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Report by - Dr Ashley J. Frisch - 2013 Churchill Fellow

THE DR DOROTHEA SANDARS AND IRENE LEE CHURCHILL FELLOWSHIP to develop robust methods for measuring and monitoring reef shark populations

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Signed Ashley Frisch Dated 31 / 12 / 2013

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INTRODUCTION

The Dr Dorothea Sandars and Irene Lee Churchill Fellowship enabled me to travel to the United States of America, where I was based at the Pacific Islands Fisheries Science Centre (Hawaii) and the Rosenstiel School of Marine and Atmospheric Science (Florida). The aim of my project was to develop robust methods for measuring and monitoring the condition of reef shark populations. In Australia and around the world, shark populations are thought to have declined substantially, with direct consequences for fisheries and dive-tourism as well as potentially serious indirect consequences for the structure and function of marine ecosystems. The development of robust methods to census shark populations will lead to better conservation and sustainable use of shark populations. This is critical given the threats facing sharks and the need for effective management regimes based on defensible census methods.

ACKNOWLEDGEMENTS

I sincerely thank Dorothea Sandars and Irene Lee for their generosity in sponsoring the Churchill Fellowship for the study of an issue in the field of marine science. I am extremely grateful to the Winston Churchill Memorial Trust for providing me with the opportunity to further my research overseas. I would also like to thank the indigenous Hawaiians of the Ka'ena district in Oahu for granting permission to undertake my research on their coral reefs. The Australian Research Council's *Centre of Excellence for Coral Reef Studies* at James Cook University in Townsville provided additional financial and logistical support during my Churchill Fellowship. I would also like to acknowledge the significant contributions by individuals who provided detailed instruction, advice, and critical logistical support for my project:

- Dr Ivor Williams – Pacific Islands Fisheries Science Centre, Honolulu, U.S.A.
- Dr Marc Nadon – National Oceanographic & Atmospheric Administration, Honolulu, U.S.A.
- Prof. Neil Hammerschlag – Rosenstiel School of Marine & Atmospheric Science, Miami, U.S.A.
- Prof. Carl Meyer – Hawaii Institute of Marine Biology, Coconut Island, U.S.A.
- Kaylyn McCoy – University of Hawaii, Honolulu, U.S.A.
- Dr Kevin Lino – Pacific Islands Fisheries Science Centre, Honolulu, U.S.A.
- Dr Ben Richards - Pacific Islands Fisheries Science Centre, Honolulu, U.S.A.
- Jake Asher - Pacific Islands Fisheries Science Centre, Honolulu, U.S.A.
- Justin Rizzari – School of Marine and Tropical Biology, Townsville, Australia.

EXECUTIVE SUMMARY

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Project Description

Sharks, like other large predators, are critically important because they help to maintain the ecological balance among numerous marine organisms. The ability to accurately measure and monitor shark populations is paramount for their effective conservation and management, but robust methods for rapid census of shark populations are lacking in Australia. The aim of my project was to investigate the limitations of existing methods and, where possible, develop new methods that improve accuracy and efficiency of shark monitoring projects. Ultimately, this research will lead to improved management and sustainable use of sharks, which are currently being captured at unprecedented rates.

Highlights

The Dr Dorothea Sandars and Irene Lee Churchill Fellowship enabled me to travel to the U.S.A. where I was based at the Pacific Islands Fisheries Science Centre (Hawaii) and the Rosenstiel School of Marine and Atmospheric Science (Florida). I worked closely with eminent scientists such as Dr. Ivor Williams, Dr. Marc Nadon, Dr. Carl Meyer and Dr. Neil Hammerschlag, who routinely perform shark counts across vast archipelagos of coral reefs and are widely regarded as world experts in measuring and monitoring shark populations. During my six week visit, I attended numerous workshops, seminars and fieldtrips, as well as compiled a robust dataset to rigorously evaluate the effectiveness of several underwater census methods. I learned about the design, accuracy, and limitations of advanced census methods such as baited remote underwater video (BRUV), diver-based GPS belt transect (DBT) and stereo-video transects (SVT), and I assisted in the development of a new census method known as audible stationary count (ASC). I also learned about the characteristics of shark behavior that may lead to biased estimates of shark populations and how to overcome these problems.

Conclusions, Implementation and Dissemination

Due to the heterogeneous spatial distribution of sharks and their tendency to respond variably to divers, noise, boats and bait, it was concluded that large variation exists in the outputs of different survey methods, and that each method has a range of advantages and disadvantages with respect to cost, convenience, detection capacity and opportunities for bias. In most situations, diver-based surveys were found to produce reliable results, but only when (1) transect length was relatively long, to minimize upward bias associated with initial shark attraction to divers, (2) water depth was shallow enough to enable SCUBA diving but deep enough to encompass the depth distribution of coastal sharks, and (3) water visibility was sufficient to enable wide transects and a clear view of sharks, thereby ensuring that sharks were properly identified and not incorrectly double-counted. Results from this study form the basis of a scientific publication which has been submitted to the internationally recognised *Journal of Animal Ecology*. Research funding is also being sought to expand this research to the Great Barrier Reef and provide necessary training for marine park managers and university students in this field.

