detections (30 min blocks) of tagged sharks at North Neptune Island 2010-2011 during berley and non-berley periods at the northern berley site (Site 2); n = number of detections of tagged sharks.

Previous study (2001-2003)

Data were similarly plotted for both berley sites from the 2001-2003 study period (Figures 20 and 21). The amount of data (number of detections) during berley periods were considerably less than non-berley periods at both sites due to the lower frequency of berley days during that study period.

A clear diel pattern in the detections of tagged sharks was observed inside the bay at the North Neptune Islands (Site 1). However, no such pattern was evident in detections north of the bay at Site 2, where detections were more evenly distributed throughout the 24 hour cycle with minor peaks at 0700-0900 and at 2100-2200. Detections on berley days inside the bay were more concentrated during the 0700-2000 period with peak in detections around 1200 and a secondary peak around 1600. During non-berley days, detections were more broadly distributed between approximately 0500 and 2000 with a peak at approximately 1200-1300. The hourly distribution of detections at Site 2 showed little difference between berley and non-berley periods.

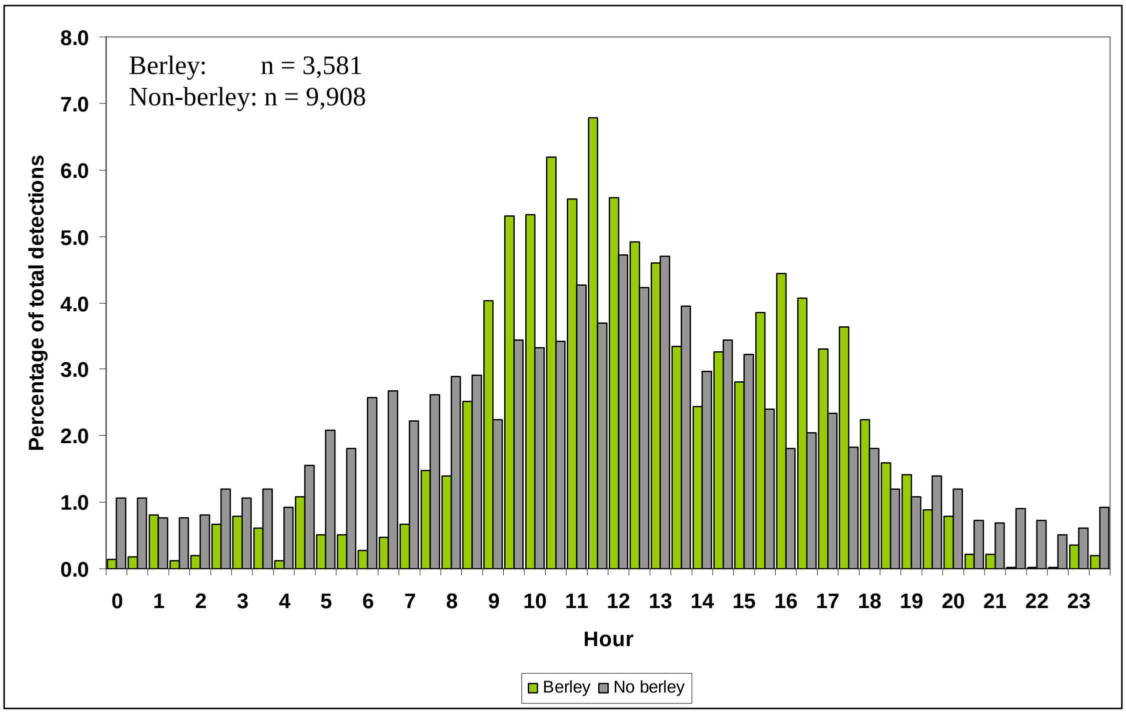

Figure 20: Diel pattern of detections (30 min blocks) of tagged sharks at North Neptune Island 2001-2003 during berley and non-berley periods at the berley site inside the Bay (Site 1); n = number of detections of tagged sharks.

