CORAL REEFS

Plastic waste associated with disease on coral reefs

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Plastic waste can promote microbial colonization by pathogens implicated in outbreaks of disease in the ocean. We assessed the influence of plastic waste on disease risk in 124,000 reef-building corals from 159 reefs in the Asia-Pacific region. The likelihood of disease increases from 4% to 89% when corals are in contact with plastic. Structurally complex corals are eight times more likely to be affected by plastic, suggesting that microhabitats for reef-associated organisms and valuable fisheries will be disproportionately affected. Plastic levels on coral reefs correspond to estimates of terrestrial mismanaged plastic waste entering the ocean. We estimate that 11.1 billion plastic items are entangled on coral reefs across the Asia-Pacific and project this number to increase 40% by 2025. Plastic waste management is critical for reducing diseases that threaten ecosystem health and human livelihoods.

Outbreaks of disease on coral reefs threaten one of the most biodiverse ecosystems on the planet (*1*), jeopardizing the U.S. $375 billion in goods and services that they provide to people each year through fisheries, tourism, and coastal protection (*2*). Plastic waste can host pathogens that are frequently implicated as triggers of disease outbreaks on coral reefs (*3–9*). For example, microbial communities colonizing polypropylene marine debris were dominated by the genus *Vibrio* (*10*), an opportunistic pathogenic bacteria of a globally devastating group of coral diseases known as white syndromes (*11*). Although an estimated 4.8 million to 12.7 million metric tons of plastic waste enter the ocean in a single year (*12*), the resulting influence on disease susceptibility in the marine environment is unknown. Microbial rafting on plastic debris has been shown to strongly control surface longevity (*13*) and is highest in tropical regions near the equator compared with more polar regions (*14*), suggesting that coral reef ecosystems could have high levels of colonized plastic waste.

We surveyed 159 coral reefs spanning eight latitudinal regions from four countries in the Asia-Pacific for plastic waste and evaluated the influence of plastic on diseases that affect keystone reef-building corals (*15*) (benthic area = 12,840 m^2) (Fig. 1). The Asia-Pacific region contains 55.5% of global coral reefs (*2*) and encompasses 73.0% of the global human population residing within 50 km of a coast (*12*) (table S1). Overall, we documented benthic plastic waste (defined as an item with a diameter >50 mm) on one-third of the coral reefs surveyed, amounting to 2.0 to 10.9 plastic items per 100 m^2 of reef area [95% confidence interval (CI), n = 8 survey regions]. The number of plastic items observed on each reef varied markedly among countries, from

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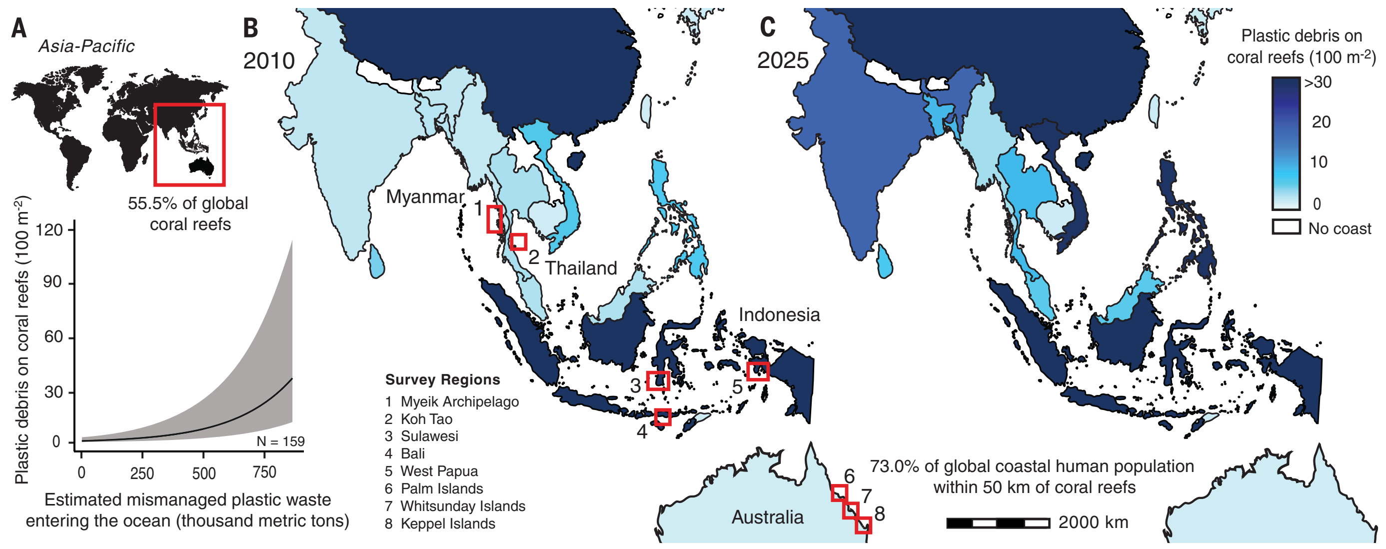

