

Risk analysis reveals global hotspots for marine debris ingestion by sea turtles

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Abstract

Plastic marine debris pollution is rapidly becoming one of the critical environmental concerns facing wildlife in the 21st century. Here we present a risk analysis for plastic ingestion by sea turtles on a global scale. We combined global marine plastic distributions based on ocean drifter data with sea turtle habitat maps to predict exposure levels to plastic pollution. Empirical data from necropsies of deceased animals were then utilised to assess the consequence of exposure to plastics. We modelled the risk (probability of debris ingestion) by incorporating exposure to debris and consequence of exposure, and included life history stage, species of sea turtle and date of stranding observation as possible additional explanatory factors. Life history stage is the best predictor of debris ingestion, but the best-fit model also incorporates encounter rates within a limited distance from stranding location, marine debris predictions specific to the date of the stranding study and turtle species. There is no difference in ingestion rates between stranded turtles vs. those caught as bycatch from fishing activity, suggesting that stranded animals are not a biased representation of debris ingestion rates in the background population. Oceanic life-stage sea turtles are at the highest risk of debris ingestion, and olive ridley turtles are the most at-risk species. The regions of highest risk to global sea turtle populations are off of the east coasts of the USA, Australia and South Africa; the east Indian Ocean, and South-east Asia. Model results can be used to predict the number of sea turtles globally at risk of debris ingestion. Based on currently available data, initial calculations indicate that up to 52% of sea turtles may have ingested debris.

Keywords: *Caretta caretta*, *Chelonia mydas*, debris ingestion, *Dermochelys coriacea*, *Eretmochelys imbricata*, *Lepidochelys kempi*, *Lepidochelys olivacea*, marine plastics, *Natator depressus*, risk analysis

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Introduction

With an estimated 4–12 million tonnes of plastic entering the oceans annually (Jambeck *et al.*, 2015), plastic marine debris (hereafter debris) has rapidly become one of the key factors affecting marine biodiversity in the 21st century (Secretariat of the Convention on Biological Diversity and the Scientific and Technical Advisory Panel (GEF), 2012). Among a variety of problems posed by marine debris is an increasing threat to marine wildlife from debris ingestion and entanglement (Schuyler *et al.*, 2014). Of the 693 different species

recorded to have interacted with marine debris (Gall & Thompson, 2015), two of the top six species most heavily impacted are sea turtles (GEF, 2012)); however, quantifying these impacts remains a high priority for research in the field of plastic marine pollution as well as for sea turtle conservation (Hamann *et al.*, 2010; Vegter *et al.*, 2014). A global analysis assessing a variety of threats to sea turtles was unable to characterise the risk from pollution and pathogens due to a lack of data, leading to a call for greater monitoring of these impacts (Wallace *et al.*, 2011). To understand the influence of plastic and other debris on turtles and other wildlife, we must determine which factors are most influential in predicting debris interaction rates.

Globally, few large-scale studies have empirically investigated the location of ocean-borne debris (Moore *et al.*, 2001; Law *et al.*, 2010, 2014; Eriksen *et al.*, 2013),

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and most of these have only reported on data collected within the past few years (but see Law *et al.*, 2010). Although data on the distribution of marine debris are sparse, ocean drifter data have been successfully used to model debris distribution (e.g. Maximenko *et al.*, 2012; Van Sebille *et al.*, 2012). Ground truthing of these models has shown them to be accurate with respect to predicting locations of debris maxima, but less successful at predicting relative quantities of debris (Eriksen *et al.*, 2013; Law *et al.*, 2014). Models can be improved by incorporating factors such as coastal population density to scale release points and amounts (*sensu* Van Sebille *et al.*, 2012).

Most studies investigating marine debris focus on cataloguing effects on individual animals or local populations (e.g. Beck & Barros, 1991; Tourinho *et al.*, 2010), or use mathematical models to predict the distribution of marine debris (e.g. Lebreton *et al.*, 2012; Eriksen *et al.*, 2013). Wilcox *et al.* (2013) pioneered a new approach, using a combination of ocean drift models and empirical data to predict encounter rates for marine turtles with ghost nets. Predicted encounter rates were strongly correlated with observed entanglement events, suggesting that encounter rates are a useful predictor of the risk of debris interactions for sea turtles and other wildlife. In addition to encounter data, other factors such as foraging strategy, availability of food sources and life history stage may also play a role in determining the risk of debris ingestion to an individual. For example, for both seabirds and turtles, different species and life history stages were shown to experience significantly different frequencies of debris ingestion (Day *et al.*, 1985; Moser & Lee, 1992; Acampora *et al.*, 2013; Schuyler *et al.*, 2014).