PROGRAMME

1st Sep – Departed Townsville, Australia

1st Sep – Arrived Honolulu (via Brisbane and Sydney)

2nd Sep to 1st Oct – Based at the Pacific Islands Fisheries Science Centre (PIFSC), Honolulu, Hawaii, U.S.A.

- 3rd Sep – Site induction and safety induction at PIFSC
- 4th Sep – Project scoping workshop with Dr Ivor Williams of PIFSC and Dr Marc Nadon of NOAA
- 6th Sep – Acquisition of field data from Coral Reef Ecosystem Division (CRED) of the National Oceanographic and Atmospheric Administration (NOAA)
- 9th Sep – Analysis of CRED field data with Dr Kevin Lino of PIFSC
- 12th Sep – Meeting with Prof. Carl Meyer at Hawaii Institute of Marine Biology (HIMB) to discuss (1) spatial and temporal distribution of sharks in relation to sampling frame of diver-based survey methods, and (2) feasibility of automated vehicles to conduct underwater surveys.
- 13th Sep – Workshop with Dr Ivor Williams to learn about underwater visual census methods (n.b. I met with Dr Williams every day for the next two weeks to discuss different survey methods and to design new experiments)
- 17th Sep – Attended a seminar about Pacific Island fisheries (Ms Eva Salas from Samoa)
- 19th Sep – Attended a seminar about effects of fishing on coral reef ecosystems (Prof. Morgan Pratchett, CoE Coral Reef Studies)
- 20th Sep – Visit Kaneohe Bay and Ka’ena District to investigate the feasibility of field research
- 23rd Sep – Met with traditional owners (indigenous Hawaiians) to request permission to undertake field research on local coral reefs
- 24th Sep – Met with Jake Asher to learn about baited remote underwater video (BRUV) and their utility for monitoring shark populations
- 26th Sep – Met with Kaylin McCoy (spatial information specialist) of University of Hawaii to analyse CRED dataset
- 30th Sep – Met with Dr Ben Richards of PIFSC to learn about tow-based methods for surveying shark populations

1st Oct to 11th Oct – Fieldwork (n.b. due to official shutdown of the United States Government from 1-16 October, I was unable to continue working at PIFSC and I was unable to meet with any Government employees. Therefore, I used the available time to undertake fieldwork on local coral reefs)

- 1st to 7th Oct – Fieldwork to evaluate existing survey methods and to develop a novel survey method (audible stationary count).

- 8th Oct – Invited public seminar by Dr Ashley Frisch at the Waikiki Aquarium, hosted by the Hawaiian Conservation Alliance (HCA) and the Pacific Islands Climate Change Cooperative. Seminar title: *Apex predators, climate change and coral reefs*: *the need for urgent action*

12th Oct to 20th Oct – Private travel

20th Oct – Travel to Florida Keys (via Dallas and Miami)

- 21st to 27th Oct – Continuation of fieldwork, taking advantage of the network of marine reserves in the Florida Keys.

28th Oct – Travel to Miami

- 30th Oct – Meet with Prof. Neil Hammerschlag at Rosenstiel School of Marine and Atmospheric Science (RSMAS) to learn about biases in diver-based survey methods and the utility of fisheries-dependent methods such as long-lines.
- 2nd Nov – Meet with graduate students to learn about their shark-related research projects

4th Nov – Depart Miami

6th Nov – Arrive in Townsville, Australia (via Dallas and Brisbane)

MAIN BODY

Background and importance

The Great Barrier Reef (GBR) is an international tourist icon that supports over 43000 jobs and injects $3.7 billion annually into Australia's economy. Reef sharks contribute significantly to the GBR tourism industry, both directly and indirectly. Firstly, opportunities to view reef sharks are a major factor in attracting tourists to the GBR – sightings of reef sharks have been valued at $1375 each, more than any other reef creature (www.rrrc.org.au). Secondly, sharks contribute to the overall health and attractiveness of marine ecosystems by stabilising the ecological balance among smaller, more numerous prey organisms. Reef sharks are also captured and sold for their flesh and fins, and thus contribute significantly to the economic value of coastal fisheries. Because of the unique biological characteristics of reef sharks (e.g. late maturity, few offspring), they are exceptionally vulnerable to over-fishing. Significant declines in reef shark populations have already occurred in many parts of the world, including the GBR (Robbins et al. 2006; Ward-Paige et al. 2010; Nadon et al. 2012). It is expected that further declines in reef shark populations will have serious economic consequences for the tourism and fishing industries.

To understand the ecological role of sharks, assess the effects of fishing, and evaluate the effectiveness of current management regimes, it is essential to develop reliable and standardized methods for estimation of reef shark abundance and population size. To date, this objective has proven to be problematic, partly because sharks are naturally rare and highly mobile, and partly because sharks respond variably to different stimuli such as noise, bait, people and boats. Consequently, there is a high degree of uncertainty in population assessments of sharks, and an even higher degree of uncertainty in the effectiveness of current management regimes. This shortcoming distracts critical conservation and management efforts, and puts sharks at risk of further declines in abundance. A thorough assessment of the performance of shark survey methods is therefore warranted. Where necessary, new methods will be required to improve accuracy and efficiency, and to overcome the problems of existing survey methods.

