Improving ecological function of polluted coasts under a tide of plastic waste

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Unprecedented levels of plastics are entering coastal seas, which are already subject to another insidious pollutant: excess nitrogen. Both pollutants were created to enhance human well-being on land but once in the sea they impair the function of filter-feeding organisms that help maintain coastal water quality. We conceptualized evidence to show that oysters (*Ostrea* spp), the reefs of which can provide a biological solution for managing water quality, can effectively reduce the threat of algal blooms caused by excess nitrogen pollution, even when exposed to moderate microplastic pollution. Yet the functional collapse of this ecosystem service (filter-feeding by oysters) is at risk if current trends in plastic pollution continue, and pollution thresholds that predict functional collapse have already been exceeded in the world's most polluted rivers. Nevertheless, although the plastic problem is daunting, growing social and political awareness of the need to reduce plastic waste provides hope that a sustainable material society can be attained.

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Marine plastic pollution is everywhere. From coastal waters to the deepest ocean, marine organisms are being exposed to increasing amounts of plastic waste, with uncertain consequences for ecosystem function (Rochman *et al*. 2016). This is concerning because functional marine ecosystems are essential for a sustainable society; the abundant food, economic basis of livelihoods, cultural opportunities, and nutrient regulation that coastal systems provide are foundational to human socioeconomic well-being (Costanza *et al*. 2014; Nash *et al*. 2021). But waste from our material culture increasingly drains to the world's seas via catchments and rivers (Jambeck *et al*. 2015; Isobe *et al*. 2019). Once in coastal waters, plastics can combine with other insidious pollutants that threaten coastal function (eg excess nutrient runoff), further risking the capacity of marine organisms to provide the ecological services that support society (eg maintenance of water quality). Without changes to our waste management and consumer choices, the growing plastic problem could destabilize coastal systems.

In a nutshell:

- Unprecedented levels of plastic and nitrogen pollution are entering coastal seas and challenging the function of filter-feeding organisms that help maintain water quality
- We suggest that – when exposed to moderate plastic pollution – oysters can mitigate algal blooms caused by excess nitrogen, but some major rivers already discharge plastic concentrations exceeding levels projected to lead to the functional collapse of oyster filter-feeding
- Recent social and political actions to reduce single-use plastics offer hope that the amount of plastic pollution entering the sea can be reduced
- If we can change our consumptive behavior to reduce plastic, we can work with nature to support the ecosystems that support our social well-being

Many "wicked" problems threaten coastal seas, with coastal algal blooms fueled by nutrient enrichment (eutrophication) and plastic pollution constituting two of the most visible threats. Our "plastic age" is also a time of industrial-scale food production reliant on nitrogen fertilizers, which fuel not only food production but also nutrient runoff that drives coastal algal blooms worldwide (Smetacek and Zingone 2013). The release of nitrogen from urban and agricultural catchments degrades coastal water quality and threatens the ecological functions on which societies' socioeconomic well-being depends (Tilman and Lehman 2001; Smetacek and Zingone 2013). Nitrogen transforms ecologically diverse ecosystems (eg kelp forests, coral reefs, seagrass meadows) into simplified ecosystems of low biodiversity and productivity (Tilman and Lehman 2001; Connell *et al*. 2008). Although both plastics and nitrogen are fundamental to the world economy and human well-being, their manufacture (refined fossil fuels versus nitrogen fixed by human activities) and application on land frequently ends with their discharge into the sea. Unsurprisingly, these pollutants are the focus of global sustainability goals to reduce marine pollution, "in particular debris from land-based activities, including marine debris and nutrient pollution" (UN Sustainable Development Goal 14.1).

Despite these pressures, ecosystem services can remain robust to moderate human stressors where functional marine communities persist. For example, filter-feeding communities,

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such as oyster reefs, can periodically withstand and effectively mitigate eutrophication events, offering a biological solution for managing coastal water quality (Kellogg *et al*. 2014). Oyster communities remove excess phytoplankton from the water column and can maintain water quality and ecological function of large coastal systems when aggregated en masse (eg pre-20th century Chesapeake Bay in the eastern US; Newell 1988). Although oyster reefs have been decimated worldwide (85% loss globally; Beck *et al*. 2011), interest in restoring oyster reefs as a solution to clean coastal waters continues to grow (Petersen *et al*. 2016; Rose *et al*. 2021). However, as continual filterers of tiny waterborne particles, oysters are vulnerable to rapid ingestion of microplastics that may impair their filtration function (Green *et al*. 2017) and capacity to benefit coastal society.

