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Tracking fish using 'buoy-based' GPS telemetry

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ABSTRACT: The marine environment imposes severe constraints on the means by which location information can be obtained from submerged, freely swimming animals. Standard methods of tracking marine organisms are often labour intensive, expensive, or of low spatial and temporal resolution. Here, we describe a new method by which larger species of fish that live in shallow or surface waters can be tracked using an inexpensive telemetry device based on the global positioning system (GPS). We fixed small GPS data-logger units configured to record position fixes at 90 to 150 s intervals to low-drag tow-bodies and then attached these units by means of a tether to New Zealand eagle rays *Myliobatis tenuicaudatus*. After deployment periods lasting up to 29 h we recovered the tracking gear and downloaded the location data, which were stored onboard. The GPS units worked well, with mean fix-success rates >90%, and allowed accurate reconstruction of the movements of the rays throughout an estuary in Northland, New Zealand. Although our method is restricted to animals that swim on or near the surface of the water, it does provide a means of cheaply describing the movement patterns of suitable species for substantial periods of time at heretofore unprecedented spatial and temporal scales.

KEY WORDS: Animal movement · Global positioning system · GPS · *Myliobatis* · Tow-buoy

INTRODUCTION

Knowledge of where and when marine animals move can provide important insights into the basic processes influencing their ecology and behaviour. For example, such information has been used to study aspects of migration (Block et al. 1998, Bonfil et al. 2005), homing (Bonfil et al. 2005, Svedang et al. 2007), habitat use (Deutsch et al. 1998, Shepard et al. 2006) and site fidelity (Godley et al. 2003). Knowledge of movement patterns facilitates understanding of how animals forage (Shepard et al. 2006) and navigate (Atema et al. 2002), and contributes to their conservation and management (Block et al. 1998).

Currently, there are 4 principal methods for tracking freely swimming marine animals: visual (Danylchuk et al. 2007), acoustic (Solomon & Potter 1988), light-based geo-location (Teo et al. 2004) and satellite telemetry (Timko & Kolz 1982). These methods each have notable advantages, but generally all are unable to provide accurate location estimates at high sampling frequencies for animals moving over extensive areas. Visual and active acoustic tracking requires observers to be in close proximity to study animals, which can affect their behaviour (De Girolamo & Mazzoldi 2001, Sara et al. 2007, Watson & Harvey 2007). Normally, these 2 methods are restricted to one animal per observer and, thus, are labour intensive (Deutsch et al. 1998); both work best with species that are slow moving or have small home ranges (Ropert-Coudert et al. 2007). With *in situ* acoustic arrays, tracking can occur only within the ranges of transmitters and receivers (typically 200 to 300 m; Sundstrom et al. 2001), and results are highly dependent on hydrographic and bathymetric conditions. Moreover, tagged fish can be difficult to follow for extended periods (Potter et al. 1992), and track resolution is generally ≤100 m (Klimley et al. 2001). Un-manned radio-acoustic-positioning (RAP) systems can triangulate positions with an accuracy of 2 to 10 m (Klimley et al. 2001); however, this

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method is expensive (Heupel et al. 2006) and only practical over smaller areas (<1 km^2). Intelligent buoy systems (Alcocer et al. 2007) can give highly accurate fixes (ca. ±10 cm), but require the use of multiple research vessels and are even more expensive than RAP systems. Archival geo-location tags (Svedang et al. 2007) and pop-up archival tags (PAT) (Block et al. 1998) typically have low spatial accuracy, on the order of 100s of kilometres (Teo et al. 2004). ARGOS-based systems are capable of higher accuracy (10s of metres) and temporal resolution, but this can only be achieved when the animals are at the water's surface. Newer technologies that integrate archival systems with near-instant-fix global positioning systems (GPS; such as Wildlife Technologies Mk-10AF or SirTrack KiwiSat 101) are expensive (3300 to 5000 USD) and still rely on the ARGOS system for transmission of highly compressed information (unless units are retrieved). Finally, the capture, restraint, and attachment of acoustic, geolocation and satellite-based tracking devices can affect both the behaviour and survivability of study animals (Bridger & Booth 2003).

