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November 8, 2021

PUBLISHED IN REVIEWS IN FISH BIOLOGY AND FISHERIES: https://doi.org/10.1007/s11160-021-09674-8

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This paper is part of the Future Seas project (www.futureseas2030.org), and has been submitted to the Future Seas special issue in Reviews in Fish Biology & Fisheries to be published in 2021.

Graphical abstract:

Abstract:

In the age of the Anthropocene, the Ocean have typically been viewed as a sink for our pollution. Pollution is varied, ranging from human-made plastics and pharmaceutical compounds, to human-altered abiotic factors, such as sediment and nutrient runoff. As the global population, wealth and resource consumption continues to grow, so too does the amount of pollution we produce. This presents us with a grand challenge which requires interdisciplinary knowledge to solve. While there is sufficient data on the human health, social economic, and environmental risks of marine pollution, a significant lag exists when implementing strategies to address this issue. We gathered 17 experts from the fields of social sciences, marine science, visual arts, logistics and traditional and first nations knowledge holders to present two futures; the Business-as-usual, based on current trends and observations of growing marine pollution, and a More Sustainable Future, which imagines what our Ocean could look like if we implemented current knowledge and technologies. We identified priority actions that governments, industry and consumers can implement at pollution sources, vectors and sinks, over the next decade to reduce marine pollution and steer us towards the More Sustainable Future.

Keywords: future scenario, Sustainable Development Goals (SDGs), pollution, ocean decade, 2030, sustainable solutions

Introduction

The Ocean has historically been a sink for pollution, leaving modern society with significant ocean pollution legacy issues to manage (Elliott and Elliott 2013; O'Shea et al. 2018). People continue to pollute the Ocean at increasing rates creating further damage to marine ecosystems. This results in detrimental impacts on livelihoods, food security, marine navigation, wildlife and well-being, among others (Krushelnytska 2018; Lebreton and Andrady 2019; Nichols 2014; Seitzinger et al. 2002). As pollution presents a multitude of stressors for ocean life, it cannot be explored in isolation (Khan et al., 2018). Thus, global coordinated efforts are essential to manage the current and future state of the Ocean and to minimise further damage from pollution (Krushelnytska 2018; Macleod et al. 2016; O'Brien et al. 2019; Williams et al. 2015). Efforts are also needed to tackle key questions, such as how do pollutants function in different environments, and interact with each other?

Pollution can be broadly defined as any natural or human-derived substance or energy that is introduced into the environment by humans and that can have a detrimental effect on living organisms and natural environments (UNEP 1982). Pollutants, including light and sound in addition to the more commonly recognised forms, can enter the marine environment from a multitude of sources and transport mechanisms (Carroll et al. 2017; Depledge et al. 2010; Longcore and Rich 2004; Williams et al. 2015). These may include long range atmospheric movement (Amunsen et al. 1992) and transport from inland waterways (Lebreton et al. 2017).

Current pollutant concentrations in the marine environment are expected to continue increasing with global population growth and product production. For example, global plastic production increased by 13 million tonnes in a single year (PlasticsEurope 2018), with rising oceanic plastic linked to such trends (Wilcox et al. 2020). Pharmaceutical pollution is predicted to increase with population growth, resulting in a greater range of chemicals entering the Ocean through stormwater drains and rivers (Bernhardt et al. 2017; Rzymski et al. 2017). Additionally, each year new chemical compounds are produced whose impacts on the marine environment are untested (Landrigan et al. 2018).

Marine pollution harms organisms throughout the food-web in diverse ways. Trace amounts of heavy metals and persistent organic pollutants (POPs) in organisms have the capacity to cause physiological harm (Capaldo et al. 2018; Hoffman et al. 2011; Salamat et al. 2014) and alter behaviours (Brodin et al. 2014; Mattsson et al. 2017). Artificial lights along coasts at night can disrupt organism navigation, predation and vertical migration (Depledge et al. 2010). Pharmaceutical pollutants, such as contraceptive drugs, have induced reproductive failure and sex changes in a range of fish species (Lange et al. 2011; Nash et al. 2004). Furthermore, some pollutants also have the capacity to bioaccumulate, which means they may become more concentrated in higher trophic marine species (Bustamante et al. 1998; Eagles-Smith et al. 2009).

Pollution also poses a huge economic risk. Typically, the majority of consequences from pollution disproportionately impact poorer nations who have less resources to manage and remediate these impacts (Alario and Freudenburg 2010; Beaumont et al. 2019; Golden et al. 2016; Landrigan et al. 2018). Marine pollution can negatively impact coastal tourism (Jang et al. 2014), waterfront real estate (Ofiara and Seneca 2006), shipping (Moore 2018) and fisheries (Hong et al. 2017; Uhrin 2016). Contamination of seafood poses a perceived risk to human health, but also incurs a significant financial cost for producers and communities (Ofiara and Seneca 2006; White et al. 2000). Additionally, current remediation strategies for most pollutants in marine and coastal ecosystems are costly, time consuming and may not prove viable in global contexts (Ryan and Jewitt 1996; Smith et al. 1997; Uhrin 2016).