In this article, we discuss how curbing plastic pollution can provide opportunities for supporting the functioning of marine ecosystems that maintain coastal water quality on which society depends. We begin by providing proof-of-concept for the reduced functional capacity of an ecologically important filter-feeding organism, the oyster. These mollusks can build vast habitats that help maintain water quality, but they are susceptible to (micro)plastic ingestion, which may prevent them from controlling runaway algal blooms under the combined effects of microplastics and nitrogen enrichment. Therefore, we merged the global challenges of plastic and nitrogen pollution to investigate whether oysters can maintain their filtration function under gradients of pollution that already plague the world's most polluted coastlines, but where oyster reefs still persist (eg Quan *et al*. 2020). We then examined how recent social, industrial, and political actions to reduce plastic pollution may help galvanize the transition toward a more sustainable socioecological future. Finally, we argue that when people feel empowered to make positive change, be they members of the public or policy makers, we can work with nature to address global challenges by tackling them at our scale of influence.

Filtering Anthropocene seas

Healthy coastal systems are needed to achieve a sustainable future. Coastal seas have been subject to the increasingly heavy imprint of humanity over thousands of years (eg Jerardino 2012), with the addition of industrial pollutants over more recent centuries; yet they still provide services and goods essential to humanity. Marine ecosystems can be resilient to human stressors, but stress levels have never been greater than at present. To ground this discussion, we first explored estimates of the more extreme microplastic and nitrogen concentrations that coastal filter-feeding organisms may experience along coastlines subject to extreme pollution discharged by the world's most plastic-contaminated rivers (Schmidt *et al*. 2017). Using this information, we then exposed an ecologically important filter-feeder, the Australian flat oyster (*Ostrea angasi*), to real-world gradients of microplastic and nitrogen pollution to assess their capacity to mitigate algal blooms as pollution levels increase (see WebPanel 1 for detailed methods). Flat oysters (*Ostrea* spp) are increasingly recognized as important components of healthy coastal systems, and restoration of their ecosystem functions, including their capacity to filter coastal waters, has become the focus of large-scale restoration programs in Australia, Europe, and North America (Pogoda *et al*. 2019; McAfee *et al*. 2022).

Coastal pollution hotspots

Our analysis revealed that several of the world's major river systems discharge microplastics into coastal seas at concentrations that impair the filter-feeding function of oysters over even short exposure times (Figure 1; WebPanel 2). To determine this, we converted microplastic discharge (metric tons yr^{-1}) of the world's 25 most plastic-polluted rivers, as estimated by Schmidt *et al*. (2017), to micrograms of microplastics discharged per liter ($\mu g\ L^{-1}$) using the mean volume of water discharged per river system calculated by Milliman and Farnsworth (2011). For each of these 25 rivers, we estimated nitrogen pollution levels in each catchment from distribution maps of global agricultural nitrogen use (Lu and Tian 2017; WebPanel 1).

Consistent with other analyses on plastic waste entering the ocean (Jambeck *et al*. 2015), we found that the majority of the world's most plastic-polluted rivers are located in Asia (15 of the top 25), with four of the top eight rivers in China (WebTable 1). Combined with high concentrations of nitrogen runoff in rural China, where 31% of global nitrogen fertilizer is used (Lu and Tian 2017), several of China's rivers are "in the red" in their likelihood of destabilizing coastal ecosystems (Figure 1). Currently, this manifests as China's annual "green tides" that bloom in nitrogen-rich coastal waters, which incur substantial socioeconomic and ecological costs (Smetacek and Zingone 2013).