Determining ecological risk typically involves two stages; first assessing *exposure* to an environmental contaminant or threat, and characterising the effects (*consequence*) stemming from variations in the level of exposure (Suter, 2006). Next, these two inputs are integrated to estimate the *risk*, or the probability of a particular outcome (*endpoint*) given the predicted exposure (Hunsaker *et al.*, 1990). In other words, risk (*endpoint*) = exposure*consequence. For the model of debris ingestion risk to sea turtles created in this study, we estimated exposure rates to debris by mapping the overlap between global predictions of debris distribution and geographical species ranges. We then used necropsy data from both stranded and by-caught sea turtles to feed into a logistic regression model to assess the consequence of exposure: ingestion of plastic marine debris. The regression model incorporated not only exposure measures but also potential confounding factors (life history stage, species and time) to determine the endpoint, the

probability of a turtle ingesting debris, given its exposure to debris and other factors.

We focused on sea turtles as they are highly susceptible to debris ingestion (Gall & Thompson, 2015). From our risk assessment, we developed both global and population-scale risk predictions of debris ingestion rates for six marine turtle species, predictions of risk at different life history stages and a synthesis map showing the combined global risk to all turtle species.

Materials and methods

Debris mapping

We computed the spatial and temporal distribution of marine plastics using trajectories from observational surface drifting buoys launched in the Global Drifter Program gridded onto a one degree square global grid (Van Sebille, 2014). In brief, these gridded trajectories are summarised in a set of six transit matrices, one for each 2-month period in the year. The entries of these transit matrices depict, for each grid $1^\circ \times 1^\circ$ oceanic cell, the probability of arriving at any of the other grid cells 2 months later. By iteratively multiplying this matrix with a vector of plastic concentrations in the ocean, the evolution of plastic from any point in the ocean can be tracked.

There are no data on local plastic use around the world for every country, let alone data on the amount of plastics entering the ocean. To achieve a spatially and temporally varying source distribution for plastic, we assumed that plastic waste is spatially proportional to local population and temporally proportional to global plastic production. We modelled the plastic input into the ocean by continually releasing simulated particles (essentially virtual plastic) from all coastlines around the world, in a quantity proportional to the number of people living within 100 km from each point on the shoreline, with new releases at every 2-month time step. The amount of tracer entering the ocean from each coastal grid cell increased exponentially with time, using parameters from the EU report on global plastic production (PlasticsEurope, 2009). The quantity of tracer entering the ocean is therefore a function of both the number of people living near the coast in any given area and of the total amount of plastic produced globally in that year. The tracer is conserved, so sinking and/or beaching particles are not taken into account in the model. The model incorporates floats both with (48%) and without (52%) drogues, or sea anchors. The latter are much more influenced by wind than the former, and because ocean plastics are a combination of floating plastics (subject to wind stress) and neutrally buoyant plastics in the mixed layer, combining the two gives a good indication of the actual forces that would be acting on ocean plastics (Van Sebille *et al.*, 2012).

The evolution of plastic concentration was computed for 50 years, from 1960 to 2010, and the output was saved every 2 months. Note that the plastic concentration is a dimensionless quantity, as the plastic source function is only proportional to local population size and global plastic production; the proportionality constants are presently unknown

(i.e. the fraction of plastic produced that gets into the ocean), and hence, the relative densities cannot be converted to actual mass.

Turtle distribution

To determine the likely distribution of sea turtle populations, regional management unit (RMU) shapefiles for all seven turtle species were accessed from OBIS-SEAMAP (<http://seamap.env.duke.edu/swot>, access date 2 April 2012) (Halpin *et al.*, 2009; Wallace *et al.*, 2010, 2011; Kot *et al.*, 2012). RMUs are based on a variety of data, including genetics, tag returns, satellite tracking and population dynamics. These RMU shapefiles are more specific than general species distribution maps and represent areas shared by individuals from multiple nesting sites and genetic origins, defined by biogeographic boundaries. Each RMU is unique to a single species, and RMUs from different species may have dramatically different boundaries. For example, the RMU for leatherback turtles that includes the Mediterranean ocean (RMU 51) also includes most of the Atlantic Ocean, while for green turtles it does not extend beyond the Mediterranean (RMU 48).

Consequence (necropsy data)

To understand the likely outcome of interactions between turtles and debris, we conducted a comprehensive literature search for papers on diet and debris ingestion in turtles, which were published between 1985 and 2012. We searched ISI Web of Knowledge and the Aquatic Sciences and Fisheries Abstracts for the terms *feeding ecology*, *foraging ecology*, or *diet* and *plastic*, *debris*, *marine debris*, *litter*, *flotsam*, *detritus* or *tar balls*. We selected only studies that had completed a systematic survey of at least seven necropsied individuals. Diet studies in which necropsies were conducted were included whether or not they found plastics. We excluded studies in which only hook and line were ingested, because we could not determine whether ingestion was of an item of debris or from active fishery encounters. Where possible, animals were assigned to either neritic or oceanic life history stages. If not specified in the paper, animals were assumed to be oceanic when they were below a minimum recruitment CCL for that species [40 cm for green turtles in the Pacific (Limpus, 2009) and 30 cm in the Atlantic (Bjørndal *et al.*, 2000a), 35 cm for hawksbill turtles in the Pacific (Limpus, 2009) and 25 cm in the Atlantic (León & Diez, 1999), 65 cm for loggerhead sea turtles (Limpus, 2009) in the Pacific and 53 cm in the Atlantic (Bjørndal *et al.*, 2000b), and 20 cm for Kemp's ridley turtles (Ogren, 1989)]. Leatherback turtles were always presumed to be oceanic and flatback turtles to be neritic. All olive ridley turtles in this analysis were caught on longlines, so were considered oceanic. For some of the model data points, life history stage could not be determined, so they were categorised as unknown. The centre point of the geographic range of the study was used to determine the closest RMU for the stranded animals, and we assumed animals were drawn from that RMU. The data were parsed by species and by year of stranding when the study contained enough information to do so,