Fig. 1. Estimated plastic debris levels on coral reefs. (**A**) Modeled association between plastic debris on coral reefs from surveys of 159 reefs in eight regions [red squares in (B)] from 2011–2014 and estimated levels of mismanaged plastic waste (thousand metric tons), assuming that 25% of waste entered the ocean in 2010 from human populations living within 50 km of the coast for each country (*12*). Reef locations can be found in table S14. The Asia-Pacific region encompasses 9 of 10 countries with the highest global levels of estimated mismanaged plastic waste entering the ocean (table S3). Gray shading represents the upper and lower 95% CIs for the model. (**B** and **C**) Modeled plastic debris levels on coral reefs (100 m^{-2}), as projected using the association between estimated mismanaged plastic waste entering the ocean in 2010 for each sovereign country (*12*) and plastic debris surveys between 2011–2014 [shown in (A)]. The color scale represents the minima and maxima model estimates of mismanaged plastic waste on coral reefs from 2010 (table S5). Projections of plastic debris on coral reefs for Indonesia and China in 2025 were set to the maxima from 2010, owing to the limitations of the model range. Countries without a coastline are shown in white.

maxima in Indonesia [25.6 items per 100 ± 12.2 m^2 (here and elsewhere, the number after the ± symbol denotes SEM)] to minima in Australia (0.4 items per 100 ± 0.3 m^2) (table S2).

Terrestrially derived pollutants have been implicated in several disease outbreaks in the ocean (*16*). However, no studies have examined the influence of plastic waste on disease risk in a marine organism. In this work, we visually examined 124,884 reef-building corals for signs of tissue loss characteristic of active disease lesions (*15*) (fig. S1). We found plastic debris on 17 genera from eight families of reef-forming corals. When corals were not in contact with plastic debris, the likelihood of disease was 4.4 ± 0.2% across all eight regions (range = 2.8 to 8.4%, generalized linear mixed model, likelihood ratio test among regions: $\chi^2_7 = 10.382$, $P = 0.168$) (Fig. 2A). In contrast, in the presence of plastic debris, the likelihood of disease occurrence in corals increased significantly by more than a factor of 20 to 89.1 ± 3.2% (generalized linear mixed model: *z* score = 27.24, $P < 0.001$, $n = 331$ transects) (Fig. 2B and table S3).