Currently, the most popular methods for assessing reef shark populations are visual or video techniques because they are relatively quick and easy to perform, independent of fisheries, and permissible in highly protected or sensitive areas where manipulative sampling is prohibited or unethical. Visual survey methods are often criticized due to potential bias caused by attraction or repulsion of sharks to/from humans (divers), depending on situation and/or prior experience. For example, if sharks are less accustomed to people at protected or remote locations, then they may be more likely to approach divers, leading to over-estimates of abundance. Therefore, better knowledge of shark behavior is required, including an evaluation of how shark responses to divers may bias estimates of shark populations.

The objectives of my Churchill Fellowship were to:

1. learn about the behavior of sharks and how this might influence the outputs of shark surveys;
2. evaluate the utility of existing survey methods for sharks;
3. develop new mathematical models to improve accuracy of population estimates; and
4. develop new methods to monitor shark populations.

Evaluation of shark behaviour

Whilst in Hawaii, I had many detailed discussions with Dr Williams, Dr Nadon and Prof. Meyer about the effect of shark behavior on the outputs of diver-based surveys. Two principal concerns were highlighted: sharks may be attracted to divers because divers represent novel prey-like items, or sharks may be repelled by divers because sharks are naturally cryptic and have learned that divers are not prey. The former case would tend to produce an over-estimate of abundance, while the latter case would tend to produce an under-estimate of abundance. In both cases, one would expect (A) a non-random time-frequency distribution of shark encounters over the course of a timed-swim and (B) a high proportion of sharks that respond to the diver with behaviours that are visibly attractive or evasive.

To evaluate these alternative scenarios, a series of dives were performed on local reefs in Hawaii and Florida. The reefs in these locations are well developed with a high proportion of scleractinian corals and a diverse fish community dominated by lutjanids (snappers), acanthurids (surgeon fish), scarids (parrotfish) and pomacentrids (damselfish). During each of fifty belt transects, I maintained a slow but steady swimming speed (approximately 11 m min^{-1}) for 45 min whilst following the 6m depth contour of the reef. When a shark was sighted, I recorded the time (to the nearest second), species, total length (TL, to the nearest 5 cm) and any unique identifying characteristics such as colour patterns and scars, which helped to ensure that individuals were only counted once. The behavioural response of individual sharks was recorded at the moment they were first sighted (one observation per shark). Responses were categorized as 'evasive' (immediate change of direction away from the diver), 'attracted' (direct, head-on approach or immediate change of direction toward the diver) or 'neutral' (no change of direction).

To evaluate how sharks responded to divers, and whether sharks' responses were likely to influence estimates of abundance, two types of analyses were performed. Firstly, a χ^2 homogeneity test was used to evaluate the distribution of behavioural responses (evade, approach, neutral). Secondly, if sharks are behaviourally neutral toward divers, then it was hypothesized that the encounter rate should remain constant over the course of each timed-swim and the cumulative distribution of observation times should be linear. Alternatively, if sharks are attracted to divers, then it was hypothesized that the encounter rate would be initially high, but decrease thereafter. To test this statistically, the time-frequency distribution of shark sightings was compared with an expected uniform distribution using a Kolmogorov-Smirnov (K-S) test.

RESULTS: Five species of reef shark were encountered: *Carcharhinus amblyrhynchos* (grey reef shark), *Carcharhinus melanopterus* (black-tip reef shark), *Triaenodon obesus* (white-tip reef shark), *Carcharhinus galapagensis* (Galapagos shark), *Carcharhinus perezii* (Caribbean reef shark). Except for *C. perezii*, these species are also found in Australia.

Individual sharks were found to be visibly unique (in terms of species, size, colour patterns, scars, etc.) and no shark was knowingly observed more than once during a single survey. Only a small proportion of sharks appeared to be evasive (9%) or interested (11%), while the majority (80%) of sharks showed no apparent behavioural response to the diver (Fig. 1).

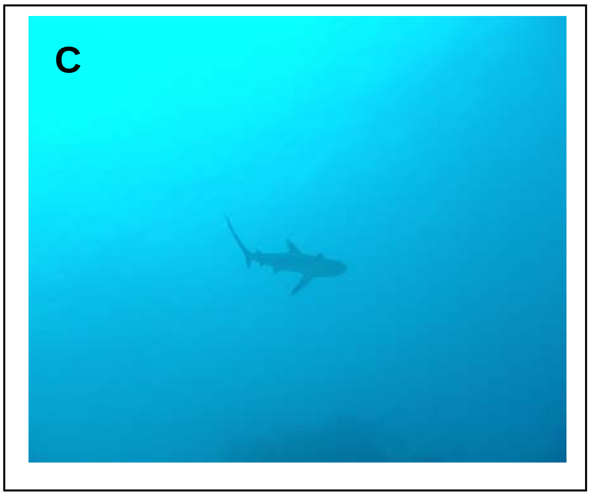

Figure 1. Behaviour of reef sharks in Hawaii and Florida. (A) White-tip reef shark attracted to the diver (head-on approach). (B) Grey reef shark evading the diver (change of direction away from the diver). (C) Galapagos shark showing neutral behavior (ignoring the diver).