meaning that each paper could contribute more than one data point to the model. Because most studies investigated animals that had been stranded coastally, we did not have a high proportion of turtles that would have likely been feeding in the mid-ocean, where debris accumulates in oceanic gyres (but see Casale *et al.*, 2008; Frick *et al.*, 2010; Parker *et al.*, 2005, 2011). To address this, we incorporated necropsy data from 69 individuals (22 green turtles, 45 olive ridley turtles and two loggerhead turtles) caught by longline fishing boats within the North Pacific (Wedemeyer-Strombel *et al.*, in press). Turtles were necropsied using standard techniques (Wyneken, 2001). We had latitude and longitude coordinates from the capture location for each turtle, so we included each one as an individual data point in the model. Because many of the studies used in this analysis reported only presence or absence of debris and did not report the consequences of that debris such as mortality or injuries, the endpoint assessed in our risk analysis was debris ingestion, as opposed to the results of that ingestion.

Exposure

To estimate exposure to debris, we determined the mean concentration of debris within the spatial bounds of each RMU, giving a measurement of the encounter rate between turtles and debris across the entire RMU. However, as individual turtles are not likely to range throughout the entire RMU, we calculated three weighted measures of encounter rate. We calculated the inverse distance from the stranding location, as well as the inverse squared distance and the inverse square root of the distance as possible weighting factors to describe the spatial distribution of stranded or by-caught turtles. Each of these weightings was then used with the predicted distribution of plastic in the ocean to calculate a weighted mean exposure to plastic. We also calculated the mean debris concentration within a radius of 250 km from the stranding location, giving us a total of four different exposure measures to compare in our risk model. We chose 250 km as it was the distance that maximised the model fit, compared to other distances between 50 and 500 km. We used the last debris map in our calculations, representing plastic distribution from 2010, and also repeated the same exposure calculations using the debris model predictions corresponding to the beginning year of each necropsy study. Thus, we could compare exposure levels relative to recent predictions of debris loads, but also exposure levels which more accurately corresponded to predicted debris levels present at the time of the study.

Risk assessment (probability of debris ingestion)

To determine which risk factors were the best predictors of debris ingestion probability, we did an *a priori* comparison of a set of posited logistic regression models including life history stage, species and the four different measures of debris encounter rate. We tested several different measures to determine whether time was a significant predictor of ingestion probability. First, we incorporated the start and end dates of each study, and secondly, we assessed encounter rates for

both the present day debris distribution map and the debris distribution maps corresponding to the start date of each individual study. The Akaike's information criteria (AIC) values for each model were calculated and compared to a null model to determine which model explained the data best. Because we only had data for a single flatback turtle, we excluded flatback turtles from analyses. To determine whether debris ingestion by stranded turtles adequately represented ingestion rates of the population as a whole, we added a regressor to compare the stranded turtles with the turtles that were bycatch from fishing vessels.

We used the results of the binomial model to estimate the risk of debris ingestion at predicted debris exposure levels for each species of turtle at each map pixel (1 degree by 1 degree) within its range (the sum of all RMUs for that species). The measurement of risk (probability of debris ingestion) can range between 0 and 1. We then assessed the risk to neritic and oceanic animals separately. We used NOAA bathymetric data to partition our risk maps by depth (Pante & Simon-Bouhet, 2013), and calculated the average risk to oceanic animals at depths >200 m, and the risk to neritic animals at depths <200 m (Hatase *et al.*, 2006). To estimate global risk levels to all turtle species, we summed the risk predictions for each map pixel over all of the species whose range overlapped that pixel. High-risk areas can therefore result from a low number of species with high-risk predictions, or a greater number of species with lower risk predictions.

We further calculated the average risk to turtles within each RMU (for each individual species) and determined the relative risk by scaling these risk factors from 0 to 1, zero representing the lowest risk observed over all RMUs and 1 representing the highest risk observed over all RMUs for all species combined.

Results

Exposure (debris mapping)

A total of 301 debris distribution map predictions were created, one at each 2-month time interval between 1960 and 2010, which we used in conjunction with species distribution maps to estimate exposure rates.

