Novel GPS tracking of sea turtles as a tool for conservation management

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Abstract

We used recently developed, low-powered, TrackTag™ GPS loggers to track the movements of female loggerhead sea turtles (Caretta caretta) at the largest breeding population in the Mediterranean (Zakynthos, Greece). Three turtles were tracked for a total of 73 days in May and June 2006, during which time 3753 GPS locations were obtained after filtering outliers (51 per day per turtle). The diving behaviour of these three turtles and three others was also monitored using time–depth recorders (TDR). The GPS data revealed that all three turtles spent most of their time in shallow water (<4 m sea bed depth) very close to the shore (<200 m), primarily ranging along an 18.5 km section of coastline. These observations were corroborated by TDR data acquired from all six turtles and frequent first-hand sightings of turtles close to shore during the breeding period. Comparison with random crawl movement models indicated that two of the tracked turtles moved with a similar non-random pattern, suggesting common biophysical processes might be driving their movements. The movement and depth data that we collected both suggest that existing legislation to safeguard sea turtles within this protected region may not include the most critical habitats for female loggerhead sea turtles during the breeding period. Our study demonstrated the feasibility of using GPS tracking to investigate fine-scale movements of a marine vertebrate, illustrating the value of GPS tracking for wildlife conservation management.

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1. Introduction

Understanding movement patterns and the factors that affect animal distribution are integral components of behavioural ecology, conservation and protected area management. Conventional animal biotelemetry systems,
such as radio and satellite transmitters, have revolutionised the ability to track wildlife movement over vast spatial and temporal scales (Maehr et al., 2002; Luschi et al., 2003; Sale et al., 2006; Sims et al., 2006). Despite this, variable accuracies and infrequent intervals between fixes (Hays et al., 2001; Hulbert and French, 2001) limit their application at finer spatial resolutions, and when quantifying movement patterns in relation to biophysical parameters at small scales (Wilson et al., 2002; Bradshaw et al., 2007). However, the acquisition of high resolution tracking information may be important in formulating rational, adaptive and dynamic management decisions for nature reserves, endangered species and related conservation policies (Argardy, 1994; Castilla, 2000; Thompson et al., 2000; Parra et al., 2006).

Loggers based on the Global Positioning System (GPS) are an important new technology allowing wildlife to be studied with unparalleled accuracy, often to within ranges of 10 m (Moen et al., 1997; Hulbert and French, 2001). However the level of accuracy has been found to vary among animals depending on terrain, habitat and behaviour (Moen et al., 1997; Friar et al., 2004). While GPS loggers, some linked to transmitters to relay the positional data, are routinely used for terrestrial and aerial animals (Douglas-Hamilton et al., 2005; Biro et al., 2006), tracking marine vertebrates with GPS loggers has proved more problematic. This is because infrequent surfacing behaviour limits the time when loggers are available for acquiring satellite signals. For marine species therefore, the current challenge is, in as short a time possible, to acquire sufficient information in order to calculate GPS positions when an animal surfaces. There are several initiatives underway to achieve this goal and some limited success has been achieved, depending on species and surfacing interval (Sisak, 1998; Jay and Garner, 2002; Ryan et al., 2004; Yasuda and Arai, 2005; Petersen et al., 2006).

While satellite and VHF telemetry studies have been effectively used to investigate sea turtle oceanic migratory routes (Luschi et al., 2003; Hays et al., 2004b; Sale et al., 2006) to coastal foraging or breeding grounds, details about behaviour and habitat use at these regions of seasonal residency remain limited (Heithaus et al., 2002a, b; Houghton et al., 2002; Seminoff et al., 2002; Hopkins-Murphy et al., 2003; Yasuda and Arai, 2005). Existing studies of female sea turtles at breeding areas using remote technology have been primarily conducted following the onset of nesting (Hays et al., 1991; Hays et al., 2002; Houghton et al., 2002; Hays et al., 2003a; Hopkins-Murphy et al., 2003). These studies indicate that inter-nesting females tend to inhabit sea depths of 15 m or less, and may be found as much as 10 km from the nesting beaches, often exhibiting movements parallel to the coast.

