Considerations for tagging and tracking fish in tropical coastal habitats: lessons from bonefish, barracuda, and sharks tagged with acoustic transmitters

Section 8.2

Considerations for Tagging and Tracking Fish in Tropical Coastal Habitats: Lessons from Bonefish, Barracuda, and Sharks Tagged with Acoustic Transmitters

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INTRODUCTION

Acoustic telemetry is proving to be a very useful tool for understanding the spatial ecology of fish and invertebrates that use tropical coastal marine environments (e.g., Simpfendorfer et al. 2002; Stark et al. 2005; Lindholm et al. 2006; Gordon and Seymour 2009). Given that radio telemetry is not effective in salt water systems due to signal attenuation (Pincock and Voegeli 1992), the development of acoustic telemetry has increased the capacity to examine the movement patterns and habitat use of highly mobile marine organisms, such as bony fishes and sharks (e.g., Meyer et al. 2007, 2009). The advent of remote logging receivers has also enabled data to be collected continuously, further increasing the capacity to examine factors such as diurnal movement patterns (e.g., Murchie et al. 2010) as well as the influence of stochastic events (e.g., tropical storms; Heupel et al. 2003) on the spatial ecology of fish in tropical coastal environments. Although telemetry has yielded a better understanding of the spatial ecology of fishes, there can be many hurdles to overcome when using acoustic telemetry in tropical coastal environments. For example, high water temperatures, shallow intertidal environments, hurricanes, and predominantly open systems can all influence the ability to address specific questions related to the movement patterns of fishes.

Our team has been studying the spatial ecology of a variety of fish species in the coastal waters of the Bahamian Archipelago since 2003. During this time we have encountered and overcome a number of challenges ranging from the collection and tagging of animals through to the deployment and maintenance of telemetry equipment, with most challenges related to the environment (Table 1). Here we summarize our experience in the form of a case study focused on bonefish *Albula vulpes*, great barracuda *Sphyraena barracuda*, and sharks (lemon sharks *Negaprion brevirostris*, Caribbean reef sharks *Carcharhinus perezi*, tiger sharks *Galeocerdo*

Table 1. Unique challenges when using acoustic telemetry in shallow tropical coastal environments.

Challenges	Summary of Challenge
Air temperature	Thermal stress for staff; Desiccation of fish while handling or performing surgery
Water temperature	Thermal stress for fish during capture, holding and tagging
Salinity	Corrosion of equipment
Depth (shallow)	Small reception ranges for tracking fish
Depth (deep)	Deploying and recovering receivers at great depths
Tides and currents	Shifting receivers that can result in equipment loss; unsafe conditions for divers
Storms and hurricanes	Noise which reduces reception range of arrays; Loss of equipment
Biofouling	Growth of algae and encrusting invertebrates on remote receivers
Predators	Predation on tagged fish; Threat to humans
Humans	Harvest of tagged fish; Theft and vandalism of telemetry equipment
Openness and connectivity	Fish can go anywhere—difficult to define array boundaries
Remoteness	Availability of anesthetics; Time required to ship and/or receive equipment; risk management
Lack of standard techniques	Fish capture techniques unique
Lack of natural history data	Environmental tolerances unknown

cuvier). Where possible, we direct the reader's attention to other studies that have considered the solution to environmental challenges. We also discuss the many applications, potential and realized, of acoustic telemetry for the study of marine life in tropical coastal habitats.

PROJECT BACKGROUND

Initially our telemetry studies were based around elucidating the spatial ecology of bonefish; a highly prized sport fish throughout their worldwide distribution (Pfeiler et al. 2000). Despite their known economic value (a billion dollar per year industry in the Florida Keys (Humston 2001) and 141 million dollars per year in The Bahamas (BFFA 2010)), large gaps exist in the scientific literature surrounding basic bonefish biology, making conservation and management strategies challenging (Ault 2008). As our questions regarding the movement patterns of bonefish evolved, so did the scale and structure of our studies. Specifically, we began using a multispecies approach to examine predator–prey relationships between bonefish, barracuda, and lemon sharks, as well as basic movement patterns of the predators alone. Much like bonefish, little is known about the biology of barracuda. Because of their abundance throughout their circumtropical distribution within the western Atlantic Ocean, Caribbean Sea, and Indo-Pacific regions, barracuda likely play a role as important apex predators in tropical waters (de Sylva 1963). Understanding the movement patterns of barracuda may also lead to an understanding of why some barracuda accumulate ciguatoxins while others do not; a human health issue of great concern in tropical communities (Bottein Dechraoui et al. 2005). Knowledge of shark movement patterns is increasingly important as populations are threatened worldwide due to overfishing and other human disturbances (Stevens et al. 2000; Baum et al. 2003). Because of their position in the food chain, sharks likely play an important role in structuring and maintaining diverse marine communities (Baum and Myers 2004;

Myers et al. 2007). As such, data on the movement patterns of lemon sharks, Caribbean reef sharks, and tiger sharks can help identify essential habitats needed to buffer shark populations against disturbance and declines in abundance.

CAPTURE AND TAGGING METHODOLOGY

A primary assumption of telemetry studies is that the postrelease behavior of tagged individuals is representative of the population of inference. As the process of surgical implantation of electronic tags has the potential to introduce bias to the sample and alter aspects of fish growth (Martin et al. 1995), physiology (Jepsen et al. 1998), swimming ability (Wagner and Stevens 2000), and survival (Jepsen et al. 1998), it is important to follow best practices at all stages of handling (i.e., capture, pre- and postoperative care, and tagging; see Brown et al. 2010). Here we describe the capture and tagging techniques that we have employed for use on three different groups of fish species. Given the different capture and surgical/attachment techniques associated with each group (see Table 2) we discuss them individually and then summarize the commonalities at the end. It should be noted that for all intracoelomic implantations, surgical equipment and transmitters were disinfected in a 5% povidone-iodine solution prior to surgery to minimize the risk of infection. We do not report information on other surgical details such as incision size etc., as incision size is dependent on the size of the transmitter, the number of sutures is dependent on the incision size, and the suture needle size and type is dependent on the size of the animal. All suture material used was absorbable monofilament (PDS II, Ethicon, Johnson and Johnson, New Jersey).

Table 2. Summary of species studied, acoustic transmitters used, and method of transmitter attachment.

