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Understanding the sources and effects of abandoned, lost, and discarded fishing gear on marine turtles in northern Australia

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Abstract: *Globally, 6.4 million tons of fishing gear are lost in the oceans annually. This gear (i.e., ghost nets), whether accidently lost, abandoned, or deliberately discarded, threatens marine wildlife as it drifts with prevailing currents and continues to entangle marine organisms indiscriminately. Northern Australia has some of the highest densities of ghost nets in the world, with up to 3 tons washing ashore per kilometer of shoreline annually. This region supports globally significant populations of internationally threatened marine fauna, including 6 of the 7 extant marine turtles. We examined the threat ghost nets pose to marine turtles and assessed whether nets associated with particular fisheries are linked with turtle entanglement by analyzing the capture rates of turtles and potential source fisheries from nearly 9000 nets found on Australia's northern coast. Nets with relatively larger mesh and smaller twine sizes (e.g., pelagic drift nets) had the highest probability of entanglement for marine turtles. Net size was important; larger nets appeared to attract turtles, which further increased their catch rates. Our results point to issues with trawl and drift-net fisheries, the former due to the large number of nets and fragments found and the latter due to the very high catch rates resulting from the net design. Catch rates for fine-mesh gill nets can reach as high as 4 turtles/100 m of net length. We estimated that the total number of turtles caught by the 8690 ghost nets we sampled was between 4866 and 14,600, assuming nets drift for 1 year. Ghost nets continue to accumulate on Australia's northern shore due to both legal and illegal fishing; over 13,000 nets have been removed since 2005. This is an important and ongoing transboundary threat to biodiversity in the region that requires attention from the countries surrounding the Arafura and Timor Seas.*

Keywords: bycatch, cryptic mortality, derelict nets, gill net, illegal fishing, IUU, trawl

Entender las Fuentes y Efectos de Equipo de Pesca Abandonado, Perdido y Desechado sobre las Tortugas Marinas del Atlántico Norte

Resumen: *A nivel global, 6.4 millones de toneladas de equipo de pesca se pierden anualmente en los océanos. Este equipo (p. ej.: redes fantasmas), ya sea perdido accidentalmente, abandonado o desechado deliberadamente, es una amenaza para la vida marina mientras se encuentre flotando con las corrientes dominantes y siga enredando organismos marinos indiscriminadamente. El norte de Australia tiene una de las densidades más altas de redes fantasmas en el mundo, con hasta tres toneladas llegando a la orilla por kilómetro de línea costera al año. Esta región es útil para poblaciones significativas a nivel global de fauna marina amenazada internacionalmente, incluyendo a seis de las siete tortugas marinas existentes. Examinamos la amenaza que las redes fantasmas presentan para las tortugas marinas y evaluamos si las redes asociadas con ciertas pesquerías están vinculadas con el enredamiento de tortugas al analizar las tasas de captura de tortugas y pesqueras potenciales de origen de casi 9,000 redes halladas en la costa norte de Australia. Las redes con mallas relativamente más grandes y un menor tamaño de cordel en nuestra muestra (p. ej.: redes de flote pelágico) tuvieron la probabilidad más alta de enredamiento para tortugas. El tamaño de la red fue importante; pareciera que las redes más grandes atraen a las tortugas, lo que incrementa su*

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tasa de captura. Nuestros resultados señalan a problemas con las pesqueras que usan redes de arrastre y de flotación, la anterior debido a un gran número de redes y la última debido a tasas altas de captura resultantes del diseño de la red. Las tasas de captura para redes de malla fina pueden alcanzar hasta 4 tortugas/100 m de largo de la red. Estimamos que el número total de tortugas capturadas por las 8,690 redes fantasmas que muestreamos se encontró entre 4,866 y 14, 600, asumiendo el uso de redes para un año. Las redes fantasmas siguen acumulándose en la costa norte de Australia debido a la pesca legal e ilegal; más de 13, 000 redes han sido removidas desde 2005. Esta es una importante amenaza continua y transfronteriza para la biodiversidad en la región que requiere de atención de los países que rodean los mares Arafura y Timor.

Palabras Clave: captura accesoria, IUU, mortalidad críptica, pesca ilegal, red de arrastre, red de malla, redes descuidadas

Introduction

Introduction of plastic debris into the marine environment is of increasing concern and has been identified as an emerging global issue under the Convention on Biological Diversity (Sutherland et al. 2010; Thompson et al. 2012). Derelict fishing gear in particular is of major concern because, although it makes up <10% of marine debris, it can have very damaging effects on marine fauna (Macfayden et al. 2009). It is estimated that 6.4 million tons of fishing gear are lost in the oceans annually (Macfayden et al. 2009). Whether they are abandoned, lost accidently, or deliberately discarded, the number of these so-called ghost nets in the world's oceans is increasing (Kiessling 2003; Macfayden et al. 2009). In areas where nets accumulate due to oceanic currents, densities can be high. For instance, Gilardi et al. (2010) report that more than 52 tons of derelict fishing gear accumulates annually in the northwest Hawaiian Islands.