Consequence (necropsy data)

We found a total of 37 published papers using our search terminology, plus the longline caught sea turtle data (Wedemeyer-Strombel *et al.*, in press). For a

comprehensive list of relevant publications see Table S1. Because some papers reported on multiple species, life history stages and dates, a total of 153 replicates were used to refine model predictions (Table 1). Each replicate is a unique combination of species, life history stage, date and location and is therefore analysed separately within the model. The sample size of the studies ranged from a minimum of seven turtles (Seminoff *et al.*, 2002a) to a maximum of 192 turtles (Quinones *et al.*, 2010). The debris levels for the replicates incorporated in the model covered a wide spread of the predicted global debris levels (Fig. S1).

Risk assessment (probability of debris ingestion)

The best-fit binomial model for debris ingestion (AIC = 810) incorporated life history stage, species and the mean debris density within 250 km of the stranding location based on the debris scenario appropriate to the starting year of the study (Table S2).

The deviance values indicate that this model accounts for approximately 30% of the variability seen in the necropsy data. The regression term for stranded vs. by-caught turtles was not significant.

Start and end date of a necropsy study were both positively correlated with debris ingestion ($P < 0.0001$), indicating that ingestion rates have increased with time. However, these parameters did not improve model results as much as using debris predictions corresponding to the study start date ($P < 0.0001$). Because the technique used in the debris predictions incorporates rising levels of plastic over time, this result also indicates increasing debris ingestion rates over time.

Oceanic life-stage turtles were significantly more likely ($P = 0.00028$) to ingest debris than turtles of an unknown life stage, while neritic life-stage turtles were less likely ($P < 0.0001$) to ingest debris. With green turtles as a reference species, Kemp's ridley and loggerhead turtles were significantly less likely to ingest debris at a given exposure level, while olive ridley turtles had a higher likelihood of debris ingestion (all significant at 0.05 level) (Table S3).

The risk of plastic ingestion to sea turtle populations is highest in the north Pacific gyre, in the eastern Indian

Table 1 Total number of studies and data points used to develop the risk model

	Green	Loggerhead	Hawksbill	Kemps ridley	Leatherback	Olive ridley	Flatback
No. of papers	23	21	2	7	5	1	1
Total no. of turtles	765	809	33	355	166	45	1
No. of replicates	54	29	11	8	5	45	1
No. of regional management units (of total) represented	9 (17)	6 (10)	2 (13)	1 (1)	2 (7)	1 (8)	1 (2)

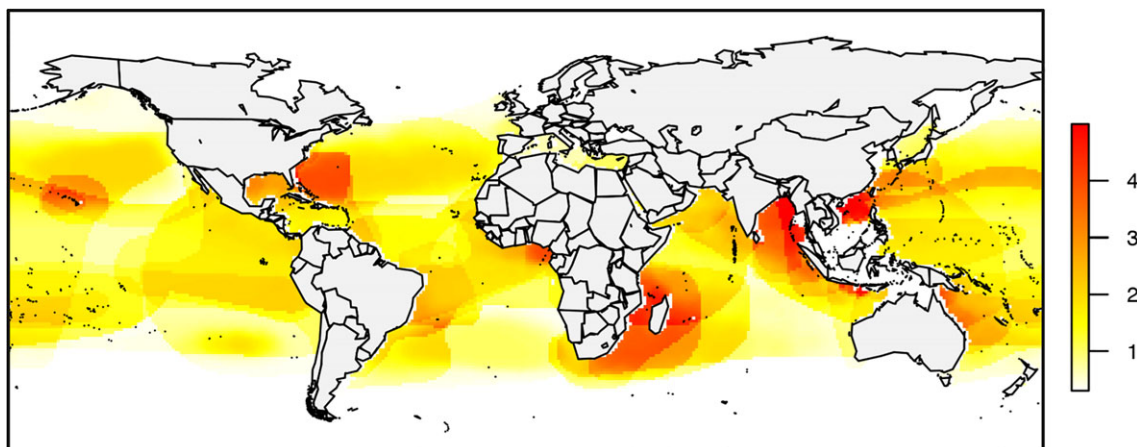


Fig. 1 Predicted probability of debris ingestion risk for all species. Red indicates a high probability of debris ingestion while lighter colours indicate lower probability of debris ingestion.

Ocean and South China Sea, and off of the east coasts of Australia, North America and southern Africa (Fig. 1). Globally, risk levels are variable, but over their entire species range, olive ridley turtles have a higher median risk of ingestion than other species, while Kemp's ridley turtles have the lowest median risk (Figs 2 and 3). Loggerhead, green, hawksbill and leatherback turtles have similar levels of overall risk.

Discussion

By utilising a combination of data sources including ocean drifters, sea turtle distributions and field necropsies, we evaluated which factors are the best predictors of debris ingestion rates in sea turtles at a given debris exposure level and also assessed the likelihood of debris ingestion across the geographic range of the species.