Tracking devices based on the world-wide NAVSTAR GPS have been used since the mid-1990s to acquire location information from a wide variety of terrestrial and volant animals (Rodgers et al. 1996, Steiner et al. 2000). Compared with other means of collecting animal-location data, GPS telemetry has several important advantages, including: (1) high spatial accuracy (10s of metres) and temporal resolution; (2) the capacity to collect large amounts of location information for individuals over comparatively long periods of time; (3) the ability to determine location without the need for human observers, thus avoiding collection (Giuggioli et al. 2006) and observer-induced behavioural biases (Bandeira de Melo et al. 2007); and (4) the ability to continuously monitor the locations of individuals, even in challenging environmental conditions or in areas where human access is limited (Rodgers et al. 1996). Unfortunately, in marine environments, the applicability of GPS tracking is limited because signals from satellites cannot be transmitted through water; thus, the method is restricted to species that spend considerable time flying, floating on, or swimming at or near the water's surface (Weimerskirch et al. 2002).

Many marine animals live at least part of their lives in shallow or surface waters where, despite its limitations, GPS telemetry may be a viable tracking option. A number of species of adequate size and suitable behaviour (e.g. foraging technique, habitat preferences) may be capable of towing a small buoy-mounted GPS receiver, able to record locations at the water's surface. Regardless of the potential of such a simple and inexpensive tracking system, to our knowledge, this method has not, until now, been employed successfully. Here, we describe such a system and demonstrate its use on the New Zealand eagle ray *Myliobatis tenuicaudatus*, a medium-sized elasmobranch fish that inhabits intertidal and shallow subtidal marine environments. Specifically, we sought to determine whether our method could reliably provide location data of sufficient spatial and temporal resolution to reconstruct fine-scale movements of the rays in the shallow waters of an estuary. We acknowledge that this technique is limited to particular environments and species, but, in the appropriate circumstances, it may be the best means yet available for obtaining high-quality location data from vagile marine animals.

MATERIALS AND METHODS

Study site. Our study was conducted between 1 September 2006 and 27 October 2006 in Taiharuru estuary, Northland, New Zealand (35° 43.6′ S, 174° 32′ E; see Fig. 2). Taiharuru estuary is approximately 6 km^2 in surface area and consists predominantly of intertidal mud-flats fringed by stands of gray mangrove *Avicennia marina* var. *resinifera*. The estuary is separated partly from the open ocean by a string of rocky islands and reefs. Within the study site there is little human commercial or recreational activity. Surrounding areas are primarily farmland.

Study animal. The New Zealand eagle ray *Myliobatis tenuicaudatus* is predominantly a coastal and estuarine species endemic to northern areas of the North Island. Eagle rays are sedentary, benthic feeders that forage widely in sandy environments for macroinfauna such as bivalves and crustaceans. Eagle rays grow to ca. 1.5 m disc width (DW) (Ayling & Cox 1982) and may weigh >50 kg (T. Riding pers. obs.). Little is known of their life history, biology, movement, or dispersal patterns, as is typical for most elasmobranchs (Sundstrom et al. 2001).

Tracking devices. The global positioning devices (GPDs; Sirtrack Ltd) used in our study were composed of a 12-channel Trimble GPS microprocessor, antennae, power supply and non-volatile memory. The GPDs were of the archival type, in that position fixes recorded during field deployments were stored in a FLASH memory until retrieved upon recovery. Information describing the date, time and the horizontal dilution of precision (HDOP; an estimate of the quality of a navigational solution in the horizontal plane) was recorded along with each location estimate. The GPS receivers were programmed to search for satellite signals for 180 s and to record locations at 90 to 150 s intervals. The 50% circular error probable (CEP) of the horizontal location error of the GPDs is ca. 6 m (Sirtrack Ltd). GPDs were mounted on a 25 cm 'yacht'-