Derelict gear from fisheries has been recognized as a threat to marine wildlife since the 1980s (Laist 1987; Macfayden et al. 2009). Once lost, derelict gear drifts and can continue to entangle wildlife indiscriminately for periods from days to multiple decades (Matsuoka et al. 2005; Gilardi et al. 2010). Entanglement can lead to drowning, inflict severe lacerations, increase drag while swimming and foraging, prevent diving and feeding, and increase exposure to predators (Ceccarelli 2009; Macfayden et al. 2009; Gilardi et al. 2010). The advent of synthetic materials made nets cheaper, more durable, lighter weight, and stronger (Laist 1987). These properties, while beneficial for fishing, also make them more buoyant, longer lasting, and more difficult for trapped animals to break free from, substantially increasing the damage associated with lost gear (Laist 1987; Derraik 2002; Gilardi et al. 2010).

A recent review documented that 663 species are affected by marine debris: a large fraction of those effects are due to entanglement (Thompson et al. 2012). Entanglement in marine debris, and derelict fishing gear specifically, is a source of mortality in a wide range of species including pinnipeds, cetaceans, marine turtles, seabirds, cephalopods, fish, crustaceans, corals, and sponges (Macfayden et al. 2009; Gilardi et al. 2010; Gilman et al. 2010). Turtles, in particular, are affected by ghost nets due to their tendency to use floating objects for shelter and as foraging stations (Kiessling 2003; White 2006).

The northern Australia coastline has one of the highest densities of derelict gear that washes ashore globally: up to 3 t $\cdot$ km^{-1} $\cdot$ year^{-1} (Gunn et al. 2010; Wilcox et al. 2013). Based on oceanographic modeling, these nets likely originate from fisheries operating in the Arafura and Timor Seas, to the north of Australia (Gunn et al. 2010; Wilcox et al. 2013). Fisheries in the region target prawns, tropical snappers, sharks, squid, and tuna with a mix of gears including trawl nets, gill nets, purse seine, longline, and traps (Northridge 1991; Morgan & Staples 2006; Wagey et al. 2009; Alongi et al. 2011; Stacey et al. 2011). Additionally, there is considerable illegal, unreported, and unregulated (IUU) fishing activity occurring in the region (Resosudarmo et al. 2009; Wagey et al. 2009).

This is cause for concern because the waters of the gulf support important foraging, breeding, and nesting grounds for 6 of the world's 7 marine turtle species (Department of Environment, Water, Heritage and the Arts 2008), most of which are affected by derelict fishing gear globally (Donohue et al. 2001). Limpus (2008) stated that "turtle mortality in the Gulf of Carpentaria's 'ghost net' fishery is unquantified but appears to be hundreds, if not thousands of turtles annually."

We examined the threat ghost nets pose to marine turtles in a tropical environment. We analyzed stranding data to determine which net characteristics are associated with capture rates of marine turtles; classified the types of nets according to their characteristics to allow identification of the fisheries losing gear in the region; and linked the estimates of capture rates with the net classifications to provide predictions of damage by fishery and gear type.

Methods

Study Region and Surveys

We focused on the northern Australian coastline from east of the Gulf of Carpentaria (the gulf) across the northern Australian coastline to the northwestern coast of

