Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia

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Abstract

As human population growth continues, so too does our waste, often with unintended consequences for wildlife. The estimated 640,000 tons of fishing gear lost, abandoned, or discarded annually exerts a large but uncertain impact on marine species. These "ghostnets" drift in the ocean and can fish unattended for decades (ghost fishing), killing huge numbers of commercially valuable or threatened species. We developed an integrated analysis combining physical models of oceanic drift with ecological data on marine turtle species distribution and vulnerability to make quantitative predictions of threat. Using data from beach cleanups and fisheries in northern Australia, we assessed this biodiversity threat in an area where high densities of ghostnets encounter globally threatened turtles. Entanglement risk is well-predicted by our model, as verified by independent strandings data. We identified a number of previously unknown high-risk areas. We are also able to recommend efficient locations for surveillance and interception of abandoned fishing gear. Our work points the way forward for understanding the global threat from marine debris and making predictions that can guide regulation, enforcement, and conservation action.

Introduction

Human activities impact nearly all ecosystems (Glover & Smith 2003; Halpern *et al.* 2007, 2008), with the exponentially increasing flood of human debris and rubbish being one of the major threats to marine ecosystems (Ryan & Moloney 1993; Derraik 2002; Thompson *et al.* 2004). Annually, an estimated 640,000 tons of fishing gear is lost, abandoned, or discarded (Macfayden *et al.* 2009) exerting a large but uncertain impact on marine wildlife. This waste can "ghost fish" unattended for years or even decades, killing huge numbers of commercially valuable or threatened species (Laist 1987, 1997) resulting in loss of food resources and decreased biodiversity. Although we know there are tremendous quantities of rubbish in our oceans (Thompson *et al.* 2004), far less is known about where the debris occurs, what species it interacts with and what the direct impacts are of those interactions (Derraik 2002; Mrosovsky *et al.* 2009).

Much available information on marine debris comes from coastal cleanups. Data on the distribution of debris at sea are scarce, largely due to the expense of collecting these data, which requires use of aircraft or vessels (e.g., Thompson *et al.* 2004; Barnes & Milner 2005; Pichel *et al.* 2007). Progress has been made in predicting the distribution of marine debris at sea (Maximenko *et al.* 2012), although predictions have only recently incorporated any aspects of debris sources as driving variables (Lebreton *et al.* 2012). Critically, to date none of these efforts at modeling the distribution and fate of debris has taken the next step and analyzed the ecological effects of the debris.

Our work extends existing analyses beyond a description of where debris occurs, to estimating its impact on biodiversity. We accomplish this by adding two fundamental innovations to existing analyses of marine debris. First, we use empirical data from coastal surveys as a driving variable in a model of oceanic drift to estimate the density of marine debris across a large geographic region.

Previously, debris density has been estimated based on equilibrium assumptions without empirical data on debris sources (e.g., Maximenko *et al.* 2012), meaning that density estimates are only equilibrium estimates and are not useful for estimating ecological impact of debris. Second, we use a risk analysis approach to model impacts of debris on species affected by ghostnets. We identify species impacted using coastal survey data, and then model the encounter rate for these species using the spatial overlap in the predicted density of debris and the vulnerable species.

We focus on ghostnets for three reasons. First, ghostnets are expected to exert a disproportionate impact on marine species. Composing only 20% of marine debris, the 640,000 tons of fishing gear lost annually by commercial fisheries (Derraik 2002) is designed to capture wildlife—often killing unintended species. For example, up to 40,000 fur seals were killed each year by unintentional entanglement which resulted in an annual population decline estimated at 4–6% (Weisskopf 1988; Derraik 2002). Second, ghostnets are a global problem. They are even found on remote islands such as Midway Atoll, thousands of kilometers from commercial ports or local net-based fishing operations (Hardesty 1998, personal observation). Therefore, developing tools to understand their impacts and to suggest potential solutions has broad applications. Third, ghostnets are a particular issue along the northern coast of Australia, with concentrations of derelict nets washing onshore in the Gulf of Carpentaria (GOC) of up to 3 tons/km in some areas, as high as or higher than any other area in Oceana and southeast Asia (Kiessling 2002). Derelict gear in this region has been observed to entangle invertebrates, teleost fish, sharks, turtles, crocodiles, and dugongs (Gunn *et al.* 2010). Addressing this issue requires understanding the sources of these nets. To date, it has been possible to identify the country of manufacture or flag state of the vessels for ca. 55% of the nets, which include trawl, gillnet, and longline gear originating from fisheries in Taiwan, Indonesia, Korea, Australia, Japan, and Thailand (Gunn *et al.* 2010). However, it is unclear where this fishing gear was lost due to the high volume of illegal and unreported fishing in the region.