Reducing marine pollution is a global challenge that needs to be addressed for the health of the Ocean and the communities and industries it supports. The United Nations proposed and adopted 17 Sustainable Development Goals (SDGs) designed to guide future developments and intended to be achieved by 2030. It has flagged the reduction of marine pollution as a key issue underpinning the achievement of SDG 14, Life

Under Water, with target 14.1 defined as "prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution" by 2025 (United Nations General Assembly 2015). In the UN Decade of Ocean Science (2021-2030), one of the six ocean outcomes relate specifically to the reduction and identification of marine pollution (A Clean Ocean; UN DOS SD). The task of reducing marine pollution is daunting - the Ocean is so vast that cleaning it seems almost impossible. However, effective management of pollution at its source is an effective way to reduce it and protect the Ocean (DeGeorges et al. 2010; Rochman 2016; Simmonds et al. 2014; Zhu et al. 2008). Strategies, implemented locally, nationally and globally, to prevent, or considerably reduce pollution inputs in combination with removing pollutants from the marine environment (Sherman and van Sebille 2016) will allow healthy ocean life and processes to continue into the future.

To help explain how we can most effectively address pollution sources and clean the Ocean, we depict two different future seas scenarios by 2030. The first is a business-as-usual scenario, where we continue to adhere to current management and global trends. The second is a technically achievable, more sustainable future that is congruent with the SDGs, and where we actively take actions and adopt sustainable solutions. We then explore pollution in three 'zones' of action; at the source(s), along the way, and at sink, in the context of river or estuarine systems, as water-transported pollution is commonly associated with urban centres alongside river systems (Alongi and McKinnon 2005; Lebreton et al. 2017; Lohmann et al. 2012; Seitzinger and Mayorga 2016).

2. Methods

As a group of interdisciplinary scientists, with expertise in marine pollution, we participated in the Future Seas project (www.FutureSeas2030.org) and followed the method outlined in Nash et al. (2020). The project involved a structured three-step discussion process, (Step 1: problem identification, trust and awareness building, step 2: future discovery and development, step 3: learning) to explore the direction of marine social-ecological systems over the course of the UN Decade of Ocean Science. The three-step process resulted in developing two alternate future scenarios of marine pollution, a 'business-as-usual' future that is the current trajectory based on published evidence, and a 'more sustainable' future that is technically achievable using existing and emerging knowledge and is consistent with the UN's Sustainable Development Goals. To ensure a wide range of world views were present in the future scenarios, Indigenous Leaders and Traditional Knowledge Holders from around the world came together and presented their views, experiences and identified their priorities to remove and reduce marine pollution (Nash et al. 2020; Fischer et al. 2020).

We defined the scope of our paper by identifying key pollutant sources, types and drivers of marine pollution (Table 1 for pollutant sources and types; section 3.2 for drivers).We then developed a list of feasible actions that could drive the current state of the Ocean towards a cleaner, more sustainable future (supplementary Table 1). From these actions we deliberated as a group and identified ten that have high potential to be implemented within the next decade and significantly reduce marine pollution (Figure 1). The linkages between our ten priority actions and the SDGs are outlined in supplementary Table 2.

Future Narratives

We identified three broad sources of marine pollution: land-based industry, sea-based industry and municipal-based sources (Table 1). We framed our two contrasting future scenarios (business-as-usual and a technically feasible sustainable future), around these pollutants and their sources (Box 1). In addition to these future narratives, we (the initial participants) reflect on the present impacts that pollution is currently having on the livelihoods and cultures of First Nations peoples and traditional knowledge holders. We include the narratives of the palawa pakana people, from lutruwita/Tasmania (Box 2), and the Greenlandic Inuit people (Box 3).

Drivers

We identified three key drivers that will substantially contribute to an increasingly polluted ocean if no actions are taken to intervene; societal behaviours, equity and access to technologies, and governance and policy.

Alternatively, these pollution drivers can be viewed as opportunities to implement strategic measures that shift the dial from a polluted marine environment to a healthier marine environment. Below we highlight how current societal behaviours, lack of implementation of technological advancements, and ocean governance and policy making contribute to an increasingly polluted ocean and drive society towards a BAU future (Box 1). Importantly, we discuss how changes in these behaviours, and improvements in technologies and governance can lead to reduced marine pollution, ultimately driving a cleaner, more sustainable Ocean for the future.

