Global Ecology and Biogeography, (Global Ecol. Biogeogr.) (2016)

Global Ecology and Biogeography A Journal of Macroecology

RESEARCH PAPER

The value of migration information for conservation prioritization of sea turtles in the Mediterranean

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ABSTRACT

Aim Conservation plans often struggle to account for connectivity in spatial prioritization approaches for the protection of migratory species. Protection of such species is challenging because their movements may be uncertain and variable, span vast distances, cross international borders and traverse land and sea habitats. Often we are faced with small samples of information from various sources and the collection of additional data can be costly and time-consuming. Therefore it is important to evaluate what degree of spatial information provides sufficient results for directing management actions. Here we develop and evaluate an approach that incorporates habitat and movement information to advance the conservation of migratory species. We test our approach using information on threatened loggerhead sea turtles (*Caretta caretta*) in the Mediterranean.

Location The Mediterranean Sea.

Methods We use Marxan, a spatially explicit decision support tool, to select priority conservation areas. Four approaches with increasing amounts of information about the loggerhead sea turtle are compared, ranging from (1) the broad distribution, (2) multiple habitat types that represent foraging, nesting and inter-nesting habitats, (3) mark–recapture movement information to (4) telemetry-derived migration tracks.

Results We find that spatial priorities for sea turtle conservation are sensitive to the information used in the prioritization process. Setting conservation targets for migration tracks altered the location of conservation priorities, indicating that conservation plans designed without such data would miss important sea turtle habitat. We discover that even a small number of tracks make a significant contribution to a spatial conservation plan if those tracks are substantially different.

Main conclusions This study presents a novel approach to improving spatial prioritization for conserving migratory species. We propose that future telemetry studies tailor their efforts towards conservation prioritization needs, meaning that spatially dispersed samples rather than just large numbers should be obtained. This work highlights the valuable information that telemetry research contributes to the conservation of migratory species.

Keywords
***Caretta caretta*, connectivity, Marxan, Mediterranean Sea, migratory species, sea turtles, systematic conservation planning, value of information.**

DOI: 10.1111/geb.12434
http://wileyonlinelibrary.com/journal/geb

INTRODUCTION

The increase in anthropogenic activities over the last two centuries has disrupted the movement of many organisms (Bolger *et al.*, 2008; Harris *et al.*, 2009). Migration and movement are essential for the persistence of many terrestrial and marine animals. Such species rely on movement between specific habitats or regions for reproduction, feeding or thermal regulation (Alerstam *et al.*, 2003). The destruction of movement pathways, and threats to individuals that move (e.g. as bycatch), affect the fitness and survival success of migratory species (Beger *et al.*, 2015). The protection of mobile species presents a great challenge due to the vast distances that such animals often traverse, sometimes across international borders and in other cases between land and sea habitats (Martin *et al.*, 2007). Most conservation plans fail to incorporate the spatial connectivity that is needed to adequately protect migratory species (Martin *et al.*, 2007; Runge *et al.*, 2014).

Sea turtles are an example of an ecologically, economically and culturally important globally threatened migratory species group (IUCN, 2013). The thousands of kilometres these species travel between nesting and feeding habitats makes them highly vulnerable to an array of anthropogenic threats (Shillinger *et al.*, 2010; Mazaris *et al.*, 2014). These threats include disturbance to nesting beaches from coastal development and sea level rise (Fuentes *et al.*, 2011; Katselidis *et al.*, 2014), turtle egg harvesting (Koch *et al.*, 2006; Wallace *et al.*, 2011), incidental catch in fishing gear (Lewison *et al.*, 2004; Peckham *et al.*, 2007), collision with boats and the ingestion of plastic material (Casale & Margaritoulis, 2010). Marine turtles are particularly vulnerable because of their long life spans, late age of reproductive maturity (in loggerheads this can be 40–50 years; Casale, 2011; Scott *et al.*, 2012a; Avens & Snover, 2013) and different male versus female breeding patterns (Schofield *et al.*, 2013a). Given the need for protection and conservation of sea turtles, there is a lack of large-scale conservation plans that explicitly incorporate their complete habitat needs and migratory behaviours.

Previous efforts at sea turtle conservation have primarily focused on protecting nesting sites (Casale & Margaritoulis, 2010; Mazaris *et al.*, 2013). The central aim of these recovery efforts has been to protect female sea turtles and their nests, with little focus on males and the younger developmental stages (Schofield *et al.*, 2013b). However, while some sea turtle populations are recovering (Tapilatu *et al.*, 2013; Lamont *et al.*, 2014) others continue to decline (Stewart *et al.*, 2014; Weber *et al.*, 2014), suggesting that there are limitations to a conservation approach that focuses on only a subset of the life-history stages. Population models indicate that just conserving sea turtle nesting areas without considering other key habitats is insufficient for species recovery (Heppell *et al.*, 1996; Lazar *et al.*, 2004). Currently, there are limited management actions (e.g. turtle exclusion devices) to conserve sea turtles within marine waters, and only recently have conservation efforts been directed towards protecting offshore sea turtle populations and their migration corridors (Pendoley *et al.*, 2014; Seminoff *et al.*, 2014; Baudouin *et al.*, 2015). Successful conservation planning for sea turtles must explicitly protect all the life stages and link their terrestrial and marine habitat requirements (Beger *et al.*, 2015). One of the major impediments to minimizing mortality in the sea is that information on the offshore distribution and movements of sea turtles is limited (Casale *et al.*, 2007a).