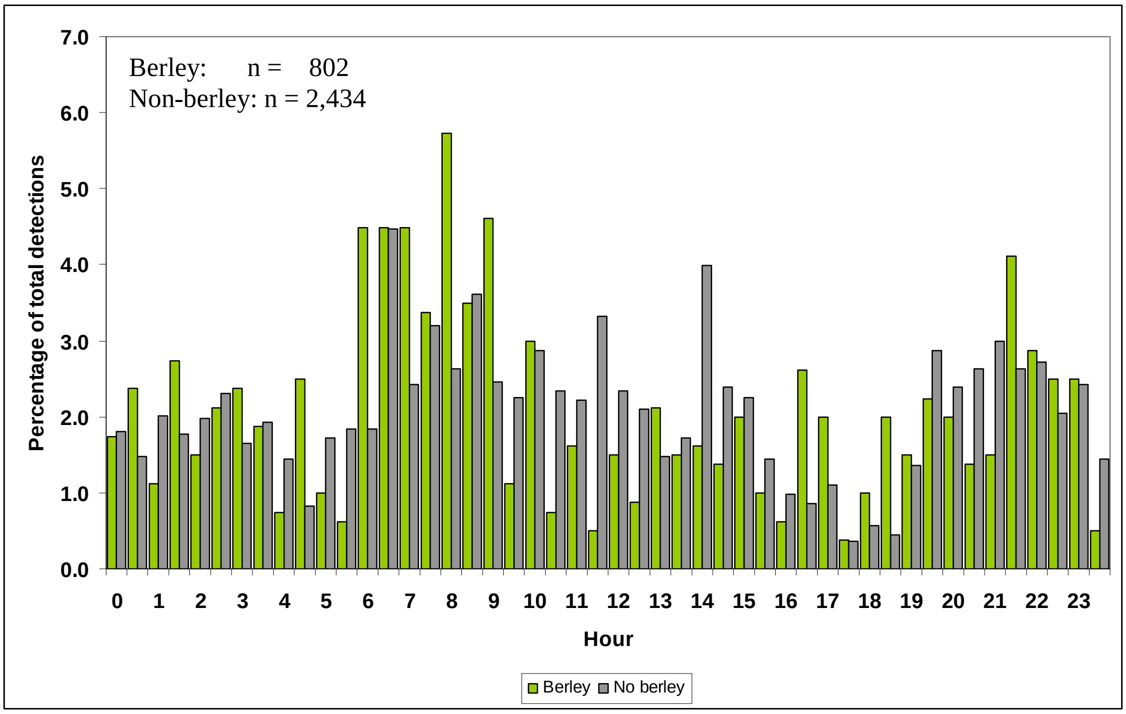

Figure 21: Diel pattern of detections (30 min blocks) of tagged sharks at North Neptune Island 2001-2003 during berley and non-berley periods at the northern berley site (Site 2); n = number of detections of tagged sharks.

These differences in diel patterns suggest that there has been a significant change in the daily pattern of shark activity at berley Site 2 from the 2001-2003 to 2010-2011 periods with a shift to a high degree of daytime activity similar to the pattern observed within the bay at Site 1.

Arrival and departure of sharks

The arrival and departure times for sharks were calculated based on acoustic detection data. An arrival time was registered when a shark was first detected on any one of the North Neptune Island array receivers and sharks were deemed to have departed if the period between detections exceed 3 hrs. Three hours was chosen on the basis that 75% of all gaps between detections during visits were less than this period (Figure 22).

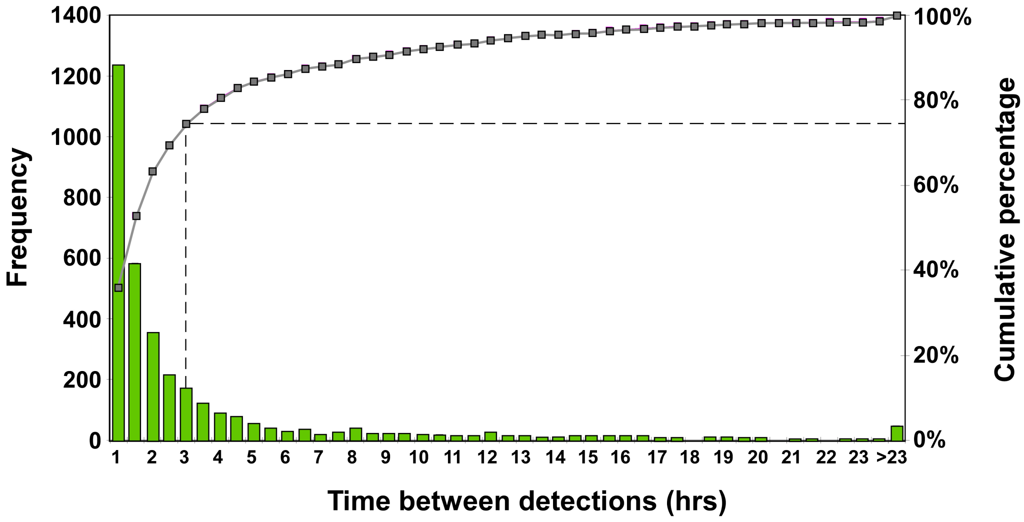

Figure 22: Cumulative histogram of the length of time between successive detections of individual sharks (binned by 30 minute blocks) for all tagged white sharks (2010-2011 data).

Examination of the 2001-2003 data by 30 minute time blocks indicated that arrivals and departures of sharks were evenly distributed over a 24 hour period during berley and non-berley days (Figures 23 and 24; Table 3).

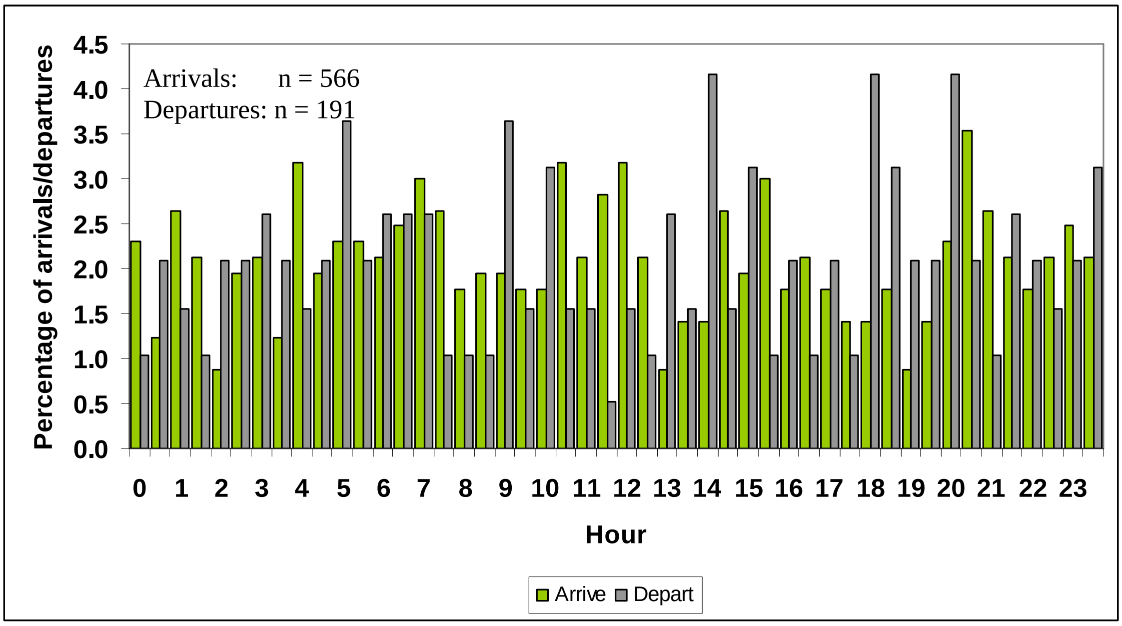

Figure 23: Hourly frequency of arrivals and departures of tagged sharks at North Neptune Island on berley days (2001-2003 data); n = number of recorded arrivals or departures.