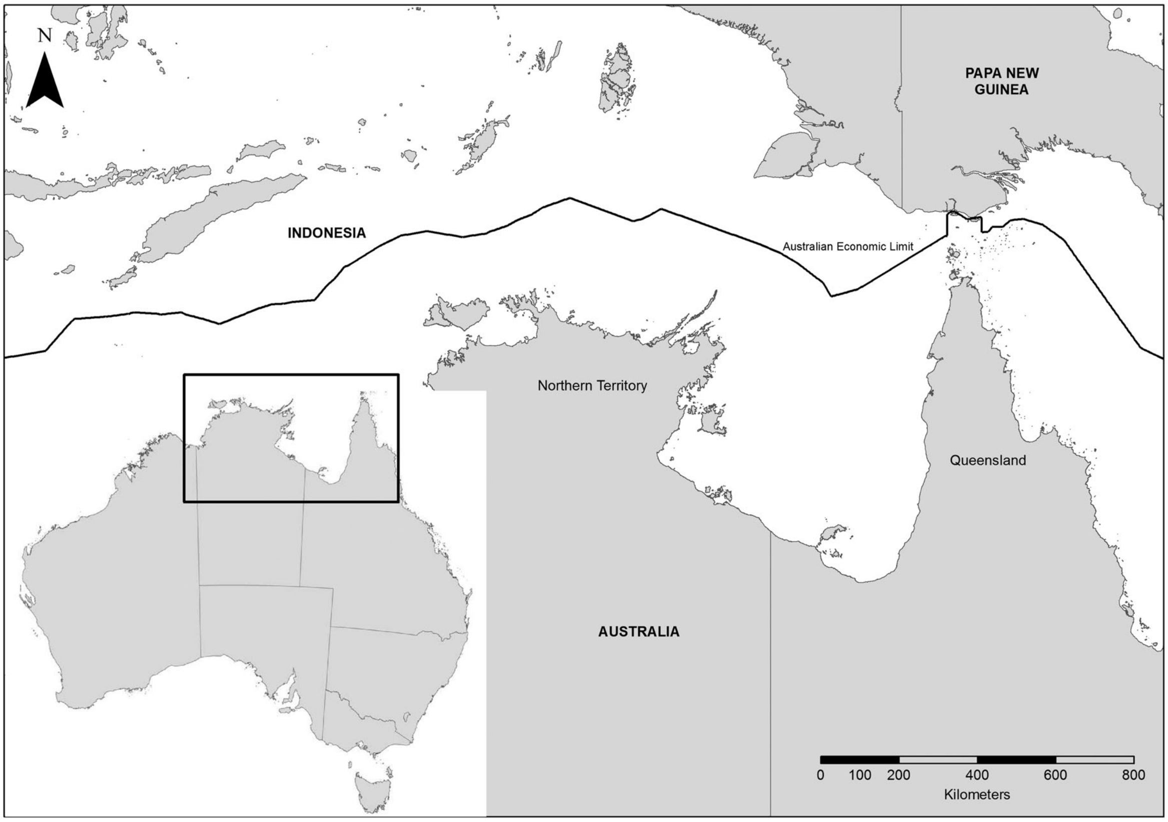

Figure 1. Study area in relation to economic exclusion zone and neighboring countries.

Western Australia (Fig. 1). Coastal debris in this region is driven by oceanic currents that circulate in a clockwise gyre. Materials are transported into the gulf by southeasterly trade winds. These winds become northwesterly during the monsoon season (Wilcox et al. 2013).

Data on stranded nets and entangled animals were collected between 2005 and 2012 by local indigenous rangers. Commercial fishers, government agencies (Australian Fisheries Management Agency, Great Barrier Reef Marine Park Authority), community groups, volunteers (Conservation Volunteers Australia), and individuals provided additional data. Data recorded included GPS position, survey date, and net information such as length, width, and height of net bundle; color; presence of attached items (lead lines, floats, wood, squid jigs, etc.); twine composition (monofilament or multistrand); twine structure (braided or twisted and single or double strands); number of strands; mesh size; twine size; and mesh knotting (presence or absence). Samples were frequently collected prior to disposal of the net. Animals associated with nets were recorded and identified to species where possible.

Data Analyses

There were 11,867 independent net records with 442 entangled animals, 76% of which were turtles. Sharks, rays, dugong, a variety of fish, and some invertebrates were also found entangled. These animals were not included in analysis due to inconsistent reporting. We anticipated data recording and entry errors, due to the limited literacy and numeracy skills of some observers. After quality control and exclusion of records with incomplete data, we retained 8690 net records, of which 137 had turtles caught in them.

We used logistic regression to investigate the effect of net size on the probability that a net contained a turtle. We were limited to using the longest dimension as a proxy for area, due to low reporting rates. There is a theoretical expectation that a larger net is more likely to catch a turtle because it samples a larger area, and thus, this effect should be included in all analyses if it is established. We evaluated both first- and second-order linear models to allow for some flexibility in the relationship between net size and probability of capture. After evaluating the effect of net size, we explored possible additional covariates in the logistic regression model with a stepwise model building approach based on Akaike's information criterion (AIC), allowing both forward and backward steps, implemented in the R statistical language (Venables & Ripley 1994; R Development Core Team 2011). We aggregated whether the net was made from monofilament or multistrand twine, and if it was multistrand, we included the number of strands (range = 1–13).

We used regression trees implemented in a conditional inference framework to explore the relationship between the catch per unit effort, expressed as turtles per meter of net length, and the various net characteristics recorded (Party package in R; Hothorn et al. 2006). This approach was a complement to our linear regression analysis, primarily to ensure that we captured the main explanatory variables and higher order interactions.