shaped tow-buoy constructed from polystyrene foam, with a stainless steel (1 mm) 'keel' and 'bow' and were mounted with Velcro and elasticised straps (to secure the GPD and associated equipment) directly on the foam body (Fig. 1b). Fibreglass matting and epoxy resin were laid over the hulls. Surfaces of the buoys were smoothed with sandpaper and covered with marine epoxy paint. The buoy was equipped with a LED flashing light and a VHF radio-transmitter to facilitate recovery. The units weighed 244 to 247 g in air, and had approximately 50 g of buoyancy in water.

We measured the force of drag induced by the buoy using a spring balance, both in a laboratory tank and under field conditions. During these assessments we recorded the mean and maximum drag attained over a 5 min period, in conditions of both calm and rough water (i.e. wave height ≥0.25 m).

Ray capture and GPD attachment. We fixed the buoys carrying the GPDs to the rays with 4 to 7 m of monofilament tether of 30 kg breaking strength. After pilot studies, which utilised 7 rays, we evaluated 2 methods of attaching the tethers. For Rays 8 to 11 we used set nets to capture the rays and then immediately transferred them to a live tank where we determined their sex and physical measurements. We then secured the GPDs to the rays' barbs using plastic cable ties. For Rays 12 to 19 we fixed the tethers to the rays using an intramuscular (IM) tag (Floy FH-69 Stainless Steel Dart), which we embedded in their backs using a jab-stick. During all field trials we monitored the rays for the first several hours from a dinghy to ensure that they exhibited normal behaviour; at no time until the recovery of the GPD units were we positioned any closer than 100 m from the buoy.

GPD recovery, data retrieval and data analysis. We recovered the buoys and GPDs from the rays 1 to 29 h after deployment, the time of retrieval largely depending on whether the rays attempted to leave the estuary for the open ocean, where we thought recovery of the tracking gear would have been more difficult. We used the VHF transmitter to locate the buoys if they were out of sight; we found that the transmitters were effective at distances of up to several kilometres. For the rays with GPDs attached using cable ties, we recovered the devices simply by retrieving the buoy and then cutting the cable ties. For rays with GPDs attached by IM tags, we retrieved the buoy and then sharply pulled on the tether, which caused the 1 kg