Our integrated analysis successfully utilizes disparate data types in a novel way: we combine physical models of oceanic drift and beach cleanup data to estimate the distribution of ghostnet fishing in the Gulf. We combine these estimates with ecological data on species distribution and vulnerability to make quantitative predictions of threat. Finally, we test our predictions of threat using independent data on entanglements, to ensure that our model accurately captures the system dynamics. Our analysis integrates existing information and tools in a novel manner, pointing a way forward in understanding the global marine debris threat by making predictions that can guide regulation, enforcement, and conservation action.

Methods

The 5,491 ghostnets used in our analyses were collected from beaches around the GOC as part of a large-scale coastal cleanup (2005–2009). Each cleanup site was exhaustively searched and nets were removed or destroyed onsite. Based on comparison with net observations from a systematic aerial survey, the cleanup data were representative of the spatial distribution of nets in the GOC region. For each net in the cleanup data, net size and any animals caught were recorded. Because >80% of animals recorded in nets were marine turtles, we concentrated on evaluating the expected interactions between nets and turtles. Turtles identified in nets and used in analyses included 53 Olive Ridley, 35 Hawksbill, 14 Green, and 3 Flatback turtles.

We created potential paths of drifting nets by simulating nets lost at sea in the region and following their tracks over time. Because the actual sources of the nets are unknown, simulated drifting nets were released on a regular grid spanning 115–152°E and 16–10°S on a daily basis (1996–2007). Each release was at a random location within a 4° × 4° grid cell. Simulated nets were tracked for 2 years, or until they drifted outside 110–156° longitude or 8–20° latitude (Figure 1A). Paths were estimated using a Runge–Kutta fourth order integration of daily velocity estimates based on velocity fields generated by the Bluelink Ocean Data Assimilation System for the relevant period for each net (Oke *et al.* 2008).

We recorded the track of any drifting net that came within 25 km of an observed net from beach cleanup data. We used this proximity approach because available oceanographic models are unlikely to be accurate enough near shore to use exact point locations of nets (Wolanski & Ridd 1990; Burford *et al.* 2009). We determined whether we had an adequate sample of simulated drifting nets by examining the change in the distribution predicted for nets from a site as nets were added to the data set of potential net tracks. When the number of new grid cells did not increase as additional potential tracks were added, we assumed all likely pathways for nets to arrive at a site had been sampled and were included in the data set. We evaluated the sample size of our simulated nets applied to four locations around the GOC, including sites with high and low net densities. We used 48,148 tracks in total: with this number the spatial distribution of nets from our four evaluation sites had stabilized.