Various methods have been trialled to understand the movement of sea turtles in offshore habitats. Since the 1950s, the most common method has been mark–recapture approaches, in which tags are affixed to sea turtles at nesting sites and their location of recapture is documented (Carr & Giovannoli, 1957; Hendrickson, 1958; Caldwell, 1962). Mark–recapture methods have contributed to our knowledge of the extent of sea turtle migration, links between release and capture sites (recaptures at sea; Casale *et al.*, 2007b), nesting populations and growth rates (recaptures at the same nesting beaches; Monk *et al.*, 2011). However, this method is unable to provide information about entire migratory paths and remains labour intensive (Stewart *et al.*, 2013), characterized by low recapture rates (Avens & Snover, 2013) and a slow accumulation of knowledge (Godley *et al.*, 2008). In recent decades, with the expansion of telemetry systems such as radio trackers, satellite transmitters and GPS loggers, tracking programmes have proliferated (Godley *et al.*, 2008; Hussey *et al.*, 2015). These technologies actively improve our understanding of sea turtle migration pathways at sea (Pendoley *et al.*, 2014; Stokes *et al.*, 2015). While there is an increasing emphasis on telemetry to improve our understanding of sea turtle distribution, physiology and behaviour (e.g. Hochscheid *et al.*, 2007; McCarthy *et al.*, 2010), there is comparatively less attention paid to how this knowledge can improve management and identify conservation areas. Recent tracking studies link adult foraging grounds to existing marine protected areas and identify new areas for protection (e.g. Scott *et al.*, 2012b; Schofield *et al.*, 2013a); however, analyses that link habitat and movement information into spatial conservation prioritization (Beger *et al.*, 2015) remain scarce.

Sea turtle tagging and telemetry programmes are rarely explicitly shaped by conservation planning objectives, and their execution is logistically difficult and expensive (the cost of satellite transmitters ranges from USD 2000–5000 each; Godley *et al.*, 2008; seaturtle.org, 2013). Furthermore, such information often remains in the literature on sea turtle behaviour and ecology without any attempt to use it for conservation (Godley *et al.*, 2008). Recent studies that have used telemetry to inform and improve conservation have been restricted to examining species movements (Stokes *et al.*, 2015) and building distribution models (Schofield *et al.*, 2013a). Currently there are few attempts to use sea turtle migration information to enhance systematic conservation planning (Beger *et al.*, 2015), and the sensitivity of conservation outcomes to the number and quality of tracks used has never been assessed. Furthermore, conservation plans are often being made for mobile species such as sea turtles without considering the potential contribution of migration information (Martin *et al.*, 2007; Runge *et al.*, 2014).

Here, we aim to develop and test approaches for incorporating information on habitat use and migration into conservation prioritization for migratory species. The Mediterranean Sea and

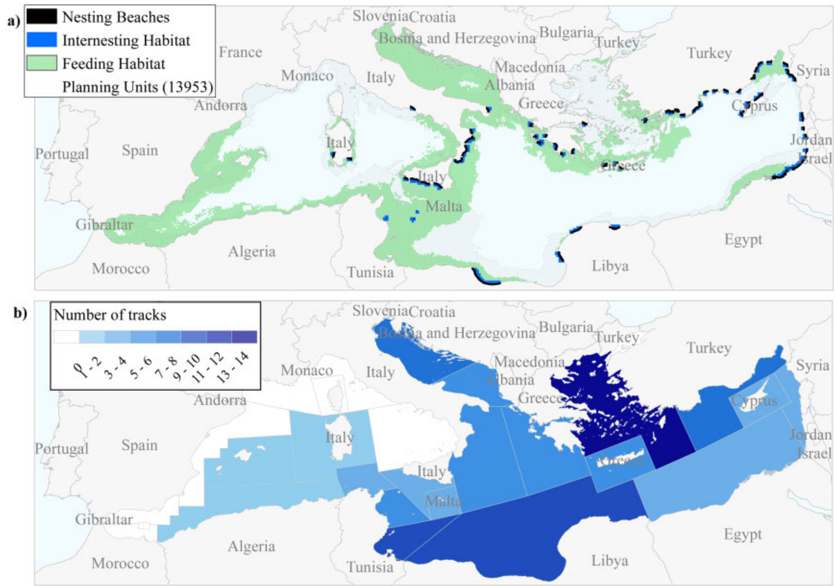

Figure 1 (a) Three types of loggerhead sea turtle (*Caretta caretta*) habitat: nesting habitat, inter-nesting habitat and foraging habitat. (b) Map of the Mediterranean Sea divided by geographical sub-areas as determined by the General Fisheries Commission of the Mediterranean Sea. The total number of sea turtles tracks that cross each sub-area was calculated and they are represented in this map. Individual tracks were unable to be displayed due to reasons of data confidentiality (see Appendix S2 for further information on data sources).

its endangered population of loggerhead sea turtles, *Caretta caretta* (Linnaeus, 1758) (IUCN, 2013), provide an excellent case study for tackling this issue. We assess the potential impact of data limitations on conservation prioritization outcomes by examining the value of different kinds of spatial information for identifying the location of areas that are a priority for sea turtle conservation.