Human population size in coastal regions and the quality of waste management systems largely determine which countries contribute the greatest plastic loads entering the ocean, given that an estimated 80% of marine plastic debris originates from land (*12*). Accordingly, we modeled the relationship between our documented levels of plastic debris on coral reefs ($n = 437$ transects from Australia, Myanmar, Thailand, and Indonesia) and Jambeck *et al.*'s estimated levels of mismanaged plastic waste entering the ocean (*12*) from these four countries in 2010 (*15*) (generalized linear mixed model: Akaike information criterion = 662.3, $z = 3.95$, $P < 0.001$) (Fig. 1A, fig. S2, and table S4). Our model encompasses the range of mismanaged plastic waste entering the ocean introduced by coastal populations from 15 of the 17 (88%) sovereign countries in the Asia-Pacific region (maximum = 804,214 metric tons, minimum = 3472 metric tons), of which 9 are among the top 10 plastic-polluting countries globally (table S5). Assuming that improvements in waste management infrastructure did not occur during our survey period (2011–2014) and that the plastic waste emanated from adjacent terrestrial point sources, we estimate that levels of plastic debris on coral reefs for each country in the Asia-Pacific ranged from 0.9 to 26.6 plastic items per 100 m^2 in 2010 (95% CI) (Fig. 1B and table S5). This amounts to an estimated 11.1 billion items of plastic on coral reefs across the Asia-Pacific (95% CI = 1.2 billion to 105.5 billion items, $n = 15$ countries), which is likely underestimated owing to the exclusion of China and Singapore because they fall outside of the model range (table S5).

By 2025, the cumulative quantity of plastic waste potentially entering the marine environment from land is predicted to increase by one order of magnitude (*12*). Using this projection and assuming that the area encompassed by coral reefs remains constant, we estimate that 15.7 billion plastic items will be entangled on coral reefs across the Asia-Pacific by 2025 (the "business-as-usual" scenario for global infrastructure: 95% CI = 1.7 billion to 149.2 billion items) (Fig. 1C and table S5). According to our model, the predicted geographic distribution of plastic debris on coral reefs does not change substantially between now and 2025 (Fig. 1, B and C), but the disparity in quantities of accumulated plastic waste between developing and industrialized countries grows considerably. For example, plastic debris on coral reefs increases by only ~1% in high-income countries such as Australia but nearly doubles in a similarly populated low-income country such as Myanmar (Fig. 1C and table S5).

Comparative analyses of disease prevalence among different diseases in the presence versus absence of plastics can offer insights into potential mechanisms that increase disease susceptibility in corals. Reef-building corals in contact with plastic debris were affected by four of six common diseases globally (*17*), whereas corals without plastic debris were affected by all six diseases but at much lower prevalence levels (table S6). Disease assemblages on reef-building corals differ distinctly when contact with plastic waste is present versus absent, as visualized by a principal coordinates ordination analysis (*15*) (permutational multivariate analysis of variance: $F = 11.86$, $P < 0.001$, $n = 75$ paired transects) (Fig. 3). In particular, three key diseases associated with rapid coral mortality increased markedly when plastic debris was in contact with coral tissues: Skeletal eroding band disease increased from 1.2 ± 0.1% to 43.9 ± 5.1% (increased likelihood = 24%), white syndromes increased from 1.9 ± 0.2% to 19.0 ± 4.0% (increased likelihood = 17%), and black band disease increased from 0.6 ± 0.1% to 14.7 ± 3.9% (increased likelihood = 5%) (tables S7 to S10).

Given the widespread distribution of plastic debris on coral reefs and the consequent increased