Sharks were observed at random intervals throughout each dive, with no apparent aggregation of sharks near the diver at the beginning of a dive. When data were pooled across multiple surveys, the cumulative frequency distribution of observation times was approximately linear (Fig. 2). Together, these results suggest that reef sharks are neither innately attracted to, nor repelled by divers on coral reefs in Hawaii and Florida.

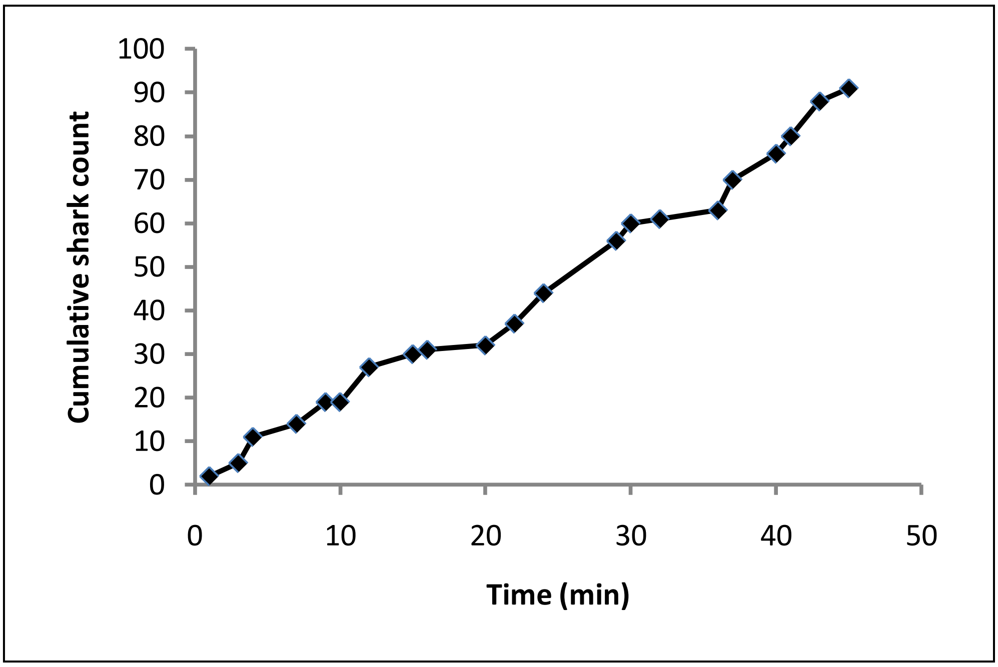

Figure 2. Cumulative distribution of shark observation times during diver-based belt transects. The relationship between shark count and survey time is approximately linear and indicates that sharks were observed at random intervals throughout each transect. A linear relationship suggests that sharks are not attracted to the diver.

The research presented here was undertaken on reefs in Hawaii and Florida where it is reasonable to assume that most sharks have previously seen people and become accustomed to them. However, it is important to remember that the behaviour of sharks towards humans may be a product of prior experience. For example, if sharks are less accustomed to people at unfished or remote locations, then they may be more likely to approach divers, leading to over-estimates of abundance. According to scientists in Hawaii, sharks in remote places (such as the northern Line Islands) aggregate around divers, particularly at the beginning of a dive, presumably because divers resemble food to naïve sharks. In some locations (such as the Northwestern Hawaiian Islands), sharks may be attracted to people because divers resemble monk seals, which enhance sharks' foraging success by flushing potential prey from the seafloor (Parrish et al. 2008). Therefore, it is recommended that future studies evaluate shark behavior during each underwater survey to enable independent assessments of sampling bias on a case-by-case basis. This will be particularly important for places like the Great Barrier Reef where management zoning creates a strong gradient in the potential for interactions between sharks and humans. In particular, naïve sharks may be attracted to divers in Preservation Zones, which are strictly enforced exclusion zones (no-entry zones). Experiments are currently underway on the Great Barrier Reef to resolve this issue.

Evaluation of existing survey methods

In the past, a range of survey methods were used to estimate population sizes of reef sharks. However, little consideration was given to factors that might influence those estimates, such as the spatial distribution of sharks and the relative efficacy of each method (i.e. how well each method detects sharks). To count and monitor shark populations with a high degree of efficiency and accuracy, it is essential that survey methods are standardized. Previously, it was assumed that sharks were naturally cryptic and therefore methods that generated the highest estimates of density were always considered to be the most accurate (McCauley et al. 2012). However, there is mounting evidence that this is not necessarily true. With the help of scientists at PIFC and HIMB, I compared the effectiveness and limitations of several existing survey methods.

Large, long-term datasets (>40,000 records) were kindly shared by Prof. Carl Meyer and Dr Ivor Williams. Much of my time in Hawaii was spent analyzing these complex datasets. The first dataset (owned by Prof. Meyer) documents the spatial distribution of reef sharks using underwater telemetry. Sharks were captured by baited long-line and then tagged with an ultrasonic transmitter, which enables scientists to track their movements and quantify habitat utilization in three dimensions. Reef sharks were found to predominantly inhabit deeper water (>20m) at the edge of coral reefs, although some species moved into the shallows at night. Given that most diver-based survey methods operate in shallow water (<20m) during the day, it is possible that these methods underestimate shark populations. This shortfall needs to be considered when estimates of population size are interpreted. One solution to the problem is to use re-breather systems, since they allow divers to go deeper for longer and therefore encounter a higher proportion of sharks that inhabit coral reefs.