METHODS

Study area and database

The study area was the entire Mediterranean Sea to a seafloor depth of 1000 m.[1] We divided the resulting shallow Mediterranean Sea including coastal land areas with nesting beaches into planning units of 10 km × 10 km, consistent with European Union (EU) guidelines (Directive 2007/2/EC) and other large-scale regional planning studies (e.g. Mazor *et al.*, 2014).

We assembled available sea turtle data (for data sources see Appendix 1) to create maps of three sea turtle habitat types: nesting, inter-nesting and foraging (Fig. 1a).

Nesting habitat

First, the locations of 131 loggerhead nesting beaches were collated from over 30 published resources (Table S1 in Supporting Information). We did not aim to predict potential additional (unreported) locations of beaches using species distribution modelling methods because female sea turtles display natal homing and the factors that affect their site selection within this homing range are not well known (Garcon *et al.*, 2009). Planning units along the beach within a 10-km radius of each known nesting site were designated as nesting beach habitat. We note here that we did not aim to differentiate between major and minor nesting sites, but rather map the majority of nesting sites (defined as sites averaging ≥ 20 nests per year, to capture smaller nesting beaches) to represent the distribution of sea turtles.

Inter-nesting habitat

We created inter-nesting habitat data using a 10-km buffer from nesting beaches (Tucker *et al.*, 1995; Waayers *et al.*, 2011). These neritic areas are important habitat for female sea turtles during the times between laying clutches (Schofield *et al.*, 2010) and for juvenile turtles making their way to the ocean post-hatching (Bolten, 2003).

Foraging habitat

Given that sea turtle foraging habitat is not yet fully mapped in the Mediterranean, we modelled foraging habitats using MaxEnt (v.3.3.3k, https://www.cs.princeton.edu/~schapire/maxent/; Phillips *et al.*, 2004, 2006; Appendix S1). This model is intended as a simplified baseline representation of foraging grounds in the Mediterranean Sea as it incorporates location data from both adult and juvenile sea turtles. The MaxEnt species distribution modelling software models occupancy across space using presence-only species data. We collated sea turtle sighting locations from EurOBIS (2014), several scientific papers and location and telemetry data contributed by seaturtle.org (2013; Table S2). Telemetry data points that were spatially aggregated and exhibited high sinuosity on the con-

[1]Areas below 1000 m were excluded because: (1) most important foraging habitats for sea turtles in the Mediterranean Sea are generally classified in shallow waters along the continental shelf; (2) anthropogenic threats are mainly concentrated along the coast; and (3) the General Fisheries Commission for the Mediterranean (GFCM) recommended the prohibition of towed dredges and trawl nets fisheries at depths beyond 1000 m (Recommendation GFCM/2005/1 on the 'Management of certain fisheries exploiting demersal and deep-water species') which has been adopted by the EU (Regulation 1967/2006).

tinental shelf (defined by the 200-m isobaths; Kallianiotis *et al.*, 2000; Sardà *et al.*, 2004) were included because such patterns indicate foraging (McCarthy *et al.*, 2010; Dodge *et al.*, 2014). Thus, transiting movements (and those off the continental shelf) were excluded, resulting in a total of 9058 data points (see Fig. S1). These point data were combined with 22 environmental variables (for a list of variables see Table S3). The resulting model was validated by a random subsampling method that was repeated 15 times and used 25% of the data (Phillips *et al.*, 2004, 2006). To create a distribution map of suitable foraging habitat we used the tenth percentile training presence logistic threshold (> 0.36). By using this threshold, we defined suitable habitat to include 90% of the data we used to develop the model. Our resulting map of foraging habitat was consistent with findings from localized studies that identified foraging grounds in the region (Broderick *et al.*, 2007; Casale *et al.*, 2013; Stokes *et al.*, 2015).

Migration information

For our analyses of loggerhead turtle migration movements we compiled available satellite tracking data from EurOBIS http://www.eurobis.org/ and seaturtle.org (http://seaturtle.org/; Table S4). A total of 34 individual tracks were collected from a variety of sources across the Mediterranean Sea and used in this study (Fig. 1b, individual tracks cannot be shown due to data protection considerations; Appendix S3). More tracking data should be obtained if this method is to be used to robustly assign priority conservation areas for the region's sea turtle population.