Societal behaviour

Societal behaviours that drive increasing pollution in the world's Ocean

A consumer culture that prioritizes linear production and consumption of cheap, single-use materials and products over circular product design and use, ultimately drives the increased creation of materials. Current production culture is often aligned with little consideration for the socioeconomic and environmental externalities associated with the pollution that is generated from a product's creation to its disposal (Foltete et al. 2011; Schnurr et al. 2018). Without a dedicated management strategy for the fate of products after they have met their varying, often single-use objectives, these materials will enter and accumulate in the surrounding environment as pollution (Krushelnytska 2018; Sun et al. 2012). Three examples of unsustainable social behaviours that lead to products and materials ending up as marine pollution are: i) the design and creation of products that are inherently polluting. For example, agricultural chemicals or microplastics and chemicals in personal care and cosmetic products. ii) social behaviours that normalize and encourage consumption of single-use products and materials. For example, individually wrapped vegetables or take-away food containers. iii) low awareness of the impacts and consequences and therefore the normalization of polluting behaviours. For example, noise generation by ships at sea (Hildebrand 2009) or the large application of fertilizers to agricultural products (Sun et al. 2012).

Shifting societal behaviours towards sustainable production and consumption

A cleaner Ocean with reduced pollution will require a shift in production practices across a wide array of industries, as well as a shift in consumer behaviour. Presently, consumers and industry alike are seeking science-based information to inform decision making (Englehardt 1994; Vergragt et al. 2016). Consumers have the power to demand change from industries through purchasing power and social license to operate (Saeed et al. 2019). Policymakers have the power to enforce change from industries through regulations and reporting. Aligning the values between producers, consumers and policymakers will ensure best practices of sustainable consumption and production are adopted (Huntington 2017; Moktadir et al. 2018; Mont and Plepys 2008). Improved understanding of the full life cycle of costs, consequences (including internalised externalities, such as the polluter-pays-principle (Schwartz 2018)), materials used, and pollution potential of products could substantially shift the dial in both production and consumerism towards cleaner, more sustainable seas (Grappi et al. 2017; Liu et al. 2016; Lorek and Spangenberg 2014; Sun et al. 2012). For example, economic policy instruments (Abbott and Sumaila 2019), production transparency (Joakim Larsson and Fick 2009), recirculation of materials (Michael 1998; Sharma and Henriques 2005), changes in supply-chains (Ouardighi et al. 2016).

Equity and access to technologies

Inequitable access to available technologies

Despite major advancements in technology and innovation for waste management, much of the current waste infrastructure employed around the world is outdated, underutilised, or abandoned. This is particularly the case for rapidly developing countries with large populations who have not had access to waste reduction and mitigation technologies and systems employed in upper income countries (Velis 2014; Wilson et al. 2015). The informal recycling sector (IRS) performs the critical waste management role in many of the world's most populous countries.

Harnessing technologies for today and the future

Arguably, in today's world we see an unprecedented number and types of technological advances stemming from but not limited to seismic exploration (Malehmir et al. 2012), resource mining (Jennings and Revill 2007; Kampmann et al. 2018; Parker et al. 2016), product movement (Goodchild and Toy 2018; Tournadre 2014) and product manufacturing (Bennett 2013; Mahalik and Nambiar 2010). Applying long term vision rather than short term economic gain could include supporting technologies and innovations that provide substantial improvements over business-as-usual. For example, supporting businesses or industries that improve recyclability of products (Umeda et al. 2013; Yang et al. 2014), utilize waste (Korhonen et al. 2018; Pan et al. 2015), reduce noise (Simmonds et al. 2014), and increase overall production efficiency will substantially increase the health of the global ocean. Efforts should be made wherever possible to maintain current waste management infrastructure where proven and effective, in addition to ensuring reliance and durability of new technologies and innovations for improved lifespan and end of life product management. Consumer demand, taxation and subsidies will play a necessary roll to ensure the appropriate technologies are adopted (Ando and Freitas 2011; Krass et al. 2013).

Governance and Policy

Lack of Ocean Governance and Policy Making

The governance arrangements that address marine pollution on global, regional and national levels are complex and multifaceted. Success requires hard-to-achieve integrated responses. In addition to the challenges discussed in Alexander et al. (*2020*), which largley focuses on the marine environment, we highlight that land-based waste is the largest contributor to marine pollution and therefore requires governance and policies that focus on pollution at the source. Current regulations, laws and policies do not always reflect or address this grand challenge. The Ocean has traditionally been governed through sectoral approaches such as fisheries, tourism, offshore oil and mining. Unfortunately, this sector approach has caused policy overlap, conflict, inefficiencies and inconsistencies regarding marine pollution governance (Haward 2018; Vince and Hardesty 2016). Although production, manufacturing, and polluting may largely take place under geopolitical boundaries, pollution in the high seas is often hard to assign to a country of origin. This makes identifying and convicting polluters very difficult (Urbina 2019). For example, the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) has been criticised as ineffective in reducing marine pollution, largely due to the lack of easily monitoring, identifying and convicting offenders (Henderson 2001; Mattson 2006).