The second dataset (owned by PIFSC and shared by Dr Williams) used towed-diver (TD) surveys to document the abundance of sharks at U.S. Pacific islands and territories, such as Palmyra Atoll, Mariana Islands, Guam, and the Northwest Hawaiian Islands. Some of these locations were independently visited by other scientists who used different survey methods, particularly diver-based belt transects, which involve a diver swimming a predetermined distance (usually 50 or 100m) and counting sharks as he/she proceeds (see Friedlander and DeMartini 2002; Stevenson et al. 2007; Sandin et al. 2008; Richards et al. 2011; Williams et al. 2011; Nadon et al. 2012). For each of Williams' ~5000 surveys, a diver was towed 60m behind a small outboard-powered vessel for 60min at a constant speed of approximately 1.5 knots. By comparing the results of these separate studies, it was possible to draw conclusions about the relative effectiveness of different survey methods.

RESULTS: Towed-diver surveys generated estimates of shark density that were three- to twenty-fold lower than those generated by small belt transects. This is surprising because the towed-diver method typically covers larger areas at a faster rate than any other underwater survey method, which theoretically should increase encounter rates for low-density species such as reef sharks. Dr Nadon and Dr Williams reconcile the differences between methods by advocating that towed-diver surveys reduce the positive bias of shark behaviour towards divers by rapidly moving divers into new areas to prevent aggregation effects in places where sharks are naïve towards divers (i.e. remote or seldom-visited reefs). However, it is also possible that towed-diver surveys under-estimate shark density, perhaps due to negative bias caused by noise from the tow-vessel. In any case, the magnitude and consistency of differences in outputs between towed-diver and transect surveys dictate that caution be heeded when interpreting previous research results, and suggest that more sophisticated techniques are required to resolve why these two survey methods yield such disparate estimates of density. Further research is currently underway on the Great barrier Reef to resolve this conundrum.

It is well known that different reef shark species have different behaviours (e.g. *T. obesus* are often unafraid of divers and frequently rest on the seafloor, whereas *C. melanopterus* and *C. amblyrhinchos* are more timid and swim continuously) and thus may be differentially detected by the various survey methods. When analyzing the abovementioned datasets, it became apparent that some survey methods were highly selective for certain species of shark. In particular, the catch of baited long-lines was dominated by Galapagos, tiger and grey reef sharks, with almost no white-tip sharks. In contrast, sightings from diver-based surveys were dominated by Galapagos, white-tip and grey reef sharks, with no tiger sharks (Table 1). According to Jake Asher (PIFSC), BRUV surveys mostly record white-tip, tiger, grey reef and sand-bar sharks. Together, these results highlight the species-specificity of different survey methods. Which method (if any) detects each species in proportion to its true abundance is not known and is exceedingly difficult to resolve. Therefore, caution is warranted when interpreting the results of previous studies that report species-specific abundances derived using a single survey method. Use of multiple methods is therefore recommended to ensure that all shark species are accurately represented.

Table 1. Differential species composition of sharks at the Northwestern Hawaiian Islands, as recorded by diver tows and baited longlines. Data courtesy of Prof. Carl Meyer, HIMB.

Survey method	Galapagos shark	White-tip shark	Grey reef shark	Tiger shark	Sand-bar shark
Towed-diver	50	33	17	0	0
Baited long-line	37	3	27	20	11

<u>New models to improve accuracy of population estimates</u>

Baited remote underwater video (BRUV) is a relatively new method that can be used to monitor shark populations without the need for divers. It is being used extensively in Hawaii by Jake Asher at PIFSC to overcome the problems associated with shark behavior towards divers. While in Hawaii, I learned a lot about the benefits and limitations of BRUV surveys through detailed discussions with Jake and his team at PIFSC.

A typical BRUV unit consists of a steel frame and centrally-mounted video-camera. A steel cage containing dead fish is mounted in front of the camera to attract sharks, and filming occurs continuously for a pre-determined time after the BRUV unit is deployed (Fig. 3).