Species	Transmitter type*	Method of transmitter attachment
Bonefish	V13 coded	Intracoelomic implantation
(*Albula vulpes*)	V9AP-2L coded acceleration	
	& pressure sensors	Intracoelomic implantation
	V9 continuous pingers	Gastric implantation
Great barracuda	V13 coded	Intracoelomic implantation
(*Sphyraena barracuda*)	V9A-2L coded acceleration	
	& pressure sensors	Intracoelomic implantation
Lemon sharks	V16-4L coded	Intracoelomic implantation
(*Negaprion brevirostris*)		
Caribbean reef sharks	V16 coded	Intracoelomic implantation
(*Carcharhinus perezi*)	V16 coded with temperature	Intracoelomic implantation
	& pressure sensors	
	V9AP-2L coded acceleration	
	& pressure sensors	External attachment
Tiger sharks		
(*Galeocerdo cuvier*)	V16 coded	Intracoelomic implantation

*note that all acoustic transmitters were manufactured by Vemco Inc., Shad Bay, NS

Bonefish

Although bonefish are the pinnacle species for many recreational anglers, catch-per-unit-effort can be low making catching bonefish via hook and line an unsuitable technique for collecting sufficient numbers of individuals for tagging purposes. In fact, Larkin et al. (2008) emphasized this by stating "owing to the difficulty of obtaining bonefish for our study, we employed a professional bonefish captain to help catch bonefish and then bring them to holding pens with recirculating seawater at the University of Miami's Rosenstiel School…" To overcome the problem of capturing large numbers of bonefish slated for transmitter implantation, we have successfully refined the use of a seine net deployed at the mouth of tidal creeks to intercept schools of bonefish on the incoming and outgoing tides. Used as a block net, a large (>30 m in length) soft, small mesh (3.2 cm or smaller) seine net can be stretched across the entire width of a creek mouth to impede the movement of bonefish. The use of small mesh nets helps to avoid gilling or entanglement of bonefish (see Murchie et al. 2009). When a school of bonefish approaches, the two terminal ends of the net are quickly pulled together to encircle the fish. Field assistants positioned along the shoreline or in the shallows can also help herd the bonefish into the net as it is closed. Dip nets, cradles and bare (wet) hands can then be used to transfer individual fish from the net to flow-through holding pens (1.3 m × 0.8 m × 1.25 m tall, 3.1 cm extruded plastic mesh) submerged in a minimum of 0.6 m of water, where the fish remain until sorting and transmitter implantation. Dip nets and bare hands can also be used to quickly remove nontarget species, thus minimizing the stress and potential mortality of bycatch. Collecting a large number of bonefish in one capture event allows for the selection of fish of a certain size and sex based on the specific criteria or purpose of the study. This technique also allows for all transmitters to be deployed within the same short period of time, avoiding potential complications related to small numbers of tagged fish being released at temporally discontinuous intervals. Moreover, deploying transmitters using temporally concentrated effort helps to increase efficiencies associated with field logistics, especially continuity with field staff (in particular, trained surgeons; see Wagner and Cooke 2005).

When working with bonefish, pre- and postoperative care is as important as the intracoelomic implantation itself. Holding fish in flow-through pens provides fish time to recover in ambient, well-oxygenated seawater prior to surgery, as well as following the surgical procedure itself. Because of the tidal nature of many tropical shallow coastal environments, it is often necessary to move the holding pens to deeper areas where the water is cooler and more oxygenated. This is especially the case during slack low tide in the summer months where the water draining from shallow tidal creeks can be greater that 35°C (Murchie et al. 2011). It is also important to have multiple pens available to distribute the fish and not hold fish at high densities for fear of local depletion of dissolved oxygen as well as stress associated with confinement with a large number of conspecifics (Murchie et al. 2009). Because great barracuda and sharks coexist with bonefish in shallow tropical waters, it is important to remain vigilant when holding bonefish in pens and chase away any potential predators (Cooke and Philipp 2004).

Surgeries to implant transmitters can be conducted on a stable boat with ample room for the surgeon, assistants, anesthetic bath, and field surgery table. Conducting surgery on a boat rather than on shore provides easy access to the holding pens for retrieving fish slated for transmitter implantation as well as returning fish to the pens to recover from the anesthetic. Pumps and any other equipment requiring power can be run via a power inverter connected to the boat battery. A canvas top for the boat can provide shade from the hot tropical sun for field staff, as well as provide shade to the fish during the surgical procedure.

Because of its ease of transport and use, we chose tricaine methanesulfonate (MS-222) for anesthetizing bonefish prior to surgery. Creating a situation where the fish is immobile can allow the surgeon to work expeditiously, reduce the duration of anesthesia, and ultimately expedite recovery. Studies that do not anesthetize fish when implanting transmitters (e.g., Humston et al. 2005) may confound their results if stresses associated with the surgical procedure influence postrelease behavior and survival. Regardless of the type of anesthetic, we suggest that an experienced field staff member be specifically assigned to the task of anesthetizing the fish so that they can provide focused care and promptly determine when the fish is ready for surgery (i.e., stage 4 of anesthesia; Summerfelt and Smith 1990).

For bonefish, we used a portable surgery table constructed out of a plastic tote (approx. 100 L, Figure 1a). The lid of the tote was inverted to act as the surgery platform and fitted over the opening of the bin below. Small holes were drilled in the lid to allow water to drain back into the bin, with the bin acting as a sump. A small bilge pump (approx. 175 L/h) was placed in the bottom of the bin and the outflow tube was fitted through a small hole in the vertical wall of the bin near the top. The bilge pump was used to provide continual irrigation of the fish's gills and to keep the skin of the fish damp during surgery. Fish were placed on a rectangular piece of high-density foam during the surgical procedure, providing a soft

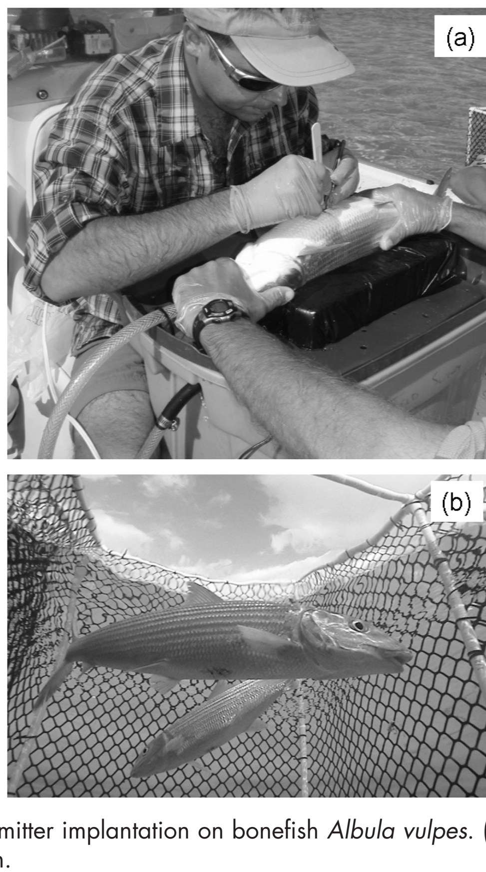

Figure 1. (a) Intracoelomic transmitter implantation on bonefish *Albula vulpes*. (b) Bonefish recover from surgery in a flow through net pen.