Model parameters

Debris encounter rates are a significant factor; the more debris present in an area, the greater the likelihood that a turtle will ingest it. The best-fit model incorporated debris encounter rates within a 250 km radius of the necropsied animals, indicating that they are likely ingesting debris within a limited range of their stranding location. Although the 250 km radius from a stranding site is considerably larger than the home range for most species of turtle during foraging (Renaud & Carpenter, 1994; Van Dam & Diez, 1998; Seminoff *et al.*, 2002b), turtle carcasses may have drifted some distance from where the animal died, and study regions often encompassed a much larger area than the single central point that was chosen as the location of death in the absence of more detailed information. Additionally, animals in these studies included not only juvenile turtles that might have only recently

recruited from ocean waters, but also adults that might have completed or were in the process of reproductive migrations. The published necropsy studies do not discriminate between migration, foraging and developmental life stages. Hence, the 250 km range, which optimises the model output, integrates turtles from all life history stages and behaviours. While knowing whether an animal was migrating or feeding at time of death could add to the predictive capacity of the model, we did not have the detailed data necessary to incorporate this into the model.

Contrary to what was found for sea turtle entanglement in ghost nets (Wilcox *et al.*, 2013), encounter rates alone do not adequately predict debris ingestion by sea turtles. This suggests that selectivity plays a more important role in ingestion than in entanglement, with turtles either preferentially ingesting or avoiding particular types of debris. The same appears to be true for the northern fur seal, which also exhibits no selectivity with respect to entanglement (Fowler, 1987), although the species does appear to selectively ingest particles of a particular size range (Eriksson & Burton, 2003). The concept of selectivity of marine debris with respect to ingestion has been investigated in a variety of taxa, including seabirds (Acampora *et al.*, 2013) and turtles (Schuyler *et al.*, 2012), and is critical to designing effective conservation measures. Many factors may influence this selectivity, including life history stage, foraging strategy, physical characteristics of debris and the visual capacity of the animal. Further iterations of this model could potentially incorporate varying debris characteristics to refine debris distribution maps, tailoring them to the preferences of individual species or life history stages.

The results of our model indicate that life history stage is a critical factor governing debris ingestion (Figs 2 and Table S3). As can be seen from the global

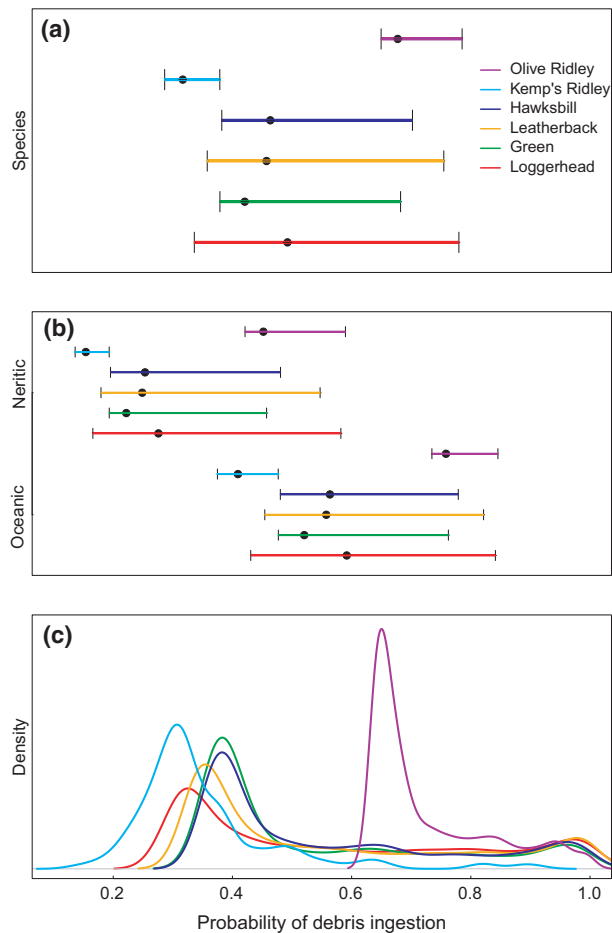


Fig. 2 Predicted probability (0–1) of risk of debris ingestion (a) for all turtles, and (b) for oceanic and neritic animals. Boxplot lines extend from the first quartile to the third quartile, and the central dot indicates the median risk value for each species. (c) density plot of the spread of risk predictions for each species.

risk maps, individuals that pass through oceanic gyres experience an increased likelihood of debris ingestion (Fig. S2). Thus, oceanic turtles are more likely to ingest debris than their benthic-feeding counterparts not only because of their life history stage, but also because of their behaviour and distribution (Balazs, 1985; Plotkin & Amos, 1990; Schuyler *et al.*, 2012). Although oceanic-feeding turtles tend to be early stage juveniles, there are certain populations of loggerhead and green sea turtles (Hatase *et al.*, 2002, 2006) that utilise oceanic habitats even as adults. Increased mortality from plastic ingestion at these stages could have an even greater population-level impact than at a juvenile stage. Further modelling of the effects of debris ingestion by different life history stages on population dynamics could assist managers in focusing remediation efforts (Fig. 3).