We classified the nets based on their characteristics (described above), on the assertion that the resulting groupings would correspond to different types of fishing operations. For instance, larger mesh sizes should correspond to fisheries targeting larger species (Gabriel et al. 2008). Similarly, monofilament nets and light twine might correspond to gill nets, while heavier multistrand twine could be more indicative of trawl nets (Gabriel et al. 2008). We applied a mixture-model-based cluster analysis that allowed for both continuously distributed and discrete characteristics (McLachan & Peel 2000). Parameters in the cluster analysis were estimated using the EM algorithm (sensu Dempster et al. 1977). We estimated the most parsimonious number of clusters following the established method of starting at a model with 1 cluster and adding additional clusters until the AIC reached a local minima (McLachlan & Peel 2000). We then evaluated which of these inferred types of nets (i.e., clusters) was the most environmentally harmful in terms of catch of turtles, as inferred from our logistic regression and regression tree analyses.

We calculated the total expected catch across all nets and net fragments with the fitted regression model. Due to missing data, we excluded some of the 8690 net records from these predictions: we included only the nets that had the relevant characteristics recorded. We then expanded these estimates by multiplying the sum of the expected catches across the nets we included from each net type by the ratio between the total number of nets of that type and the number included in the regression predictions. This allowed us to expand our predictions to include all 8690 nets. We assumed that nets with missing data were a random subset of the nets with all available data within each net type.

Results

Turtles found in nets on the gulf coast included flatback (*Natator depressus*, 9.9%), green (*Chelonia mydas*, 13.8%), hawksbill (*Eretmochelys imbricate*, 32.6%), loggerhead (*Caretta caretta*, 1.1%), and olive Ridleys turtles (*Lepidochelys olivacea*, 42.5%); approximately 24% of turtles were unidentified. Due to inconsistent identification, we considered all turtles together.

There was a strong effect of the length of the net on the probability that it contained turtles: longer nets caught more turtles. This effect appeared to be nonlinear because the second-order model including length and its square had a lower AIC score (1082.1) than a first-order model with length alone (1101.5). Both the length and the square of the length had highly significant coefficients (Supporting Information). The positive first-order and negative second-order terms indicated that although longer nets caught more turtles, the effect of a unit increase in length on the probability of capture decreased as the length of nets increased (Supporting Information).

Table 1. Regression coefficients for a logistic regression predicting whether a ghost net is found with a turtle in it or not based on stepwise model selection with the Akaike information criterion.

*Covariate**	*Estimate*	*SE*	*z*	*Pr(>|z|)*
Intercept	−1.90E+01	5.51E + 02	−0.035	0.97242
Length	2.48E−02	8.63E−03	2.871	0.00409
Length^2	−8.07E−05	4.57E−05	−1.766	0.07746
Multi/mono (multi)	−2.17E + 00	1.08E + 00	−2.011	0.04435
No. of strands	1.19E + 00	1.14E−01	10.388	<2e−16
Double/single (single)	1.55E + 01	5.51E + 02	0.028	0.97751
Mesh size	8.54E−04	4.30E−04	1.985	0.04714
Twine size	−1.09E + 00	1.24E−01	−8.756	<2e−16

**For factors, the code in parentheses gives the relevant level of the factor for the coefficients. For instance, in the case of Multi mono, the coefficient applies to the multi level, and the mono level has a coefficient of 0. See Supporting Information for details on net characteristics.*

The best fitting model for predicting the capture of turtles in nets included the number of strands, whether the net was double- or single-strand twine, and the size of the twine (Supporting Information, Table 1). Monofilament nets were more likely to contain turtles. For nonmonofilament nets, twines with larger numbers of strands, but smaller diameters, were more likely to contain turtles. Capture rates also increased with mesh size. The term describing whether the net has single or double twine construction was included based on the decrease in AIC; however, this parameter was not significant at the $P < 0.05$ level. Results of the regression tree analysis were consistent with these patterns: nets with twine thickness of 1–2 mm and with 3 or more strands had higher catch rates. The regression tree did not identify any complex interactions that were not included in the linear regression.