surface that minimized mucus loss. Once surgery was completed, fish were returned to a holding pen to recover from the anesthetic (Figure 1b). Because bonefish typically reside in schools, individuals surgically implanted with transmitters were released with a large number of conspecifics that were also captured using the block net. Releasing fish in a large school could potentially reduce the likelihood of short-term postrelease mortality via predation by barracuda and sharks.

One alternative to the intracoelomic implantation of transmitters in bonefish is gastric tagging. Gastric tagging employs the use of a small plunger to insert the acoustic tag through the esophagus and into the stomach of the bonefish (see Cooke and Philipp 2004; Danylchuk et al. 2007a). Benefits to this technique are that the fish do not need to be anesthetized, which greatly reduces the duration of the procedure as well as recovery time for the tagged fish. Potential challenges to the use of gastric tagging include the possible regurgitation of the transmitter, the need to use smaller tags (both in diameter and length), as well as reduced duration for tracking since the tag will eventually be defecated.

Although bonefish naturally reside in shallow tropical flats that can become very warm in the summer months, water temperature should still be considered a potential stressor especially when combined with the capture and surgical implantation of transmitters (see Beyers and Rice 2002; Murchie et al. 2011). At higher water temperatures metabolic rates increase (Brett 1995), and stress responses of fish are intensified (Wilkie et al. 1997). Indeed, at the warmest water temperatures during tagging (29°C; end of August), the survival rate of tagged bonefish diminished to less than 43% within two weeks following surgery, compared to an average survival rate of 80% for fish tagged at cooler water temperatures (20–25°C; November–March) (Figure 2). Unless the purpose of the study is to examine variation in movement patterns and postrelease mortality as it relates to water temperature, we would strongly discourage the capture and deployment of transmitters in bonefish during the hot, tropical summer months (i.e., July–September).

Great Barracuda

Unlike bonefish, using rod and reel to capture barracuda for telemetry studies can be quite effective. Angling for barracuda typically does not require a highly skilled angler (especially when spinning gear is used), is relatively inexpensive, and enables standardized sampling from a variety of habitats including mangrove creeks and tidal flats, to deeper offshore areas. Although there is risk of bycatch, anglers can target specific species by regulating the type of lure, bait, lure retrieval, and trolling speed. Success, however, is often dictated by environmental conditions such as water temperature, season, habitat, and tides how these factors influence the behavior of the targeted species (Wall et al. 2009). Angling may also present a biased sample of the population by selecting for more aggressive, healthier, or genetically vulnerable individuals (Cooke et al. 2007). A size bias may also result, depending upon the size and type of hook, lure and bait used. Fish that are captured via angling may be exposed to physiological stress, injury, barotrauma, and predation due to an angling event (Skomal and Chase 2002; Bartholomew and Bohnsack 2005; Danylchuk et al. 2007b), which could hinder the chance of survival when combined with the stress associated with the surgical procedure (including anesthesia) to implant acoustic transmitters. Nevertheless, the effects of capture can be easily reduced by landing the fish quickly, using barbless hooks, employing correct handling methods, and fishing at lower water temperatures, all of which are practices that will

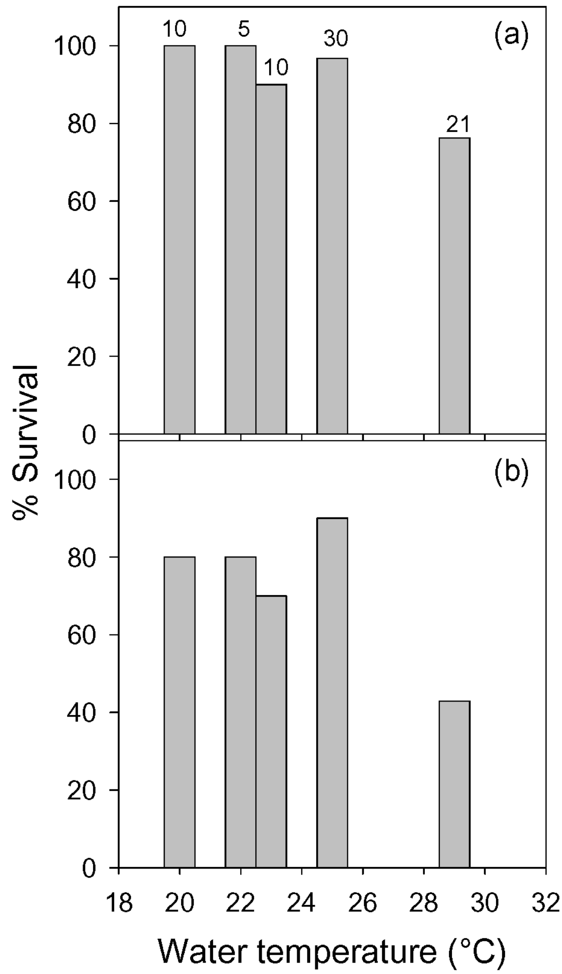

Figure 2. Survival of bonefish *Albula vulpes* tagged at a range of water temperatures after (a) 48 h and (b) 2 weeks. Numbers above the bars represent the total sample size of bonefish at each tagging temperature.

increase the chance of the postrelease survival (Schaeffer and Hoffman 2002; Bartholomew and Bohnsack 2005; Cooke and Suski 2005).

When capturing barracuda for intracoelomic implantation of acoustic tags, we have found that trolling with heavy action recreational gear and artificial lures at speeds of 6–9 knots to be most effective. Because great barracuda are excellent burst swimmers, trolling at higher speeds reduces the number of bycatch species encountered such as yellowtail snapper *Ocyurus chrysurus*. Barracuda have proven to be relatively tolerant of physiological stress and injury associated with capture using rod and reel (O'Toole et al. 2010a), however it is not recommended that barracuda be angled at high water temperatures during the summer months prior to the performance of a surgery. It is important to restrict the amount of time the fish is played and landed; a large mesh cradle can be used to handle great barracuda in a safe and appropriate manner. Further, barracuda seldom exhibit excessive bleeding, rarely are deeply hooked in critical areas, and tend to recover well after surgery (O'Toole et al. 2010a, 2010b).