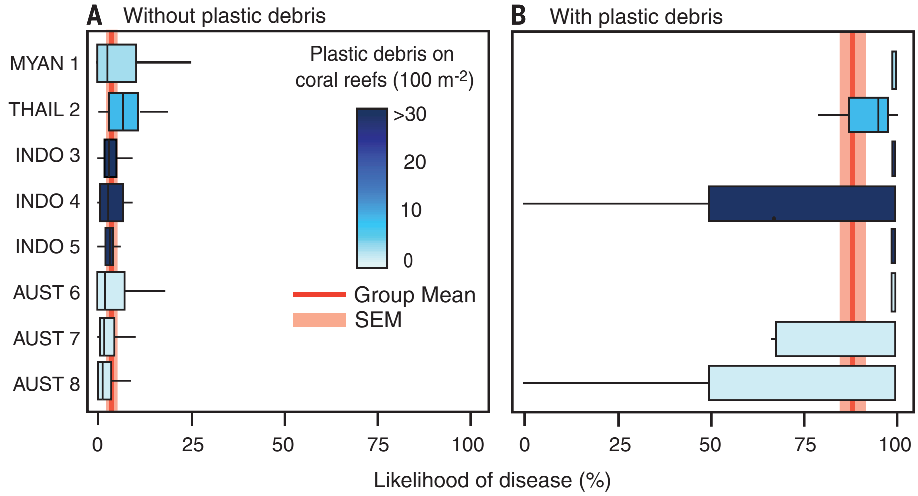

Fig. 2. Plastic waste influences disease susceptibility of reef-building corals. (**A** and **B**) Box (median and 50% quantile) and whisker (95% quantile) plots of coral disease likelihood for each of eight regions in four countries in the Asia-Pacific when no plastic waste is present (A) ($n = 362$ transects) and when plastic waste is present (B) ($n = 75$ transects). The red line represents the mean and the light red bar denotes ±1 SEM across all eight regions. Boxes are shaded according to model estimates of plastic debris on coral reefs per 100 m^2 from Fig. 1C. MYAN, Myanmar; THAIL, Thailand; INDO, Indonesia; AUST, Australia.

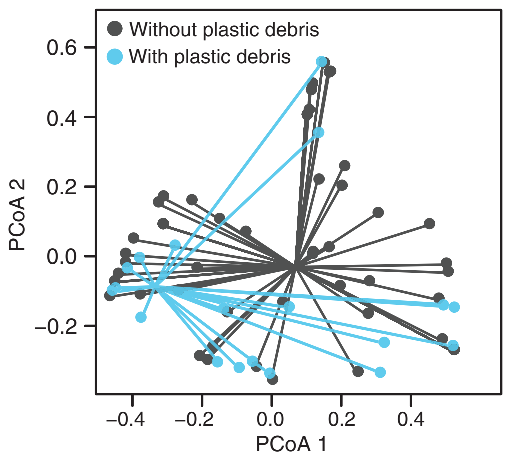

Fig. 3. Reef-building corals with plastic debris have different disease assemblages than corals without plastic debris. Multivariate spatial representation of the relative abundance and composition of coral disease assemblages, as determined by a principal coordinates analysis (PCoA) ($n = 75$ paired transects). Vectors for each group illustrate the median spatial distance within the group. Disease assemblages represent six diseases—skeletal eroding band, white syndromes, black band, growth anomalies, brown band, and atramentous necrosis—recorded commonly across the globe.