The value of sea turtle information for conservation

We examined the value of sea turtle information for conservation by exploring scenarios using Marxan, a commonly used decision-support tool, and its derivative algorithm, Marxan with Connectivity (Beger *et al.*, 2010a,b). For each scenario (approach) we developed a set of spatial plans that met our conservation targets and connectivity objectives for the lowest possible cost (Ball *et al.*, 2009). Below, we describe each planning approach highlighting the incorporation of additional data layers. To focus on the effects that different kinds of information have on spatial priorities, we kept the number of iterations (1000 runs) and the associated cost (equal cost per planning unit) consistent in all planning approaches.

The changes in spatial priorities signify the potential knowledge gained from investing in additional and more complex information. For new information to be useful for planning, it must improve our ability to make a decision or modify a plan (Maxwell *et al.*, 2015). In the context of this analysis, we want to explore what information helps us better identify conservation priority sites that protect the entire turtle life cycle. First, we prioritize using the extant distribution range of sea turtles (Approach 1 – Range), then by multiple habitat types (nesting, inter-nesting and foraging) (Approach 2 – Habitats), followed by movement information extracted from mark–recapture data (Approach 3 – Mark–recapture) and finally the incorporation of satellite tracking data (Approach 4 – Tracks). Within Approach 4, we tested the influence of the number of tracks used on the resulting conservation priorities. Our conservation objectives to protect a given percentage of the sea turtle spatial distribution (targets) varied according to approach (Table 1, Appendix S2).

We parameterized Marxan both without representing any connections between planning units (Approach 1 – Range and Approach 2 – Habitats; Ball *et al.*, 2009; Table 1) and by incorporating ecological connectivity into the objective function (Approach 3 – Mark–recapture and Approach 4 – Tracks; Beger *et al.*, 2010a,b; Table 1). When including connectivity, we calibrated the connectivity strength modifier (for methods see Beger *et al.*, 2010b) to 50 (Fig. S2).

Approach 1 – Range

In this approach we represented the overall distribution of loggerhead sea turtles by a single broad distribution map in the

Table 1 Summary of the planning approaches, including increasing amounts of data and information on the distribution and movement of sea turtles. Each plan aims to derive conservation priorities for loggerhead sea turtles (*Caretta caretta*) in the Mediterranean Sea, and uses the systematic conservation decision tool Marxan.

Approach for sea turtle conservation planning	Targets	How connectivity was incorporated
1. Range	The distribution of sea turtles as a whole (not per habitat type) overall. Target = 20%	Not at all
2. Habitats	Nesting = 60% Inter-nesting habitat = 40% Foraging habitat = 20%	Targets for habitats used in different life stages
3. Mark–recapture	Nesting = 60% Inter-nesting habitat = 40% Foraging habitat = 20%	Connections between the priority habitats
4. Tracks	Nesting = 60% Inter-nesting habitat = 40% Foraging habitat = 20%	Connections between each track is prioritized

Mediterranean Sea, combining nesting, inter-nesting and foraging habitat data into one single distribution range (the target was 20% of the species distribution) This is a basic approach that is commonly used in conservation planning given the normal paucity of fine-scale spatial habitat data (e.g. IUCN distribution ranges).

Approach 2 – Habitats

For this approach we set specific conservation targets for nesting (target 60%), inter-nesting (target 40%) and foraging habitat (target 20%), simulating a situation where the three main habitats used by turtles are known. Dividing the broad distribution range into specific habitats with set targets ensures that priority conservation areas will be selected for each habitat type.

Approach 3 – Mark–recapture

Mark–recapture studies define at least two points on a turtle's travel, its starting point (tagging location) and end point (recapture location). To represent this type of information in conservation planning, we targeted the three habitats used by turtles while also ensuring connectivity between nesting and foraging sites. Here, we simulated mark–recapture data using tracking routes (34 tracks) to select planning units associated with nesting beaches and foraging habitat. For this purpose we considered foraging and nesting habitat to be planning units where tracks demonstrated sinuosity (obvious foraging behaviour; McCarthy *et al*., 2010) and overlapped with our modelled foraging grounds and our mapped nesting beaches (Fig. 1a). Tracks that did not move across more than 50 planning units were discarded from the analysis based on typical distances that Mediterranean loggerhead sea turtles move between nesting and foraging grounds (Zbinden *et al*., 2008; Schofield *et al*., 2013a). This analysis enabled us to allocate connectivity links between the identified foraging and nesting planning units at either end of the track, assuming non-directional connectivity in Marxan and ignoring the remaining tracked pathways (Beger *et al*., 2010b).