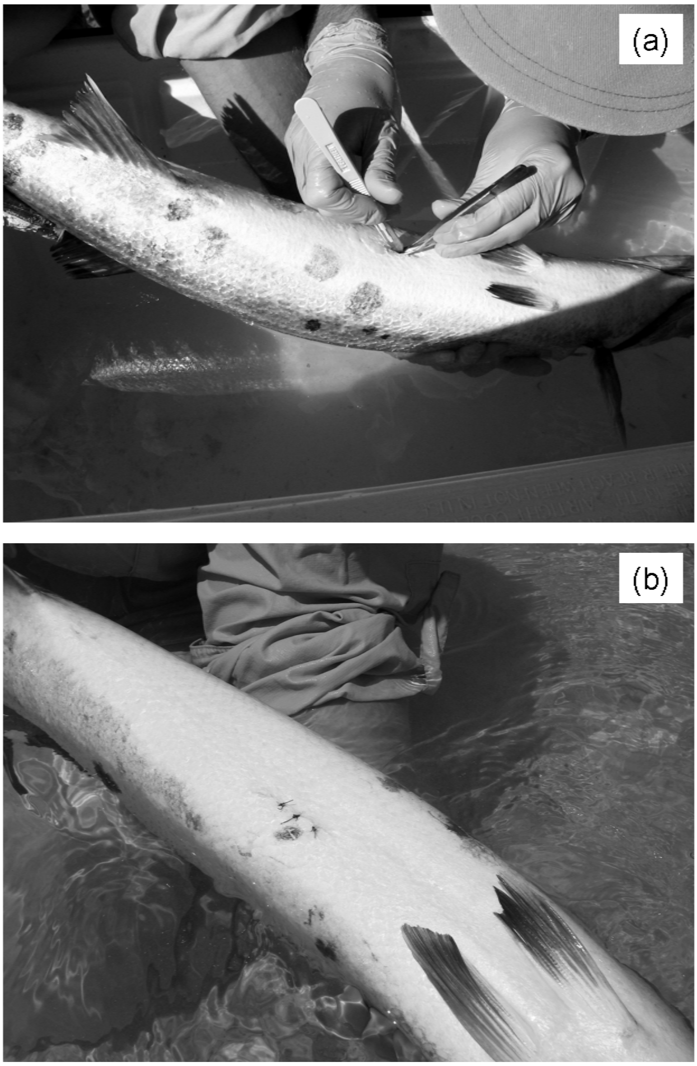

Figure 3. Intracoelomic transmitter implantation on barracuda *Sphyraena barracuda* (a) in a cooler on the boat and (b) kneeling in the tidal flats.

As stated above, we recommend anesthetization prior to surgery. For barracuda, surgeries can take place either on the boat with an assistant holding the fish in a cooler of water, or surgeries can occur in shallow tidal flats where the assistant kneels and holds the fish directly in the ocean (Figure 3a and b, respectively). While barracuda are predators, we recommend holding the fish either in a cooler of fresh seawater or in the ocean directly, until they are fully recovered before release.

Sharks

The intra- and inter-specific size range of sharks in tropical coastal waters varies considerably, as does the specific region of the coastal zone in which the sharks inhabit. As such, the most effective capture method for sharks intended to be deployed with acoustic transmitters will be dependent on a number of experimental, site, and species specific variables. The two most important variables include the ability of the target species to withstand the physiological and physical stress associated with capture, and the abundance of the target species. The short and long term consequences of the intense anaerobic exercise associated with capture events is poorly understood for most species of sharks (Skomal 2007). Where research exists it has focused of the effects of recreational catch and release angling in predominantly temperate species of sharks (e.g., Brill et al. 2008). All research suggests a linear relationship between hooking duration and the magnitude of the homeostatic disruption and as such hooking and handling durations for transmitter attachment or surgery should be minimized to ensure postrelease viability.

For sharks inhabiting shallow (<1 m) coastal flats (e.g., juvenile lemon sharks) conventional recreational angling equipment with rod and reel can be an effective and efficient capture method (Murchie et al. 2010). Clear, shallow coastal waters allows for active sight-fishing of individual sharks, which greatly reduces the amount of field time needed for capture sharks for tagging. Although longlines (see below) can also be used in shallow water, there is the potential for multiple sharks to be caught, increasing the hooking duration and likely the physiological stress associated with capture for some individuals (if sharks are to be processed sequentially). Using heavy rods and reels can permit the rapid retrieval of sharks as a means to reduce landing times and physiological impacts prior to tagging with acoustic transmitters.

In deeper coastal waters, longlines offer the most efficient and adaptable way of capturing sharks (e.g., Caribbean reef and tiger sharks), and can also yield additional diversity, relative abundance and demographic data at the same time. Longlines use a large number of baited hooks that catch sharks efficiently, especially when abundances are relatively low. Mainline lengths of longlines can vary with the number of hooks to be deployed as well as the length of the gangions. To avoid tangling of two sharks hooked side by side, the spacing between gangions must be at least 2.5 times the gangion length. Longer gangions provide a larger range of movement for the captured animal but can reduce the number of hooks that can be placed on any given length of line. Fewer hooks will allow for shorter hooking durations as lines can be checked or hauled quickly and regularly; however more hooks will increase the catch rate especially if the target species is less abundant. Hook timers (e.g., Lindgren-Pitman, Pompano Beach, Florida) can easily be incorporated into the gangion to provide a quantitative way of monitoring hooking duration that can, in turn, provide guidance for suitable transmitter candidates. It should be ensured that mainlines have sufficient floatation or anchor points to reduce dragging and tangling among natural structures such as coral reefs. Tangled lines lead to reduced movement capacity for captured sharks which in turn increase the magnitude of the physiological stress and reduces the viability of candidate animals for tagging.