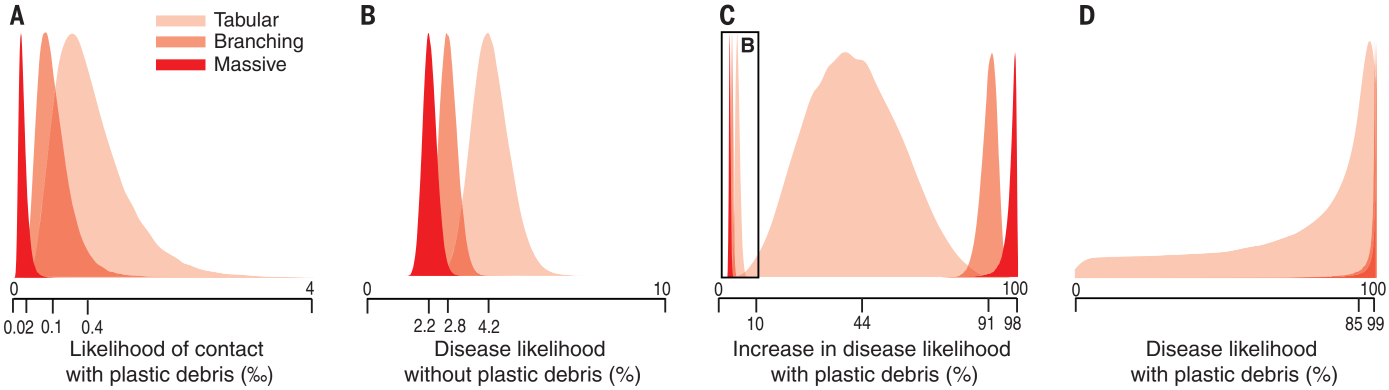

Fig. 4. Coral morphological complexity influences risk to plastic debris and disease. (**A** to **D**) Posterior probability density functions of coral species grouped into three broad morphological classifications. Structural complexity is determined by coral species (*18*); see table S11 for classifications. Minimum, maximum, and peak values are shown for each structural complexity classification group: massive (dark red), branching (medium red), and tabular (light red). For ease of comparison, the inset in (C) represents the likelihood of disease without plastic debris [as shown in (B)].

likelihood of coral mortality from disease, we evaluated the potential for plastic debris and disease to affect structural complexity provided by habitat-forming corals. The structural complexity formed by corals underpins the availability of microhabitats for coral reef–associated organisms (*18*). We grouped coral species into three broad classifications based on the increasing structural complexity of their colony morphologies (massive < branching < tabular) (table S11) and determined that plastic debris is eight times more likely to affect reef corals with greater structural complexity (tabular and branching versus massive, n = 348 transects; posterior probability functions) (Fig. 4A and table S12). Massive coral morphologies are less likely to maintain contact with plastic debris; however, they exhibit the greatest increase in disease risk when this occurs (likelihood is increased by 98%) (Fig. 4, B to D, and table S13).

Our study shows that plastic debris increases the susceptibility of reef-building corals to disease. Plastics are a previously unreported correlate of disease in the marine environment. Although the mechanisms remain to be investigated, the influence of plastic debris on disease development may differ among the three main global diseases that we observed. For example, plastic debris can cause physical injury and abrasion to coral tissues by facilitating invasion of pathogens (*19*) or by exhausting resources for immune system function during wound-healing processes (*20*). Experimental studies show that artificially inflicted wounds to corals are followed by the establishment of the ciliated protozoan *Halofolliculina corallasia*, the causative agent of skeletal eroding band disease (*21*). Plastic debris could also directly introduce resident and foreign pathogens or may indirectly alter beneficial microbial symbionts. Cross-ocean bacterial colonization of polyvinylchloride (PVC) is dominated by *Rhodobacterales* (*22*), a group of potentially opportunistic pathogens associated with outbreaks of several coral diseases (*23*). Additionally, recent studies have shown that experimental shading and low-light microenvironments can lead to anoxic conditions favoring the formation of polymicrobial mats characteristic of black band disease (*24*).

By disproportionately reducing the composition or abundance of structurally complex reef-building coral species through disease, widespread distribution of plastic waste may have negative consequences for biodiversity and people (*25*). For example, on coral reefs, the loss of structural habitat availability for reef organisms has been shown to reduce fishery productivity by a factor of 3 (*26*).

Climate-related disease outbreaks have already affected coral reefs globally and are projected to increase in frequency and severity as ocean temperatures rise (*27*). With more than 275 million people relying on coral reefs for food, coastal protection, tourism income, and cultural importance (*2*), moderating disease outbreak risks in the ocean will be vital for improving both human and ecosystem health. Our study indicates that decreasing the levels of plastic debris entering the ocean by improving waste management infrastructure is critical for reducing the amount of debris on coral reefs and the associated risk of disease and structural damage.