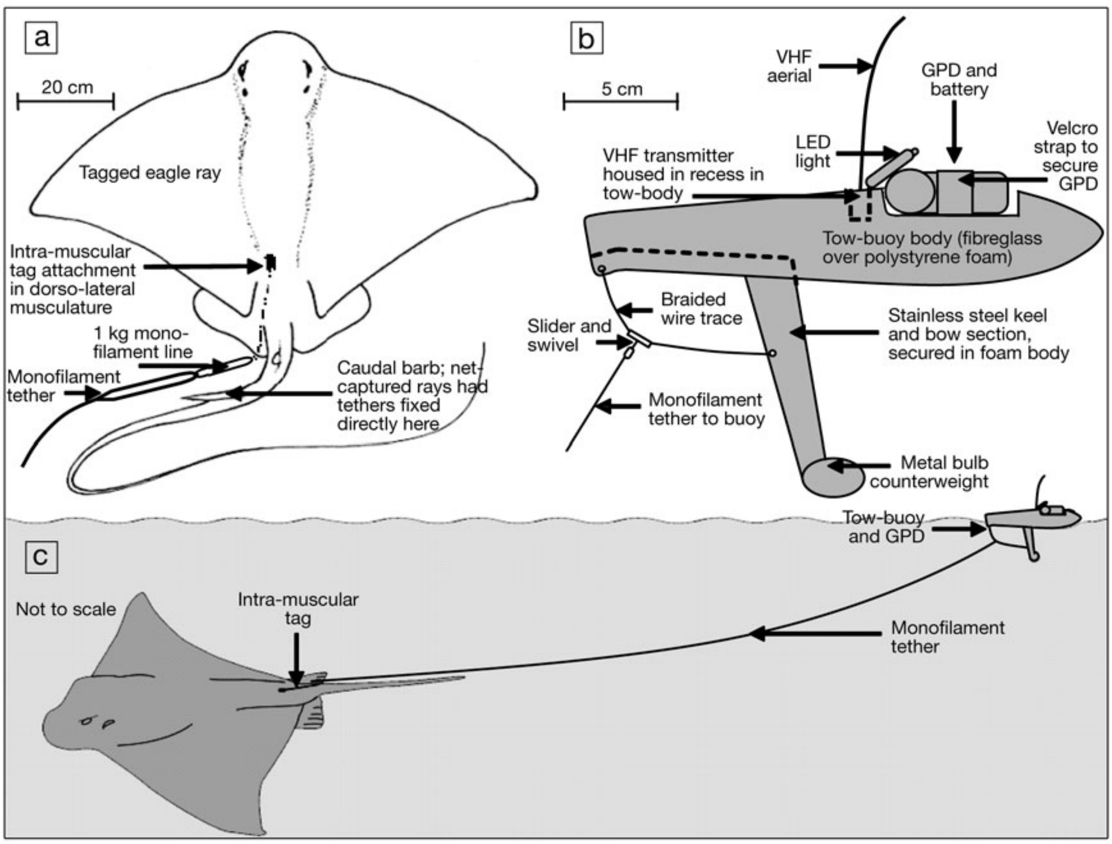

Fig. 1. Schematic diagram of buoy-mounted global positioning device and associated equipment used to track New Zealand eagle rays *Myliobatis tenuicaudatus* in Taiharuru estuary, New Zealand, from September to October 2006: (a) intramuscular tag, trace, and tether attachment; (b) side view of the tow-buoy and equipment; (c) eagle ray with tow-buoy attached

Table 1. Deployment and performance characteristics of global positioning system (GPS) devices mounted on tow-buoys and used to track New Zealand eagle rays *Myliobatis tenuicaudatus* in Taiharuru estuary, New Zealand, from September to October 2006. SE: standard error of the mean; HDOP: horizontal dilution of precision

Ray	Date tagged	Size (disc width, cm)	Time tagged (NZ std time)	Duration of record (h:m:s)	Tide at start of track	Distance to estuary mouth after release (km): Start of track	10 min	150 min	End of track	Tide at end of track	Success rate (%)	Fixes with HDOP >10 (%)	Mean no. of satellites per fix (±SE)	Distance travelled (km)	Mean speed ($m\ s^{-1}$, ±SE)
Net-caught and barb-tagged															
8	1 Sep 2006	118	9:03:30	2:11:01	Mid, rising	2.23	2.20	n/a	0.34	High, rising	54	0.0	4.21 ± 0.26	1.9	0.25 ± 0.02
9	2 Sep 2006	106	8:02:00	3:11:36	Low, rising	2.48	2.25	0.71	0.12	Mid, rising	96	4.1	4.66 ± 0.12	4.5	0.39 ± 0.02
10	3 Sep 2006	121	12:29:35	3:31:12	Mid, rising	2.80	2.79	2.39	0.10	High, falling	95	0.0	3.68 ± 0.09	7.1	0.56 ± 0.02
11	6 Sep 2006	47	14:55:36	5:01:00	Mid, rising	3.05	3.10	3.41	0.49	High, falling	96	1.7	4.57 ± 0.11	5.2	0.29 ± 0.02
Mean				3:28:42		2.64	2.58	2.17	0.26		85	1.4	4.32 ± 0.06[b]	4.7	0.40 ± 0.01[b]
Intra-muscularly tagged															
13	6 Oct 2006	120[a]	11:06:24	0:52:37	Low, falling	2.38	1.92	n/a	0.00	Low, falling	100	0.0	4.29 ± 0.12	2.9	0.92 ± 0.02
15	14 Oct 2006	95[a]	14:44:12	3:51:24	High, falling	4.93	4.85	3.38	1.97	Low, falling	100	0.0	3.51 ± 0.09	5.3	0.38 ± 0.02
16	15 Oct 2006	110[a]	12:24:21	7:06:00	High, rising	4.36	4.56	5.13	1.66	Low, falling	88	3.2	3.55 ± 0.04	7.3	0.29 ± 0.01
17	24 Oct 2006	100[a]	18:03:48	23:43:12	Mid, rising	1.90	1.93	3.89	1.38	Mid, rising	91	2.7	3.86 ± 0.04	18.7	0.22 ± 0.01
18	27 Oct 2006	115[a]	12:31:30	28:54:12	High, falling	4.54	4.25	3.16	1.03	Low, falling	92	2.4	4.01 ± 0.04	21.0	0.20 ± 0.01
19	27 Oct 2006	110[a]	13:30:38	6:48:00	Mid, falling	4.41	4.16	2.26	1.84	Mid, rising	93	2.7	3.44 ± 0.04	5.7	0.23 ± 0.01
Mean				11:52:34		3.75	3.61	3.56	1.31		94	1.8	3.83 ± 0.02[b]	10.2	0.25 ± 0.01[b]