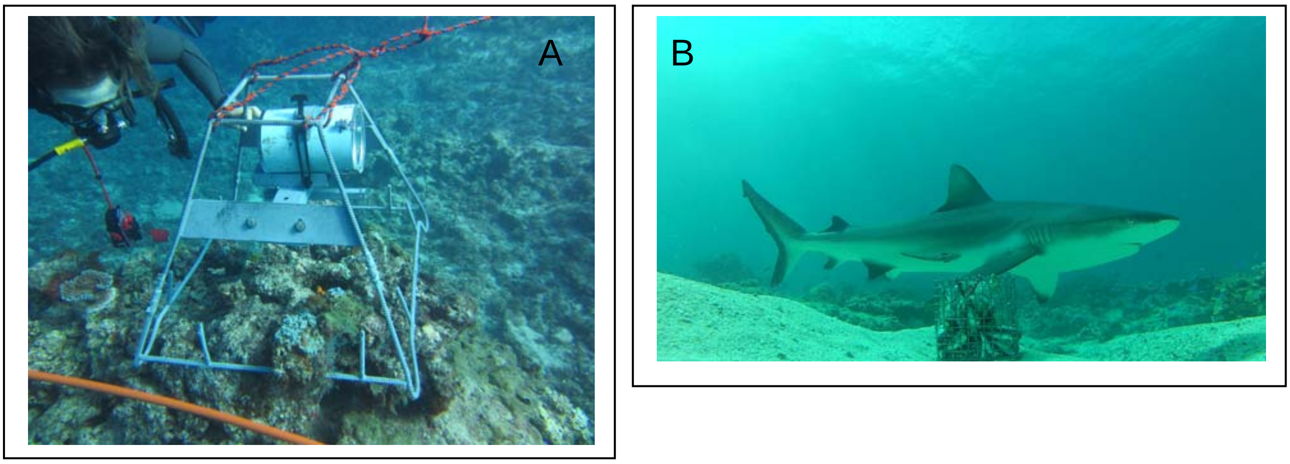

Figure 3. Baited remote underwater video (BRUV) can be used to count or monitor shark populations without the need for a diver. A video camera (A) is used to film sharks that are attracted to a steel cage containing fish bait (B). The shark shown here is a grey reef shark, *Carcharhinus amblyrhinchos*.

Although BRUV surveys represent insightful alternatives to conventional underwater methods, this method can only be used to quantify relative abundance (i.e. whether one unit of space or time has more or less sharks than another unit of space or time). Estimation of absolute abundance (i.e. the total number of sharks in a given area) is typically not possible because the area of attraction (AoA; the area of reef from which sharks are drawn) is unknown. For sharks to be recorded by the BRUV, they need to detect and home-in on the bait plume. Theoretically, the size of the bait plume will determine the quantity of sharks that will be attracted to, and recorded by, the BRUV. Development of AoA models that enable estimation of absolute density is therefore an important step for refinement of BRUV surveys.

With assistance from expert scientists in Hawaii and Florida, an experiment was devised to estimate the AoA and subsequently convert BRUV data from relative units to absolute units. Fifty milliliters of red food dye (non-toxic) was released underwater while diving at 5m depth. After 5 min, the distance and angle of dye dispersal was calculated via tape measure and trigonometry. After ten trials at representative locations and tide cycles, average current velocity and dispersal angle was calculated to be 3.40 m min^{-1} and 23.5^{o} respectively. These results are similar to published hydrodynamic data for coral reefs (Cresswell and Greig 1978; Wolanski and Jones 1980) and correspond to observed dispersal patterns of fish oil at the surface (author's personal observations). Accordingly, the AoA was estimated as:

$$AoA_{BRUV} = \pi(T_{soak} \times V_{current})^2 \times A_d \; / \; 10^4,$$

where T_{soak} is the duration of filming (nominally 60 min), $V_{current}$ is the water current velocity (3.40 m min^{-1}), A_d is the angle of dispersal (23.5^{o}; expressed as a proportion of 360^{o}), and 10^4 converts m^2 into hectares. Using this simple model, we estimated that the AoA for BRUV surveys was 0.85 ha. The utility of this model is best illustrated with a hypothetical example. If five sharks are filmed during a 60 min video, then the density of sharks is estimated to be approximately six sharks per hectare. Similarly, if the average number of sharks per video from a series of BRUV deployments is five and the total size of the reef is 40 ha, then the population size of sharks on this hypothetical reef is estimated to be 240. Estimates of this nature are very important because they help resource managers to set sustainable fishing quotas and to determine the effectiveness of management instruments such as marine reserves.

It is well recognized that the AoA model presented here is very simple (e.g. assumes constant water velocity and angle of dispersal) and does not account for all of the factors that may influence sharks' ability to detect and home-in on the bait plume (e.g. water turbulence, time of day). Therefore, estimates of absolute density from BRUV surveys still require further refinement, so caution is urged with respect to interpretation of data that are analysed using my AoA model. Nonetheless, my AoA model provides a useful starting point that can be used for preliminary exploration of data and as a foundation for future research.

A new method to monitor shark populations

An important disadvantage of diver-based transects and BRUV is that individual surveys take a considerable amount of time (60-90 mins per sample). Given the high spatial variability in shark distributions and the need for substantial replication (i.e. lots of samples), research projects that use transect or BRUV methods can become expensive and laborious. This is a big problem for scientists and resource managers that operate using limited funds and limited staff. Therefore, a new method that is quick and reliable is needed to census shark populations. When I was in Hawaii and Florida, I learned of new research that is underway to develop a suite of new and efficient methods that could potentially be used to census shark populations. One such method is the audible stationary count (ASC) which functions by attracting sharks to a stationary point (the diver) when he/she rapidly and repeatedly squeezes the sides of an empty plastic bottle. This method is known to recreational divers as the ‘squeaky-bottle’ technique because it attracts sharks via emission of low frequency sound, which presumably resembles the sound of a wounded fish.