Time was also an important factor in predicting ingestion rates. The best-fit model included debris

predictions relevant to the start date of each study. Because these debris predictions incorporate rising global plastic production rates, they correspond to ingestion rates that have increased over time (Schuyler *et al.*, 2014). If these rates continue on their current trajectory, we would expect corresponding increases in the probability of debris ingestion by turtles at all stages of life.

Incorporating species identities in the model also improved its predictive capability, as different species have different likelihoods of debris ingestion (Fig. 2). The modelling combined with the risk analysis gives us several different ways of assessing differences between species. For example, model results indicate that loggerhead turtles are less likely than green turtles (the reference species) to ingest debris at a given debris exposure level. However, the median risk to loggerheads is greater than to green turtles, because the loggerheads' range has a greater overlap with oceanic gyres, where debris concentrations are highest. Conversely, Kemp's ridley turtles have a much lower risk, as their range is much more limited. Olive ridley turtles were more likely than other turtles to ingest debris at a given debris concentration. This may be in part due to their diet and foraging behaviour. Unlike postpelagic green turtles, Kemp's ridley turtles and leatherback turtles, adult olive ridley turtles are generalist omnivores. Their diet ranges widely and varies among locations, but jellyfish are a common dietary component (Bjorndal, 1997). This propensity for generalist foraging, and particularly in foraging on organisms in the mid-water column, may lead to increased incidences of plastic ingestion. While loggerheads are also generalists, they typically select carnivorous prey, often hard shelled crabs and molluscs and typically feed on organisms on the benthos (Dodd, 1988; Bjorndal, 1997). Kemp's ridley turtles too are carnivorous, primarily subsisting on crabs (Burke *et al.*, 1994). Feeding on benthic organisms means that these species are less likely to encounter and ingest floating marine plastics.

Risk analysis

Combining the risk maps for individual species provides a global perspective that can be used to prioritise efforts to reduce debris ingestion by sea turtles. Areas that have high concentrations of marine debris, high turtle species diversity or a combination of the two will tend to have a high degree of risk. It is clear from the risk map (Fig. 1) that the coastlines of southern China and Southeast Asia, the east coasts of Australia, the USA and southern Africa, and the Pacific gyre are hot-spots for debris ingestion and a high priority should be placed both on reducing debris inputs in these areas, and cleaning existing debris.