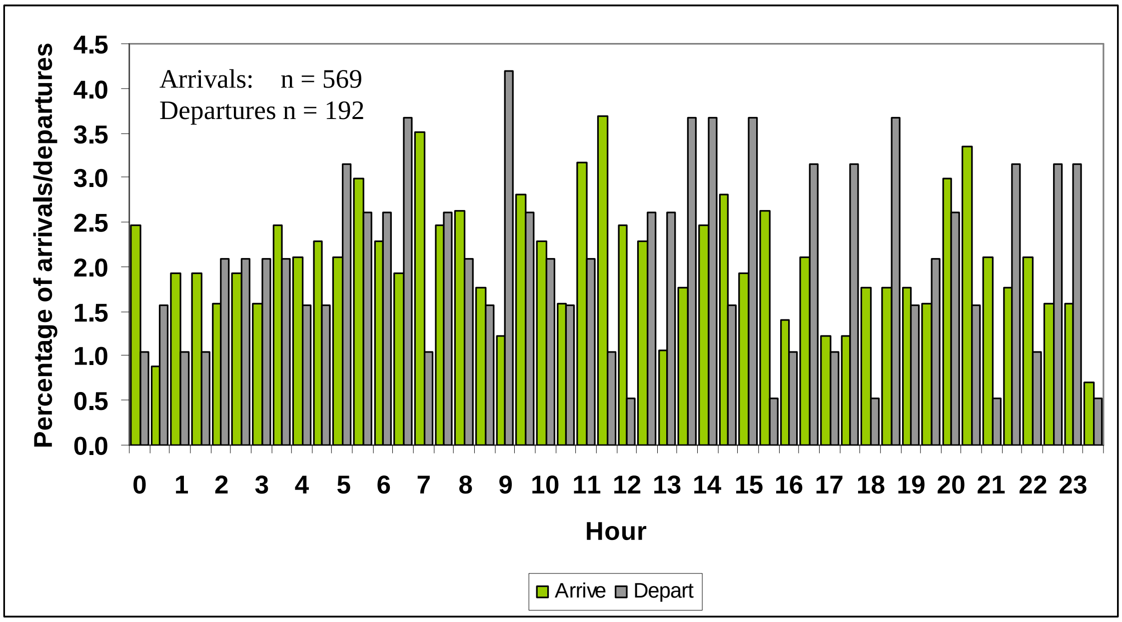

Figure 24: Hourly frequency of arrivals and departures of tagged sharks at North Neptune Island on non-berley days (2001-2003 data); n = number of recorded arrivals or departures.

During the 2010-2011 study, arrivals on days when berleying occurred showed a clear peak in frequency between 0730-0830 (Figure 25). A similar, although slightly broader peak (0700-0900) was also evident in arrivals on non-berley days (Figure 26). These patterns were significantly different to the 2001-2003 data (Table 3).

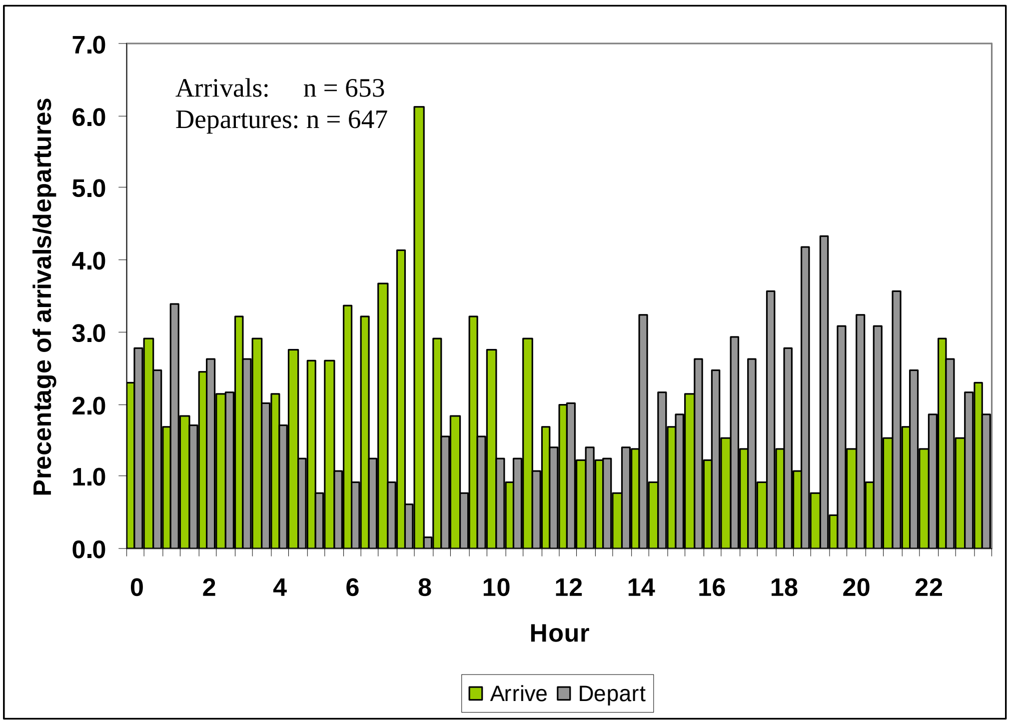

Figure 25: Hourly frequency of arrivals and departures of tagged sharks at North Neptune Island on berley days (2010-2011 data); n = number of recorded arrivals or departures.