Based on advice from researchers at PIFSC and the Rosenstiel School of Marine and Atmospheric Research (RSMAS), I undertook a preliminary evaluation of ASC on coral reefs in Hawaii and Florida. For each of thirty replicates, an empty plastic bottle was repeatedly squeezed for 10min and all sharks within a 15 m radius were recorded. The time of arrival was noted for each shark, as well as their unique identifying characteristics (to avoid double-counting).

RESULTS: Sharks responded to the squeaky-bottle with intense interest and curiosity. They arrived very quickly and then made two or three close passes, after which they appeared to lose interest and swam away. On average, three sharks were seen per replicate survey, and 80% of sightings occurred during the first 5 min of each survey (Fig. 4). After 10 min, the rate of shark encounters approached zero (i.e. asymptotic curve), suggesting that all sharks in the immediate area had already been seen and recorded. Thus, ASC is very effective at attracting reef sharks to a stationary point where they can be rapidly counted, since 10 min is sufficient to detect most (if not all) of the sharks within the immediate area. This method would be ideal for studies with limited budgets or that utilize catch-mark-resight methodology.

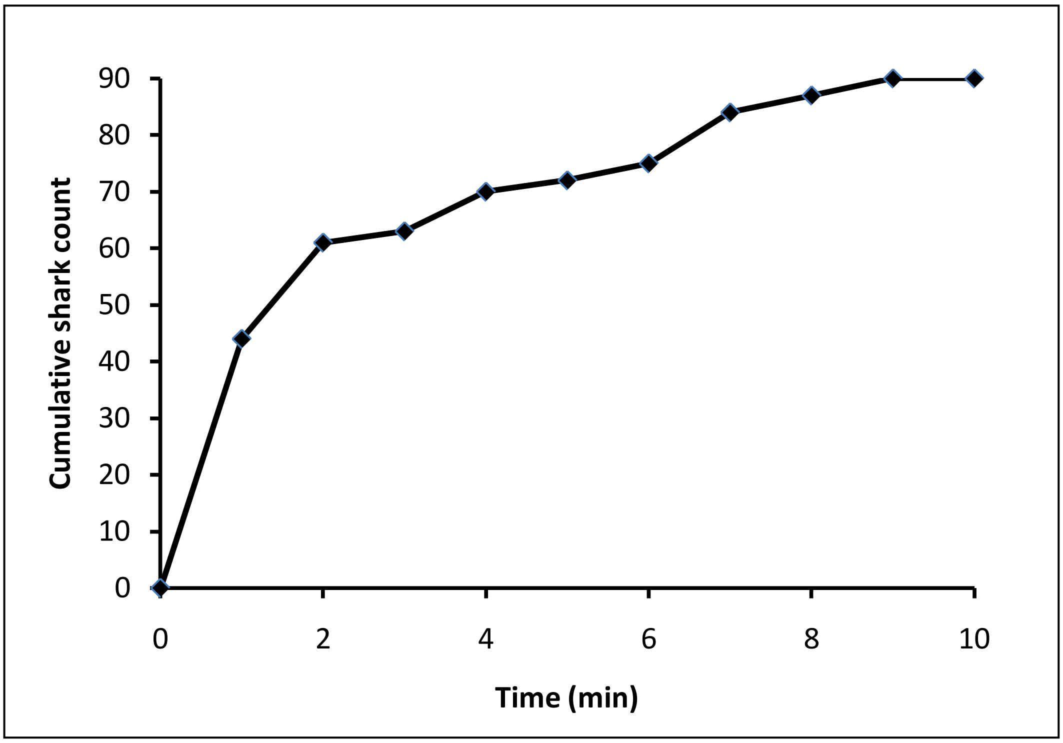

Figure 4. Cumulative distribution of shark observation times during diver-based belt transects. The relationship between shark count and survey time is approximately asymptotic, suggesting that 10 min is sufficient time to attract and record all the sharks in the immediate area.

To calculate absolute density (and enable comparison of ASC with other methods), it was necessary to estimate the distance over which reef sharks responded to the auditory stimulus (i.e. estimate the area of attraction, AoA). Sharks have excellent hearing that enables them to rapidly localize and home-in toward low frequency sounds that are up to 250 m away (Myberg 2001). However, the average response distance is likely to be considerably less than 250 m because of individual variation. By placing an acoustic transmitter at a known distance from a multi-species shark aggregation site in the Bahamas, Myberg et al. (1976) demonstrated that a suite of sharks could be reliably attracted to low frequency sound at a distance of 80 m, with a modal response time of approximately 1 min. During my study in Hawaii and Florida, I found that reef sharks (*T. obesus*, *C. amblyrhynchos, C. perezii*) responded to the ‘squeaky-bottle’ with temporal characteristics (e.g. average time to first arrival and modal response time) that were almost identical to those reported by Myberg et al. (1976). Therefore, the response distance for the present study was assumed to be 80 m and the theoretical AoA was estimated as:

$$AoA_{ASC} = \pi r^2 / 10^4,$$

where r is the radius (80 m) and 10^4 converts m^2 into hectares. Using this simple model, I estimated that the AoA for ASC surveys was 2.01 ha. This estimate of AoA is highly useful because can be used to calculate absolute population size in the same way as that described above for BRUV.