Approach 4 – Tracks

To capture information about the pathways that turtles take to cross vast distances and incorporate links between habitats along the entire journey, we applied a method that incorporates telemetry-derived movement information into Marxan with Connectivity (Beger *et al*., 2015). This approach allows for connectivity strength values to be assigned between and across sites by deriving a connectivity matrix that connects all planning units along each satellite track (Fig. 2). By symmetrically linking all planning units along an individual turtle's pathway, this method allows for spatial dependences to exist between places that are not adjacent to each other (Beger *et al*., 2010b). Planning units that are travelled through by more than one individual turtle are deemed increasingly important for migration and contribute more to the connectivity of the solutions. Applying this method, we targeted the three habitats (i.e. nesting, inter-nesting, foraging) used by turtles and the connectivity information provided from our 34 telemetry tracks (see the section 'Migration information').

Comparing planning approaches

We compared the four approaches by calculating the Spearman rank correlation between the selection frequency outputs from Marxan and mapping the resulting spatial conservation priorities. Selection frequency is the number of times that a planning unit is selected as part of a near-optimal solution in Marxan. This frequency can be seen as a measure of relative importance, where units that are selected a high percentage of times could be considered more valuable than those appearing less frequently in solutions.

We then tested how the number of telemetry tracks altered the resulting conservation plan. To investigate the value of new spatial information for identifying conservation priorities we randomly selected an increasing number of tracks from the pool of known tracks: 0 (no tracks), 5, 10, 15, 20, 25, 30, 34 (maximum). The Marxan analysis was repeated 10 times for each group of tracks to account for variability in the selected tracks. From these solutions we calculated the Spearman rank

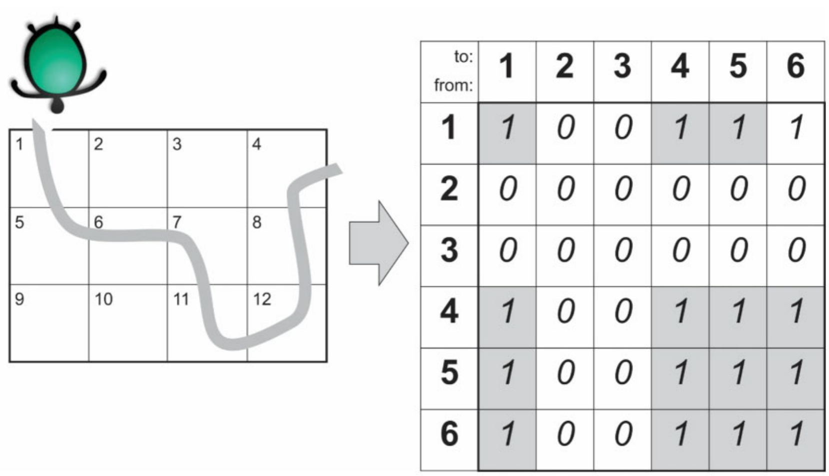

Figure 2 Assignment of connectivity values derived from sea turtle telemetry paths. The squares correspond to planning units of this study (10 km × 10 km; consistent with EU guidelines (Directive 2007/2/EC) and other large-scale regional planning studies (Levin *et al*., 2013; Mazor *et al*., 2014) and result in a connectivity matrix.

correlation of the selection frequency outputs and compared it with that of a solution that includes all 34 tracks. To further examine the increased inclusion of telemetry tracks, we used a Bray–Curtis dissimilarity matrix method as described in Linke *et al.* (2012) and displayed our results in a dendrogram. This method compared the Marxan best solution outputs (the solution with the lowest objective function score) when run with different numbers of tracks.

RESULTS

Conservation priorities that were evident in Approach 4 (Tracks) were not well represented in the other three approaches. For example, Approach 3 (Mark–recapture), which had the highest Spearman rank correlation coefficient of the three approaches when compared with a plan that incorporates tracking data (Approach 4 – Tracks), indicated that the spatial priority areas from the plans do not significantly overlap (rho = 0.08). Thus, results show that links between habitats are not protected by chance when protecting sea turtle habitat but need to be separately represented.

We found that conservation priorities substantially changed as we added different aspects of information on turtles (Figs 3a & 4). Despite the weak correlations, approaches that incorporated more habitat and movement information (e.g. Approach 2 – Habitats, rho = –0.12; Approach 3 – Mark–recapture, rho = –0.23) than a broad species distribution range (Approach 1 – Range, rho = –0.08), were more successful at capturing migration pathways (compared with Approach 4 – Tracks) in the resulting spatial plans. The inclusion of movement data can also increase the cost of conservation plans as movement corridors may mean that more area or costly planning units are needed to reach conservation targets (see Table S5).

We found that when sample sizes are low, which is often the case when tracking sea turtles and other large marine animals, even a small number of tracks (about five) can substantially increase the correlation (rho = 0.6) with plans that include all 34 tracks (Fig. 3b). We discovered that the largest Bray–Curtis dissimilarity was between conservation plans that did include sea turtle tracks and those that did not (see Group A versus Group C in Fig. 5). The second largest dissimilarity was between plans that had a small number of tracks (Group B and Group D in Fig. 5) and a corresponding low Spearman rank correlation (rho < *c.* 0.7, Table S6) when compared with solutions that included 20 or more tracks and resulted in a higher Spearman rank correlation (rho > *c.* 0.7; Group C in Fig. 5). This dissimilarity was due to the small number of tracks (5–15) included in the plans and because the spatial variability captured was insufficient for the entire region. Given these results it seems that plans with more than 20 tracks were needed to capture the spatial heterogeneity of turtle movement across the Mediterranean Sea from our given sample size (34 tracks). Thus, plans with more than 20 tracks did not vary considerably from those with 34 tracks.