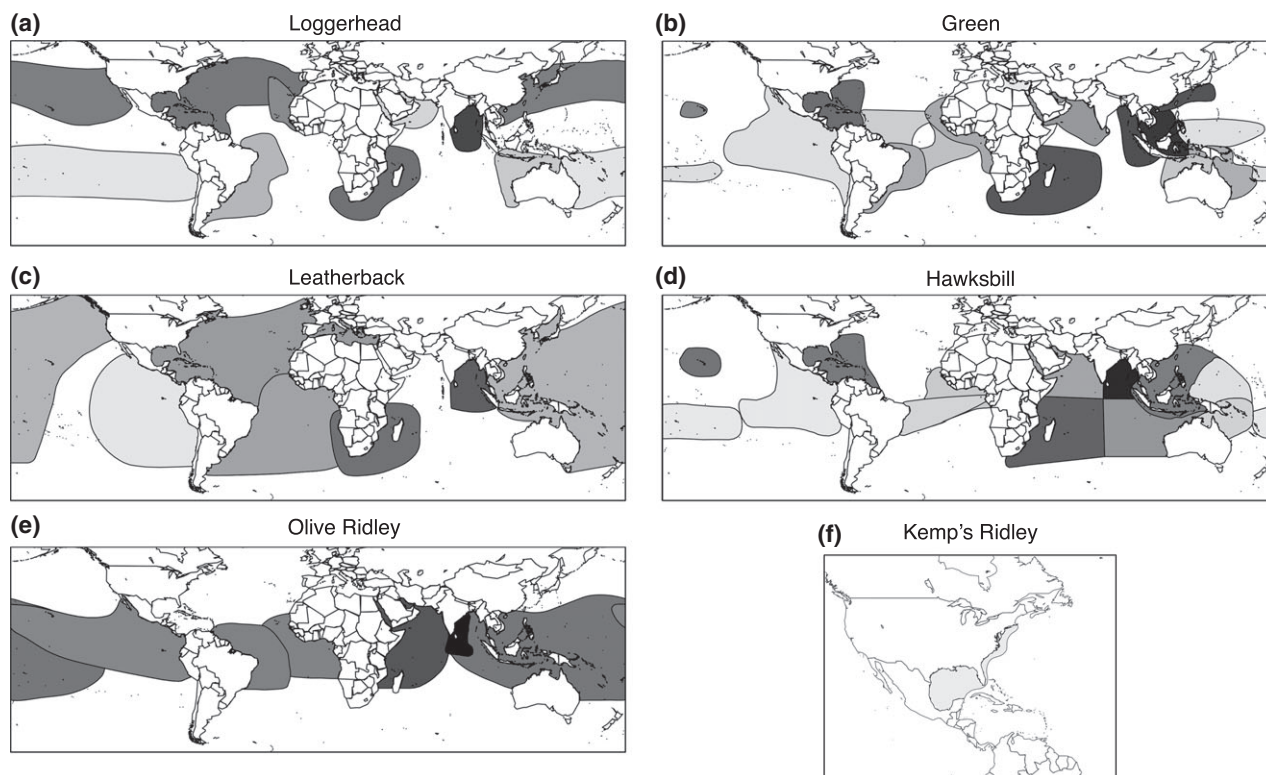


Fig. 3 Locations and relative risk values [scaled from lowest risk (white) to high risk (black)] of each regional management unit (RMU). (a) Loggerhead turtles, (b) green turtles, (c) leatherback turtles, (d) hawksbill turtles, (e) olive ridley turtles, and (f) Kemp's ridley turtles. Values are scaled across all species to allow comparison between species.

Unfortunately, debris ingestion is only one of the threats facing these sea turtle populations. A recent study characterised the overall threats to turtles from bycatch, take and coastal development in conjunction with the risk of extinction (based on a variety of population measures). A total of 11 RMUs were characterised as High Risk–High Threat and therefore at greatest risk of extinction (Wallace *et al.*, 2011). Of these, five fell within our eight most heavily impacted RMUs (Fig. 3, Table S4). Debris ingestion is not only a problem on its own, but is an additional threat to turtles that already face a multitude of stressors.

Caveats and data gaps

Clearly, there are limits to the predictive capacity of any model, based on the quality and availability of data to input into it. Our model relies on two key pieces of information, the amount and distribution of plastic at sea, and the location where turtles ingest that plastic. Unfortunately, neither of these data sets is directly available, so we infer them using proxy measures, and incorporate the resulting uncertainty using a statistical model to connect these proxy measures to observed ingestion rates in necropsied turtles.

To determine the amount of plastic at sea, we use oceanographic modelling based on drifters. Limitations of this approach include the unavailability of drifters in certain areas of the ocean, particularly within the Indonesian archipelago. This means that we are unable to predict ingestion rates in these areas. Secondly, the global scale debris modelling has areas of under-fit and over-fit. Empirical data indicate that models underestimate the debris in the Mediterranean Sea (unpublished data). Conversely, the model predicts a very high risk of debris ingestion for turtles in oceanic gyres. Recent empirical observations of debris at sea indicate that surface debris levels in the gyres are lower than debris predictions would indicate (Law *et al.*, 2010; C3zar *et al.*, 2014). Currently, however, there are inadequate observational data to be able to build such global scale plastic distributions, so we must rely on the best available modelling data to approximate debris levels. Fortunately, recent evaluations indicate that models are, on the whole, relatively accurate in predicting the location of debris maxima, although of course debris levels can fluctuate both spatially and temporally with weather and oceanographic conditions (Law *et al.*, 2014).

Determining where turtles ingest plastic, and indeed, ingestion rates for the general population of animals is

also problematic. To estimate these parameters, we have used data from necropsied individuals. To assess where they may have ingested the plastics, we compared multiple measures of exposure in our modelling. We found that the best-fit model indicates that turtles have ingested plastics within a limited distance of their stranding location. Although stranded sea turtles are not necessarily representative of live turtle populations, the only methods for detecting debris in live turtle populations are lavage and faecal analysis, both of which are challenging to conduct on a large scale, and dramatically underestimate debris levels (Seminoff *et al.*, 2002a). In order to assess whether stranded turtles provided an overestimate of debris ingestion as compared to the background population, we tested whether there was a statistically significant difference between turtles caught by fishing vessels in our sample and those found stranded. Turtles caught by vessels are presumed to have died of a known cause unrelated to plastic ingestion, and so should be representative of the background level of plastic in the population as a whole. The differences between the two were insignificant, indicating that debris ingestion by stranded turtles is equally as representative of the general population as from by-caught turtles.

We were also unable to find data from benthic-feeding olive ridley turtles. Presuming that the relationship between life history stages is similar for olive ridley turtles as in other species, model parameters should be able to accommodate this data gap. Additional data from under-represented species, such as hawksbill turtles, leatherback turtles and benthic-feeding olive ridleys, would further improve model results.