[a]Estimated disc width; [b]Grouped for each tag method

weak-link to break, leaving the IM tag in place. Upon recovery of the GPDs we downloaded the location data via the communication port to a laptop computer. Because fixes with values of HDOP >10 are of questionable accuracy (K. Lay, Sirtrack Ltd), only position fixes with HDOP ≤10 were included in analyses.

RESULTS

Drag parameters of GPDs

The force of drag due to the buoys depended largely upon the conditions of the surface water, but at a typical swimming speed of 0.5 $m\ s^{-1}$, drag force averaged 0.12 N and never exceeded 0.20 N in flat water (this equates to a reading of 20 g on a spring balance). In rough water, drag averaged 0.39 N, with a maximum of 0.75 N. A common index used to quantify the effects of tag-induced drag on swimming animals like *Myliobatis tenuicaudatus* is the tag-to-animal frontal-area ratio (Ropert-Coudert et al. 2007). This was 2% for the largest ray (121 cm DW, Ray 10) and 5% for the smallest (47 cm DW, Ray 11).

Capture methods and post-release behaviour

We fixed the tethers of the GPDs to 4 rays using the barb-attachment method. However, we noted that net capture and restraint clearly affected the animals' behaviour. Of the 4 rays captured with nets, 3 moved against the tide and towards the estuary mouth within 10 min of release; eventually, all closely approached or crossed the estuary mouth where they were intercepted to retrieve the tracking device. *In situ* IM tag attachment proved to be far less disruptive to the animals' behaviour, so another 8 rays were fitted with IM tags. Attachment of 2 of the buoys fixed with IM tags failed due to broken 1 kg weak-links (Rays 12 and 14); otherwise, we successfully recovered all remaining buoys after times at liberty of up to 29 h. At the end of the tracking period, only 1 ray tagged using the IM method had moved close enough to the estuary mouth to warrant interception and removal of its tracking device (Table 1).

Fix-success rates and track resolution

Fix-success rates (the proportion of successful fixes out of the total number attempted) of the 10 deployments were generally very high, ranging from 54 to 100% (Table 1). The percentage of fixes with values of HDOP >10, and the median number of satellites used to calculate each fix were <2% and 4, respectively. The median HDOP of all fixes was 2.3. The high fix-success rates, positional accuracy and temporal 'granularity' of the sampling intervals of the GPDs provided location data at sufficient resolution to reveal fine-scale details of the movements of the rays as they alternately foraged and rested in the estuary, in some deployments over several tidal cycles (Fig. 2).