The extreme levels of river pollution in China are symptomatic of growing consumption following the recent alleviation of millions from poverty. Over the past 35 years, a 74% increase in grain production has greatly improved China's food security (Guo *et al*. 2020), driven by a near fourfold increase in fertilizer use. Reflecting this economic growth, China has become the planet's largest producer and consumer of plastics and, until 2017, imported almost half the world's plastic waste for manufacturing (Brooks *et al*. 2018). Consequently, China contains many of the most polluted rivers on Earth; it has been estimated that half of the world's ten most plastic-polluted rivers are in China, with these ten rivers carrying 88–95% of global riverine plastic pollution to the sea (Schmidt *et al*. 2017). Although alarming, this extreme concentration of the world's plastic pollution provides an opportunity to demonstrate global leadership. Steps to halve the plastic pollution in these ten rivers could reduce global plastic discharge to the sea by 45% (Schmidt

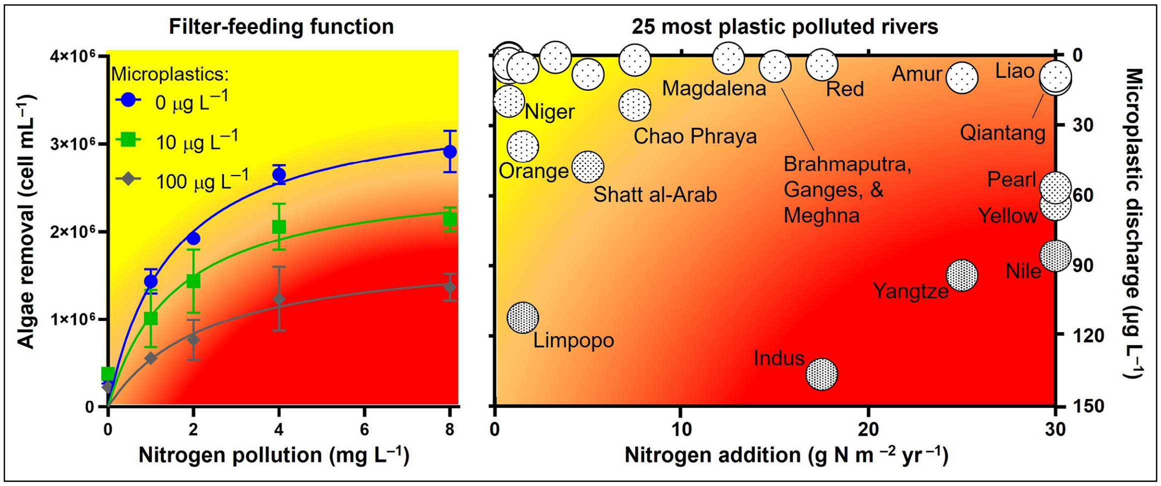

Figure 1. The filter-feeding function of oysters (left panel) increases as algal growth (mean ± standard error [SE]) is increasingly fueled by nitrogen (N) pollution, reducing the likelihood of algal blooms. However, this function is impaired when microplastic concentrations increase in tandem with rising N levels. Several of the world's major rivers discharge microplastic and N concentrations (right panel; number and density of dots within white circles signify intensity of microplastic pollution) that exceed the capacity of filter-feeding organisms to suppress algal blooms (green and gray lines in left panel), whereas most of the world's most polluted rivers discharge pollution (circles at top in right panel) that filter-feeders can suppress (blue line in left panel). Note: only 16 of the 25 rivers are labeled in the right panel, with the Ganges-Brahmaputra-Meghna collectively treated as one system.

et al. 2017). Together with China's growing ambition to rapidly reduce plastic pollution, including a national policy to phase out single-use plastics by 2025, there is increasing optimism that substantial reductions can be achieved. Despite the challenges, China's commitment to reduce plastic waste signifies a political will – one that is attentive and ambitious – to manage the world's plastic problem.