Based on AIC scores, there was statistical support for a total of 14 types of net among the nets recovered from beaches (Fig. 2). Because we were not concerned with the length of the nets, but only their characteristics, we were able to include several thousand records that had been excluded from the regression analysis, which increased the sample size to 8690 nets. Mean mesh size for the net types ranged from 50 to >900 mm; mean twine sizes also varied widely (from 1 to >6 mm (Fig. 3). Some net types, such as those in cluster 3, were relatively homogenous, in this case consisting largely of fine mesh

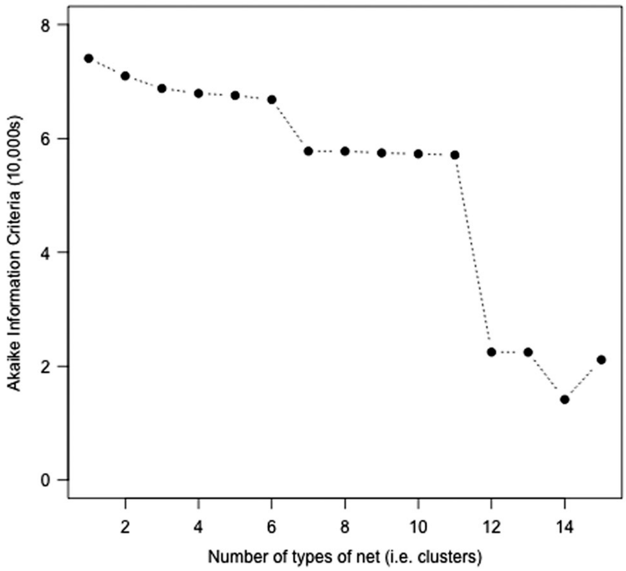

Figure 2. Statistical support for the number of types of net washing ashore in northern Australia. Net types are identified through cluster analysis, and model selection is via Akaike information criterion.

gill nets (Fig. 3). Other net types, such as those in cluster 13, included a wider range of mesh sizes and twine thickness. In this case, the range of mesh sizes was a result of the group being composed of trawl net fragments, which increase in mesh size moving out from the central section of the net.

Net types varied widely in their predicted catch rates (Fig. 4). Nets in cluster 3 had by far the highest catch rate; the expected value was just over 4 turtles/100 m of net. Net type 9 had the 2nd highest predicted catch rate. It had an expected value of approximately 3 turtles/100 m of net. It is possible that both of these nets were gill nets. Type 3 was a fine mesh gill net (e.g., for small fish) and type 9 was a larger gill net for demersal or pelagic shark. Net type 2 also fell in this group; it was likely a relatively fine mesh gill net, although with slightly heavier construction than type 3. Two of the heavy twine nets, types 5 and 14, had intermediate catch rates; expected values were approximately 1 turtle/100 m of net. In the case of type 14, this was due to the very large mesh, which increased the expected catch rate. For type 5, the increased catch rate could be due to a slightly different construction in the twisted 4 strand single twine nets because both the heavy twine and small mesh would otherwise predict low catch rates for nets with these characteristics (R.G., unpublished data). Most of the remaining net types had relatively heavy twine and medium to fine mesh, both of which were expected to have low catch rates.

We predicted that 202 turtles would be captured across all nets in each of the 14 net types based on our fitted regression model (Table 2). These predictions scaled fairly closely with the observed captures (Table 2). Nets differed widely in their abundances. Types 2, 3, 7, and 10 composed most of the nets found and thus contributed most of the expected catch. Net type 2, a smaller mesh and twine trawl net, was by far the most common. Types 2 and 10, which were slightly heavier trawl nets, also occurred in the largest fragments. Although less common, net type 3 had a relatively high expected catch, owing to a combination of net characteristics that lead to high catch rates. Net type 9, which was composed of large mesh and fine twine, had the second highest catch rate of all the net types, but it had a relatively low expected total catch due to its relative rarity (Fig. 4, Table 2).

Discussion

Ghost Nets with the Largest Effect

As mesh size increased, nets were more likely to ensnare marine turtles. This result was similar to those from southern Brazil (Lopez-Barrera et al. 2012) and the U.S. mid-Atlantic (Murray 2009). According to Gilman et al. (2010), gill net fisheries that target marine turtles often use nets with a relatively large mesh size (from 20 to 60 cm). Nets with small twine sizes, from 1.1 to 2 mm, had the highest probability of catching marine turtles of those in our sample. Few studies have related twine size and turtle entanglements in fishing nets, although the sizes recorded for nets with high bycatch in other studies were mostly smaller than 2.5 mm (Trent et al. 1997; Romero 2008; Solarin et al. 2008; Alfaro-Shigueto et al. 2010).

Based on net design principles, larger mesh size and finer twine would be expected to increase the level of ensnarement for turtles coming in contact with nets (Gabriel et al. 2008). In a study of catch rates of turtles, Lopez-Barrera et al. (2012) found this to be the case, a result that suggests finer twine causes a more thorough entrapment. Macfayden et al. (2009) argue that the relatively thicker twine diameter of trawl netting makes it more visible and increases the encrusting community on the net, both of which decrease its effectiveness in ensnaring turtles.