DISCUSSION

Fix-success rates and data quality

The ability of GPS-based tracking devices to describe the movement trajectories of animals is dependant, in part, on the accuracy and number of location estimates made during sampling periods. In coastal or offshore areas, reception of GPS-satellite signals should be as good as or better than that in most terrestrial environments, due to the greater amount of 'available sky' (for discussion of available sky see D'Eon et al. 2002). However, aquatic environments pose another challenge: GPS devices cannot function if they are directly attached to submerged organisms. Towing GPDs on a float circumvents this issue provided that the device stays at the surface. Rapid movements by tagged animals, climatic and wave conditions, and swimming in deep water may submerge the GPS receivers, thereby rendering the devices temporarily inoperable.

We designed our tow-buoy to work best at low speeds (≤1 m s^{-1}), because New Zealand eagle rays *Myliobatis tenuicaudatus* generally are slow moving. When the rays exhibited normal behaviour and swam slowly, the GPDs achieved a surprisingly high overall fix-success rate of 90.5%. The 'quality' of the fixes was also good, with values of HDOP and number of satellites per fix falling well within the ranges of values of GPDs used for tracking terrestrial animals (e.g. Hebblewhite et al. 2007, Sager-Fradkin et al. 2007, Hansen & Riggs 2008). Compared with acoustic tracking methods, the GPDs performed well, in terms of both the spatial accuracy and the number of fixes obtained within a given time (e.g. Solomon & Potter 1988, Heupel et al. 2004). In our study the GPS units sampled locations at a rate of 24 to 40 fixes h^{-1}; however, sampling rates are determined by users; sampling frequencies of current GPS microprocessors are as high as 4 fixes s^{-1} (e.g. ANTARIS 4, u-blox AG). Furthermore, new battery and memory technologies allow for >100 000 fixes to be stored before retrieval is required. Such high sampling- and fix-success rates provide far greater temporal resolution than is currently possible using standard hand-held methods of acoustic tracking.

Effects on animals

The rays responded differently to the 2 methods of capture and tether attachment. Rays that we caught in nets and had GPDs attached to their barbs with cable ties retained 100% of the buoys during the deployment periods. However, capturing and restraining the rays seemed to significantly affect their behaviour after they were released from fixing the tethers. All rays that were tagged using this method fled rapidly from the release area and then moved toward the mouth of the estuary, requiring us to recover the tow-buoys prematurely to avoid possible loss of the tracking equipment. The behaviour of rays that were tagged intramuscularly (without being captured or restrained) was markedly different. Only 3 of 8 rays reacted to the IM tag attachment with a short burst of speed, and only one of these moved toward the mouth of the estuary after release. However, this individual was captured on an outgoing tide, and was oriented toward the mouth of the estuary when it was tagged, so perhaps after release it simply continued on its way and was not greatly affected by the tagging procedures. Overall, movement behaviour with IM tag attachment matched behaviour of undisturbed rays observed in the wild, whereas net capture resulted in flight from the estuary. Capture and handling stress is common in marine animals and can lead to significant changes in behaviour (Portz et al. 2006), so methods of fitting tracking devices that limit stress are preferable. Although further studies are needed to properly assess any subtle behavioural effects of attaching tethers, from what we observed, the IM tagging method resulted in little noticeable change in the rays' swimming and resting behaviour and it became the method of choice.

Minimizing the drag of tracking devices is important, as the shape and size of externally attached units can affect the behaviour of fish (Bridger & Booth 2003), dolphins (Pavlov et al. 2007) and birds (Ropert-Coudert et al. 2007). Greater swimming velocities equate to higher drag; therefore, at higher swimming speeds, tags are more likely to influence behaviour (Bridger & Booth 2003). Eagle rays are sedentary by nature and usually swim at <0.5 m s^{-1} unless disturbed, when they can swim in excess of 8 m s^{-1} for short bursts (T. Riding pers. obs.). Thus, for typical behaviour (low velocity movement), drag is less of an issue. Grusha & Patterson (2005) measured the drag induced by PAT tags in conditions similar to the 'flat water' state we evaluated (the only condition which occurred in our trials); drag reported under these circumstances (0.15 to 0.21 N) was very similar to that we observed for our tow-buoys (0.12 to 0.20 N). PAT tags are the accepted standard for tagging similarly sized fish, and PAT tags are often