DISCUSSION

We demonstrated that migratory pathways provide critical information for identifying habitats for inclusion in spatial

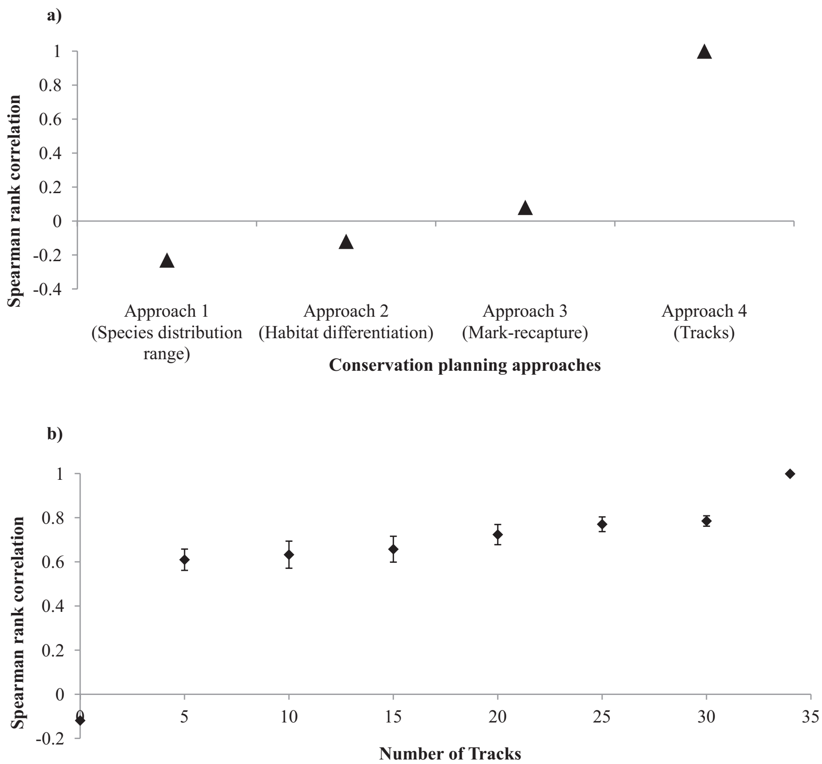

Figure 3 (a) Spearman rank correlation of selection frequency outputs, comparing four conservation plans with increasing complexity of sea turtle movement and habitat data: Approach 1 – single species distribution range; Approach 2 – habitat differentiation (nesting, inter-nesting, foraging); Approach 3 – three habitat types and movement information from mark–recapture data; and Approach 4 – three habitat types and movement information from 34 sea turtle tracks. (b) Graph of the average Spearman rank correlation of selection frequency outputs, comparing scenarios with a subset of tracks versus scenarios with all 34 tracks. The standard deviation is shown for each scenario (calculated from 10 repeated Marxan runs). This analysis used an equal cost for each planning unit.