Here we have estimated the probability that turtles ingest marine debris, but what happens as a result of that ingestion is of critical importance. Even as little as 0.5 g of ingested debris can cause mortality (Santos *et al.*, 2015), but turtles are also subject to a number of sublethal impacts such as dietary dilution, reduced fitness and absorption of toxic compounds (Ryan & Jackson, 1987; McCauley & Bjorndal, 1999; Talsness *et al.*, 2009). Unfortunately, there were not sufficient data to model the impacts from plastic ingestion in this analysis. Of the studies incorporated in our model, relatively few report the result of debris ingestion by sea turtles, those that do are highly variable in their estimates of death caused by plastics (e.g. Plotkin & Amos, 1990; Lazar & Gracan, 2011). One reason for this uncertainty is that death due to plastic ingestion may be masked by other ancillary conditions. Santos and colleagues reported that while 10.7% of turtles were definitively killed by plastic ingestion, 39.4% had ingested enough plastic to have killed them (2015). Our risk analysis focuses on predicting the likelihood of debris ingestion by sea

turtles, but we believe that further research into predicting population and species level impacts from that ingestion is of critical importance.

For such a large, multivariate study, there are multiple potential sources of error, and reporting confidence limits for map-based predictions is also complex. We elaborate on these potential error sources in the Supplemental Information (Data S6) and provide a graphic representation of the error due to the regression model (Fig. S3).

Applications

Despite the limitations imposed on the model by the availability of data inputs, the information it yields fills a critical research gap both in the fields of plastic marine pollution (Vegter *et al.*, 2014) and in sea turtle conservation and ecology (Hamann *et al.*, 2010). Applying a risk analysis approach is an effective way of prioritising which factors are most relevant on which to focus conservation resources. We have used the most comprehensive and accurate data sources currently available, and the predictions yielded by this method will only become stronger as the data inputs are refined and improved.

One potential product of our risk analysis is an estimate of the total number of turtles that have ingested plastics globally. For example, SWOT data include population estimates for nesting adult females for 35 of the 55 RMUs in our model (Table S4). The total population estimate for these 35 RMUs is 647 971. Multiplying these population data by the likelihood that a turtle in a particular RMU has ingested debris gives us a total estimate of just over 340 000 individuals, or 52% of the turtles for which population estimates exist. This estimate is certainly within the bounds of ingestion rates that have been reported regionally (e.g. Bugoni *et al.*, 2001; Tomas *et al.*, 2002; Tourinho *et al.*, 2010). However, while the SWOT sea turtle RMUs represent the best data currently available to describe global sea turtle distributions, these distributions and associated population estimates are merely that estimates based on expert data, with no confidence limits reported. Thus, this figure of the number of turtles having ingested debris is currently highly speculative. However, as estimates are refined and updated, these outputs will become more accurate and thus more useful. We can also use the model results to predict the outcomes of various management actions, or as inputs to population dynamic modelling to determine population-level effects.

The map of global risk to sea turtles highlights the areas of greatest concern and pinpoints where to focus limited resources on amelioration. The developed nations of Australia and the USA both adjoin high-risk

areas for debris ingestion, and we urge resources to be put towards reducing debris inputs into the ocean from these countries in particular. Similarly, Southeast Asia and the east Indian Ocean are not only areas of high risk to turtle populations, but are also extremely data poor, both with respect to sea turtle population dynamics (Wallace *et al.*, 2011) as well as oceanographic models (Van Sebille *et al.*, 2012). This region therefore represents a critical location on which to focus research efforts.

Importantly, this methodology is applicable not only to the sea turtle example profiled in this work, but also can be extended to address similar problems for other species. Other studies have assessed risk from a variety of human impacts (e.g. Halpern *et al.*, 2008; Wallace *et al.*, 2011), but few studies have taken the next step in using empirical data to fit and validate the models. This technique has already been successful in predicting sea turtle interactions with ghost nets (Wilcox *et al.*, 2013), and could also be utilised in investigating impacts from oil spills on migratory animals, or to assess the risks from habitat loss due to urban development on land, among others.

Promisingly, data from seabirds in the north Atlantic indicate that as ocean debris levels decline, debris ingestion rates also decrease (Van Franeker *et al.*, 2011). If source reduction efforts are targeted to items that are most commonly ingested by turtles [e.g. clear soft plastics (Schuyler *et al.*, 2012)], and overall exposure levels can be reduced, model results predict a corresponding drop in ingestion rates.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Studies used to determine debris ingestion likelihood.

Figure S1. Comparison of the range of debris concentrations covered by study observations and by global debris map predictions.

Table S2. AIC and deviance values for the logistic regression models tested.

Table S3. Model coefficients for best-fit model, incorporating life history stage (LHS), species (SP), and debris concentrations within 250 km of stranding location, utilising debris predictions corresponding to the start date of each study (TIME CUT).

Figure S2. Predicted probability of debris ingestion risk for each species (from 0 to 1). Red indicates a high probability of debris ingestion while lighter colours indicate lower probability of debris ingestion. Blue dots indicate the location of studies used to parameterize the risk model.

Data S1. Uncertainty in the risk analysis model.

Figure S3. Standard error maps for regression model predictions. Darker red values indicate a higher standard error, while lighter values are a lower standard error.

Table S4. RMU boundaries, population estimate, and relative risk level for each RMU, scaled from 0 (low risk) to 1 (high risk).