Laganas Bay, on the island of Zakynthos in Greece, is the largest loggerhead sea turtle (Caretta caretta) rookery in the Mediterranean (Margaritoulis, 2005). It is visited by several hundred sea turtles and several hundred thousand tourists each summer (Arianoutsou, 1988). Sea turtles often begin residency in Laganas Bay as early as April, before nesting starts in late May, and are frequently observed in close proximity to shore (Schofield et al., 2006). Nesting beach locations and relative nesting densities were used to delineate the degree of protection offered by marine protection zones in Laganas Bay (Arapis and Margaritoulis, 1994). The no-boating zone encompassing three nesting beaches (out of a total of six), which account

Fig. 1. Map of Laganas Bay containing National Marine Park of Zakynthos (NMPZ) marine protection and ecotourism zones. Zone A = no-boating zone, zone B = boating permitted at 6 km h$^{-1}$ but no mooring, zone C = boating permitted at 6 km h$^{-1}$ and mooring, Ecotourism zone = including a swim zone 0–200 m from shore and an NMPZ endorsed turtle-watching business zone 200–1400 m from shore (adapted from map of NMPZ www.nmp-zak.org).

Fig. 2. Loggerhead sea turtle following TrackTag™ GPS logger attachment.
for about 70% of nesting activity (Margaritoulis, 2005). Since establishment of the National Marine Park of Zakynthos (NMPZ) in 1999, stricter regulation of near-shore tourism and turtle-watching activities in the two boating zones has been introduced, however empirical data about in-water sea turtle movement is necessary to validate and improve existing management actions.

Many coastal regions are subject to anthropogenic pressure, in the form of fisheries, coastal development and tourism (Arianoutsou, 1988; Hays et al., 2003b; Parra et al., 2006). It is therefore important to obtain information about where, when and why endangered species, such as sea turtles, use these areas, in order to implement rational and effective protective legislation and management of human activities (Argardy, 1994; Thompson et al., 2000). The aim of this study was to investigate sea turtle movement and habitat use at the internationally important rookery of Zakynthos. We used recently developed, low-powered, TrackTag™ GPS loggers to follow individual sea turtle movements and evaluate the effectiveness of existing marine protection zones.

2. Methods

2.1. Study animal

TrackTag™ GPS loggers were deployed onto four adult female loggerhead sea turtles (curved carapace lengths 81–89 cm) in Laganas Bay, Zakynthos, Greece (Fig. 1, 37°43′N 20°53′E), during the pre-nesting period in May 2006 and removed during the inter-nesting period in June 2006. In one case, deployment problems caused the logger to malfunction so that no data were collected. Hence data were collected from three turtles. In addition, six time–depth recorders (TDR) were deployed and retrieved from all four turtles plus another two female turtles. The attachment of all devices was conducted under licenses from the Greek Ministry of Agriculture. A 4 m research boat was used to find turtles resting on the seabed at depths less than 1.5 m. The turtles were captured using the turtle-rodeo technique (Ehrhart and Ogren, 1999) and lifted onto the boat. Following capture, the curved carapace length was measured and then a GPS logger and/or TDR attached using a standard method we have widely employed before with various transmitters and loggers (Hays et al., 2003a). In brief, the carapace was cleaned and then the logger embedded in quick-setting two-part epoxy resin (Powerfastners Inc., New Rochelle, NY, USA) with wooden baffles positioned at the anterior to help prevent impacts to the equipment (see Fig. 2). Loggers and TDRs were removed from the animals by one of two methods.

Table 1

| GPS | Turtle parameter | Date of nesting | Full no. days attached | In-water GPS locations | All GPS locations | Locations removed | Visually erroneous | Total Av. fix/ day | Speed | SD | DOP | Hourly Total Av. fix/ day | Speed SV | DOP | Hourly Total Av. fix/ day |
|-----|------------------|----------------|------------------------|------------------------|-------------------|------------------|------------------|------------------|-----------------|-----|-----|-----|------------------------|-----------|-----|------------------------|
| GPS2 | 81 | 73.5 | 19/5/2006 | 214 | 802 | 51 | 734 | 45 | 53 | 31 | 519 | 21 | 181 | 10 |
| GPS3 | 89 | 76 | 23/5/2006 | 231 | 31 | 307 | 99 | 817 | 2260 | 73 | 2007 | 6 | 2189 | 69 | 1741 | 7 | 1607 | 37 | 479 | 5 |
| GPS4 | 87 | 72 | 24/5/2006 | 254 | 36 | 1335 | 53 | 247 | 1008 | 44 | 1012 | 40 | 1024 | 32 | 1761 | 57 | 508 | 24 | 266 | 11 |

(CCL = curved carapace length of turtle, CCW = curved carapace width of turtle).