The size of nets and net fragments also had a major effect on the probability that a net contained turtles as it washed ashore. This was likely due to a combination of 2 mechanisms. First, a larger net will sweep through more water volume as it moves; thus, one would expect the probability of capture to increase with net size. Second, floating objects that provide habitat heterogeneity are well known to have aggregations of marine life around them (Castro et al. 2001). This is the reason for the use of fish aggregating devices (FADs) (i.e., to increase fish density and thus rates of commercial harvest in an area) (Castro et al. 2001; Dagorn et al. 2013). FADs are frequently constructed with discarded fishing net or other net designed for the purpose (Castro et al. 2001). There

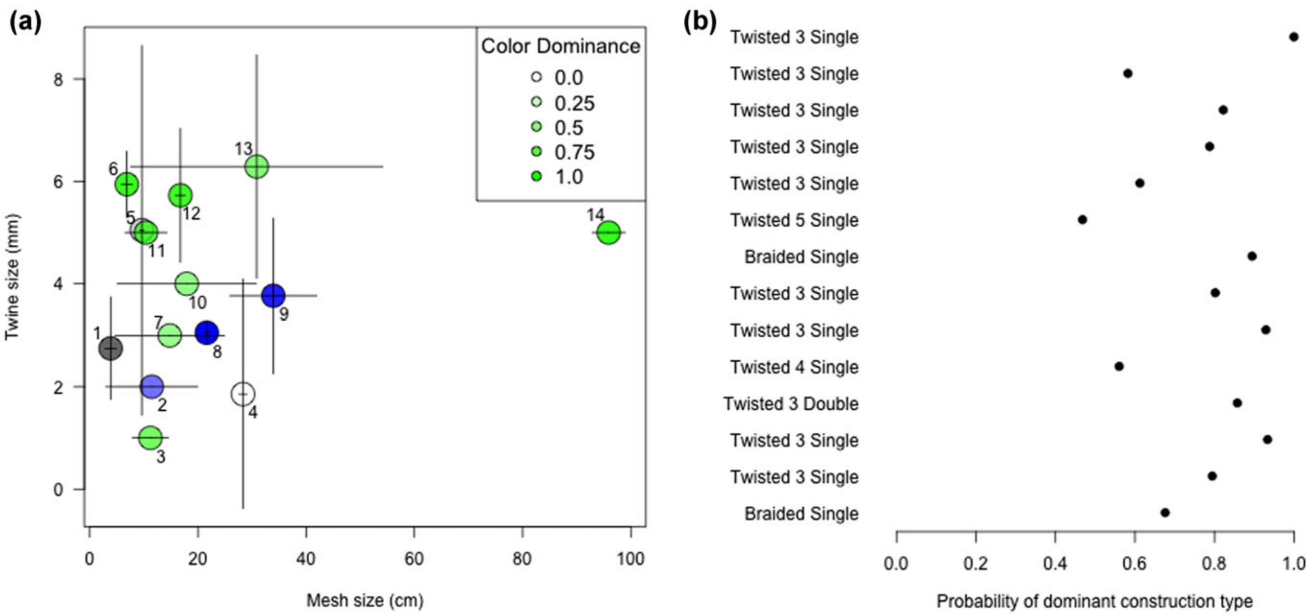

Figure 3. Characteristics of ghost nets in each of the 14 net types identified with a cluster analysis: (a) mean mesh and twine sizes and dominant color for each cluster (lines, SD of the distribution for mesh and twine size distributions; colors, dominant color of the nets in the cluster; intensity of the color, relative dominance of that color in comparison with all other colors in that cluster; numbers next to markers, cluster numbers) and (b) probability of the most common construction for each type of net from net cluster 1 just above the origin to cluster 14 at the top.

Table 2. Sizes of ghost nets, total number of fragments, and captures of turtles across all 8690 nets.

		Net size[b] (m)					Captures	
Net type[a]	*Number of nets*	*min*	*median*	*mean*	*max*	*Proportion of nets with data*	*predicted*	*observed*
1	80	0	3	4.5	42	0.57	0.27	0
2	3459	0	5	9.6	375	0.61	89.69	73
3	1403	0	4	7.7	150	0.64	65.53	70
4	14	1	7.5	9.8	23	0.86	0.0000002	0
5	48	1	5	9.6	78	0.81	0.54	0
6	56	1	5	7.3	29	0.61	0.01	0
7	2081	0	5	9.2	300	0.64	31.88	18
8	19	0	2	6.3	29	0.79	0.00000005	0
9	38	1	3.5	4.3	20	0.47	2.89	0
10	1009	0	5	9.7	555	0.66	9.98	13
11	345	0	4	8.8	300	0.61	0.61	2
12	24	1	6	12.1	31	0.67	0.01	0
13	97	0	2	3.7	33	0.51	0.89	3
14	17	1	8	8.4	25	0.53	0.08	0

[a] *Net types are the net categories identified in the cluster analysis.*
[b] *Net sizes are rounded to the nearest 0.5 m for presentation.*

is suggestive evidence that turtles aggregate near these FADs based on catch rates by purse seiners from the Indian Ocean (Dagorn et al. 2013).