Departures on berley days occurred over a more extensive period than arrivals and peaked between 1400 and 2200. Departures on non-berley days were also more broadly spread, peaking between 1200 and 2100.

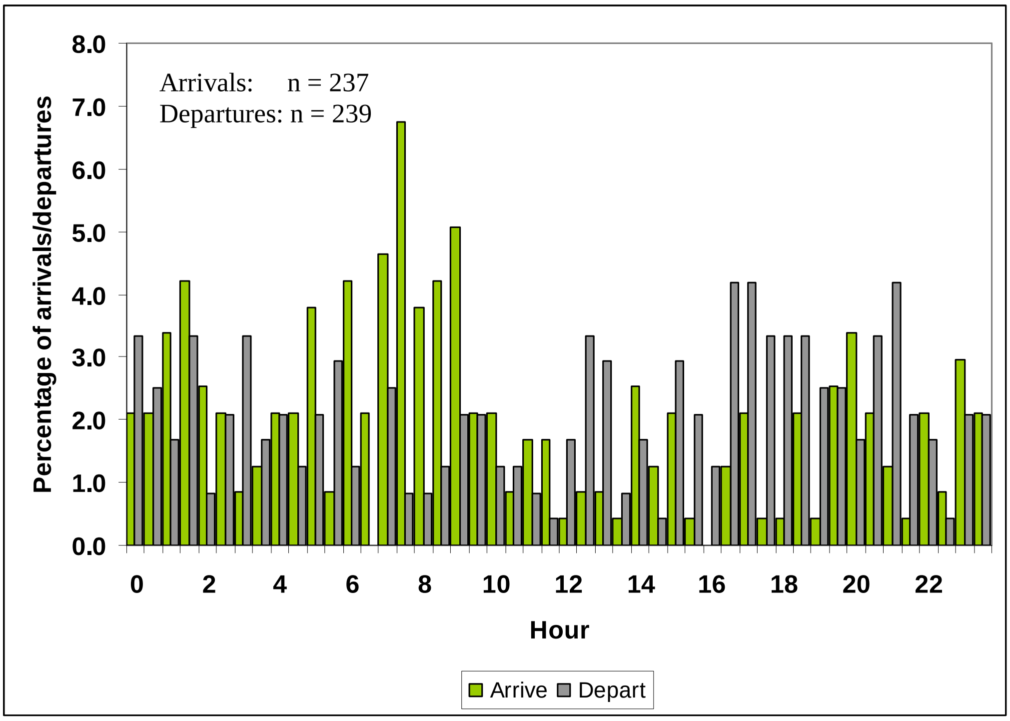

Figure 26: Hourly frequency of arrivals and departures of tagged sharks at North Neptune Island on non-berley days (2010-2011 data); n = number of recorded arrivals or departures.

Table 3: The results of χ^2 goodness-of-fit analyses of arrival and departure times during berley and non-berley periods. Bold values for *p* indicate a significant variation from an even distribution over a 24 hour cycle.

Activity and period	χ^2 value	*p* value
2001-2003		
Berley days - arrival time	50.367	0.342
Berley days departure time	36.500	0.867
Non-berley days arrival time	57.025	0.150
Non-berley days departure time	44.476	0.578
2010-2011		
Berley days - arrival time	164.911	**<0.0001**
Berley days departure time	136.357	**<0.0001**
Non-berley days arrival time	110.747	**<0.0001**
Non-berley days departure time	62.456	0.065

The timing of arrival and departure of SCDO (a proxy for the commencement and completion of berleying at North Neptune sites) was extracted from daily logbook data (2010-2011). Arrival of operators at the North Neptune Islands ranged from 0600-1600 but showed a very distinct peak at 0930-1000 (Figure 27). Operators departed the site between 1000 and 2000, with a less well defined peak ranging from 1400-1800.