(CCL* = curved carapace length of turtle, CCW* = curved carapace width of turtle).
using the rodeo capture technique, or (ii) by recovery on the beach immediately following nesting.

2.2. GPS loggers

We used recently developed, low-powered, archival Navsys Ltd. TrackTag™ GPS devices (http://www.navsys.com). Battery-life is saved due to TrackTag requiring < 60 ms to be powered up and acquire enough data for a navigational fix. This speed of acquisition is made possible because the positions are calculated during post-processing. Our devices had a memory capacity of 32,750 positions. The logger was housed in a stream-lined, pressure tight, ABS plastic casing measuring 101–34–26 mm (L x W x H). The mass of the device, including battery and housing, was 55 g (c. 0.001% of estimated sea turtle mass). Loggers had a saltwater switch so that they only attempted to acquire information from the GPS satellites when the turtle was at the surface. This system helps to extend memory capacity along with battery life. Navsys estimates accuracy of locations to be around 30 m (2dRMS) 95% of the time using a horizontal and stationary receiver in the UK. Prior to deployment, the GPS loggers were charged and programmed using Navsys TrackTag™ software to record in continuous mode at 30 s intervals when the saltwater switch indicated the units were not submerged. The housing was sealed using ABS water-resistant glue requiring a 6 h drying period. GPS co-ordinates were recorded with a spatial resolution of 0.0001° (11 m for latitude and 8.8 m for longitude at 37°N).

On retrieval, all GPS locations were plotted to examine the turtles’ movements. Data when the turtles were ashore (nesting or on aborted nesting attempts) were removed from all analysis and were confirmed by direct field observation, GPS onshore location and/or by TDR analysis of depth and temperature values. Due to the surfeit of data we also explored various filters to remove potentially erroneous locations. These methods included (1) removal of visually erroneous locations, such as those that fell well on land or were completely spatially different to previous and successive fixes within the same timeframe, (2) using a maximum rate of travel of 5 km h⁻¹ between successive locations (Hays et al., 2004a; Tremblay et al., 2006) which was selected based on calculations from 3 or more consecutive fixes occurring at 10–20 min intervals, (3) using the ‘dilution of precision’ (DOP), measuring the quality of satellite geometry, in which values below 10 are retained (Adrados et al., 2002) and (4) using the ‘satellite visibility’ (SV) with a threshold of > 4 satellites following previous work (Sea Mammal Research Unit SMRU, http://smub.st-and.ac.uk).

2.3. TDR devices

To record the diving behaviour of turtles we used time–depth recorders (TDRs): LOTEK LTD_1100 model TDRs (LOTEK Marine Technologies, St. John’s, Newfoundland). The TDRs weighed 5 g in air, sampled depth with a precision of 2 cm, temperature with a precision of 0.2 °C and stored up to 16,384 readings for each parameter (http://www.lotek.com/ltd1100.htm). The TDRs employed “time-extension” sampling whereby the sampling interval was adjusted so that data continued to be collected regardless of the length of deployments. Hence, the sampling frequency was approximately the length of the deployment divided by 16,384, which, in our study, equated to a sampling interval of < 1 min to around 4 min. For each data set we conducted a zero point offset, whereby we determined the shallowest depth recorded every 4 h. We would expect this depth to be the surface (0 m) and so all the raw depth values from the loggers were adjusted accordingly, typically by a maximum of a few 10 s of cm. This process of zero point calibration is standard within TDR studies (see for example, Hays et al., 2007).

Fig. 3. Histograms of the number of daily GPS locations for each turtle. (a) GPS2. (b) GPS3. (c) GPS4.
Data when the turtles were ashore (nesting or on aborted nesting attempts) were removed from further analysis. These events were confirmed by direct field observation and/or by analysis of depth and temperature values indicating that the turtle was ashore.