Sources of Ghost Nets

Despite the dominance of trawl fishing in the region, the most frequently found ghost net in northern Australian waters was gill nets with a mesh size of 11.5–12.4 cm and twine size of 7 mm (cluster type 3). These nets composed 611 out of the 8690 nets in our data (7%). The combination of large mesh sizes and small twine diameters is characteristic of gear that is light, fine, and buoyant and is therefore ideal for use in targeting large pelagic species, such as tuna, shark, and mackerel, near the surface of the water (R.G. et al., unpublished data).

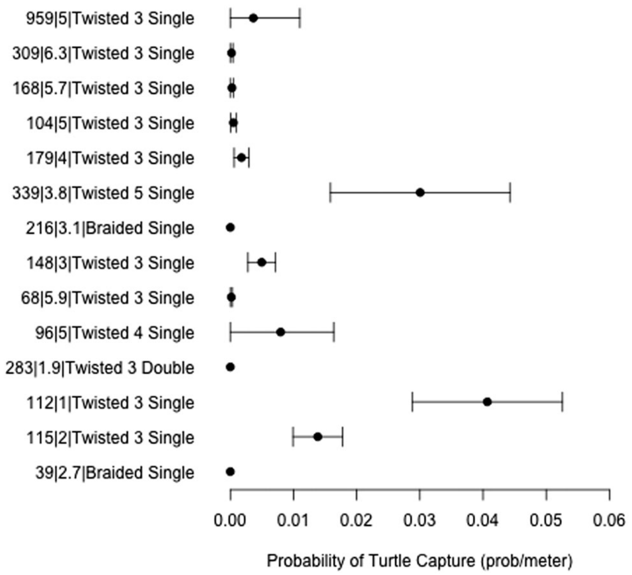

Figure 4. Turtle capture probability for each type of net identified with a cluster analysis. Net types are ordered from net cluster 1 just above the origin to cluster 14 at the top. Numbers to the left of the net types are (from left to right) mesh size (mm), twine size (mm), and net construction type. Error bars show 95% CIs around the estimated probability.

This suggests that drift nets, a type of floating gill net set at the surface that targets pelagic species, may have a disproportionate effect on marine turtles in the Gulf of Carpentaria region.

Fisheries in the region known to use drift nets similar to the cluster 3 nets include the Javanese tuna fisheries (Northridge 1991) and a Thai shark drift net fishery (R.G. et al., unpublished). Gillnetting accounts for 3% of the licensed fisheries in the Arafura Sea (Wagey et al. 2009). However, approximately 6000 gill net fishers operate from Timor L'Este to the west (Stacey et al. 2011). In addition, the presence of a large number of IUU vessels in the region makes it difficult to accurately assess the composition of nets being used (Wagey et al. 2009). In some areas north of the Arafura and Timor Seas, IUU catch is estimated at up to 1.5 times the legal catch (Varkey et al. 2010) and licensed fishers operating in the region suggest that some of these vessels use drift nets (R.G., unpublished data).

The World Wildlife Fund developed an identification key for nets that were washing up in northern Australia, which we had hoped to use in this analysis (Hamilton et al. 2002). However, the identification key had 3 characteristics that required us to develop our net classification system. First, variation in measurements led to nets being incorrectly assigned, sometimes to entirely different categories such as trawl to gill net because the key did not include variation in measurements around its values. Second, there was ambiguity in the net origin information; manufacturer, country of use, and fishery were used interchangeably as the source. Third, the key is not dynamic and thus requires updating as net designs change to incorporate new technologies, fishing approaches, and target species. Our statistical method groups nets based on size and construction, on the argument that nets used for similar target species in a similar mode of operation will generally be constructed in a similar way. Thus, while our clustering approach could not identify specific fisheries, it provided a means to link derelict gear to general types of fishing in an unambiguous way. In our view, this approach accommodated issues with measurement error and changing numbers of categories, either due to new fisheries emerging or an increasing sample of abandoned nets.