REFERENCES AND NOTES

1. C. D. Harvell *et al.*, *Science* **296**, 2158–2162 (2002).
2. L. Burke, K. Reytar, M. Spalding, A. Perry, *Reefs at Risk Revisted* (World Resources Institute, 2011).
3. I. V. Kirstein *et al.*, *Mar. Environ. Res.* **120**, 1–8 (2016).
4. S. Oberbeckmann, M. G. Löder, M. Labrenz, *Environ. Chem.* **12**, 551–562 (2015).
5. C. A. De Tender *et al.*, *Environ. Sci. Technol.* **49**, 9629–9638 (2015).
6. K. M. Morrow, R. Ritson-Williams, C. Ross, M. R. Liles, V. J. Paul, *PLOS ONE* **7**, e44859 (2012).
7. M. M. Nugues, G. W. Smith, R. J. Hooidonk, M. I. Seabra, R. P. Bak, *Ecol. Lett.* **7**, 919–923 (2004).
8. J. E. Smith *et al.*, *Ecol. Lett.* **9**, 835–845 (2006).
9. M. J. Sweet, J. C. Bythell, M. M. Nugues, *PLOS ONE* **8**, e69717 (2013).
10. E. R. Zettler, T. J. Mincer, L. A. Amaral-Zettler, *Environ. Sci. Technol.* **47**, 7137–7146 (2013).
11. D. Bourne, T. Ainsworth, F. Pollock, B. Willis, *Coral Reefs* **34**, 233–242 (2015).
12. J. R. Jambeck *et al.*, *Science* **347**, 768–771 (2015).
13. F. M. Fazey, P. G. Ryan, *Environ. Pollut.* **210**, 354–360 (2016).
14. D. K. Barnes, *Nature* **416**, 808–809 (2002).
15. Materials and methods are available as supplementary materials.
16. S. Altizer, R. S. Ostfeld, P. T. J. Johnson, S. Kutz, C. D. Harvell, *Science* **341**, 514–519 (2013).
17. J. B. Lamb, D. H. Williamson, G. R. Russ, B. L. Willis, *Ecology* **96**, 2555–2567 (2015).
18. L. E. Richardson, N. A. J. Graham, A. S. Hoey, *Sci. Rep.* **7**, 7557 (2017).
19. J. B. Lamb *et al.*, *Philos. Trans. R. Soc. London Ser. B* **371**, 20150210 (2016).
20. L. D. Mydlarz, L. E. Jones, C. D. Harvell, *Annu. Rev. Ecol. Evol. Syst.* **37**, 251–288 (2006).
21. C. A. Page, B. L. Willis, *Coral Reefs* **27**, 257–272 (2008).
22. H. Dang, T. Li, M. Chen, G. Huang, *Appl. Environ. Microbiol.* **74**, 52–60 (2008).
23. N. Soffer, J. Zaneveld, R. Vega Thurber, *Environ. Microbiol.* **17**, 1203–1218 (2015).
24. M. S. Glas, Y. Sato, K. E. Ulstrup, D. G. Bourne, *ISME J.* **6**, 1526–1534 (2012).
25. B. Worm *et al.*, *Science* **314**, 787–790 (2006).
26. A. Rogers, J. L. Blanchard, P. J. Mumby, *Curr. Biol.* **24**, 1000–1005 (2014).
27. J. Maynard *et al.*, *Nat. Clim. Chang.* **5**, 688–694 (2015).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/359/6374/460/suppl/DC1
Materials and Methods
Figs. S1 and S2
Tables S1 to S14
References (*28*–*30*)

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Corals wrapped in plastic

Coral reefs provide vital fisheries and coastal defense, and they urgently need protection from the damaging effects of plastic waste. Lamb *et al.* surveyed 159 coral reefs in the Asia-Pacific region. Billions of plastic items were entangled in the reefs. The more spikey the coral species, the more likely they were to snag plastic. Disease likelihood increased 20-fold once a coral was draped in plastic. Plastic debris stresses coral through light deprivation, toxin release, and anoxia, giving pathogens a foothold for invasion.

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