Data are sparse for at-sea distribution of marine turtles in the GOC. Although most nesting sites are known
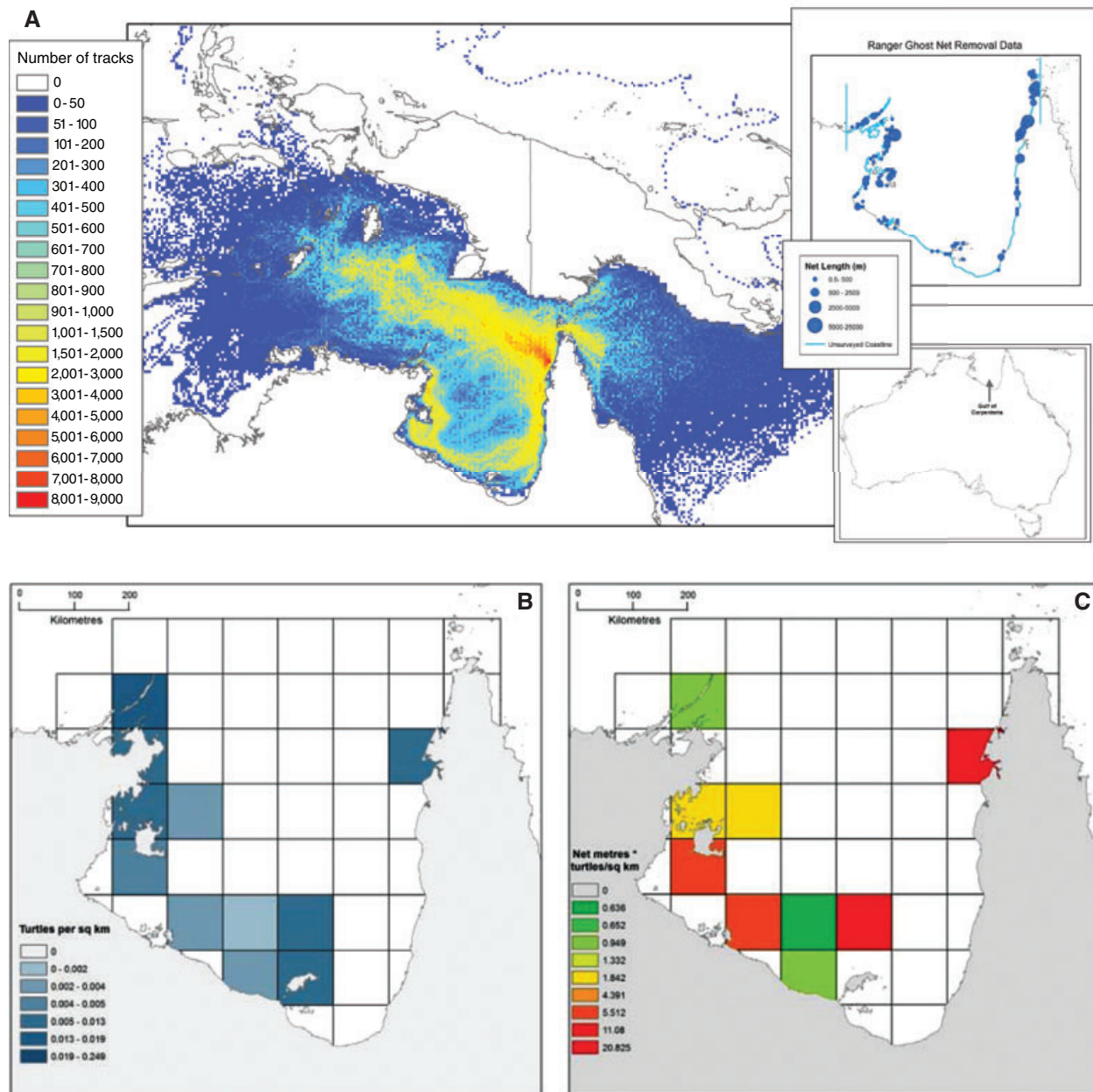
Figure 1 Components of a risk model for ghostnet impacts to turtles. (A) Potential ghostnet tracks based on daily particles releases (1996–2008) and (inset) total length of net found at sites along the GOC coastline. (B) Estimated at-sea distribution of marine turtles in the GOC based on catch per unit of effort by research and commercial trawl vessels. (C) Predicted threat to turtles from ghostnets in the GOC. Threat is based on the proba- bility of encounter, where encounter is predicted as the product of relative turtle density (measured as turtles caught per unit of trawl effort) and ghost fishing effort (expected value of the number of meters of abandoned fish- ing net passing through each cell). Final units are expected relative rate of turtle-net encounters.

and there are data on the number of individuals nesting at each location (see http://www.environment.gov.au/ coasts/species/turtles/), the distribution of nesting sites is not representative of the at-sea distribution of tur- tles. The best information on turtle densities at-sea in the GOC are bycatch records from trawl data taken as part of the prawn trawl fishery operating in the region. We used these data to estimate the spatial distribution of ma- rine turtles, calculating the relative density in 51 5° lati- tude × 5° longitude cells covering the region. The data set

contained 178,056 trawl records (1990–2009) with start location, net size, trawl duration, and number of turtles caught. Turtles caught included 105 Flatback, 52 Olive Ridley, 12 Loggerhead, 10 Green, 6 Hawksbill, and 66 unidentified turtles. We aggregated species and ignored time of year when estimating the spatial distribution of turtles, as there were no significant differences based on the data. The area swept (km^2) was calculated based on net size and trawl duration as a measure of sampling effort. Relative densities were based on the catch of turtles per unit of fishing effort calculated by number of turtles caught/area swept.

We validated the risk model by comparing model predictions to observations collected by ranger groups of the turtles in nets that washed up on beaches. We did this using the following logic: to be observed once caught in a high-risk area, a turtle had to remain in the net until it reached a location near the coast, and once in that area it had to wash onshore.