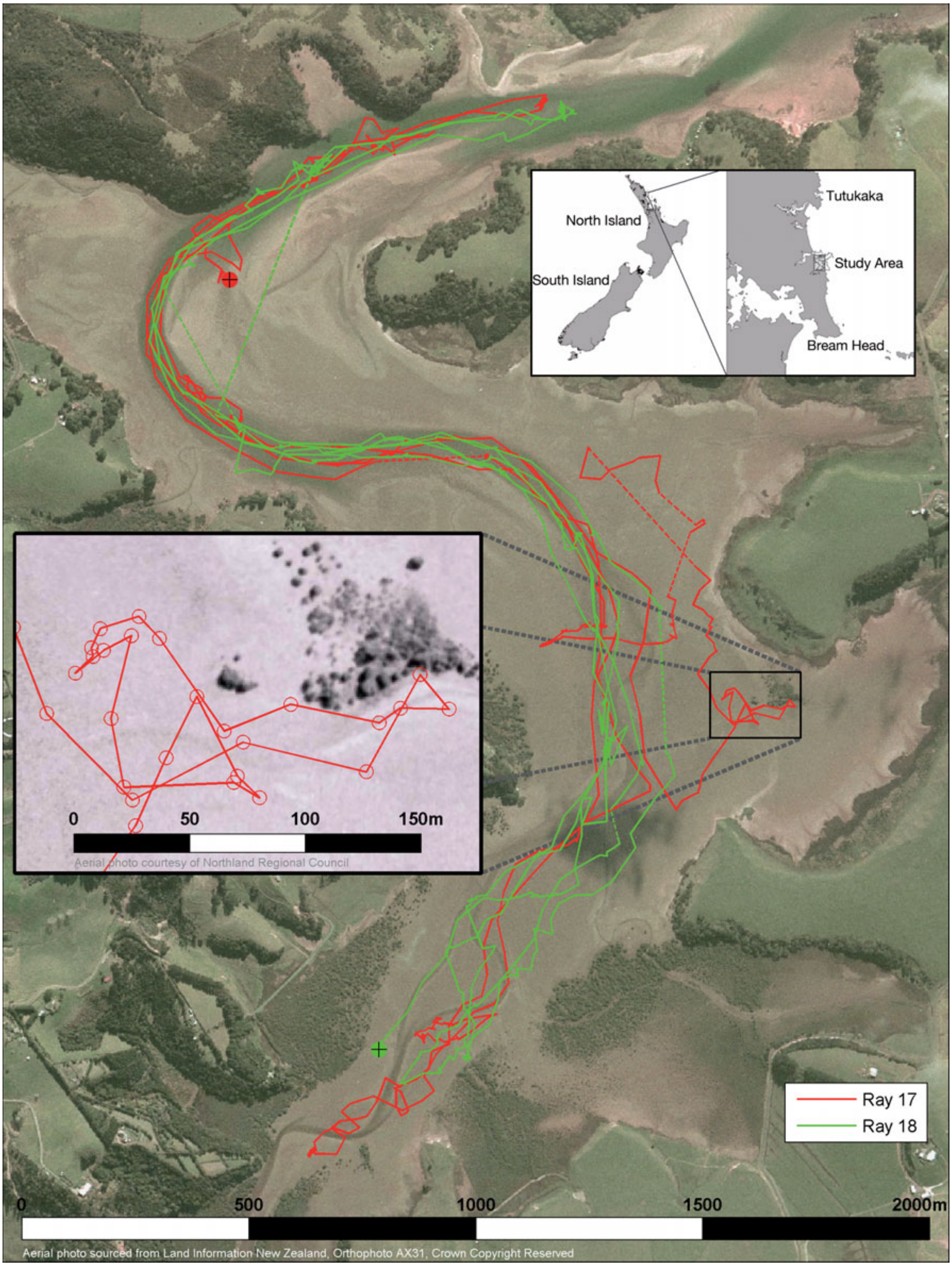

Fig. 2. *Myliobatis tenuicaudatus*. Movement trajectories of 2 individuals (Rays 17 and 18) in Taiharuru estuary, New Zealand, in 2006. The entrance to the estuary from the Pacific Ocean is at the top right-hand side of the picture. Coloured circles represent the locations where global positioning devices on buoys were attached to rays with monofilament tethers (4 to 7 m in length). Dashed lines connect points where fixes were >10 min apart (i.e. indicate areas where instantaneous fix rates were very low). Left inset: close-up of Ray 17 swimming at the edge of a stand of gray mangroves *Avicennia marina* var. *resinifera*; open circles are locations of fixes made at a sampling interval of 150 s

attached using the IM method. Moreover, Blaylock (1990) found that a transmitter-to-ray-mass ratio of 0.03 had no discernable effect on the behaviour of cownose rays *Rhinoptera bonasus*. Using our tow-buoys, a ray weighing 8.2 kg with a DW of 77 cm or larger is required to achieve such a ratio. In our study, all rays except one immature male favourably exceeded this threshold. Thus, any behavioural and physiological impacts induced by tow-buoy tagging should be well within accepted levels.

Design considerations

Successful design and construction of buoy-mounted GPDs require thoughtful consideration of the behaviour of study animals and the environments in which they live. For slow-swimming animals (e.g. ≤1 m s^{-1}) or to guarantee high fix-success rates, buoys of higher displacement can be used to ensure adequate reception of satellite signals. Alternatively, for fast-swimming animals or those living in areas where surface waves are high or 'choppy', buoys should be smaller to minimise drag. The length of tethers can be adjusted to suit the environment; areas with deep channels, high currents, or marked tidal ranges may require longer tethers to ensure that buoys remain on the surface.