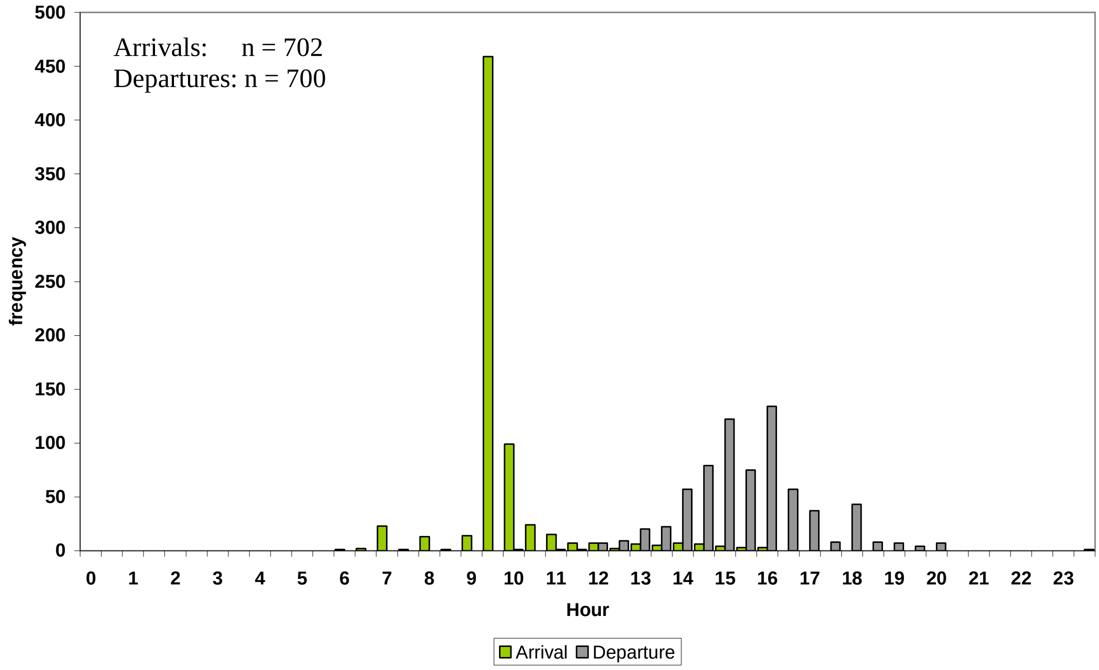

Figure 27: Distribution of arrival and departure times by shark cage dive operators at North Neptune Island (2010-2011) based on daily logbook data.

These data indicate that there has been a significant change in the daily patterns of arrivals and departure of sharks at the North Neptune Islands between the 2001-2003 and 2010-2011 periods, with shark arrivals and departures now following a diel pattern and approximating the arrivals and departures of shark cage dive operators.

Discussion

The Neptune Islands, situated 60 km south of Port Lincoln, South Australia, have been the focus of activities (including berleying) to view, film and cage dive with white sharks since the 1960s. Currently, shark cage dive operator activities occur primarily at the North Neptune Islands due to their close proximity to Port Lincoln, the area's protected anchorages and, for the area's reliable shark encounters. Activities are relatively rare at the slightly more distant, and less well protected, South Neptune Islands. Berleying activities at the South Neptune Islands accounted for only 4.1% of all berley days prior to 2007 (total number of days, n = 979) and only 1.1% of all berley days post-2007 (total number of days, n = 1026).

Acoustic monitoring at the North Neptune Islands indicated that tagged white sharks change their distribution to align with areas of active berleying over small spatial and temporal scales. Berleying by shark cage dive operators (SCDO) at the North Neptune Islands occurs at two primary sites: one inside a small bay and the other to the north of a gap between two islands that make up the group. These sites are separated by approximately 700-800 m and the centre of activity of sharks changed between them in unison with the presence of berleying activity. This was consistent with SCDO observations where visual contact with individual sharks could be readily re-established after moving berleying operations between the two sites. Strong *et al*. (1996) concluded that the attracting effects of berley can extend over a scale of several kilometres and thus the distance between the two berleying sites falls well within the range for attracting sharks from one site to another. This response to berleying is an expected result. The success of tourism ventures designed to view white sharks is reliant on attracting sharks already present in the area to within the visual range of the vessel (Laroche *et al*. 2007). However, this result also demonstrates that the acoustic receiver system deployed at the Neptune Islands was able to adequately monitor the response of sharks to SCDO activities in the area and provides confidence that the arrays also adequately captured the pattern of habitat use by sharks in the Neptunes Islands system in general.

The two berley sites are located off eastern sectors of the North Neptune Islands. These sites are adjacent to the areas where seals and sealions are most common (Shaughnessy and Mckeown 2002, Simon Goldsworthy, SARDI, pers. comm.). Shark activity (regardless of berleying) was significantly higher in these eastern sectors than in any other areas surrounding the North Neptune Islands. Similar, uneven distributions of white sharks have been reported around other seal colonies, with sharks showing a general preference to occur in areas close to the maximum concentration of seals, or within the areas of common corridors that seals use to approach and depart island systems (Klimley and Anderson 1999, Martin *et al.* 2005). These observations suggest that the uneven distribution of sharks at the North Neptune Islands may be a result of their natural propensity to reside off the eastern sectors rather than being driven by berleying operations alone. However, within this area of naturally focussed shark activity, it is clear that berleying influences the specific sites occupied by sharks on small spatial and temporal scales.

Acoustic monitoring demonstrated that sharks were temporary residents of the Neptune Islands and that individual residency periods commonly comprised a series of visits (consecutive days of detections) interspersed with days where sharks were not detected. This was consistent with observations on habitat use by white sharks at the Neptune Islands during a similar 2001-2003 study by Bruce *et al*. (2005) and is consistent with acoustic monitoring of tagged white sharks in other areas of the species' range (e.g. California - see Jorgensen *et al*. 2009). A lack of detections did not necessarily mean that sharks had completely departed the Neptunes Islands system, as sharks had only to move > 500 m from the acoustic array for detections to cease. However, periods of extended absence were generally few when sharks were resident, indicating a propensity for sharks to remain in the close vicinity of the islands when present. Confirmed departures of sharks were apparent when they were detected by acoustic receivers at other sites. Sharks, for example, made several return transits between the North and South Neptune Islands and, in several cases, the transit times indicated rapid and direct travel between these sites. These transits occurred regardless of berleying activity at the North Neptune Islands. Directed travel between sites of temporary residency has been demonstrated for juvenile, sub-adult and adult white sharks over both small (< 10s km) and large (1000s km) spatial scales (Bonfil *et al*. 2005, Bruce *et* *al.* 2006, Johnson *et al.* 2009, Jorgensen *et al.* 2009, Bruce and Bradford *in press*). This behaviour appears to be a common, and thus presumably normal, feature of the species across its range. Detection records for many sharks ceased well prior to the end of the study suggesting they had departed the Neptune Islands system. This was confirmed in three sharks which were all detected on acoustic receivers set approximately 2000 km to the west (Chatham Island, Western Australia) after their last detection at the Neptune Islands. Sharks tagged with acoustic tags at the Neptune Islands prior to the 2010-2011 study have also been detected on Western Australian arrays off Bremer Bay, Albany, Rottnest Island (Perth) and off Ningaloo Reef. These observations support the common westerly movement of white sharks after their departure from the Neptune Islands described for satellite-tracked individuals by Bruce *et al*. (2006). These data support that although berleying influences the local spatial scale of white activity at the Neptune Islands, individuals still depart the area and undertake broad-scale movements across southern and western Australia consistent with other studies of their behaviour.