We identified a buffer along the coastline extending 25 km seaward from the coast dividing this buffer into 1 km × 1 km cells (Figures 2A and B). We then assembled all drift trajectories that left any of the 5° cells identified as having both high turtle density and high ghostnet fishing effort and subsequently crossed the boundary of the 25 km coastal buffer. For each track, we identified each contiguous period during which it was in one of the 1 km × 1 km cells in the coastal buffer. We used this sample of tracks to estimate the relative frequency of turtles washing up entangled in nets along the GOC coast.

Considering a single drifting track and event j as the continuous presence of a net (i.e., the drifting net) in a single cell in the coastal buffer for some period of time, pr$\{T_j\}$, the probability of the net washing onshore with a turtle in it as the net passes through the coastal cell is

$$\text{pr}\{T_j\} = 1 - \prod_{t_j = t'_j}^{t_j = t''_j} (1 - ((1 - \text{pr}\{loss\})^{t'_j - 1}$$

$$\times (1 - \text{pr}\{loss\})^{t_j - t'_j} \text{pr}\{strand\})), \qquad (1)$$

where t'_j is the first time (i.e., day) in event j, t''_j is the last time for event j, i.e., the final time the track is in the cell during event j. Here, pr$\{loss\}$ is the chance that a turtle caught in a net is lost from that net in a day, and pr$\{strand\}$ is the chance a net within 25 km of the coast washes onshore in a given day. We also account for pr$\{F_j\}$, the probability that the net did not wash ashore from a different coastal cell, prior to the time the drifting track entered the cell of interest. This is

$$\text{pr}\{F_j\} = \prod_{t=1}^{t = t'_j} ((1 - \text{Pr}\{strand\})^{\Theta(t)}),$$

where $\Theta(t)$ is an indicator function, taking the value of 1 if the net is in any coastal cell on day t and 0 if it is not. We combine the two equations above to get pr$\{O_j\}$, the probability of observing a turtle during event j as

$$\text{pr}\{O_j\} = \left(1 - \prod_{t_j = t'_j}^{t_j = t''_j} (1 - ((1 - \text{pr}\{loss\})^{t'_j - 1} (1 - \text{pr}\{loss\})^{t_j}\right.$$

$$\left. \times \text{pr}\{strand\}))\right) \prod_{t=1}^{t = t'_j} ((1 - \text{Pr}\{strand\})^{\Theta(t)}). \qquad (2)$$

To calculate the expected number of turtles stranding in nets from each cell, we search for any event j for each cell in the coastal buffer from our data set of tracks that entered the buffer. We sum (2) for each of those events for a given cell, yielding the expected number of turtles stranding in nets from that cell in the coastal buffer. We assume that strandings from a cell in the buffer occur at the nearest point on the coastline to that cell. Summing all coastal cells we then get the relative density of nets strandings with turtles. This is a relative density, as the daily probabilities of loss from net or stranding are unknown. However, based on a sensitivity analysis with pr$\{loss\}$ and pr$\{strand\}$ taking a range of values between 0.01 and 0.2, these probabilities rescale the predicted relative density of strandings, but do not affect the spatial pattern across sites.

Results

We took a risk-based approach to understanding the biodiversity impacts of ghostnets, focusing on estimating the rate and spatial distribution of encounters with turtles. Accordingly, we estimated likely tracks of ghostnets using an ocean current model, given final locations of actual nets observed onshore in the GOC (Figure 1A). Net tracks are concentrated along the shore of the GOC and northwest into the Arafura Sea (Figure 1A). Accounting for net size (Figure 1A, inset), we find that these are areas of concentrated fishing effort by ghostnets. Taking into account the distribution of turtles in the GOC (Figure 1B), we find that entanglement risk is concentrated in one area along the eastern margin of the GOC, and in a wide section in the southwest extending up the west coast (Figure 1C).