2.4. Turtle spatial area use

Using the Geographic Information Systems (GIS) package ArcView 3.1 we identified key area use by overlaying the turtle GPS fixes on existing features, including (i) sea depth parameters, (ii) Natura 2000 marine habitats and (iii) National Marine Park of Zakynthos maritime zones. To obtain an objective measure of sea turtle key area use in relation to the selected features, we initially filtered the GPS fixes by selecting one fix per hour for each turtle (Tremblay et al., 2006). The GIS programme provided the attributes of the polygons for each feature within the maps. The location of turtle GPS fixes was analysed (using the “query” and “summarise” tools) with respect to the chosen features, to indicate areas that are in need of increased protection.

2.5. Turtle movement model simulations

Two turtles that were tracked moving around Laganas Bay at the same time (GPS2 and GPS3) seemed to show broadly the same pattern of movement rather than moving randomly with respect to each other. We therefore compared their movements against two random walk models. First we calculated the distance separating these two turtles every 3 h between 24/5/2006 and 6/6/2006, excluding days on which turtles nested (31/5/2006). In model 1 we assumed that each turtle moved randomly within Laganas Bay (defined by latitudes 37°70′–37°74′ N and longitudes 20°84′–20°96′E). Given that the bay at its widest point is about 12 km, we assumed that within 3 h a turtle could travel anywhere in the bay. We therefore divided the bay into grid squares (178 m in latitude by 211 m longitude) and randomly selected grid squares for each modelled turtle at 3 h intervals. At each time we calculated the distance apart between the two modelled turtles. In model 2, we constrained the movements of the modelled turtles so that they moved randomly but only within 900 m of the shore in Laganas Bay. For both models, 1000 movement steps were generated. The
differences in observed distribution of actual and random walks were calculated using Kolmogorov–Smirnov tests.

3. Results

3.1. TrackTag™ GPS loggers

Excluding deployment and retrieval days, the three turtles equipped with GPS loggers were tracked for a total of 73 complete days (17, 31 and 25 days respectively) between 20 May and 23 June 2006. All three turtles nested at the same beach (Sekania, in maritime zone A) during the period of GPS logger attachment.

A total of 5488 GPS fixes were obtained, of which 1278 were from when the turtles were making nesting attempts, leaving 4210 in-water locations. On filtering the data for visually erroneous locations, 457 fixes were removed, leaving 3753 GPS fixes (89%), with an average daily fix rate of 51 locations (Table 1, Fig. 3a–c). Alternative filtration methods of the in-water locations, using the speed filter left 64% of locations, while 40% and 62% of locations were retained respectively using the DOP and SV based filtration methods (Table 1). In all cases the tracks, either with raw or filtered locations, were very similar and the high number of daily locations allowed accurate assessment of each turtle’s movement (Fig. 4a–f) (Hays et al., 2004a). Hence, we selected to base subsequent data analysis on GPS locations that remained following the removal of ‘visually erroneous’ locations.

The GPS loggers indicated that all three turtles primarily used an 18.5 km section of the 27.8 km coastline of Laganas Bay; with 100%, 100% and 84% of in-water GPS locations for each turtle respectively (Fig. 5a–c and Appendix A). Only GPS4 left the breeding area during the survey period. Analysis of hourly turtle locations against bathymetry, corroborated this coastal preference, suggesting that 79% of time was spent at sea bed depths < 5 m. Analysis of turtle distance from shore at hourly intervals indicated that 89% of hourly locations occurred within 0.5 km of shore, 76% within 0.2 km of shore and 56% within 0.1 km of shore (Figs. 6 and 7a). Analysis of our dataset using GIS overlays of Natura 2000 habitats suggested that the turtles do not uniformly inhabit shallow waters, but prefer habitats comprising submerged sandbanks (63% fixes) over other near-shore habitats, such as shallow rocky reefs (37% fixes) (Fig. 7b).
Analysis of hourly GPS locations with respect to the National Park maritime zones indicated that turtles spent on average 25%, 29% and 42% GPS of time in maritime protection zones A, B and C respectively. The turtles spent on average 56% (range 34% – 94%) of time within the ecotourism zone straddling maritime zones B–C. GPS4 spent 4% of the survey period outside of the three protection zones (Fig 7c).