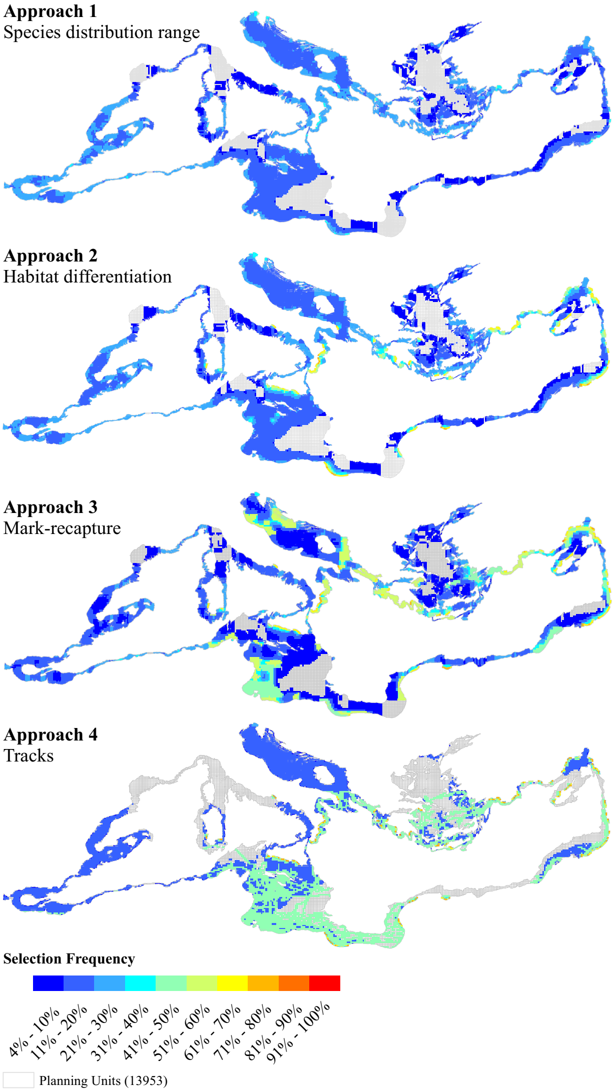

Figure 4 Maps of four conservation plans in the Mediterranean Sea with increasing complexity of sea turtle movement data: Approach 1 – Range; Approach 2 – Habitats (nesting, inter-nesting, foraging); Approach 3 – Mark–recapture; and Approach 4 – Tracks (34 telemetry tracks). Priority areas are those planning units that have a high percentage of selection (selection frequency).

planning. We discovered that the inclusion of satellite tracking data makes a substantial difference to spatial priorities. Moreover, prioritization without the use of such tracks is suboptimal for wide-ranging species that move between multiple habitats.

This study highlights the value of incorporating critical habitat and migration information for conservation planning of migratory species. Our example system of loggerhead sea turtles in the Mediterranean Sea showed significant changes in spatial priorities when increasing the amount of sea turtle information (cf. the four approaches; Figs 3 & 4). Sea turtle migration was best captured by incorporating the entire movement track rather than critical habitat information (Approach 2 – Habitats), species range (Approach 1 – Range), or mark–recapture data (starting and end points of movements; Approach 3 – Mark–recapture; Figs 3 & 4). We managed to collate data from 34 sea turtle tracks in this study and discovered that even a small number of very different tracks (e.g. five) can substantially alter conservation priority sites and help capture the known spatial extent of the migratory life cycle of sea turtles (Figs 3b & 5). As new methods emerge, we suggest that future conservation plans for sea turtles and other migratory species should where possible attempt to incorporate available habitat and telemetry data.

Our results suggest that in order to capture sea turtle habitat connectivity in conservation plans, a good number of heterogeneous tracks across the study area are needed (Fig. 5). Our case study example in the Mediterranean, with a limited sample size (34 tracks; Fig. S3), found that more than 20 sea turtle tracks widely sampled across the study region were able to capture sea turtle movement. While we stress that more data are always better and higher sample sizes are preferable, such information is not always readily available and conservation decisions are often made with scarce data (Bottrill *et al.*, 2008). This study suggests that limited data that are well dispersed across the study region can actually contribute valuable information to begin conservation planning. Given our findings that more heterogeneously placed tracks provide the best value information, future data collection efforts could be made more useful for conservation by taking a complementary sampling approach and targeting regions that currently have fewer or no tracking studies (e.g. the eastern Mediterranean; Fig. 1b; Stokes *et al.*, 2015).

Telemetry studies provide a wealth of connectivity information that is not often applied to conservation planning. We found that a limited but heterogeneous assemblage of tracks makes a substantial contribution to improving a spatial conservation plan and better representing turtles' life cycles. This result could perhaps provide better direction for the timely and costly collection of telemetry data. We recommend that currently available telemetry data be extracted where possible, perhaps using monetary incentives or intellectual safeguards, and compiled into databases for the incorporation of species migration information into conservation plans. Established collaborative frameworks such as the EU or the IUCN could be potential starting points. Future work should aim to carry out value-of-information analyses (e.g. Maxwell *et al.*, 2015; Canessa *et al.*, 2015) in order to assess the trade-off between investing in the collection of more tracking data and gaining new information for improved conservation outcomes. This type of analysis can help inform cost-effective conservation decisions.

Another challenge in addressing species movements is determining how much connectivity information is needed. Relying on too few tracks means there is also a risk of over-fitting to a limited number of data tracks. In an attempt to overcome these challenges, this study used a calibration method in which planning units that contained a track were selected over 50% of the time (Fig. S2). The method ensures that connectivity is represented, but it does not necessarily mean that 50% of all migration links are captured in the solution. Determining the level of connectivity that is needed will largely depend on the species of