Previous studies on the effects of berleying on white shark behaviour have concluded that impacts are localised and relatively minor (Bruce *et al*. 2005, Laroche *et al.* 2007). However, both studies suffered from a lack of baseline or control data with which to compare results, and in both cases the amount of berleying activity relative to the current situation at the Neptune Islands was relatively low, albeit effort had been ongoing for many years. The previous study of white shark residency and habitat use at the Neptune Islands by Bruce *et al*. (2005) was prior to the 2007 (and subsequent) increase in berley effort. This previous data set thus provided the opportunity to compare current shark behaviour after three years of significantly increased berleying effort (post-2007).

Temporarily altering the behaviour of sharks is one of the key elements of a successful and economically viable shark cage diving operation and an essential element for client satisfaction. Sharks are attracted to the vessel and contact time is encouraged so as to enable clients to view sharks that would otherwise not be reliably seen. However, wildlife tourism that involves provisioning (feeding), attraction, or some form of reward for the animals involved, can often result in changes to behaviour in target species that last over different time scales and may give rise to unintentional effects on those species and the ecosystem within which they reside (Orams 2002). Behavioural changes in the context of provisioning or berleying operations may manifest as an acceleration in response time and/or increased contact time between target species and the tourism operation (Laroche *et al.* 2007, Maljkovic and Cote 2011), arrival at the 'provisioning' site in anticipation of vessel arrival (Meyer *et al*. 2009), changes in the duration that target species remain in specific areas, and/or changes in diel activity, residency patterns and depth-swimming behaviour (Semeniuk and Rothley 2008, Fitzpatrick *et al*. 2011).

Comparisons between the behaviour of sharks acoustically monitored during the 2001-2003 and the 2010-2011 periods, as well as data from the VR4G mooring and SCDO daily logbooks over more extensive time periods, all detected significant changes in shark behaviour and residency at the North Neptune Islands since berleying effort and its regularity increased from 2007 onwards.

Logbook data indicate that there has been a significant increase in the number of sharks sighted per day by SCDO since 2007 and that this increase is apparent across every month. It is tempting to assume that this increase in shark sightings is a result of an increase in population size in response to the species protection in the late 1990s (Malcolm *et al*. 2001). Long-term monitoring of shark activity from the same logbook data indicates that the pattern of shark activity varies with season and between years (Figure 28), with periods of below, or of no, shark activity occurring at the North Neptune Islands both pre and post-2007, regardless of an overall average increase in sharks sightings. It is unclear what drives these variations in shark activity, but it is likely that they relate to environmental influences and manifest over far broader areas than the North Neptune Islands alone. These interannual variations make it difficult to determine population-level changes in abundance from these data.

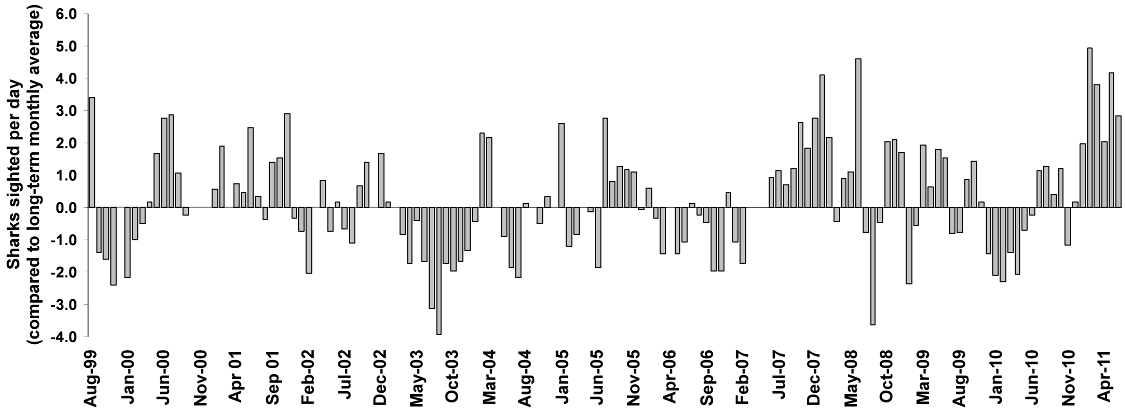

Figure 28: Long term (1999-2011) aggregated monthly data of shark activity (sharks sighted per day) at the North Neptune Islands. Data represent deviations from the long-term average for each month. Positive values indicate an above average number of sharks sighted during the month; negative values indicate a below average number of sharks sighted during that month.