Impacts on the filter-feeders that clean coastal water

Oyster reefs are being restored worldwide to return key ecological services, such as productive fisheries, shoreline protection, and improved water quality (McAfee *et al*. 2020). In support of calls to use oysters to mitigate coastal eutrophication events (Kellogg *et al*. 2014), our exposure of oysters to real-world gradients of pollution showed that they can maintain high filtration rates to reduce the likelihood of algal blooms from nitrogen pollution, even at microplastic concentrations that characterize coastlines worldwide (eg 10 µg L^{-1}; Figure 1; Ivar do Sul and Costa 2014). However, this capacity to remove algae is rapidly impaired when microplastic concentrations reach the extreme levels (100 µg L^{-1}) that plague some of the most plastic-polluted rivers (Figure 1; WebPanel 2). This suggests that if microplastic pollution can be kept to moderate levels, then oyster communities may retain the capacity to reduce coastal algal blooms fueled by nutrient runoff.

To provide insights into the effectiveness of microplastic management, we used information on discharged river pollution to inform the design of aquarium experiments that exposed adult oysters (~2 years old) to real-world gradients in microplastic concentrations (0 µg L^{-1}, 10 µg L^{-1}, and 100 µg L^{-1}) and nitrogen pollution (0 mg L^{-1}, 1 mg L^{-1}, 2 mg L^{-1}, 4 mg L^{-1}, and 8 mg L^{-1}) in the presence of a simulated algal bloom (~5×10^5 cells mL^{-1} of cultivated *Isochrysis galbana*, a readily consumed food item of *Ostrea*; Wilson 1983). All microplastic (three-level) and nitrogen (five-level) concentrations were crossed and run with and without oysters (n = three replicate tanks), with all 90 tanks positioned under ultraviolet lights to stimulate continual algal growth and run over four days (sufficient time for oysters to filter algae to background levels). We assessed (1) the capacity of oysters to mitigate algal blooms by maintaining high filtration rates as algae increasingly bloomed with increasing nitrogen, and (2) how this capacity changed with increasing microplastic pollution (see WebPanel 1 for detailed methods).

In the absence of oysters, the growth of algae significantly increased with increasing nitrogen and was unaffected by microplastics (Panel Figure 1a in WebPanel 2). The addition of oysters significantly reduced algal growth at all microplastic concentrations (Panel Figure 1b in WebPanel 2) and the magnitude of this effect increased with nitrogen, as oysters removed increasing amounts of algae as algal growth increased (Figure 1; WebTable 2). However, relative to oysters that were unexposed to microplastics, oysters exposed to microplastic concentrations considered moderate (10 µg L^{-1}) or extreme (100 µg L^{-1}) for coastal seas (Isobe *et al*. 2019) removed significantly less algae as nitrogen increased and algae bloomed (Figure 1). In the absence of nitrogen pollution, this erosion of function was negligible due to limited algal growth (Figure 1). When nitrogen was increased in combination with microplastics, filtration function soon performed "in the red" (Figure 1), with likely flow-on effects for other ecological functions. For example, oysters exposed to microplastics have been shown to support more homogenous (simplified) associated communities as a result of changes in their biodeposition (Green 2016; Green *et al*. 2017) that are known to influence the assemblage of associated biodiversity (McAfee and Bishop 2019).