Only jaw-hooked sharks should be candidates for transmitters given the physical trauma usually associated with gut hooking (Borucinska et al. 2002). Circle hooks are thought to reduce the instances of gut hooking (Cooke and Suski 2004; Kerstetter and Graves 2006). For example, 82% of all sharks captured on 16/0 Mustad circle hooks during three years of seasonal longline surveys in The Bahamas were hooked in the jaw thus providing a high proportion of candidate animals (Brooks et al., unpublished data). In general, hook removal tools, although effective, should not be used as they can inflict additional trauma on the jaw. A less traumatic option is to rotate the circle hook through the jaw until the barb is visible from the exit wound. The hook can then be cut behind the barb and the shank rotated out of the jaw. Hooks should be large enough to encircle the jaw bone of the shark and allow the point to protrude from the exit wound as far as the barb. Hooks that are too small will embed in the cartilage of the jaw and will not be removed easily.

Acoustic transmitters can be surgically implanted in the peritoneal cavity or attached to sharks externally via an anchor system. Acoustic transmitters can also be fed to sharks and subsequently retained in the gastric tract, however the retention times using this method are very variable and range from 24 h to 34 d (Brunnschweiler 2009). The method of attachment is primarily determined by the required retention time of the transmitter, the likelihood that the shark will attempt to dislodge an externally attached tag, and the overall size of the shark since surgeries may prove logistically unfeasible for large specimens (>4 m in length). To date, acoustic telemetry studies suggest that the majority of sharks surgically implanted with transmitters recover with no discernable long-term effects (see Chapman et al. 2005; Meyer et al. 2009).

To implant sharks, the candidate animal should be kept in the water. For juvenile lemon sharks captured in shallow flats areas or mangroves creeks on rod and reel, the animal can be restrained by hand (Figure 4a). For larger specimens (i.e., Caribbean reef and tiger sharks) captured by longline, individuals should be restrained next to the boat by securing the gangion to the bow and a tail rope to the stern (Figure 4b). Where possible, the shark should be oriented head towards the current to allow passive irrigation of the animal's gills. Once secured, the shark should be inverted (ventral side up), and held until the onset of tonic immobility. Tonic immobility is a reversible, coma like stasis displayed by a number of elasmobranchs (Henningsen 1994), and allows the surgery to proceed without the use of anesthetic. In the rare case that the candidate species does not exhibit tonic immobility, anesthetic compounds can be used (e.g., MS-222, Heupel and Heuter 2001).

In some cases where only short term deployments or specific experimental parameters require it, tags can be attached externally, usually with a dart tag, or in some cases, securely wired to either the first or second dorsal fin. External attachment removes the possibility of mortality due to surgery, is generally easier to perform and can be conducted, in some cases, without actually capturing the shark. This technique does however pose significant challenges in terms of transmitter retention. Acoustic transmitters are generally attached to a shark using a dart tag attachment however the retention times for most types of dart tags are relatively short, and tag shedding is a common problem even for tags that do not have an electronic transmitter attached (Dicken et al. 2006). Standard SSD dart tags (Hallprint, Australia) with no electronic transmitters, applied to Caribbean reef sharks in the Bahamas were shed in less than six months (Brooks, unpublished data). Tag shedding is likely due to a number of different factors which include bio-fouling which increases the hydrostatic drag of the tag and tissue necrosis which weakens the anchor point. It has also been hypothesized that the physical and often violent nature of mating in most shark species could cause a tag to be shed.

To externally attach acoustic acceleration transmitters (model V9AP; Vemco Inc., Shad Bay, NS) to Caribbean reef sharks, two holes were punched through the lower third of the first dorsal fin using 12 gauge piercing needles and one polyethylene backing plates as a guide. Leaving the needles in place, a second backing plate was fitted over the opposite side of the dorsal fin over the 'sharp' end of the piercing needles. The distance between the holes was measured to be exactly that of the distance between the two attachment eyes of the transmitter. Two 30 cm lengths of 0.5 mm stainless steel locking wire (Loos & Co, Naples, Florida) were passed through the eye of the transmitter at either end. The wire was wrapped twice

Figure 4. Intracoelomic transmitter implantation on sharks occurring (a) in the tidal flats, and (b) from the side of a boat in deeper waters.

through the eye at the mid point so the two loose ends of approximately 15 cm length lay at 90 degrees to the long axis of the tag. Each pair of wire ends were passed through the piercing needles in the dorsal of the shark and the needles removed. The wire ends were tightened until the transmitter and backing plates rested snuggly against the dorsal fin, and excess wire was trimmed (Figure 5).

General summary of capture and tagging

All fish surgically implanted or affixed with acoustic telemetry devices should be provided the best possible care throughout the capture, tagging, and recovery process to ensure the highest chance of survival and the least amount of influence on postrelease behavior. This includes using adequately trained personnel for surgeries and best current surgical practices (e.g., aseptic techniques, choice of tools, anesthetization, surgical incision, and wound closure)

Figure 5. External attachment of an acceleration transmitter.

within the limits of remote field conditions. While weather and environmental conditions can present challenges to field-based surgical procedures, the alternative of relocating specimens back to the laboratory can increase stress effects associated with handling and holding times. Because all species discussed above have the potential to be preyed upon, they require adequate recovery time prior to release. As such, the use of flow through net pens, or dedicating additional staff and time to the postoperative care of tagged individuals is required. We also advocate the timing of tagging programs occurs during periods of cooler water temperatures to minimize the additional effects of thermal stress to the capture, handling, and tagging procedures. The methods described above have resulted in excellent wound healing in recaptured specimens, and the continued monitoring (3+ years) of a number of tagged individuals.

TRACKING TELEMETERED FISH

Manual tracking

Unlike radio telemetry, where signals from transmitters are detected by an aerial receiving antenna, manual tracking of regular acoustic transmitters (i.e., not including pop-up satellite tags, archival tags) requires a hydrophone to be placed in the water. When transmitter-implanted fish are able to reside in very shallow water (e.g., intertidal areas of tropical flats and mangrove creeks), the detection range of the manual hydrophone can be impaired due to a lost line of sight with the transmitter (Heupel et al. 2008). In situations such as these, we have used manual tracking to determining presence-absence only at predetermined discrete stations and during tidal periods that will maximize the likelihood of a detection if a tagged bonefish is present (i.e., so as to not wrongly conclude tagged fish are absent because of limited capacity for their detection). However, a major limitation of this technique is that determining the presence or absence of tagged individuals can be confounded by the fact that personnel and gear cannot be in multiple places at once.