Harnessing ocean governance and policy

Binding domestic policies and international agreements are regulatory levers that can drive change at local, community, state, federal and international scales (Vince and Hardesty 2018). The UN Law of the Sea Convention Part XII (articles 192-237) is dedicated to the protection and preservation of the marine environment and marine pollution is addressed in article 194. It also sets out the responsibilities of states and necessary measures they need to undertake to minimise pollution their own and other states' jurisdictions. While the Law of the Sea recognises the differences between sea-based and land-based pollution, it does not address the type of pollutants and technical rules in detail. Voluntary measures including MARPOL 73/78 (IMO 1978), United Nations Environment Assembly resolutions (UNEA 2019) and the FAO voluntary guidelines for the marking of fishing gear (FAO 2019), already exist in an attempt to reduce specific components of marine pollution. However, the health of marine ecosystems would benefit from multilateral international or regional agreements that minimise the production of items or the use of processes that result in high levels of marine ecosystem harm. For example, international regulation for underwater sound (McCarthy 2004), policies to reduce waste emissions (Nie 2012) and the polluter pays principle (Gaines 1991). Global and regional governance can create a favourable context for national policy action. Policies that adapt to shifts in climate and are guided by science and indigenous knowledge could be more likely to succeed (Ban et al. 2020).

Actions to achieve a more sustainable future

The grand challenge of reducing ocean pollution can seem overwhelming. However, there are myriad actions, interventions and activities which are highly feasible to implement within the next decade to rapidly reduce the flow of pollution. Implementing these actions requires collaboration among policymakers, industry and consumers alike. To reduce pollution from sea-based industries, land-based industries including land-based sources (Table 1), we encourage the global community to consider three 'zones' of action or areas to implement change: at the source(s), along the way/along the supply chain, and at sinks (Figure 1). It is important to highlight that we cannot act at any one zone only. For example, repeated clean ups at the sink may reduce pollution in an area for a time, but will not stem the flow of pollutants.

Actions at the source(s)

Reducing pollution at its multitude of sources is the most effective way to reduce and prevent marine pollution. This is true for land-based industry pollutants, sea-based industry pollutants and municipal-based pollutants. An example for each includes; reduction in fertilizer leading to less agricultural runoff in coastal waters (Bennett et al. 2001), changes in packaging materials may see reductions in production on a per item basis, and a lowered frequency and timing of seismic blasting would result in a decrease in underwater noise pollution at the source. The benefits of acting at the source are powerful: if a pollutant is not developed or used initially, it cannot enter the marine environment. We can act at the source using various approaches such as; prevention of contaminants, outreach campaigns, introduce bans and incentives and the replacement of technologies and products for less impactful alternatives (Figure 1). However, achieving public support for step changes can be difficult and time consuming. Such changes may meet resistance (e.g. stopping or changing seismic testing) and there are other factors beyond marine pollution that must be considered (e.g. health and safety of coastal lighting in communities may be considered more important than impacts of light pollution on nearby marine ecosystems). Actions such as outreach and education campaigns (Supplementary Table 2) will be an important pathway to achieve public support.

Actions along the way

Reducing marine pollution along the way requires implementation of approaches aimed at reducing pollution once it has been released from the source and is in transit to the marine environment (Figure 1). Acting along the way does provide the opportunity to target particular pollutants (point-source pollution) which can be particularly effective in reducing those pollutants. While municipal-based pollutants can be reduced 'along the way' using infrastructure such as gross pollutant traps (GPTs) and wastewater treatment plants (WWTPs), some pollution such as light or sound may be more difficult to minimize or reduce in such a manner. WWTPs can successfully capture excess nutrients, pharmaceuticals and litter that are transported through sewerage and wastewater systems. However, pollution management '*en route* ' means there is both more production and more likelihood of leakage to the environment. In addition, infrastructure that captures pollution is often expensive, requires ongoing maintenance (and hence funding support), and if not managed properly, can become physically blocked, or result in increased risk to human health and the broader environment (e.g. flooding during heavy rainfall events). When considering management opportunities and risks for both land and sea-based pollution, the approaches required may be quite different, yielding unique challenges and opportunities for resolution in each (Alexander et al. *2020*).

Actions at the sinks

Acting at sinks essentially requires pollution removal (Figure 1). This approach is the most challenging, most expensive, and least likely to yield positive outcomes. The Ocean encompasses more than 70% of the earth's surface and extends to depths beyond ten kilometres. Hence it is a vast area for pollutants to disperse and economically and logistically prohibitive to completely clean. However, in some situations collecting pollutants and cleaning the marine environment is most viable option and there are examples of success. For example, some positive steps to remediate excess nutrients include integrated-multitrophic-aquaculture. 'Net Your Problem' is a recycling program for fishers to dispose of derelict fishing gear (netyourproblem.com). Municipal-based and sea-based industry pollutants are often reduced through clean-up events. For example, large oils spills often require community volunteers to remove and clean oil from coastal environments and wildlife. Such activities provide increased awareness of marine pollution issues, and if data are recorded, can provide a baseline or benchmark against which to compare change. However, addressing pollution at sinks means identifying those accumulating areas. Repeated removal or cleaning is unlikely to yield long term results, without managing the pollution upstream –whether along the route or at the source.