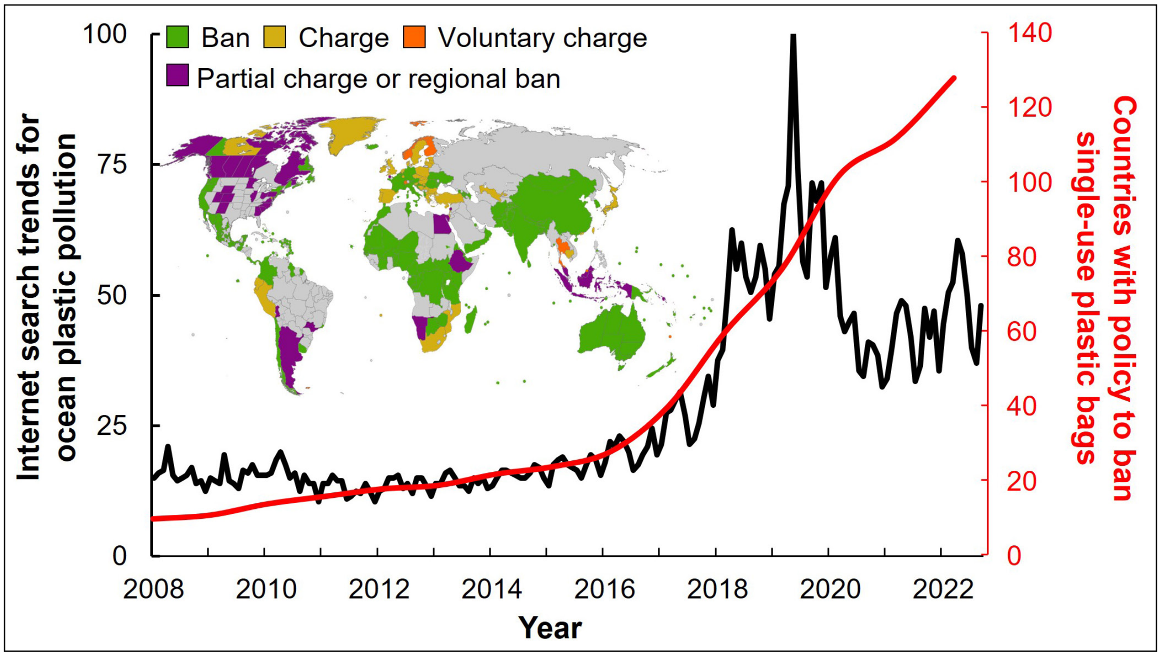

Figure 2. Public interest and legislative action on marine plastic pollution over the past 15 years (2008–2022). Public interest (black line) is represented by global search trends using the terms "ocean plastic" and "plastic pollution" relative to peak global interest (score of 100; GoogleTrends 2022, https://trends.google.com/home). Countries with legislation to ban single-use plastic bags (red line and inset map), the most common plastic pollutant on shorelines, include either national bans (68%; green shaded) or regional bans (purple shaded). Countries with payment schemes for bags (yellow and orange shaded) are also shown. Inset map adapted from: Elekhh/Wikimedia Commons (CC BY-SA 3.0).

In addition, we assessed how rapidly a catastrophic "shock event" (microplastic concentrations of 1000 μg L^{-1}), such as one resulting from an industrial-scale release or a business-as-usual future microplastic scenario, might impair filtration function. In the presence of a simulated algal bloom (as above) but in the absence of nitrogen pollution, we exposed oysters to one of four microplastic concentrations over a period of 9 hours (0 μg L^{-1}, 10 μg L^{-1}, 100 μg L^{-1}, or 1000 μg L^{-1}; n = five replicate tanks; see WebPanel 1 for methods) and found that oyster filtration rates were either unaffected or slightly reduced by moderate (10 μg L^{-1}) and extreme (100 μg L^{-1}) microplastic concentrations, but were significantly impaired at catastrophic levels (1000 μg L^{-1}) (Panel Figure 2 in WebPanel 2). Filtration rates at 100 μg L^{-1} did not significantly differ from controls but were largely reduced and did not significantly differ from those under our catastrophic scenario (Panel Figure 2 in WebPanel 2), suggesting that a threshold to healthy filtration function had been crossed. Green *et al.* (2017) observed upregulated filtration by the European flat oyster (*Ostrea edulis*) at microplastic concentrations of 25 μg L^{-1}, and therefore a threshold to high filtration function by *Ostrea* oysters may lie between concentrations of 25 and 100 μg L^{-1}. Finally, although our catastrophic microplastic concentration may not represent present-day levels, it may represent future scenarios if plastic use is not curtailed (Isobe *et al.* 2019) and it could occur today after environmental disasters, such as the *X-Press Pearl* containership disaster that spilled 1680 metric tons of microplastic pellets into the sea (Partow *et al.* 2021).