Where water depth is sufficient, manual tracking of individuals can be very informative in answering questions regarding habitat selection and home range (Morrissey and Gruber 1993a; b, respectively). In our experience, effective continual tracking of bonefish in depths of 1–30 m for well over 14 h can be achieved by using a small boat equipped with both directional and omnidirectional hydrophones. Continuous pinger-style transmitters are typically easier to follow than coded transmitters (i.e., with delayed transmission), but have the disadvantage of a considerably shorter battery life than that of coded tags (i.e., 21 d versus 700 d). Ultimately, the type of transmitters used as well as method of manual tracking should be dependent on the questions being asked, the nature of the environment, and a preliminary understanding of the movement patterns of the fish species being studied.

Passive arrays

The open nature of tropical marine coastal environments presents a challenge for configuring fixed remote acoustic receiver arrays. Great consideration should first be given to whether a fixed receiver array or even acoustic telemetry is the best technology to employ when attempting to examine the spatial ecology of highly mobile marine fishes. Some preliminary understanding of the spatial movement patterns of the focal species can be advantageous when making decisions regarding the methods for telemetry. When limited or no previous data are available for a focal species, conducting a small pilot study can help determine the scale and scope of the array needed to address specific questions related to a fish's spatial ecology.

For our work in The Bahamas, the initial goal was to use a fixed remote acoustic telemetry array to examine different elements of the spatial ecology of bonefish and juvenile lemon sharks associated with shallow tidal flats and mangrove creeks. Conducting a pilot study that involved deploying a small number of remote receivers and releasing a limited number of study fish surgically implanted with coded transmitters allowed us to determine whether questions related to site fidelity and movement patterns among habitat types could be adequately addressed with this technology. The pilot study also allowed us to test different mooring systems for the remote receivers especially because it was advantageous to ensure that the transducer of the receiver was submerged for the longest possible duration through the entire tidal cycle. The final design for mooring the receivers employed a segment of steel rebar cemented firmly into the opening of a concrete block; this allowed the receiver to be securely positioned in a number of different orientations depending on water depth and coastline morphology (Figure 6). In areas where water depths always exceeded 1 m, the mooring system could be deployed so that the receiver was vertical in the water column. In cases where water depths became shallow because of tides, the substrate was excavated to ensure the mooring system and receiver remained submerged, or in some instances, such as narrow rocky channels, the mooring system was laid horizontally on the substrate.

Our initial array for studying bonefish and lemon sharks was configured in a series of curtains of receivers extending perpendicular from shore, allowing us to determine along-shore movements among shallow flats and tidal mangrove creeks. To examine finer-scale movement patters within mangrove creek systems, we also deployed receivers at choke points, such as in narrow creek mouths, to measure the movement of tagged fish in and out of these systems. Where possible, receivers at choke points were integrated into curtains to maximize the scope

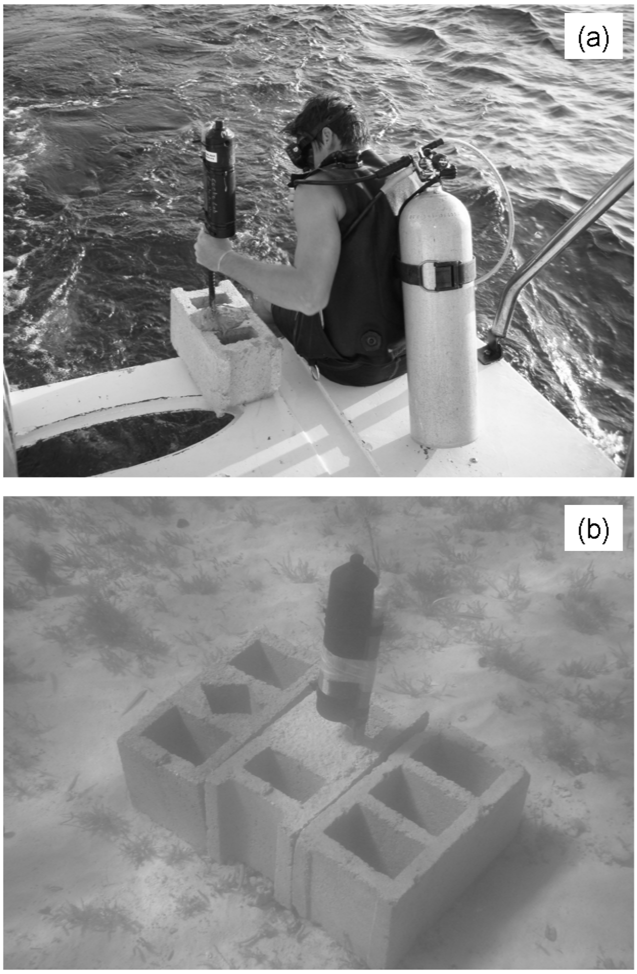

Figure 6. (a) Deployment of an acoustic receiver using scuba. (b) Underwater positioning of an acoustic receiver.

of detection while using the least number of receivers possible. In all cases, the range of detection was determined for each receiver to ensure that curtains would not allow a tagged individual through without being detected. Because biofouling can have an impact on the performance ability of the receivers (Heupel et al. 2008), regular visits to the mooring units were made to determine if anti-fouling measures were necessary. Since the accumulation of algae and other growth occurred mainly on the concrete blocks, with limited fouling on the receivers themselves, no anti-fouling products were applied. The minimal level of fouling observed was likely due to the relatively nutrient poor waters of tropical regions as well as the smooth surface of the receivers.

As we expanded our research to include great barracuda and larger, more coral reef orientated sharks (i.e., Caribbean reef sharks, tiger sharks), we continued to use the same mooring technique even though the receivers were deployed in considerably greater water depths (up to 40 m) and further offshore (>5 km). By firmly affixing the receivers to rebar and concrete blocks, the entire unit could be place on the substrate with limited chance that it would move with tidal currents and wave action. Although this technique required scuba (self contained underwater breathing apparatus) diving to deploy and retrieve receivers, the benefit was that we did not need to add surface or subsurface floats because of the clear tropical waters and the ability to get within a few meters of the deployment site using GPS. Not using floats to indicate position reduced the likelihood that the receivers would be tampered with (see Domeier 2005). Over the course of more than three years, only three out of 54 receivers were lost, likely because they were removed by local fishers as evident by the presence of cut cable ties that were used to attach the receivers to the rebar.