Conclusion

To achieve the More Sustainable Future, and significantly reduce pollution (thereby achieving the SGD targets in Supplementary Table 2), we must take ongoing action now and continue this movement beyond 2030. Prioritising the prevention of pollutants from their sources, using bans and incentives, outreach and education, and replacement technologies, is one of the most important steps we can take to shift towards a more sustainable future. Without addressing pollution from the source, we will continue to remediate rather than mitigate the damage pollution causes to the Ocean and organisms within. For pollutants that are not currently feasible to reduce at the source, collection of pollutants before they reach the Ocean should be prioritised. For example, wastewater treatment plants and gross pollutant traps located at point-source locations such as stormwater and wastewater drains. Actions at the sink should target areas where the maximum effort per quantity of pollution can be recovered from the Ocean. For example, prompt clean-up responses to large pollution events such as oil spills or flooding events and targeting clean-ups at beaches and coastal waters with large accumulations of plastic pollution.

These priority actions are not the perfect solution, but they are great examples of what *can be* and *is* feasibly done to manage marine pollution. Each action is at risk of failing to shift to a cleaner ocean without the support from governments, industries and individuals across the whole system (from the source to the sink). Governments and individuals need to push for legislation that is binding and support sustainable practices and products. Effective methods for policing also need to be established in partnership with the binding legislation. Regardless of which zone we address, our actions on sea and coastal country must be guided by Indigenous knowledge and science (Fischer et al., 2020).

We recognise the major global disruptions which have occurred in 2020, particularly the COVID-19 pandemic. The futures presented here were developed prior to this outbreak and therefore do not consider the effects of this situation on global pollution trends. In many ways, this situation allows us to consider a 'reset' in global trajectory as discussed by Pecl et al. (2020). Our sustainable future scenario may be considered a very real goal to achieve in the coming decade.

Author Contributions P.S. Puskic and K. Willis share equal lead authorship on this paper. All authors wrote sections of this manuscript and contributed to concept design and paper discussions. N.F and H.P. wrote the narratives for box 3. D.G. wrote Box 2. All authors provided edits and feedback to earlier drafts.

Acknowledgment

We thank Lola, Rex and Vanessa Greeno for sharing their knowledge of the impacts of pollution on their art and culture. Thank you to Animate Your Science, JB Creative Services and Annie Gatenby for assistance with the graphical aspects of this project. Thank you to Rupert the Boxer puppy for deciding authorship order. This paper is part of the 'Future Seas' initiative (www.FutureSeas2030.org), hosted by the Centre for Marine Socioecology at the University of Tasmania. This initiative delivers a series of journal articles addressing key challenges for the UN International Decade of Ocean Science for Sustainable Development 2021-2030. The general concepts and methods applied in many of these papers were developed in large collaborative workshops involving more participants than listed as co-authors here, and we are grateful for their collective input. Funding for Future Seas was provided by the Centre for Marine Socioecology, IMAS, MENZIES and the College of Arts, Law and Education, the College of Science and Engineering at UTAS, and Snowchange from Finland. We acknowledge support from a Research Enhancement Program grant from the DVCR Office at UTAS. Thank you to Camilla Novaglio for providing an internal project review of an earlier draft, and to X anonymous reviewers for improving the manuscript. We acknowledge and pay respect to the traditional owners and custodians of sea country all around the world, and recognise their collective wisdom and knowledge of our Ocean and coasts.