Size of the Effect on Marine Turtles

The 8690 nets we analyzed were predicted to capture 202 turtles, based on turtles observed in the nets when they washed onshore. This estimate was driven by net characteristics, net size, and the frequency with which they occurred. There was heterogeneity among nets within a given net type, both in size and design; thus, the predicted catch was not equivalent to simply multiplying the number of nets of a type times their expected catch rate. However, the expected catch rates for the net types (Fig. 4) can be taken as a general guide.

In predicting total catches by each net type, we also had to multiply up our estimates for nets in each type that had incomplete data, which precluded direct prediction based on the regression model. If nets with incomplete data are a random sample from the overall population of nets in a type, this approach should lead to accurate estimates. However, there is always the possibility that characteristics such as net size, presence of turtles, or other characteristics could lead to variation in the thoroughness of data recording. In this case, estimates would be biased, but in a potentially unknown and undetectable manner.

Transforming the estimate of the number of turtles caught in nets washing onshore into an estimate of the number of turtles captured by the nets at sea requires knowing the rate of loss of turtles from the net, either to decay or disentanglement after death. Based on a recent review by Cooper (2012), there is currently very little published information on decay rates of marine turtles. The one study providing experimental results for marine species estimated the postmortem interval (death to complete disarticulation) for hawksbill turtles in the Seychelles at 10–15 d (Meyer 1991). Our preliminary experimental results suggest a similar pattern, with a postmortem interval in subtropical or tropical marine environments of 5–14 d, depending on water temperatures, tidal currents, and other factors (H. Jones et al., unpublished data).

If we assume the nets drift for a year and that turtles are evenly distributed across the region where nets drift, then the portion of the turtles caught that would be available to be seen would be 0.0137/year (5 d/365 d) if turtles last 5 d and 0.041/year if turtles last 15 d. Given that 200 turtles were recorded, we estimate that 14,600 to 4866 turtles are killed by ghost nets in the year before the nets are stranded. Simulated net drift paths of nets entering the gulf had residence times ranging from 1 to 476 d; thus, we expect that calculating annual catch rates is not unreasonable (Wilcox et al. 2013; C.W., unpublished data). An important caveat in this estimate is that the 8690 nets in the data set were the accumulation of nets over some unknown period. Thus, the estimate of 4,866–14,600 turtles killed should be considered a cumulative estimate over this unknown period.

The estimate is most reasonably considered an approximate lower bound on the number killed, not as a point estimate of the value for several reasons. Nets are expected to decrease in catch efficiency with time, and because our data were based on the very end of a ghost net's path, the net may have been much more effective closer to the time when it ceased being actively used in a fishery (Matsuoka et al. 2005). In addition, nets continue to wash ashore in northern Australia. The current count is just over 13,000 nets removed from the gulf coast (R.G., unpublished data). Evidence from Flinders beach, on the northeast coast of the gulf, suggests that the number of nets washing ashore may even be increasing. There were 2213 nets removed from this beach between 2004 and 2012, but a large number of those arrived in the most recent years (2010: 419 nets, 2011: 526 nets, 2012: 163 nets). Thus, our estimate of turtle mortality based on the 8690 nets in our data set likely underestimates the total cumulative mortality to date.

Our estimates of catch rates suggest that management interventions should be targeted at reducing the number of large drift nets. Previous work (Wilcox et al. 2013) suggests that ghost nets drift into the gulf along a fairly narrow path that passes an industrial port just after entering the gulf, making detection by customs surveillance planes and interception near the port feasible and relatively inexpensive. Early interception before nets are caught in the gyre circulating in the gulf would likely substantially reduce their damage and would cost significantly less than the existing ad hoc removal program. Reductions in the loss of nets, particularly large drift gill nets, are also an important management priority. Anecdotal evidence suggests that many of these nets come from illegal vessels operating along the international boundary between Indonesia and Australia; thus, continued and enhanced interception and prosecution of these operators is critical in reducing the input of drift nets into the marine environment. Finally, targeted monitoring of ghost net effects on turtles and other species should be a priority, particularly given the scale of our predictions. There is currently little data available when nets are intercepted at sea, and improving this situation would cost little while allowing quantitative estimates of effects to be included in population assessments for turtles, sharks, dugongs, and other protected species thought to be affected in the region.

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Supporting Information

Parameter estimates for the logistic regression of the probability a turtle is found in a beached net on the size of the net (Appendix S1) and the net characteristics recorded by ranger groups during beach cleanup efforts (Appendix S2) are available on-line. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.
Appendix S1. Parameter estimates for the logistic regression of the probability a turtle is found in a beached net on the size of the net.
Appendix S2. Net characteristics recorded by ranger groups during beach cleanup efforts.

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