Concurrent with the increase in recorded shark sightings since 2007, sharks have significantly increased the duration of their visits at the North Neptune Islands. Increases in the population size of sharks may naturally increase shark residency times if animals were competing for access to the same resource (in this case seals/sealions) and if sharks were required to adequately provision on seals prior to their departure from the Neptunes system. This process is referred to as competitive interference (Case and Gilpin 1974, Krause and Ruston 2002). Longer residence times may ensue if competition between sharks resulted in some animals taking longer to capture sufficient seal prey to adequately provision themselves and hence requiring an extension of their visits to do so. The short-term residency of sharks to the Neptune Islands system followed by departure, long distance travel to other feeding sites where prey different to seals are targeted and then return to the Neptunes (Bruce *et al*. 2006) is consistent with provisioning on seal prey being an important, but only part component of a shark's annual diet. Although not conclusive, this is consistent with a scenario that may lead to competitive interference at the Neptune Islands when shark numbers increase. However, an increase in shark sightings is also a predictable consequence of an increase in the duration of visits even in the absence of an overall increase in population size or competitive interference. An increase in the duration of visits results in sharks accumulating on site and thus the probability of encountering (= sighting) any one particular shark is increased. Notably, the duration of visits at South Neptune Island was not significantly different between the 2001-2003 and the 2010-2011 data sets, suggesting that this change is exclusive to the North Neptune Islands where SCDO activities primarily occur. It is reasonable to expect that if the increase in the duration of visits was in response to a general and more widespread increase in population size, that a similar effect would be apparent at the South Neptune Islands. The increase in duration of visits, exclusive to the North Neptune Islands, is consistent with a response to provisioning/berleying at that site (Laroche *et al.* 2007, Maljkovic and Cote 2011).

Acoustic monitoring also recorded changes in the daily distribution of detections of tagged sharks at the North Neptune Island berley sites. In the 2001-2003 study, sharks showed a distinct diel pattern in detections at Site 1 inside the bay where, at that stage, most berleying operations occurred. Detections at Site 2, where berleying operations were comparatively infrequent, showed no evidence of a diel pattern. Post-2007 the number of days when berleying occurred at Site 2 increased substantially in line with an overall increase in berleying effort. In excess of 400 days of berleying have been registered at Site 2 since 2007 with the frequency of berleying activities also increasing at Site 1. Berleying activities at both sites followed a more regimented daily timing post-2007, occurring during daylight hours between 0600 and 1600. Sharks monitored in the 2010-2011 acoustic study showed distinct diel patterns of detections at both Sites 1 and 2, indicating a maintenance in the 2001-2003 pattern at Site 1 and a substantial change at Site 2 in-line with an increase in berleying effort at that site and matching the overall daily window of the berleying operations. Notably, the diel patterns in shark detections at both Sites 1 and 2 were maintained even on days when berleying did not occur. Diel patterns in habitat use by sharks are well documented for a variety of species (Klimley *et al*. 1988, Holland *et al.* 1993) and have been suggested for white sharks as being part of a natural diel cycle in hunting behaviour around seal colonies (Bruce *et al*. 2005). However, the change in diel behaviour at Site 2 in conjunction with a substantial increase in berleying effort at that site is consistent with a response to provisioning/berleying at that site similar to that observed in other shark and ray species in areas where provisioning occurs (Semeniuk and Rothley 2008, Fitzpatrick *et al*. 2011). Furthermore, the maintenance of this pattern on days when berleying did not occur suggests an anticipatory response by sharks to berleying operations on site.

Arrival of sharks at ‘provisioning’ sites in anticipation of vessel arrival has been observed or suggested in a number of studies (e.g. Meyer *et al*. 2009, Fitzpatrick *et al*. 2011 and references therein), but has not previously been demonstrated in white sharks. Acoustic monitoring in 2010-2011 demonstrated a marked change in the timing of arrival and departure of sharks at both Sites 1 and 2 at the North Neptune Islands compared to the 2001-2003 study. During the 2001-2003 study, shark arrival and departure times showed no diel pattern on either berley or non-berley days. In the 2010-2011 study, sharks showed a distinct diel pattern with arrivals peaking between 0700 and 0900 with a distinct, but slightly more diffuse, peak in departures between 1400 and 2200. The peak in arrival times of sharks was immediately prior to the peak in arrival times of SCDO vessels which occurred between 0900 and 1000. Departure of SCDO vessels occurred over a more extensive time window that fell within the peak window of shark departures. Strong *et al.* (1996) observed that white sharks remained present for a period up to several hours after berleying ceased, undertaking a swim behaviour they described as ‘downstream circling’. Downstream circling was regarded as a response by sharks to the presence of the berley plume until it dissipated, a process dependant on local conditions at the time. The broader peak in shark departures relative to the cessation of berleying is consistent with these observations of Strong *et al.* (1996). A similar, although slightly less pronounced, peak in arrival and departure times of sharks was also apparent on non-berley days. The reasons for the pattern being less distinct on non-berley days may be a result of there being less data for these days or that sharks did not respond as strongly when berleying activities did not occur. In any event, the shift from no daily pattern to a distinct daily peak in arrivals and departures by sharks that was in phase with the arrival and departure of SCDO vessels, and that propagated through to non-berley days, is consistent with both a change in diel activity and an anticipatory response by sharks to SCDO activities as a result of berleying/ provisioning (Semeniuk and Rothley 2008, Meyer et al 2009, Fitzpatrick *et al*. 2011).