The demonstrated capacity of oysters to maintain high filtration rates to inhibit algal blooms triggered by nitrogen pollution (Figure 1) supports advocacy for conserving oyster communities to manage coastal eutrophication (Kellogg *et al.* 2014; Petersen *et al.* 2016; Rose *et al.* 2021). Even at moderate microplastic concentrations (10 μg L^{-1}), we observed that oysters maintained a high rate of algae removal, which may reflect a higher filtration rate, as was observed among oysters exposed to increased algal concentrations (Barnes 2006) or microplastic pollution (Sussarellu *et al.* 2016; Green *et al.* 2017). Notably, according to our analysis, only a few of the world's most plastic-polluted rivers discharge microplastic concentrations exceeding 10 μg L^{-1} (eg 12 of the 25 most polluted rivers; WebTable 1), with the majority of the world's rivers discharging far less. Nevertheless, while this filtration function appears robust to pollution levels that characterize many coastlines, continual ingestion of even low concentrations of microplastics has been shown to detrimentally impact oyster health over time (Sussarellu *et al.* 2016). Therefore, for oyster reef conservation to provide a long-term biological solution to managing coastal water quality, it is vital to curb the amount of plastic reaching the sea.

Tackling the plastic problem

The versatility and low cost of plastic have changed global society; we now live in a "plastic age" of daily dependence on and excess waste of plastic-based materials (Thompson *et al.* 2009).

In the seven decades since industrial-scale plastic production first began, 6300 million metric tons (Mt) of plastic waste have been generated (as of 2015), an astonishing amount that is anticipated to nearly double by 2050 if current trends are allowed to continue (Geyer *et al.* 2017). Our plastic waste crisis already carries an estimated annual cost of US$2.2 trillion in social and environmental damage (Forrest *et al.* 2019). Indeed, the majority of the 380 Mt of plastic produced annually transitions to waste within months; for single-use items after consumer use, this is reduced to within mere seconds to minutes (Thompson *et al.* 2009). Not surprisingly, most of the estimated ~19–23 Mt of plastic entering the sea each year (Borrelle *et al.* 2020) are single-use items for carry-out or take-away consumer goods (eg plastic bags, wrappers, food containers, bottles, cutlery) that account for up to 88% of nearshore plastic waste (Morales-Caselles *et al.* 2021). Without rapid transformation in our manufacture and consumption of single-use plastic items, the world's coastal seas face an ecological catastrophe.

Society's dependence on plastic is unlikely to change as the benefits of plastic continue to diversify and enhance human well-being (eg their use in biomedical implants and construction materials). But society's love affair with single-use plastic appears to be at a crossroads. In recent years, a social movement to drastically reduce unnecessary plastic use has gained rapid global momentum. Broad recognition that the millions of metric tons of plastic entering the sea each year (Jambeck *et al.* 2015) increasingly threaten marine life has helped spur sociopolitical backlash against plastic misuse (Pahl *et al.* 2017; Soares *et al.* 2021). Consequent to the recent social, political, and growing industry response to tackle the plastic crisis, curbing the excess use of single-use plastics is now a global focus. Although plastic's entrenched use and durability means it will impact marine systems for centuries to come, there are signs that the excessive use of single-use plastics may be coming to an end, cutting the flow of the most common plastic waste (Morales-Caselles *et al.* 2021) into the sea.

In the early 1970s, after just two decades of industrial-scale plastic production, scientists were already raising the alarm about accumulating marine plastic pollution (Carpenter and Smith 1972). Yet, despite decades of research demonstrating the environmental threat of plastic pollution, it was only the recent public recognition that plastics have been incorporated into everyday items – including our shower products, cosmetics, and clothes – that galvanized broader public awareness of this threat. Catalyzed by broad-reaching media about the impacts of plastics on marine ecosystems (eg the BBC documentary series *Blue Planet II*; Males and Van Aelst 2021), public interest in the plastic problem recently peaked (Figure 2) and created social backlash against our frivolous plastic use. Despite mounting evidence of its impacts and the advocacy of scientists concerning the need to address plastic pollution, few could have foreseen the sudden, global-scale social movement – that arose during the past 5 years – to reduce plastic use. Although plastic pollution is not projected to peak until the next century (Jambeck *et al.* 2015), growing social awareness, anti-plastic movements (eg the Plastic Pollution Coalition; https://www.plasticpollutioncoalition.org), and increasing legislation to reduce single-use plastics (Figure 2; Xanthos and Walker 2017; Schnurr *et al.* 2018) offer hope that plastic pollution can be curbed over the coming decades.