CONCLUSIONS AND RECOMMENDATIONS

Reef sharks are highly important apex predators that help to maintain the ecological balance among numerous reef organisms, but populations of reef sharks are thought to be in substantial decline due to over-fishing (Robbins et al. 2006). The viability of both reef shark populations and the broader reef ecosystem is dependent on how well they are managed. The most significant outcome from my Fellowship is an enhanced capacity to manage reef sharks in the face of increasing human pressures such as over-fishing. My Churchill Fellowship will therefore help to sustain the livelihoods of people who depend on sharks for income as well as protect the ecological integrity of Australia's iconic marine ecosystems. Australia is now well-placed to lead the world in conservation and sustainable use of its shark populations.

Due to the heterogeneous spatial distribution of sharks and their tendency to respond variably to divers, noise, boats and bait, it is concluded that large variation exists in the outputs of different survey methods, and that each method has a range of advantages and disadvantages with respect to cost, convenience, detection capacity and opportunities for bias. Although different shark-related projects have different needs and constraints, it is clear that selection of survey method warrants careful consideration. In most situations, diver-based transect surveys were found to produce reliable results, but only when (1) transect length was relatively long, to minimize upward bias associated with initial shark attraction to divers, (2) water depth was shallow enough to enable SCUBA diving but deep enough to encompass the depth distribution of coastal sharks, and (3) water visibility was sufficient to enable wide transects and a clear view of sharks, thereby ensuring that sharks were properly identified and not incorrectly double-counted. Most sharks were found not to be attracted to divers (unless provoked), which is important to ensure that data from diver-based surveys are unbiased. However, further research in remote places where sharks are unlikely to have seen humans before is required to test whether sharks have learned to avoid humans in populated places like Hawaii and Florida.

The performance of a new method (audible stationary count, ASC) was field-tested and preliminary data suggest that this method can improve efficiency of shark population surveys, particularly when time is limited. This will likely be important for places like the Great Barrier Reef, which extends over a huge geographic area and necessitates efficient sampling. In addition, new mathematical models were developed to estimate the area of attraction for baited remote underwater video (BRUV) and ASC surveys. These new models facilitate estimation of absolute abundance and will help resource managers to monitor shark populations and set sustainable fishing quotas, which is paramount given the precipitous declines in shark populations in Australia and elsewhere.

Results from this study form the basis of a scientific publication which has been submitted to the internationally recognised *Journal of Animal Ecology*. My fellowship has also led to ongoing collaborations with Dr Ivor Williams, Dr Marc Nadon and Prof. Carl Meyer, which is anticipated to generate several more publications in high-profile international journals. Research funding is also being sought to expand this research to the Great Barrier Reef and provide necessary training for marine park managers and university students. Over the coming year I plan to present my findings at national conferences and seminar series, as well as provide briefings to resource managers at the Great Barrier Reef Marine Park Authority and Fisheries Queensland. I will also incorporate the contents of this report into formal lectures and tutorials that I currently deliver at James Cook University, which offers a specialised program in tropical marine biology and resource management. Since receiving the 2013 Dr Dorothea Sandars and Irene Lee Churchill Fellowship, I have been actively promoting the Churchill Trust and encouraging many others to apply for a fellowship.

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APPENDIX: Representative photographs of my trip to Hawaii and Florida in 2013

1. One of the many shark enclosures at the Hawaii Institute of Marine Biology. These large enclosures are tidal, which makes them ideal for studying the behavior of sharks in a semi-natural environment.

2. Tour of the shark enclosures at the Hawaii Institute of Marine Biology with Prof. Carl Meyer (left).

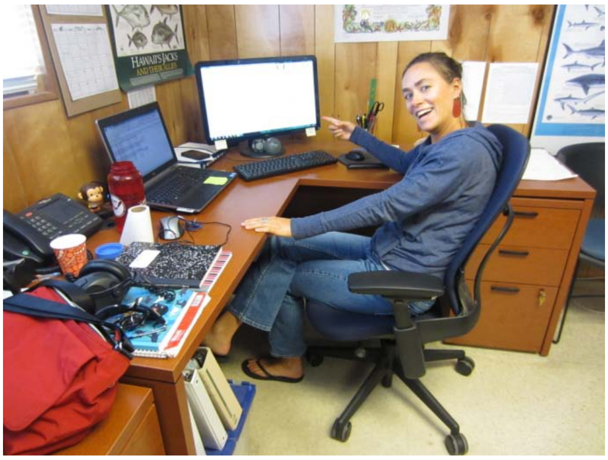
3. Discussing the limitations of baited remote underwater video (BRUV) with Jake Asher at the Pacific Islands Fisheries Science Centre in Hawaii.

4. Dockside with Dr Ivor Williams (left) and Dr Ben Richards (centre) at the Pacific Islands Fisheries Science Centre.

5. Learning about shark behavior towards people and prey with Prof. Neil Hammerschlag (right) at the Rosenstiel School of Marine and Atmospheric Science in Miami, Florida.

6. Visiting the Rosenstiel School of Marine and Atmospheric Science in Miami.


7. Being introduced for my public seminar at the famous Waikiki Aquarium.


8. Learning about geo-spatial analysis of census data with Kaylyn McCoy of University of Hawaii.