The extent of changes observed at the North Neptune Islands was unexpected based on the ambiguous results of previous studies of white shark responses to berleying operations (e.g. Laroche *et al*. 2007). Berley by itself does not constitute provisioning, the latter referring to feeding of the target species. Berley attracts sharks by providing an odour corridor over distances of up to several kilometres and visual cues over smaller spatial scales close to its source (Strong *et al*. 1996). Berley used by SCDO is a mix of tuna oil and minced fish products. While it may provision finfish in the area, berley is comprised of particles too small for white sharks to feed on. Teaser baits used to lure sharks closer to the vessel, thereby increasing the proximity experience between sharks and tourists, provide the only provisioning opportunity for sharks during SCDO operations at the Neptune Islands. Teaser baits are generally pieces of tuna in the form of head, trunk, tail sections, or gill and gut remains. Teaser baits vary in size from one to several kilograms. Normal SCDO operating procedures limit the number of teaser baits taken by sharks, but does not prevent this completely. It is unclear if the current level of inadvertent provisioning provided to sharks by them occasionally intercepting teaser baits is sufficient to generate a conditioned response. It would seem unlikely that teaser baits would be sufficiently consumed to provide a sufficient alternative, and hence a conditioned response, relative to the benefit provided by a normal seal kill. However, this cannot be ruled out and the consumption of teaser baits by individual sharks should be monitored. The size of teaser baits should be minimised and the consumption of such baits by sharks should also be limited as much as is practical.

Even without the consumption of teaser baits, it is possible that white sharks are sufficiently programmed to respond to the odour corridor that berley produces to maintain an interaction and thus become conditioned to respond to SCDO operations. Under natural circumstances odour corridors comprising biological products provide cues for sharks to locate marine animal carrion that may represent critical feeding opportunities (e.g. in the case of a marine mammal such as a dead whale). Response to such stimuli even in the case where no reward is achieved may be an overriding response in white sharks. If this is the case, sharks may forgo feeding and thus provisioning opportunities on seals when present at the Neptune Islands in preference to responding to a suboptimal feeding opportunity in the form of berley and occasional teaser baits. Such a distraction response to SCDO operations would have the potential to come at an energetic cost to sharks in the form of lost feeding opportunities. Such impacts have been recorded for other species. Williams *et al.* (2006) concluded that distraction caused by tourist vessels may reduce energy intake in killer whales by up to 18%. Such changes to behaviour may have impacts on other species in the area. If sharks are distracted from natural feeding opportunities or, occupy areas or undertake swimming patterns that are not conducive to normal predatory behaviour, then these may result in changes to the overall predatory pressure on seals and sealions in the area as suggested by Laroche *et al*. (2007) for shark-seal interactions in South Africa.

Although all parameters examined suggest behavioural changes have occurred that are consistent with those observed in other shark and ray species in response to berleying, it is inconclusive whether they represent long-term costs to white sharks visiting the Neptune Islands. Understanding the repercussions to white sharks of altered behaviours attributable to the effects of berleying is complicated as sharks are only temporary visitors to the North Neptune Islands where berleying occurs, and thus are only exposed to this activity for the periods during which they reside there. Determining the impacts of such effects are beyond the scope of this study. However, various issues have been documented in other situations where wildlife, including sharks and rays, are attracted for the purpose of tourist viewing including dependence on provisioning, overfeeding, malnourishment, increased aggression, altered behaviour, disrupted ecological relationships and an unbalancing of energetic budgets (Orams 2002, Newsome *et al*. 2004, Semeniuk and Rothey 2008, Semeniuk *et al*. 2009, Clua *et al*. 2010).

Given that white sharks are a listed threatened species and thus subject to protection provisions under both State legislation and the Commonwealth Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act), a process to minimise the impacts of berleying operations on shark behaviour at the North Neptune Islands is warranted. The challenge for managing agencies and the SCDO industry in South Australia, will be to find a balance between reducing these impacts on shark behaviour and the ecosystem within which they reside, while maintaining a successful, economically viable and world-class shark cage diving experience that fulfils client expectations, continues to contribute significantly to the local economy and provides a platform for education and research on white sharks and their conservation into the future.

Recommendations

A) Reduce berleying/provisioning effort at the North Neptune Islands:
All monitored parameters support that there have been changes in the patterns of shark behaviour at the North Neptune Islands which are consistent with impacts from berleying/provisioning operations. This suggests that the current level of berleying should be reduced, or at least capped, to minimise any further behavioural changes. Teaser baits should be of a minimum size required to be effective and all reasonable efforts should be made to minimise the number of baits taken by sharks.

B) On-going monitoring of shark behaviour:
The monitoring of shark residency periods, duration of visits and daily patterns of island contact should continue so as to evaluate the behaviour of sharks in response to any mitigation actions and provide feedback to managing agencies and the industry regarding the efficacy of management actions. This would be most cost-effectively achieved by maintaining the remotely monitored iridium-linked VR4G receiver onsite within the bay at the North Neptune Islands (berley Site 1) and continue to tag sharks with acoustic tags to monitor shark behaviour. Consideration should be given to deploying additional iridium-linked VR4G receivers at berley Site 2 (North Neptune Islands) as well as at South Neptune Island, the latter to monitor comparative shark behaviour at that site. If management actions involve opening additional sites to berleying in South Australian waters, these sites should also be monitored by acoustic receivers and the tagging of sharks at these site should be commenced at the start of any program of SCDO activities.

C) Implement an education and awareness program about the risks posed to sharks by excessive berleying or provisioning and the key tactics used in mitigating the negative impacts of tourism:
Managing the impacts on sharks of SCDO operations should be seen as achieving world's best-practice in this industry and a bench mark example for other areas where such activities are undertaken. SCDO and their clients should have access to material that clearly articulates how the industry is managed, why this management is important and, specifically, how the impacts on sharks and the environment of industry activities are mitigated. The shark cage dive industry in South Australia has a long history of supporting research on white sharks and provide an ideal platform to educate clients about shark ecology, movement patterns and conservation. Educational material detailing these research findings should be available to all clients to improve conservation awareness.

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