Driven by rising social advocacy and political responsibility to act, the past two decades have witnessed landmark policies to reduce plastic use (Xanthos and Walker 2017; Schnurr *et al.* 2018). Momentous change is now afoot. Member nations of the EU recently voted unanimously to phase out unnecessary plastic use over the coming years (the "Single-Use Plastics Directive" of 2019), China plans to ban single-use plastics by 2025, and the UN identified reducing marine pollution by 2025 as a key sustainability target (UN Sustainable Development Goal 14.1). Acting on this current social and political willingness for change provides opportunities for additional efforts. For example, The Plastic Waste Makers Index indicates that just 20 companies manufacture 50% of all single-use plastics, and just 100 companies account for 90% of global production (Charles *et al.* 2021). Plastic manufacturing is a major greenhouse-gas emitting industry, and these major plastic producers continue to prioritize new plastic production over opportunities to lead the transition to a circular plastic economy (Forrest *et al.* 2019). Focusing legislation and social pressure on these major plastic producers will help address the root cause of the plastic problem (Figure 3), encouraging industry to drive change. Clearly, both top-down management and bottom-up advocacy have driven the rapid cultural shift for reducing plastic waste. While there is far to go to ensure that measures are meaningful (Borrelle *et al.* 2020), this progress may energize the transition toward a more sustainable future, and represents a symbolic early step toward curbing plastic pollution.

Improving recognition of the nitrogen problem

Society's necessary transition away from intensive agricultural nitrogen use will take a different course to that of plastics. Like plastic pollution, nitrogen pollution is also omnipresent, but unlike plastic, nitrogen is a vital part of global food security. Its critical role in food production has seen increasing application of agricultural nitrogen (a tenfold increase, from 11 Mt to 109 Mt since the 1960s; FAOSTAT 2021), with nitrogen levels now believed to be the most transgressed of all planetary boundaries (Rockström *et al.* 2009). Yet, despite its visible impacts (eg algal blooms), the complexity of nitrogen's role in food production and its multisystem impacts (terrestrial, aquatic, and atmospheric) makes it unlikely that nitrogen use will be influenced by the sudden social stimulus that spurred action on plastic reduction. Regardless, nitrogen's contribution to declining water quality and the biodiversity and climate crises means that urgent action is needed if sustainability goals are to be met.

Encouragingly, actions to drastically reduce global nitrogen waste are underway. The 2019 "Colombo Declaration"