3.2. TDR devices

The near-shore movements of the three turtles equipped with GPS loggers was reflected in their patterns of depth utilisation with the vast majority of their time spent at very shallow depths. For example, all three turtles spent > 95% of their time at sea depths shallower than 4 m (Table 2). Similarly for a further three turtles equipped with TDR loggers only, for a total of 67 days (31, 12 and 21 days respectively) between 16 May and 27 June, their patterns of depth utilisation were also very shallow (Table 2) with all these turtles similarly spending > 95% of their time shallower than 4 m.

3.3. Turtle movement and simulations

Analysis of comparative locations of actual GPS2 and GPS3 turtles at three-hourly intervals indicated that

<table>
<thead>
<tr>
<th>Animal ID</th>
<th>Percent of time at mid-point depth bin/metres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>GPS2</td>
<td>89.92</td>
</tr>
<tr>
<td>GPS3</td>
<td>95.34</td>
</tr>
<tr>
<td>GPS4</td>
<td>80.75</td>
</tr>
<tr>
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</tr>
<tr>
<td>TDR2</td>
<td>89.23</td>
</tr>
<tr>
<td>TDR3</td>
<td>91.89</td>
</tr>
</tbody>
</table>

Fig. 7. GIS maps showing the hourly GPS logger locations of all three turtles with respect to (a) bathymetry, (b) Natura 2000 habitat of submerged sand-banks, (c) NMPZ maritime protection zones and ecotourism zone (swim 0–200 m from shore, turtle-watching 200–1400 m from shore).

Fig. 8. The cumulative frequency distribution for the distances apart of GPS2 and GPS3 turtles measured every 3 h between 24/5/2006 and 6/6/2006 (dashed line) and modelled turtles moving within the bay following random walk models. Thick solid grey line = random walk model 1, thick black solid line = random walk model 2. The observed distribution differed significantly from both random walk models (Kolmogorov–Smirnov tests, D=0.4245, P<0.001 and D=0.5031, P<0.001 respectively).
they occurred at distances of $\leq 1.5$ km apart on 55% of occasions (average 1.6 km, range 0.01–5.44). Analysis of comparative locations of GPS4 with GPS2 and GPS3 indicated that they occurred at $\leq 1.5$ km of both GPS2 and GPS3 on 38% of occasions (average 2.6 km, range 0.01–8.3).

In both models the frequency distribution for the distances apart between the two modelled turtles was different to that in the observed data (Fig. 8), with GPS2 and GPS3 generally being more closely associated than that predicted by both random walk models (Kolmogorov–Smirnov tests, $D=0.4245$, $P<0.001$ and $D=0.5031$, $P<0.001$ respectively). In other words, this evidence suggests that turtles 2 and 3 were moving in the same manner within the bay.

4. Discussion

Increasing development and settlement of human populations in coastal locations has become an important issue worldwide, threatening the sustainability of many marine and coastal resources (Arianoutsou, 1988; Argardy, 1994; Parra et al., 2006). To facilitate wildlife conservation and sustainable use of marine areas, it is essential to understand the relationship between populations and their habitats (Castilla, 2000; Canadas et al., 2005), with knowledge about the impacts of environmental and anthropogenic parameters providing additional benefit (Thompson et al., 2000; Tisdell and Wilson, 2002; Douglas-Hamilton et al., 2005; Preisler et al., 2006). However, quantification of such parameters is often difficult hence the ‘precautionary approach’ to protect wildlife is applied in many areas, whereby measures are introduced, such as the regulation of boating activity, to minimise disturbance across general regions (Thompson et al., 2000; Wilson et al., 2004; Lusseau, 2006; Sorice et al., 2006). In the case of sea turtles, nesting beach locations and relative nesting densities have been used to delineate the degree of protection offered by adjacent marine protection zones (Arapis and Margaritoulis, 1994). While this approach has shown relatively good success in general, core protection areas may not reflect actual areas of wildlife habitat use, as we have demonstrated in our study at the largest sea turtle rookery in the Mediterranean.