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Figures

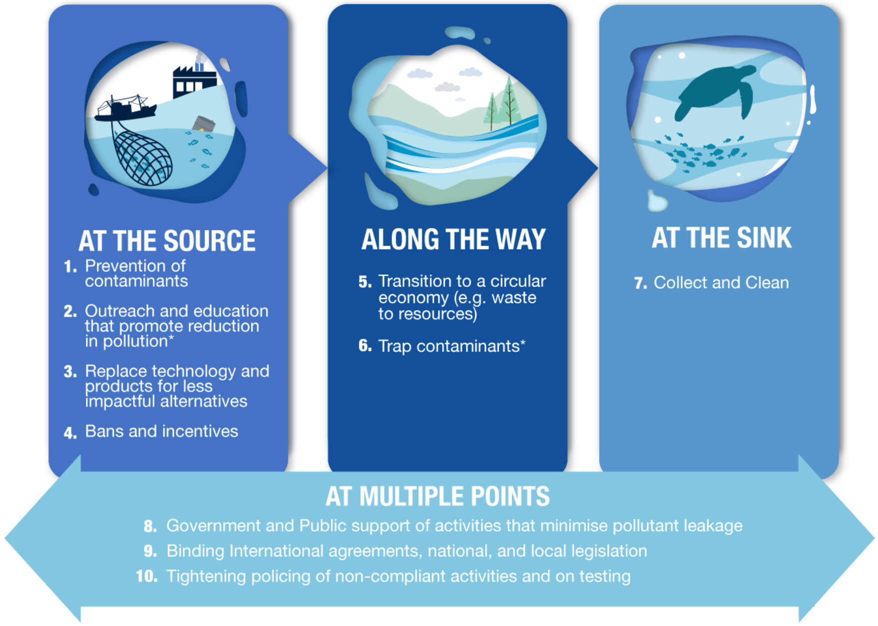

Figure 1: Ten actions that can substantially reduce the amount of pollution entering the marine environment. Actions are placed along the system at where they could have the greatest impact at reducing pollution: at the source of the pollutant (at the source), once the pollutant is released (along the way), once the pollutant has entered the Ocean (at the sink) or at multiple points along the system (bottom arrow). * indicates actions that could be successfully implemented before the next decade to significantly reduce pollution.

Boxes

A wasted opportunity (Business-as-usual future) :

People have forgotten or ignored that their world is mostly ocean. Immersed in our virtual lives, people are disconnected to their environment. Unchecked growth is status quo. Surrounded by rising quantities of pollution, people do not see the sea, although they peer in wonder at the polluted waves breaking on their shores, while peeling back the plastic from their shrink-wrapped vegetables and listening to the constant hum of marine traffic travelling across the seas. Politicians pontificate but laws are toothless, made then broken, useless distractions from the real issue. Our media is swamped with images of marine species entangled in fishing gear or plastics. Dead seabirds, turtles and fish. News of die-offs from eutrophication or toxic pollution episodes is a regular occurrence. The marketing alongside these news stories on our screens is still telling us to buy more, consume more. The growing global population in combination with an increasing rural-urban migration has intensified demands on waste collection and treatment systems, urban drainage and coastal development. Although some regions, cities and industries have adopted the sustainable practices recommended by the UN to meet the SDGs, the majority struggle to manage the resource and waste demands of their rapidly growing urban populations. As a result, the amount of untreated wastewater entering the Ocean has escalated. Grass-roots movements to educate and encourage communities to adopt sustainable, less wasteful products and practices continue to grow. Positive changes can be seen in those communities. However, the slow voluntary changes made by industry and the lack of enforcement/legislation made by governments has allowed marine pollution to increase and the warnings we heard ten years ago on the implications this will have on our health and livelihoods have become reality.

Stemming the flow and proceeding with caution (Technically feasible sustainable future) :

The ocean is acknowledged for the goods and services it provides and viewed with appreciation and opportunity. People understand our impact on the sea and its life-supporting role for us and society acts in accordance with this view. We recognise that cleaning our Ocean and addressing SDG 14, Life Below Water, we also contribute to SDG 15, Life on Land. Technology is used to prevent, filter, clean, repair and restore our shores, the water column and the seabed floor. The demand for re-useable, less-toxic and less-packaged products means that manufactures have shifted to sustainable production and packaging of goods, contributing to the achievement of SDG 12, responsible production and consumption. Government standards require recycled materials to be used in the manufacturing of new products, and there is a viable, thriving circular economy. Citizen scientists roam the shores, reporting and sharing their data with the world. Volunteer community groups continue to clean the beaches of rubbish and are starting to collect fewer items each visit. Guided by science and indigenous knowledge, politicians adopt the precautionary principle and our laws are equitable, enforced and effective. Wealthy nations have started to responsibly manage their waste and are gradually ceasing exports of their waste to poorer nations. Across the globe more and more regions, cities and industries are meeting SDG targets, adopting sustainable practices that suit their culture and landscape. Breeding grounds for marine mammals are protected from noise propagating devices and the revegetation of inland waterways and wetlands are progressing. Shifts to more sustainable agricultural practices have removed the reliance on large applications of fertilisers and as such eutrophication events are falling. The health and well-being of communities and life is on the rise.

Box 1 : The method resulted in two futures, which focuses on pollutants outlined in Table 1. The two futures are told here in a narrative format. The Business-as-usual (BAU) future has been informed by current trends and predictions in marine pollution. The Technically Feasible Sustainable Future imagines what the future may be like should we implement the actions outlined in this paper.