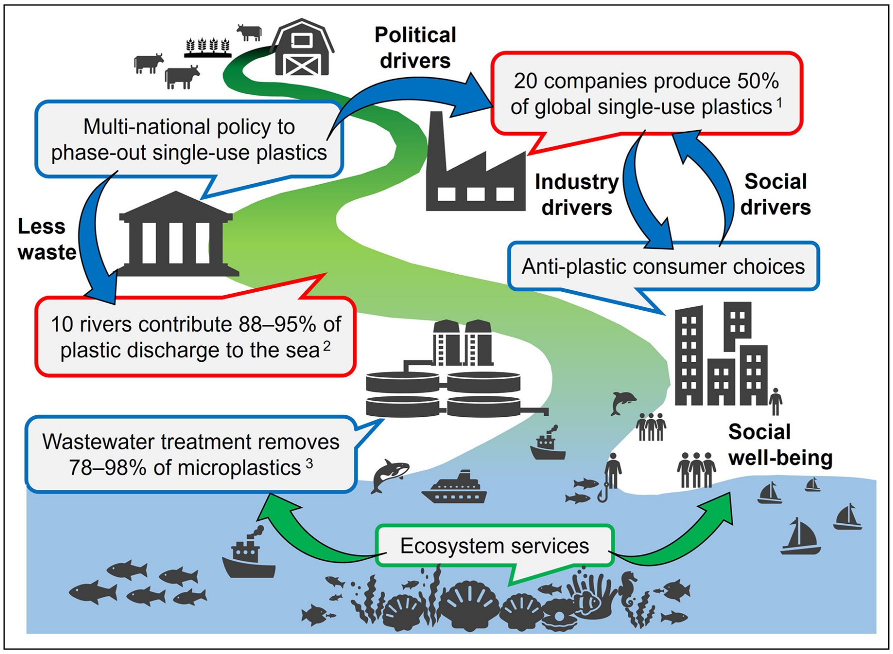

Figure 3. Acting on social, industry-based, and political opportunities to reduce plastic use could yield rapid reductions in plastic waste and the threat it poses to coastal ecosystems. Mechanisms for reducing plastic pollution (blue outlines) are strengthening, particularly the social and political drivers of change in plastic use that have the potential to drastically draw down the major sources of plastic production and waste (red outlines) entering the sea. Superscripted numbers refer to information sources: (1) Charles *et al.* (2021); (2) Schmidt *et al.* (2017); (3) Prata (2018).

carries the ambitious goal of halving global nitrogen waste by 2030, answering scientific calls for a decade on sustainable nitrogen management that could save US$100 billion per annum in nitrogen resources (Sutton *et al.* 2021). Achieving these lofty ambitions requires political will, as well as the participation of industry and society – the platforms for which are emerging. For example, China's nationally coordinated program to enhance sustainable farming practice has helped almost 21 million farmers increase food security (~11% productivity increase) while reducing nitrogen use by 15–18%, thereby reducing carbon dioxide emissions by hundreds of kilograms (Cui *et al.* 2018). Rolled out by a collaborative network of thousands of researchers, civil servants, and industry representatives over only a single decade (2005–2015), the project demonstrated that high farming productivity is not bound to high nitrogen use alone, but includes alternative forms of evidence-based management. Greater public participation is also emerging through marketing of nitrogen-responsible products, such as eco-certified agricultural products characterized by low nitrogen loss to coastal areas (eg Reef Safe Sugar). Although of limited impact relative to the global scale of the issue, such actions demonstrate the growing momentum toward sustainability. Importantly, communicating the nitrogen issue with the many co-benefits of solving it, be they of benefit to society (health and recreation), industry (reduced farming costs), the climate (lower emissions), or nature (improved ecosystem function), will remind people that everyone and every role can address the nitrogen challenge.

Conclusion

There is optimism that degraded marine ecosystems could substantially recover over the next 50 years if local-scale (eg pollution) through global-scale (eg climate change) threats are mitigated (Duarte *et al.* 2020; McAfee *et al.* 2021). Nature demonstrates that once anthropogenic threats are reduced, ecosystems can recover from even the most destructive of human disturbances (eg recovery of coral reefs on Bikini Atoll after 23 tests of nuclear weapons; Richards *et al.* 2008). Past examples of multinational action for global-scale conservation demonstrate that we can come together to solve wicked problems (eg the 1986 moratorium on commercial whaling; the 1987 Montreal Protocol to protect the ozone layer). Our next big win may be stemming the flow of plastic pollution to the world's oceans. Although the ecological impacts of marine plastics will remain a long-term issue because plastic waste continuously fragments into smaller particles, our capacity and willingness to reduce the source of plastic pollution is clear: over a matter of just a few years, people across the world rallied behind scientific concern over marine plastics and recognized that the problem starts with themselves, thereby generating social will, political responsibility, and industry opportunity for change. Politicians, industry, and the public all have roles in changing our material consumption. If we can solve the plastic waste problem, it could serve as an energizing victory for further collaboration to address other wicked problems.

Although natural systems might continue to provide valuable filtration services in the presence of moderate plastic and nitrogen pollution, this function will likely deteriorate if current trends in consumption and waste management are not altered. If, as a society, we can change our consumptive behavior and industrial practices to reduce plastic and nitrogen waste, we can work with nature to support the ecosystem services on which societal well-being depends. Both top-down and bottom-up solutions are required. As we have seen, when people feel empowered to make positive change, they can address global challenges at their scale of influence, be they policy makers or members of the public.

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Data Availability Statement

Raw data are available at doi.org/10.6084/m9.figshare.21774902.

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