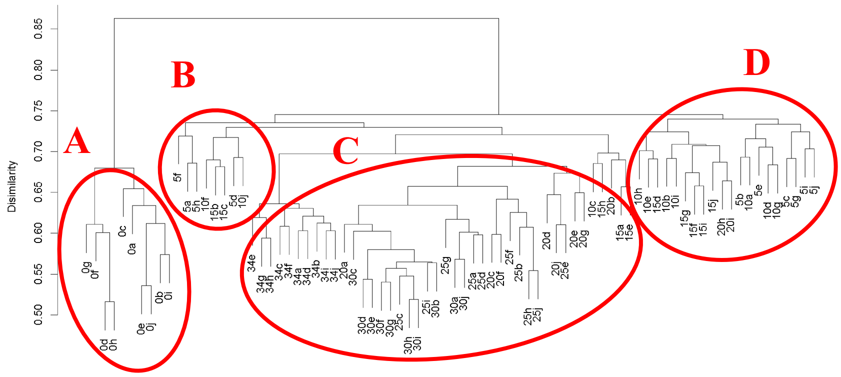

Figure 5 Dendrogram comparing the dissimilarity of solutions (Bray–Curtis dissimilarity matrix method; Linke *et al.*, 2012) with increasing numbers of tracks. Each node on the dendrogram represents the number of tracks (0, 5, 10, 15, 20, 25, 30, and 34 tracks) used in the analysis and the repetition letter (each number of tracks was run 10 times each, represented by letters a–j). These letters and numbers link to Table S6. Four groups were identified as denoted by outlines and letters A, B, C, D. The main split between solutions is between analyses without tracks and those that include tracks (Groups A and B).

interest as well as the conservation budget and conservation objectives. For example, connectivity is especially important for sea turtles, which exhibit high mortality rates within movement pathways (Lewison *et al.*, 2004; Casale, 2011). However, connectivity may not be particularly useful for species that are less threatened during the movement/migration phase or those that have large dispersal patterns without clear migration trajectories. Importantly, the area and cost of a conservation plan are likely to increase as the importance of connectivity is increased (Table S5). Hence, we suggest that the level of connectivity required could be pre-determined and a measure of minimum connectivity should be set per species.

This study demonstrates and tests a method for prioritizing the conservation of migratory species. However, such an approach could be built upon to provide priority areas for sea turtle conservation in the region. A suitable conservation plan should aim to incorporate all available telemetry studies (e.g. the 195 tracks identified by Luschi & Casale, 2014), comparable and consistent data for sea turtle habitat across the Mediterranean region and robust species distribution modelling, as well as the associated cost of conservation actions (Carwardine *et al.*, 2008). This study has touched on several of these requirements; however, comprehensive data pooling from organizations and the scientific literature is required if priorities for the region are to be robustly and transparently determined. Our method here explored connectivity between nesting and foraging grounds; however, other connectivity should be included, such as links between breeding sites, wintering habitats and developmental grounds (Casale *et al.*, 2013; Schofield *et al.*, 2013a). Similarly, migration tracks should be evaluated by different age classes and sexes and weighted by direction of usage and the number of individuals represented as a proportion of the entire region.

In summary, this study highlights the value of habitat and movement information to advance the conservation of migratory species. Our findings on loggerhead sea turtles in the Mediterranean Sea are expected to provide one example of a broader application for the protection of migratory species. We recommend future research aims to incorporate and evaluate the value of telemetry information into conservation plans for migratory species (Runge *et al.*, 2014), especially those that are threatened, to ensure that mortality is reduced across their whole life cycle. Determining the value of investing in the collection of more spatial data for species or extracting information from existing resources can help inform spatial planning more immediately. When there is only a short widow of time to act for threatened species it is critical that decision makers invest and act in those areas that will be most effective at ensuring species persistence (Bottrill *et al.*, 2008).

ACKNOWLEDGEMENTS

This research was conducted with the support of funding from the Australian Research Council Centre of Excellence for Environmental Decisions. T.M. was funded by an Australian Postgraduate Award. S.K. is an ARC Future Fellow. We thank S. Hochscheid for providing data from the Satellite Tracking Project Stazione Zoologica Anton Dohrn (SZN) and RAC/SPA (seaturtle.org) as well as project partners; C. Knot for data from SWOT (http://www.seaturtlestatus.org/) projects; and to L. Boura from MEDASSET http://www.medasset.org/ for providing data and UNEP/MAP information.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Figure S1 Map of 9058 data points used to construct the foraging habitat model as described in Appendix S1.

Figure S2 Graphs showing the trade-off curve of the connectivity strength modifier with the number of connected planning units (those containing a sea turtle track).

Figure S3 Graphs showing the length of each of the 34 tracks used in this study.

Table S1 Nesting habitat.

Table S2 Foraging habitat.

Table S3 Environmental variables.

Table S4 Migration information.

Table S5 The opportunity cost of each scenario (cost is assumed equal for each planning unit).

Table S6 Spearman rank correlation coefficient when running conservation plans in Marxan with different numbers of sea turtle tracks (0, 5, 10, 15, 20, 25, 30, 34).

Appendix S1 Sea turtle foraging distribution model created using MaxEnt.

Appendix S2 Setting conservation targets.

Appendix S3 Information for each sea turtle track.

BIOSKETCH

Tessa Mazor is a research fellow at The Commonwealth Scientific and Industrial Research Organisation (CSIRO). This work was carried out during her PhD at the University of Queensland and the Centre of Excellence for Environmental Decisions (CEED, http://ceed.edu.au/). Her research interests include conservation planning for threatened marine species, the application of systematic planning tools in the marine realm and the development of sustainable management practises for marine ecosystems.

Author contributions: all authors conceived the ideas and contributed to the writing; T.M. conducted the analysis and led the writing.

APPENDIX 1 DATA SOURCES

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