Ancillary equipment can be incorporated to buoys, depending on size and weight restrictions, to increase functionality. For example, light-level sensors, salinometers, depth gauges, or compact audio/visual equipment could be fixed to the lower ends of tethers, permitting simultaneous collection of environmental data, so that movement behaviour can be related to the physical conditions of study areas. Additionally, compact photovoltaic cells could be mounted to the surface of buoys to recharge batteries and thus increase operational life. Using existing radio transceiver technology (Clark et al. 2006) or the GSM (global system for mobile communications) cellular network, data could be transmitted in near-real time from GPDs to receiving stations, or a signal could be sent to trip remote release mechanisms, obviating the need to recapture study animals for recovery of data and GPDs.

One of the most important advantages of GPS-based tracking devices is their comparatively low expense. GPDs of the type used in this study can be made from components costing <200 USD (T. Dennis pers obs.), allowing researchers to deploy large numbers of devices. Furthermore, because towed GPDs do not require close monitoring, simultaneous deployments of multiple units are possible under appropriate conditions.

CONCLUSIONS

Despite being restricted to larger fish moving in relatively obstacle-free waters, the accuracy and quantity of location data provided by buoy-mounted GPDs can provide descriptions of the movement trajectories of marine animals at far greater spatial and temporal resolution than is typically possible with other marine tracking methods. Because of the comparatively low financial costs and labour requirements of GPS-based devices, more individuals of the species of interest can be tracked per project. Higher numbers of accurate tracks will result in greater statistical power and an increased ability to describe infrequent or short-lived movement behaviours. With the ongoing evolution of component technologies, buoy-mounted GPS tracking devices, when employed on suitable species and in suitable environments, have the potential to greatly enhance knowledge of the ecology and behaviour of many marine organisms.

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