The design of an array is a function of the specific ecological or biological questions the project is trying to answer, as well as available resources (Heupel et al. 2006). We have used a combination of curtains and nonover-lapping grids. Forming curtains of overlapping receivers at strategic points along a hypothesized movement route will allow the testing of a hypothesis with fewest resources. By placing curtains at natural choke points, the number of receivers required to form a curtain can be reduced. The distance between curtains can be fine tuned to the expected spatial scale of the movements. However, this is not the best array design for sensor tags given the likely low number of detections. Instead, a nonoverlapping grid is more appropriate for sensor tags, yielding a higher number of expected detections as an area of seabed is continuously monitored. The spacing of the grid will depend of the scale of movements a species is likely to make, and the available number of acoustic receivers (see Heupel et al. 2006).

APPLICATIONS OF BIOTELEMETRY IN TROPICAL COASTAL SYSTEMS

Protected areas

Understanding the spatial ecology of fishes and invertebrates inhabiting tropical coastal habitats is vitally important for the design and management of marine protected areas (MPAs). Marine protected areas have been advocated as effective relatively ‘low cost’ fisheries management tool that can provide ecological and fishery benefits (Murray et al. 1999; Roberts et al. 2001; Polunin 2002); especially in areas such as the tropics were biodiversity can be high and the ability to care for coastal habitats often limited. From a fisheries perspective, MPAs, and in particular marine reserves, can help conserve essential habitat and promote the buildup of biomass, which, in turn, may result in the spillover of adults into adjacent fishing grounds and the downstream export of larvae to more distant fished areas (Murray et al. 1999).

Although acoustic telemetry has become a standard tool for studying the spatial ecology of fishes, only in the past decade has this technology been used to study the function of MPAs (e.g., Heupel and Simpfendorfer 2005; Schmiing et al. 2009), and rarely has it been used to assist in boundary demarcation based on the identification of critical habitat and site fidelity of species to be protected (e.g., Chapman et al. 2005; Kerwath et al. 2009). Using acoustic telemetry for this particular application can provide greater resolution when compared to conventional passive external tagging, and can operate at a scale that enables sufficiently precise positioning to determine how much time a fish spends inside and outside specific habitats or moving across MPA boundaries (Davis 2004). Matching acoustic telemetry with the mapping of the coastline and substrate characteristics can help to identify critical habitat for tropical marine fishes. In turn, this knowledge of movement patterns, home range sizes and habitat use can then be used to determine whether proposed and existent boundaries of MPAs will be able to promote the maintenance and possibly the increase of stock biomass, and ultimately meet the management objectives for conservation.

One of the objectives of our research in the waters surrounding South Eleuthera, The Bahamas, was to determine whether a proposed no-take marine reserve (Dahlgren 2002; Danylchuk 2003) would offer protection for bonefish. As such, bonefish surgically implanted with coded acoustic transmitters were collected from two focal mangrove creeks within the proposed boundary of the reserve at various intervals spanning more than three years. Examining the spatial ecology of bonefish across several years has allowed us to examine seasonal variation in movement patters, and helped to identify critical reproductive habitats that would fall outside the current iteration of the boundaries for the proposed MPA (Danylchuk et al., unpublished data)

Locating spawning sites

Some groups of marine fishes in the tropics have evolved a reproductive strategy that involves migrating to relatively discrete locations where they form large aggregations for spawning (Domeier and Colin 1997; Claydon 2004). Such migrations to and from spawning aggregations sites can greatly broaden the spatial extent of a fishes home range; however, their time at aggregations sites can be relatively short compared to time spent in other habitats not associated with reproduction. Because movements to spawning aggregation sites occurs in such discrete periods and often a fair distance away from nonreproductive habitats, identifying the timing and location of spawning aggregations for tropical coastal marine fishes can be difficult without the use of acoustic telemetry. Understanding the dynamics of spawning aggregations has important implications for the conservation and management of fish stocks because fish that predictably aggregate at specific times and locations can be vulnerable to intense fishing pressure and overharvesting (Coleman et al. 1996; Domeier and Colin 1997; Roberts and Hawkins 1999; Sala et al. 2003). A well-studied group of fishes that form transient, site-specific spawning aggregations are the Serranidae, such as the red hind *Epinephelus guttatus* (Sadovy et al. 1994; Beats and Friedlander 1998) and Nassau grouper *Epinephelus striatus* (Bolden 2000; Whaylen et al. 2004). Documenting the location and spatial and temporal dynamics of grouper spawning aggregations has helped to characterize the biology and ecology of this important group of coral reef fishes (Whaylen et al. 2004), as well as highlighted the need to learn more about other marine fishes that aggregate to spawn (Sadovy and Domeier 2005).

A major component of our research on bonefish in The Bahamas was using acoustic telemetry to document the timing and location of spawning (Danylchuk et al., in press). Anecdotal evidence from the Caribbean and The Bahamas, as well as initial data from our telemetry work, suggested that bonefish may spawn in large aggregations in deep offshore waters, however the spatial ecology of bonefish related to spawning had never been formally quantified. Data from our initial array showed individuals moving towards the end of Cape Eleuthera in the winter and early spring (Murchie 2010), consistent with reports from the literature on their movements associated with spawning. When extending our array, we took this into account, along with accounts from local fisherman who witnessed large schools of bonefish near deeper water. The extended array included a combination of receivers at choke points, large curtains radiating out from a peninsula of land at the junction between shallow and deeper offshore waters, and overlapping 'nets' of receivers that allowed us to determine the direction of movement once bonefish moved away from the shoreline into open water. As data were collected from the array throughout the course of the suspected spawning season (see Figure 7), we made slight adjustments to the positioning of the receivers to maximize the likelihood of locating both prespawning and spawning aggregations for bonefish. This, in combination with manual tracking, proved to be instrumental for determining the timing and location of aggregations sites, especially because bonefish move offshore to spawn at night (Danylchuk et al., in press).

Biotoxins and ocean health

Acoustic telemetry can be a valuable tool in answering unique questions such as linking the spatial ecology of reef fish to the presence and of biotoxins. Ciguatera fish poisoning is caused by a naturally occurring toxin that bioaccumulates in apex predators that has the potential to make humans very ill if reef fish with high concentrations of ciguatoxin are consumed (Lehane and Lewis 2000; Dickey and Plakas 2010). Telemetry can be combined with tissue biopsies (tissue is analyzed for harmful concentrations of ciguatoxin) to help understand relationships between the spatial ecology of fish (e.g., barracuda) and the potentially harmful toxin levels.