There is good concordance between the distribution of turtles predicted to strand on beaches based on our model and the actual frequencies of turtles found in ghostnets, with all observations falling in areas that are predicted to be likely to have entangled animals, and vice versa (Figures 2A and B). Removing one outlying observation of 81 turtles in the northeast section of the GOC with an artificially high number of turtles due to more intensive
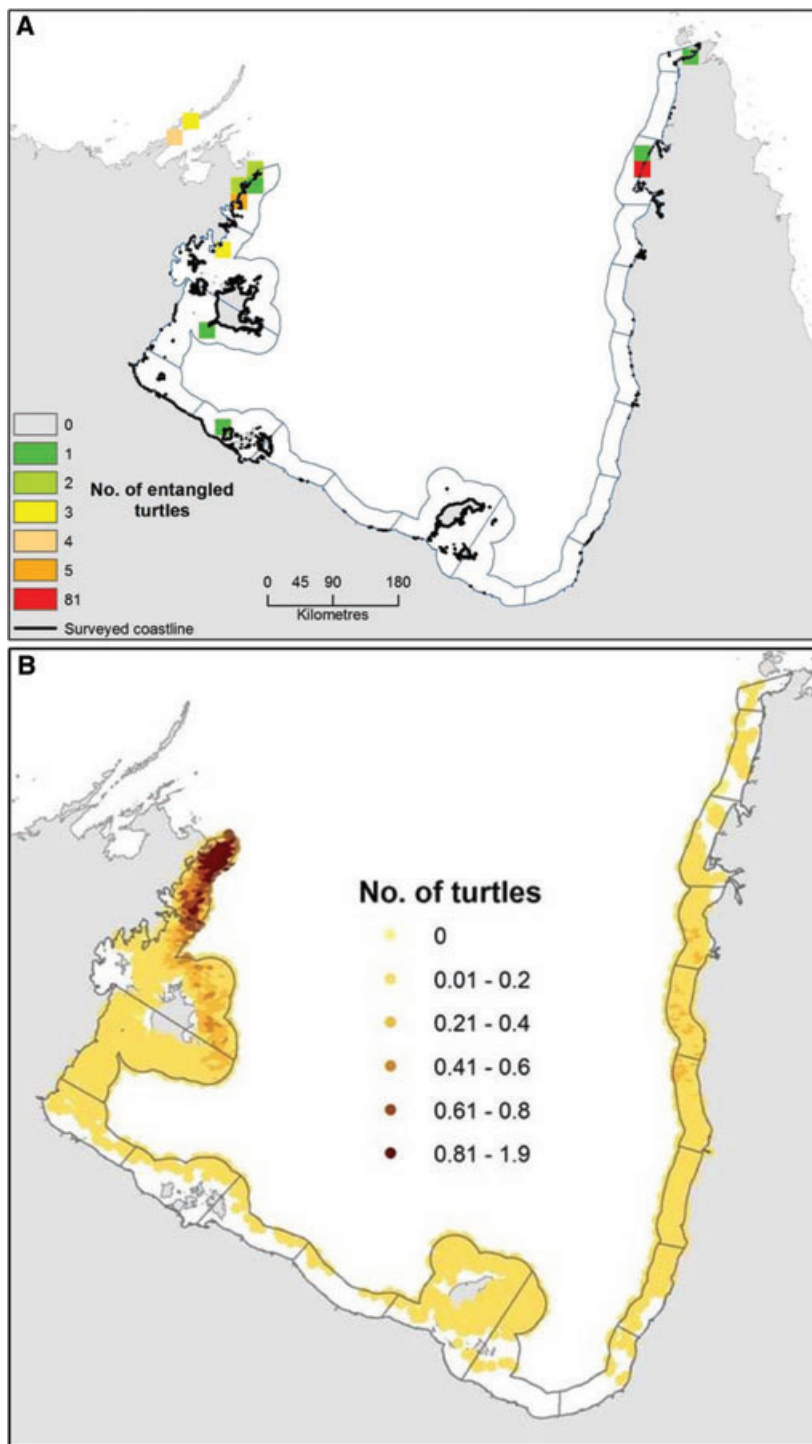
Figure 2 Validation of the risk model. Predictions were aggregated into 100-km sections along the coastline for analysis, shown by polygons. (A) Distribution of turtles entangled in ghostnets removed from beaches by ranger teams. Black outlines along the coast show areas searched, blue delineates areas that were not searched. (B) Distribution of the predicted number of turtles stranding on beaches based on the risk model.

sampling at that site, a linear regression of observed density of strandings on predicted density, weighted by proportion of the coastline searched, was highly significant ($R^2 = 0.88$, $P = 1.84$e-08), giving further confidence in the appropriateness of the model.