The fine-scale detail of movement patterns obtained using the GPS loggers during this study, could not have been replicated using conventional telemetry (Hays et al., 2001; Hulbert and French, 2001; Tremblay et al., 2006; Bradshaw et al., 2007). This has been made possible because the TrackTag™ GPS system calculates the position during post-processing rather than in real time (http://www.navsys.com). We have shown here how TrackTag™ GPS loggers can now obtain large numbers of locations for marine species. The volume of data and degree of accuracy obtained using the TrackTag™ system are greatly improved in comparison to that obtained in previous GPS studies of marine wildlife (Sisak, 1998; Arai and Ono, 2002; Jay and Garner, 2002; Yasuda and Arai, 2005; Petersen et al., 2006), facilitating fine-scale analysis and application to protected area management.

While the movement models we have used in this study are very basic, a number of more refined models could potentially be explored. For example, correlated random walk models, which randomly draw step lengths from the measured step-length frequency distribution, may provide a more refined test of whether animals are moving randomly (e.g. Heithaus et al., 2002a). Similarly techniques such as fractal analysis and first passage time analysis provide mathematical approaches for exploring the details of habitat use by tracked animals, so that habitat preferences can be identified (e.g. Pinaud and Weimerskirch, 2005; Bailey and Thompson, 2006). One of the great advantages of the high resolution tracks provided by GPS loggers (high accuracy of locations combined with very frequent locations) is that a range of quantitative movement analysis can be performed on the data, with the biological signal not being compromised by artefacts introduced by measurement errors (Bradshaw et al., 2007). Hence the technology we have introduced here has great utility for tracking a wide range of marine vertebrates that surface to breathe including mammals and birds (C.M. Bishop unpublished). Furthermore, tethered GPS data-loggers may work for those non air-breathing animals (e.g. some fish) that do not surface to breathe but nevertheless come close to the surface.

During our study, while female sea turtles spent the majority of time outside of the no-boating maritime protection zone, a significant proportion of the population nest on one or more of the beaches in this region (Katselidis et al., 2004), and our data indicated that turtles are likely to preferentially frequent the region adjacent to the nesting beach in the days preceding nesting. As a result, this zone remains one of extreme conservation importance. The movement and depth data indicated that female turtles preferentially inhabit very shallow water in areas of submerged sand-banks. These criteria are only found in the two lesser protected boating zones. Our findings clarify that for maritime zones to provide the necessary protection, they should be based on sea turtle key area use (i.e. sea depth, proximity to shore and habitat preference), and not only the location of nesting beaches as has been done until now. While the national park has acted on an existing transect based survey (Schofield et al., 2004) to
form an ‘ecotourism zone’ to improve regulation of turtle-watching activities, our data suggest that this zone needs to be extended by about another 4 km, with the implementation of stronger regulations on marine area use within this region. Since female turtles occupied this zone for over 50% of time, it is important to quantify the impact of all near-shore human activities (including wading, swimming, private boat hire and turtle-watching), as has been done with other marine vertebrate species impacted by humans (Lusseau, 2006).

Turtles spend their time at sea during the breeding season engaged in a variety of activities such as mating, cleaning and resting (Booth and Peters, 1972; Schofield et al., 2006). Resting on the sea bed has been widely reported for hard-shelled turtles including green, loggerhead and hawksbills turtles (Houghton et al., 2002; Seminoff et al., 2002; Hopkins-Murphy et al., 2003; Houghton et al., 2003). Often female turtles are reported resting at depths of 15 m or less, and this relatively deep resting is reflected in the data provided from TDR deployments. However, in this study it was striking that female loggerhead turtles at the Zakynthos rookery almost never dived to sea bed depths of more than 4 m during May and June. This pattern of shallow diving was seen both in the turtles equipped with GPS loggers and TDRs (n = 3) and those carrying only TDRs (n = 3). The fact that both groups showed similar patterns of depth utilisation implies that the near-shore movements in shallow water we saw for the three GPS-equipped individuals might occur generally for female loggerhead turtles at this time of year at the Zakynthos rookery. The turtles may be inhabiting regions close to shore to avoid males (Booth and Peters, 1972). However, since turtles appear to selectively change sites on a daily basis and individuals had similar movement patterns, this suggests other processes may drive these near-shore movements. Our study has demonstrated how GPS tracking can be used to obtain accurate spatio-temporal information about the fine-scale movement patterns of a marine vertebrate, illustrating the value of this technique for wildlife conservation management and improvement of protection measures.

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**Appendix A. Supplementary data**

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jembe.2007.03.009.

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