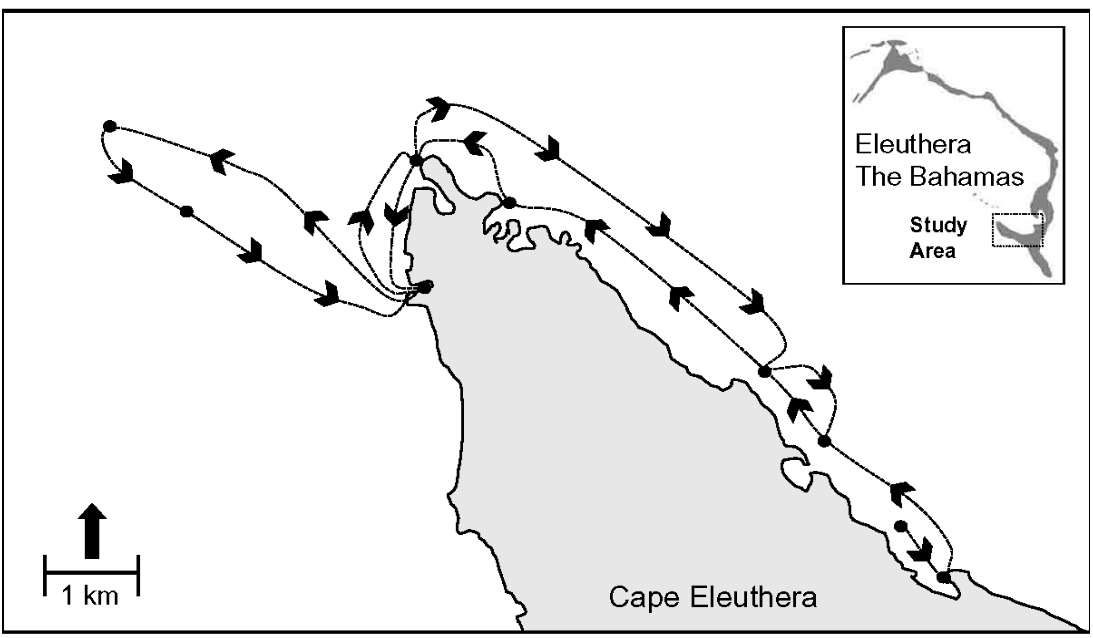

FIGURE 7. Generalized movements of bonefish 8899 in one week (December 2–9, 2008) in the study area along the coast of Cape Eleuthera, The Bahamas (N 24°50'05" and W 76°20'32"). Bonefish 8899 displays representative movements during winter months from within shallow tidal creeks to deeper offshore areas, presumably for spawning. The dashed lines with chevrons indicate the direction of the movement from one receiver (solid black circles) to the next. The inset map displays the entire island of Eleuthera with the study area highlighted.

Energy flow and connectivity

Energy is the currency of life, and having an appreciation of how energy flows through an ecosystem is one of the most basic ecological principles (Smith 1992). The active transport of nutrients via foraging migrations made by fish promotes energy flow across distinct habitat boundaries and effectively connects communities (Valentine and Heck 2005; Gaines et al. 2007). Acoustic telemetry can be used to elucidate the distribution of free-swimming fish among various habitats in their natural environment (Cooke et al. 2004), and provide information that is paramount to understanding how tropical coastal ecosystems function. Acoustic telemetry can also be used to examine energy flow at the organismal level by providing a method to approximate the cost of activity in a fish's energy budget. The use of animal-borne acceleration data loggers is gaining popularity for studying activity costs in free-swimming fish (Wilson et al. 2007). While these data loggers require retrieval to access the data (Ropert-Coudert and Wilson 2005), recent advances in onboard processing have allowed for the production transmitters capable of encoding and transmitting tri-axial accelerometer data efficiently (see Murchie et al. 2011; O'Toole et al. 2010b). Contribution to the production of a bioenergetics model for any tropical fish species not only provides fisheries managers with a useful tool for fish production, but would further assist scientists in understanding coastal ecosystem dynamics.

Fishing mortality

Fish captured by commercial and recreational fisheries are often released in accordance with harvest regulations or voluntarily due to conservation ethic or other reasons. The assumption with releasing such fish is that the majority survive and do so with few sublethal consequences. However, that assumption is rarely tested. Acoustic telemetry has great potential for monitoring post release survival and behavioural alterations in both the recreational and commercial sectors. A recent review by Donaldson et al. (2008) revealed that acoustic telemetry is increasingly being used to study postrelease mortality and can have many advantages over other methods such as holding fish in pens, tanks or cages. However, there are relatively few examples exist in the marine environment. Cooke and Philipp (2004) and Danylchuk et al. (2007a) used pinger acoustic transmitters to track bonefish after release by recreational anglers and demonstrated post release predation and short term behavioral alterations. Not only did such studies generate mortality data, but they revealed factors that were associated with mortality which provided anglers and managers with potential strategies for improving postrelease survival. Commercial bycatch studies that use acoustic telemetry have been less common; however, our group has used acoustic accelerometer tags to evaluate the fine-scale post release behavior of Caribbean reef sharks captured by long line. Given the many conservation and management concerns associated with postrelease mortality and sublethal alterations in the commercial and recreational sector, particularly in tropical marine systems that have received relatively little research attention, there is a great need for additional research and acoustic telemetry is one of the best ways to generate meaningful data.

CONCLUSIONS AND FUTURE OPPORTUNITIES

Acoustic telemetry is a powerful tool for gaining insight into the habitat use, life histories, intra- and inter-specific interactions of tropical marine organisms, as well as the potential impacts of natural and anthropogenic disturbances. Through our work on diverse taxa (e.g., bonefish, barracuda, and multiple species of sharks) we faced many challenges including dealing with different deployment dates of transmitters and receivers, as well as optimizing data collection rates and working with an array that aims to cover study questions focused on many species. We also encountered environmental challenges unique to tropical coastal ecosystems. Collectively, our experiences revealed that an adaptive approach to the use of acoustic telemetry is necessary as a means to compensate for certain limitations of this technology for understanding the movements of fish in these environments.

Future use of acoustic telemetry in tropical coastal ecosystems can include pairing the fine-scale movements of organisms with detailed environmental data such as water temperature and salinity to provide critical information for climate change modeling. There is also the opportunity to gain information on smaller species as transmitter technology and battery miniaturization develops. Because of the cost of acoustic telemetry gear, and strains on resources especially when working in remote coastal areas, we advocate communication and cooperation with other researchers in the area, and other larger groups such as the Ocean Tracking Network to look at broader scale movements. We also support the recommendation of Grothues (2009) that scientists and equipment manufacturers engage in a dialogue encouraging the use of a common code scheme and cross-equipment communication to maximize the opportunity to track fish in coastal marine systems.

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