"To harvest the marina shells, it requires the shell collector, to first study the tide level to find out what day of the month and the time of the day, that the tide level will be less than half a metre. Experienced collectors will be on the beach just before low tide, allowing time to set up as the tide runs out and gives a couple of hours to gather before the tides starts coming back into shore. The low tide needs to be during daylight hours as safety precaution. In a calendar year, the shell collectors may get two good tides for gathering. The shell collector tries to gather enough to last 12 months. They need about a sugar bowl full to freeze and mix with other shells to create her patterns for a number of pieces in a year. The regime allows time for the shells to continue to spawn. The full cycle from where the shells go out into 30 feet of water to breed drop the roe and come into shore and grown fully by end of April.

In the last 10 years we have seen a gradual change to seabeds and collection areas around Flinders Island. In some collecting seasons, very few shells available to harvest. We have seen a site close to shore, where land run-off into the sea, makes the shells have acid burnt tips. We have seen areas where the kelp is very scarce in the bay where many recreational boats are moored. The boat slip has almost wiped out one species with run off from boats paints. In one bay we saw a lot of grey algae and next bay where there is an abalone fish farm, if the abalone escape, they compete with the marina shells for food. The other competition is from the global warming of water temperature. The non-science person does not understand the pollution risks or what the warmer sea does to spawning mollusc of the marina shells."

Box 2: In lutruwita (Tasmania), Marineer Shell (*Phasianotrochus rutilus*) necklace making is a palawa pakana traditional practice that has continued over thousands of years. Shell-necklaces were once crafted as jewellery and used for trade purposes. King, Queen and standard marineers were not just palawa nicknames handed down through generations, status was allocated to each of the marineer species and the resulting necklaces. Necklaces were reflective of the status allocated to the owner from the creator, and clan as a whole. Here, Elder and shell-necklace maker, Lola Greeno, shares her account of the current impacts of pollution on her art and culture. (Photo credit: Dean Greeno).

Year in the Greenlandic Inuit language is ukioq, which is actually the same word for winter. Winter lasts most of a year. There is snow and there is ice, saltwater ice and freshwater ice, snow covered ice and icebergs. White in varying shades depending first and foremost on the angle and intensity of incoming light, be it stars, moonlight, the sky, clouds, northern lights – yes, and of course the sun. There are periods in winter and in late fall where the sun is low that give these reddish nuances at first sunrise and late sunset, similar though different, that give you flaming reddish icebergs. In overcast weather the same icebergs can radiate beautifully blue nuances. Such a description depicts pristine nature, literally clean in all aspects of the word. The air is very low on humidity the further north of the arctic circle you get. That feels fresh and clean, too.

There was once a group of scientists doing field work in the north-east of Greenland a couple of decades ago. One day they had split up into two groups, there was a smoker in one of the groups. The groups went up on both sides of a glacier on foot. In the middle of the day there was barely any wind, one group was taking a lunch break in the most magnificent weather when one of them suddenly said, "I smell cigarette smoke". They noted the time and place. When they met up with the other group it was confirmed that the smoker had smoked a cigarette around the noted time. On the map they checked where they were – they had been 5 km. apart.

Foreign scientists discovered a few years back on the Greenland inland ice that although it looked white and clean, the topsoil was polluted and most polluted in spring. Even animals, such as polar bears have high levels of PCB and other foreign materials. Most of this pollution comes from the Euro-Asian continent. This is pollution from the outer world.

From former military outposts there are often deposits of hundreds of barrels of oil and fuel, abandoned, to rust away and the oil and fuel to enter the ecosystem over a prolonged time. Another pollution from the local area is from mining sites. Mussels, fish and birds feeding in polluted inlets all had high concentrations of pollution. Harvesting was banned. Regulation now applies to this type of pollution.

Sewage from households and industry flow directly into the sea without filtration. Combustibles from households and industry are burned either in open air at dump sites (very common) or in an incinerator. The smell of the smoke is said to be terrible. Iron, chemicals, used batteries, used motor oil and more are piled up. Boats, engines, cars, and snowmobiles are left as litter in towns. In recent years some towns have begun to collect such waste and send it to treatment facilities in Denmark, some are kept for spare parts, others were supposed to go to the dump. This is consumer generated pollution.

Outside town limits and village limits where locals go fishing, hunting or go for recreational purposes, be it on day trips or longer trips, some people bring back their trash, burn it or bury it on site. Some just leave it as is to be scattered by fox, raven, gulls or the wind. Occasionally some dump it in a large plastic bag in the sea a few meters from the shore on shallow water where it is discernible. Such behaviour is new and is *absolutely banned but has been observed a few times in a few places also by rivers where there is arctic char. This might have been done by town people on a recreational trip who have begun to act counterproductively – they are known to react against foreigners, in this case usually Danes who tell them not to litter in nature. They react because in their mind it is their country and no foreigner has the right to tell them what to do with their country. It also proves that they have lost their connection to their cultural heritage. This is rash pollution.*

Box 3: Pollution disproportionally impacts first nations people. To the Inuit Greenland peoples, pollution from The Outer World presents a vast array of challenges. Documented here is a firsthand account of some types of pollutants in Greenland and impacts these have on Inuit communities. We have the capacity to influence pollution impacts on a local scale, but we require political efforts, legislation and global change to make positive impacts in communities and environments in need.