Discussion

We focused on risk to marine turtles because they comprise >80% of the observed animals entangled, entanglement is among the most common known sources of their

Figure 3 An example of the drifting pattern of a tracked net (with geolocator) in the GOC. The net (green dots show track locations) validates our model, showing the pattern we predicted and highlighting the lack of ghostnets arriving in the southern Gulf.

mortality in Australia and the primary one reported in the Gulf region, and Australia has 6 of the 7 threatened marine turtle species, including large portions of the remaining global populations for several species (Limpus & Fien 2009; Biddle & Limpus 2011). Mapping predicted encounters, we found that risk is high not only where entangled turtles have been observed, but also in the southwestern GOC in an area that was not identified from the strandings data: a prediction that could not be made in the absence of our integrated analysis. Furthermore, testing our approach in a geographic region where there are good data are critical for assessing its utility in other regions.

The match between our model predictions and observed entanglements was very close ($R^2 = 0.88$), indicating that net entanglement occurs in areas with high ghostnet density and high turtle density, and that we have accurately represented these distributions. This suggests that encounters can be used as a reasonable measure of risk (Figure 1C) and provides an excellent example of the utility of applying this approach to other marine and coastal systems. A map of an actual net tracked in the GOC provides illustration of our model as it follows the pattern predicted, sweeping clockwise through the Gulf (Figure 3).

The fit between our predictions and the observed entanglements also suggests that entanglement is driven by the frequency with which turtles encounter debris rather than based on foraging behavior of turtles. Ideally, we

would have tested for species differences in entanglement rates directly by comparing relative densities of each turtle species in an area with the observed entanglement rate in that area. However, a direct test was not possible due to the limited number of turtle strandings observed and a lack of detectable differences between species distributions.

Our approach is readily expandable to the national or even global scale for a wide range of taxa. Over 200 species are known to be affected by marine debris, including seabirds, marine mammals, and sea turtles (Laist 1997). Recently, other researchers have developed predicted global densities of oceanic marine debris (Lebreton *et al.* 2012). Combining models such as these with species distribution data, even at coarse scales, would provide estimates of relative encounter rates of debris across species and is an important next step. This analysis could identify global hotspots for impact, which might differ from the highest concentrations of debris alone, and can assist in identifying species to further investigate as those potentially heavily impacted. The end result of such a global analysis could be a list of species and their relative level of debris encounter, which might form the basis for prioritizing actions to mitigate this impact. This is critical because data from breeding sites alone underestimates the number of animals killed at sea (Good *et al.* 2010). Australia has identified exactly this information requirement as a component of the national marine debris policy (actions 2.1 and 2.4, Anonymous 2009).

Our results also suggest several direct actions for addressing ghostnet issues. It appears that most nets enter the Gulf from the northwest and move along its northeastern shore, following a clockwise path. Hence, it would be possible to effectively monitor nets arriving here, via aerial or satellite surveys, focusing on a relatively small area north of the GOC. Coastal surveillance programs might provide an opportunity for incorporating this area in their overflights. Also, tracks suggest that intercepting nets along the northeast of the Gulf would prevent much of their impact, as they sweep through the GOC and encounter most of the high-density turtle areas along the south and east margins. It would be relatively efficient to intercept ghostnets in this region as there is a major port along the northeastern GOC that could provide an operations center.

Management that incentivizes gear return or provides waste disposal sites locally may also reduce gear loss. In South Korea, a buyback program helps to reduce the 23,900 tons of fishing gear abandoned each year by recovering up to 20% of the gear by weight (Cho 2009). However, management costs money—the Korean program yields 1.2 kg of gear/U.S.\$. Cleanup data and preliminary surveys with fishers indicate that most of

the drifting nets in the Arafura and Timor Seas north of Australia are from Illegal fishing vessels or from legal Indonesian vessels, with a minor component from Australian vessels (Kiessling 2002). However, causes of gear loss/abandonment are complex and involve overcapacity leading to crowding and gear conflicts (R. Gunn, unpublished data). Thus, incentive programs like the Korean one may work in the Arafura/Timor Sea, but must be carefully designed keeping the drivers specific to this system in mind.

Prioritizing investment to tackle this global problem requires understanding the sources, locations, and species affected, pointing to a critical need for global analyses of ghost fishing and other marine debris impacts. Applying our model at a global scale and incorporating those species most likely to be impacted will allow us to focus resources appropriately to best mitigate the impacts of ghostnets and other marine debris.

Acknowledgments

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