Tables:

Table 1: A list of the three major sources of marine pollution and examples of the key types of pollution from each source considered in our future scenarios. * denotes a pollutant that is outside the scope of this paper.

	Pollutant Source	Pollutant Source	Pollutant Source
Pollutant Type	**Land-based industry**	**Municipal-based**	**Sea-based industry**
Sediment	Sediment from mining*, agriculture, or forestry	Sediment from coastal development	Sediment disruptions (e.g. dredging and aquaculture)
Nutrient	Nutrients (e.g. nitrogen, phosphorous, iron) from agriculture, forestry, livestock	Nutrients (e.g. nitrogen and phosphorous) from wastewater, stormwater	Increase in nutrients (e.g. nitrogen and phosphorous) from aquaculture
Plastics	Plastics from packaging and transport of products	Plastics from urban stormwater, and litter escaped from waste management systems	Abandoned, lost, or discarded fishing gear from vessels. Plastics from aquaculture, shipping and offshore structures
Pharmaceuticals	Pharmaceuticals used in animal agriculture	Pharmaceuticals in wastewater from household waste, and medical facilities	Pharmaceuticals (e.g. anti-biotics and antiparasitic drugs) from aquaculture
Chemicals	Chemicals, POPs and pesticides from agriculture, mining, industrial wastewater and runoff	Petroleum and household chemicals from wastewater, and stormwater outlets	Petroleum and chemicals from shipping and offshore structures

Sound	Motor noise, seismic devices and sound propagating devices

Light*		Light from coastal development*
Water*		Fresh water/ heated water* (e.g. melted sea ice, shifts in ocean c
Nuclear Waste*	Nuclear waste from power stations*	

Supplementary Information - Cleaner Seas: reducing marine pollution

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Supplementary Table 1: The full list of actions to "reduce and significantly reduce marine pollution" (SDG 14.1.), as determined by the Future Seas deliberation process.

ACTIONS AT THE SOURCE

- Bans on product use, production, and release
- Prevent creation and use of harmful chemicals
- Replace technologies for less noise/light alternatives
- Support agricultural practices that minimize topsoil loss or further deforestation
- Public outreach campaigns
- Replace plastics with non-plastic alternatives
- Shift to the use of benign chemicals in industry
- Joint-several-liability
- Increase enforcement and surveillance of international policies (e.g. MARPOL)
- Limits on fishing effort, the amount and/or types of gear used, and limits for operational characteristics

ACTIONS ALONG THE WAY

- Port facilities for commercial vessels to dispose of damaged gear easily
- Technological shift to circular economies and reusable products
- Using waste as an energy source
- Restore wetlands and native vegetation along rivers, estuaries, and coastlines
- Install small, decentralized waste water treatment plants

ACTIONS AT THE SINK

- Community beach/river clean ups
- Recover chemicals from wastewater
- Install gross pollutant traps
- Removal of pollutant from high risk areas

Supplementary Table 2: The ten actions determined by the Future Seas deliberation process as priorities in achieving a more sustainable future scenario. Each action is categorised by which area it relates to; at the source (green), along the way (light blue), at the sink (dark blue), and across the whole system (purple).

ACTION AREAS	TECHNICALLY FEASIBLE ACTIONS	RELEVANT SUSTAINABLE DEVELOPMENT GOALS
AT THE SOURCE	Prevention of Contaminants	
	Outreach and Education thar promote reduction in pollution	
	Replace technology and products for less impactful alternatives	
	Bans and incentives	
ALONG THE WAY	Transition to a circular economy	
	Trap pollutants	
AT THE SINK	Collection and clean-ups	
ACROSS THE WHOLE SYSTEM	Government and public support of activities that minimise pollutant leakage	
	Binding international agreements, national and local legislation	

ACTION AREAS	TECHNICALLY FEASIBLE ACTIONS	RELEVANT SUSTAINABLE DEVELOPMENT GOALS
	Tightening policy of non-compliant activities and on testing pollutants	

List of United Nations Sustainable Development Goals (SDGs) that are linked to reducing and preventing marine pollution (Cleaner Seas):

2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality.

3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.

6.A By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies

6.B Support and strengthen the participation of local communities in improving water and sanitation management

6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally

6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes

9.B Support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities

9.5 Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending

11.B By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels

11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management

12.A Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production

12.B Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products

12.C Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities

12.1 Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries

12.2 By 2030, achieve the sustainable management and efficient use of natural resources

12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses

12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment

12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle

12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities

12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature

14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution

14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans

15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements

15.A Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems