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Published in:
Marine Pollution Bulletin

DOI:
10.1016/j.marpolbul.2021.112263

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Marine Pollution Bulletin 167 (2021) 112263

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Leverage points for addressing marine and coastal pollution: A review

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ARTICLE INFO

Keywords:
Plastics
Oil spills
Social-ecological systems
Sustainability transformations
Marine litter
Marine debris

ABSTRACT

Despite an increasing understanding of the issue of marine pollution, humanity continues on a largely unsustainable trajectory. This study aimed to identify and classify the range of scientific studies and interventions to address coastal and marine pollution. We reviewed 2417 scientific papers published between 2000 and 2018, 741 of which we analysed in depth. To classify pollution interventions, we applied the systems-oriented concept of leverage points, which focuses on places to intervene in complex systems to bring about systemic change. We found that pollution is largely studied as a technical problem and fewer studies engage with pollution as a systemic social-ecological issue. While recognising the importance of technical solutions, we highlight the need to focus on under-researched areas pertaining to the deeper drivers of pollution (e.g. institutions, values) which are needed to fundamentally alter system trajectories.

1. Introduction

Marine and coastal ecosystems are polluted at an alarming rate, degrading their ecosystems and biodiversity (Cole et al., 2011; Derraik, 2002). The negative effects of marine pollution on ecology also impacts human health (Carbery et al., 2018; Thompson et al., 2009) and well-being (Williams et al., 2016) and threaten food security and livelihoods (Hennessey and Sutinen, 2005; Possatto et al., 2011; Shahidul Islam and Tanaka, 2004). Some of the most prominent examples of marine pollution are the large-scale oil spills of the Exxon Valdez (Xia and Boufadel, 2010) and Deepwater Horizon (Beyer et al., 2016; Incardona et al., 2014) and the rising frequency of hypoxic dead zones in the oceans due to eutrophication (Diaz and Rosenberg, 2008). Furthermore, microplastics are accumulating even in remote regions (Lavers and Bond, 2017), such as the Arctic Ocean (Bergmann et al., 2017; Peeken et al., 2018) and deep seas (Peng et al., 2018; Woodall et al., 2014). The loss of iconic ecosystems such as coral reefs (Carpenter et al., 2008) and seagrass meadows (Orth et al., 2006) are accelerated by marine pollution. Additionally, climate change (Lu et al., 2018) and ocean acidification (Doney et al., 2009; Kroeker et al., 2013) alter biochemical processes and physical parameters, further increasing the pressure on marine and coastal ecosystems.

Knowledge of the quantification, characteristics and mechanisms of marine pollution (be it discrete or chronic, from a non-point source or point source) is increasing exponentially (Borja and Elliott, 2019; Lebreton et al., 2017). Further, high social awareness and knowledge about the problems at hand is available (Gelcich et al., 2014). Awareness is increasing, in part due to the Sustainable Development Goals that target responsible consumption and production (SDG 12) and life below water (SDG 14) (UN, 2015). For instance, in 2019 the European Parliament approved a law to ban single-use plastics by 2021 within the European Union (EU, 2019). Yet, projections still show an increase of plastic use driven by plastic production, with global production exceeding 350 million tonnes in 2018, of which about 62 million tonnes (17.7%) were

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https://doi.org/10.1016/j.marpolbul.2021.112263
Received 1 December 2020; Received in revised form 3 March 2021; Accepted 10 March 2021
Available online 31 March 2021
0025-326X/

produced in Europe (Jambeck et al., 2015; Plastics Europe, 2019). In the same year, 2018, 29.1 million tonnes of post-consumer plastic waste was collected (Plastics Europe, 2019). It was estimated that in 2010, about 5 to 13 million tonnes of produced plastics entered the ocean and this amount is likely to increase as it was estimated that about 12,000 million tons of plastic waste are likely to end up in the natural environment by 2050 (Geyer et al., 2017; Jambeck et al., 2015). With this paradoxical development of rising knowledge about the negative impacts of pollution and rising pollution, we have to ask ourselves: What drives this ongoing pollution and how can knowledge be more effectively deployed to address this problem?

One hypothesis is that interventions for sustainability have been primarily focused on "easy to fix" aspects and short-term interventions, which achieve a quicker but less transformative result (Fischer et al., 2012). Such a focus on "quick-fixes" prevents transformative systemic shifts (Sala and Torchio, 2019). Yet, such shifts are urgently necessary to combat marine pollution at its source. In this systematic review of scientific literature, we investigate this hypothesis of a focus on "quick-fixes" by extracting and evaluating interventions for cleaner marine and coastal ecosystems in scientific discourse. In this systematic review we aim to (i) determine the pollutants studied and their sources as named in the academic literature; (ii) focus on a subset of papers that state concrete interventions (as opposed to purely descriptive and monitoring approaches) and analyse the spatial distribution and characteristics of these interventions; and (iii) characterise the interventions according to the leverage points perspective, i.e. indicating their scientific approach or the type of framing used, identifying who is perceived to be responsible to intervene and the transformative potential of the interventions.

1.1. Leverage points perspective

We draw on the systemic leverage points perspective (Fischer and Riechers, 2019) as an analytical tool to scrutinise the transformative potential of interventions aimed at coastal and marine pollution in academic publications. The leverage points perspective is based on social-ecological systems thinking linking social and environmental phenomena (Berkes and Folke, 1998). To achieve a transformation to a more sustainable state, i.e. clean marine and coastal ecosystems, it is important to consider where to intervene in the system to attain the most transformative results. Meadows (1999) proposed a hierarchy of intervention points for leveraging change. These leverage points range from shallow interventions (e.g. changes in parameters or feedbacks) to deep and powerful interventions (e.g. changes in system intent, goals and paradigms) (Abson et al., 2017) (Table 1). The distinction between shallow and deep leverage points pertain to the depth at which a leverage point is located within a social-ecological system and the extent to which it can alter a system's trajectory. Following Meadows (1999), places to intervene include *parameters*, which are constants (e.g. subsidies or taxes as interventions), the size of buffer stocks and structure of material stocks and flows (such as transport networks or population age structures). In a marine and coastal context, an example of a parameter would be the concentration of a specific pollutant in a defined area. *Feedbacks* are leverage points that constitute the length of delay, strength of negative feedback and gain around driving positive feedback loops. Intervention in both of these system characteristics, parameters and feedbacks, has only a shallow leverage to transform a system. A deeper leverage point is the design of a system – defined by the structure of information flows (who does and does not have access to information), the rules of the system or institutions (e.g. incentives, punishments, constraints and other tools for regulation) and the power to add, change, or self-organise the system structure. The deepest leverage points consist of the system intent, i.e. the goal of the system or the mind-set/paradigm out of which the system arises (including value or beliefs systems). Based on the hierarchical structure from shallow to deep leverage points, changing the system intent would automatically influence the structure, rules, delays and parameters of a system (Abson et al., 2017; Meadows, 1999, 2008) (Table 1; see Table 3 for specific examples). Through this categorisation, we can use the leverage points perspective as an analytical tool to assess the transformative potential of interventions aimed to combat coastal and marine pollution.

Table 1
Twelve leverage points sensu Meadows (1999) and their corresponding system characteristics sensu Abson et al. (2017) from shallow to deep leverage.

Leverage points	System characteristics
12. Constants, parameters, numbers	Parameters
11. The size of buffers and other stabilising stocks, relative to their flows	
10. Structure of material stocks and flows	
9. Length of delays, relative to the rate of system changes	Feedbacks
8. Strength of negative feedback loops, relative to the effect they are trying to correct against	
7. Gain around driving positive feedback loops	
6. Structure of information flow	Design
5. Rules of the system	
4. Power to add, change, evolve, or self-organise system structure	
3. Goal of the system	Intent
2. Mind-set or paradigm that the system — its goals, structure, rules, delays, parameters — arises from	
1. Power to transcend paradigms	

Interventions at deep leverage points have greater power to influence and shift a system, while interventions targeting relatively shallow leverage points would produce smaller changes in the system as a whole. Many sustainability interventions target highly tangible but essentially weak leverage points, i.e. using interventions that are easy, but have limited potential for transformational change such as taxation on fossil fuels – instead of changing a fossil fuel based economy. Thus, there is an urgent need to focus on less obvious but potentially far more powerful areas of intervention (Fischer and Riechers, 2019). We do not want to suggest that interventions addressing more shallow leverage points are inherently and indiscriminately ineffective. They are both highly necessary and beneficial. Instead, we highlight that an intentional focus on deep leverage points and interactions between interventions is necessary and requires further attention. Key strengths of a leverage points perspective are (sensu Fischer and Riechers, 2019): (1) the explicit recognition of difficult to act upon but influential, "deep" leverage points (Dorninger et al., 2020) and enabling the examination of interactions between shallow and deep system changes (Manlosa et al., 2018); (2) the combination of causal (nothing can happen without a cause) and teleological modes (events and developments are meant to achieve a purpose and happen because of that) of research; and (3) the ability to function as a methodological boundary object for inter- and transdisciplinary research.

In the following, we present our findings on the concrete interventions suggested and deployed and how these can be analysed according to the leverage points perspective as described above. We then discuss the implications of our review according to the three key strengths of the leverage points perspective. We conclude by identifying opportunities for extending the transformative potential of the global fight against marine and coastal pollution.

2. Methods

2.1. Data collection

Our systematic review followed the guidelines for the "Preferred reporting items for systematic reviews and meta-analyses" (PRISMA) framework as described by Moher et al. (2009). We developed a search string, to encompass the diversity of marine pollution types and marine and coastal ecosystems (see S1). In September 2019, we applied our search string to the databases of Scopus (www.scopus.com) and the ISI Web of Science (www.webofknowledge.com). Our search string includes publications from 2000 to 2018. The year 2000 is when the EU Water Framework Directive was adopted which changed the academic narratives towards a more comprehensive assessment. The search string was restricted to articles in English - including both conceptual and empirical observations, but excluding reviews – that focus on various forms of marine pollution and referred to interventions (see search string, Supplementary S1) in their title, abstract or keywords. After removing duplicates, the search string resulted in 4846 articles.

We screened the title, abstract and keywords of these 4846 papers (Fig. S1) based on our inclusion and exclusion criteria. Papers not concerned with marine and coastal ecosystems or the pollution thereof were excluded. Further, purely descriptive or evaluative empirical studies, i.e. with no reference to a possible intervention proposed or described in the abstract (or when a decision could not be made based solely on the abstract, based on reading the full paper) were excluded from the review ($n = 2492$). The goal was to include papers that describe a specific and intentional intervention targeting marine pollution. The remaining 2417 papers were downloaded and analysed full-text. These papers were included after screening because they mentioned either potential interventions in the title, abstract or keywords. A full text analysis revealed that interventions were not given substantive focus in all 2417 articles. Hence, for the in-depth coding on interventions, we included a total of 741 papers, which mentioned solutions and interventions to combat marine and coastal pollution.

2.2. Data analysis

Data were analysed using SPSS 26 (IBM Deutschland GmbH, Ehningen, Germany). Data analysis consisted of qualitative and quantitative analyses. The coding scheme used in the systematic review was partly based on Dorninger et al. (2020). It was tested and refined on 50 randomly selected papers before being applied. To ensure inter-coder reliability, tandems of two conducted preliminary coding separately. The results were crosschecked between the reviewers for consistency in the application of the coding scheme. We coded for 12 variables, each representing one question that was applied to the reviewed articles. The 12 variables filled in by the authors were standardised and turned into 96 distinct variables with a mostly dichotomous structure to account for the multiple occurrences of, for example, pollutants, ecosystems or spatial scale. The variables "sources of pollution" and "interventions against pollution" were analysed using a qualitative content analysis to summarise the results into distinct categories and groups (Mayring, 2008). The overarching categories were also coded numerically for further statistical analysis. To assess the leverage points or system characteristic of interventions, three experts on leverage points (IAD, AM, MR) first had a group discussion on the tasks, then separately grouped the interventions into the four system characteristic by Abson et al. (2017) and lastly compared and discussed their categorisation for more reliability.

The resulting codes were mainly analysed descriptively. Further, we conducted a hierarchical (agglomerative) cluster analysis (HCA) using Ward's method (Ward, 1963) and squared Euclidian distance to identify groups of papers that were similar with regards to the leverage points (i.e. the system characteristics of the named, often multiple, interventions: parameter, feedback, design and intent) addressed in the interventions. The HCA does not require a pre-specified number of clusters and the resulting clusters were chosen after a set of clusters from three to nine were analysed with descriptive statistics on their coherence and explanatory power. We used the results from the HCA to correlate the clusters with variables such as pollutants, scientific framing, spatial scale, reactive or proactive approach and agency for intervention using the standardised residuals of each correlation for graphical presentation.

3. Results

3.1. Foci of the academic literature on marine and coastal pollution

In total, our analysis of 2417 papers showed a research focus on chemicals (28% of the papers), followed by metals and metalloids (19%), nutrients (18%) and oil (14%). Microplastics (6%), plastics in general (4%) and a focus on the general topic of marine pollution (i.e. unspecified pollution, such as "marine litter" or "debris") (5%) received less attention ($n = 2417$). Other pollutants such as emissions, bacteria, noise and gas together accounted for 6% of all papers coded. Results also indicated a change of research foci over the last 20 years as, proportionally, research on pollutants such as chemicals, metals, nutrients and oil decreased over time, while studies on (micro)plastics increased (Fig. 1).

While our search string was designed to capture papers mentioning interventions for addressing pollution (see Supplementary S1) the vast majority of papers still described and measured pollution occurrences without naming any intervention to address it (53%). Around 16% of papers addressed pollution through monitoring, without suggesting further and more specific interventions to solve the problem. Almost a third of the papers (31%) named specific interventions. Of the interventions stated in these papers, 61% were reactive, i.e. dealing with the pollution when it had happened and 39% had proactive elements, i.e. aiming to prevent the pollution from happening.

For the subsequent stages of analysis, we excluded papers that did not cover concrete interventions beyond monitoring activities and we focused exclusively on the 31% of the 2417 papers that proposed clearly defined interventions ($n = 741$).

3.2. Interventions to combat marine pollution

While the proportion of papers with a focus on reactive interventions has grown over time, the percentage of papers stating proactive interventions to prevent pollution does not show a clear trend (Fig. S3).

The sources of pollution named in these papers (Table 2, $n = 1362$) were predominantly oil spills (18.4%) and wastewater (14.5%), followed by agriculture (11.8%), but also often left unnamed (general 10.2%). To address these pollution sources, research on concrete interventions were mostly lab studies (46.1%), with 11.9% papers having a regional (sub-national) spatial focus, followed by the smaller spatial scales of studying pollution at the landscape scale (9.6%) and in locally specific areas (9.3%). Most interventions were proposed (76.2%) and fewer were implemented (23.8%) (Fig. 3).

Using qualitative content analysis, we classified the interventions into 44 categories, of which the top 20 cover over 75% of interventions named for each pollutant. The main intervention categories to combat marine pollution were (bio)remediation (incl. (bio)sorption), followed by more and/or improved cleaning strategies, technologies and mathematical models to increase the effectiveness and speed of responses after a pollution event. The third most frequently mentioned intervention to combat marine pollution was the call for stronger and/or better regulations and laws to prevent pollution from happening in the first place, as well as the coordination of clean-ups (Table 3).

3.3. A leverage points perspective on interventions against marine and coastal pollution

Using the leverage points perspective as an analytical tool to categorise the interventions, we found that most interventions addressed parameter system characteristics (51.3%) (Table 3). Feedback system characteristics were addressed in 4.6% of interventions. The system design was addressed in 34.6% and the system intent in 9.1% of the interventions.

When analysed in relation to the pollutant (Fig. 3), results showed that at least half of the papers on interventions against chemicals, oil,

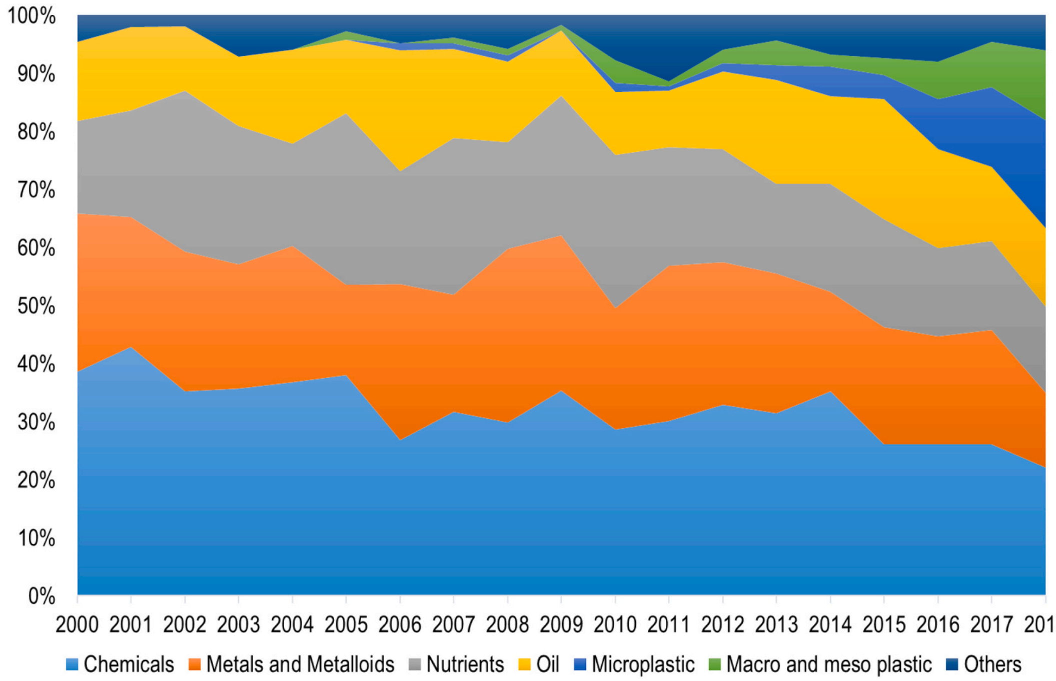

Fig. 1. Proportion of pollutants studied by year. To account for the general increase in academic papers (Fig. S2 shows the increase of papers from 37 in 2000 to 359 in 2018) data are shown in proportion to the papers published the respective year ($n = 2417$).

Table 2
Pollution sources and major subcategories as resulting from the qualitative content analysis of n = 741 papers. Total number of source statement = 1362, multiple sources can be named in one paper.

Pollution source	Largest subcategories (% of total poll. source)	Percentage of total
Oil spills		18.4%
Industry	Dyes (7.1%)	16.5%
	Nuclear energy (5.8%)	
	Tourism (4.9%)	
	Military (3.1%)	
	Flame-retardants (1.8%)	
Wastewater		14.5%
Agriculture	Pesticides (2.5%)	11.8%
	Fertiliser (1.9%)	
General	Land-based (14.4%)	10.2%
Shipping	Anti-fouling items (21.3%)	7.9%
	Fishing (15.7%)	
	Harbours (11.1%)	
Domestic items	Plastics (26.6%)	6.9%
	Single-use items (23.4%)	
	Pharmaceuticals (17.0%)	
	Cosmetics (9.6%)	
	Domestic solid waste (5.3%)	
Urbanisation		3.3%
Runoff		2.6%
Aqua/ mariculture		2.5%
Emissions		2.4%
Mining	Drilling (11.4%)	2.6%
Others		0.5%

nutrient and metal pollution addressed system parameters (see also Fig. S4). System design (mainly an intervention addressing laws and regulations regarding pollution) was the focus of 59.4% of the interventions in papers addressing pollution in general and 54.8% and 55.4% of those against macroplastics and microplastics pollution, respectively. With 13.6%, system feedbacks were most commonly addressed in terms of interventions against oil pollution. Of the interventions against macroplastics and microplastics pollution, 16.1% and 15.7% respectively focused on the system intent, followed by papers on nutrient pollution (13.7%). Fig. 3 shows the distribution of the intervention categories by pollutant and classified according to the leverage points perspective, highlighting the dominance of individual interventions in the scientific discourse on pollutants.

Further, we looked at the scientific approaches taken in the research papers (multiple approaches within one paper are possible). Fig. 4 highlights that more than half of the papers (53.6%) used a technical framing for their interventions, followed by a political framing (18.6%). Agency for interventions was framed to be mainly with scientists (44.3%) and national politicians (22.6%), while 14.9% of the papers stated that companies and businesses are responsible for the interventions.

Our cluster analysis resulted in three distinct clusters: 1) Parameters, 2) Feedbacks, 3) Design and Intent. Fig. 5 shows that the system characteristic of parameters was mainly addressed by studies on chemical and metal pollution through lab studies. The interventions named in these studies tended to be reactive, have a technological and ecological framing and consider scientists to be responsible for the interventions.

Interventions that address the system characteristic of feedbacks have a focus on metal pollution and covered predominantly a regional (sub-national) scale. The interventions tended to be reactive, framed technologically and scientists were identified as being responsible for interventions.

The design and intent system characteristics were addressed by studies on general pollution; plastics, microplastics and nutrients tended to be done on a national scale. Interventions in this cluster were mainly proactive, have diverse scientific framings and named a wide range of actors for the intervention.

4. Discussion

Whereas there exists a large amount of scientific knowledge on the problems and sources of coastal and marine pollution (Lebreton et al., 2017; Löhr et al., 2017), the problem itself is still as prevalent as ever. The current sustainability crises are not “fixed” by more research or better technology (Orr, 2004) but through agency and action in real-

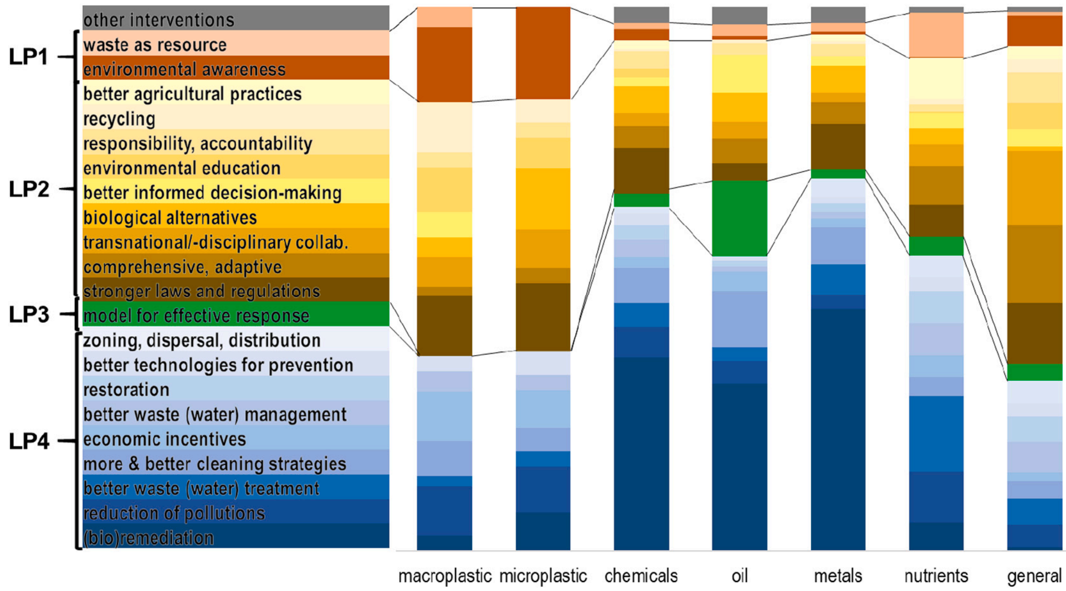

Fig. 3. Distribution of the 20 most named interventions against marine pollution classified by the system characteristic they address: LP4 = system parameters (blue), LP3 = system feedbacks (green), LP2 = system design (orange), LP1 = system intent (red). Remaining interventions were grouped into "others" and not classified according to the leverage points perspective. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Percentage of the four system characteristics according to Abson et al. (2017); percentage of interventions named in the literature; categories as resulting from the qualitative content analysis. Interventions named less than 1.5% have been excluded from this presentation for simplifications.

System characteristics	Specific interventions identified from content analysis	Percentage of all interventions named (n = 1171)
System parameters (51.4%)	(Bio)remediation, incl.(bio) sorption;	22.9%
	More & better cleaning strategies;	11.6%
	Better waste (water) treatment;	6.8%
	Reduction of pollutant;	4.4%
	Economic incentives;	3.4%
	Better waste (water) management;	2.9%
	Restoration;	2.8%
	Better technologies for prevention;	2.1%
	Zoning, dispersal, distribution	2.1%
System feedbacks (5.0%)	Model for effective response	5.5%
System design (34.6%)	Stronger laws and regulations;	7.9%
	Comprehensive, adaptive and/or spatial management;	4.8%
	Stronger transnational, transdisciplinary collaborations;	4.4%
	Biological, non-toxic, alternatives;	4.3%
	Better informed decision-making, incl. risk assessment/ inclusion;	3.7%
	Responsibility, accountability for polluters;	2.1%
	Better agricultural practices;	2.1%
	Recycling;	1.5%
	Environmental education	1.5%
System intent (9.0%)	Waste as resource;	3.8%
	Environmental awareness	2.8%

world settings (Colloff et al., 2017). It is important to note that the research on plastics (micro-, meso- and macro-) increased significantly from the first study in 2005 to 122 in 2018, both in proportion and in absolute numbers. In 2018, nearly 31% of all marine pollution studies were researching plastics. No other pollutant picked up research interest so fast in our record, showing the agility of science to re-focus on emergent threats.

We showed that oils spills were mentioned most often as source of pollution, followed by different industrial sources, waste water and agriculture. The most often named interventions for these particular sources were framed around cleaning (e.g. remediation/absorption, waste water management) and were rarely concerned with interventions for oil-alternatives or more sustainable industrial production processes. Indeed, even though our search string was designed to include interventions, over half of the papers were purely descriptive and did not mention clearly defined intervention strategies. Of those papers that suggested interventions, the majority focused on reactive (mainly cleaning up), rather than on proactive, preventive ones. Based on our stated hypotheses regarding a scientific focus on "quick-fixes", which are most often related to reactive interventions and cleaning up measures, our findings highlight a diversity of reactive and proactive approaches showing 61% of the named interventions to be reactive, while 39% were proactive. The interventions mentioned to address marine pollution are mostly technological advancements – often based on studies done in the lab - with the agency of intervention in the hands of scientists, which is a general bias of science (Dorninger et al., 2020). We, however, also showed the existence of a more social-ecological approach in which articles mentioned the agency of multiple actors (e.g. politicians, society and business) to intervene to combat marine pollution. Beyond our focus on academic papers, a leverage points analysis of interventions against marine and coastal pollution in other sources such as government and non-government reports to enable a comparison between science and policy foci. In addition, further research could focus on characterising and comparing interventions to combat pollution from point and non-point sources and chronic and discrete types. A leverage points perspective could help determine whether interventions for chronic pollution from non-point sources differ from interventions from an oil spill and whether interventions for the former will tend to focus on deep leverage points. However, due to limitations in our data, this

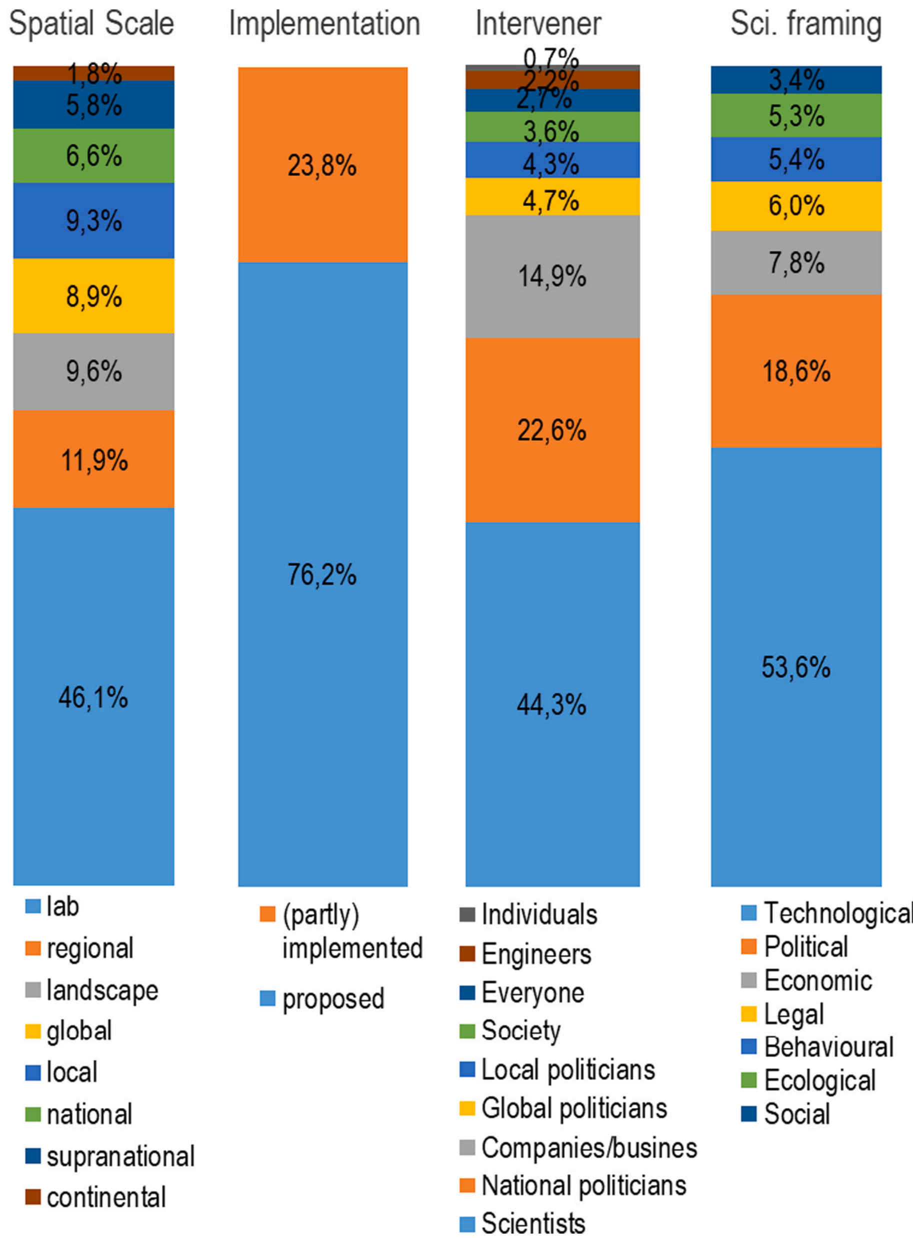

Fig. 4. Categorisation of 741 papers (in percentage) regarding the spatial scope of study, whether interventions are proposed or implemented, whose responsibility it is to act and the scientific framing of the intervention. One paper can use several scientific framings, refer to multiple agents for intervention and use multiple scientific framings.

question was not covered by this study.

In the following, we synthesise lessons learned from applying a leverage points perspective to interventions against marine pollution, drawing on the three key strengths of this perspective: 1) focusing on deep leverage points and links between them, 2) the combination of causal and teleological approaches and 3) how the leverage points perspective can be used as a practical and methodological boundary object. Based on these insights we identify opportunities to develop and implement interventions to address the issue of marine and coastal pollution more effectively.

4.1. Operationalising the leverage points perspective for cleaner marine and coastal ecosystems

4.1.1. Focus on deep leverage points and interactions

Our review of the literature demonstrated that interventions, which take a rather short amount of time to be implemented are common in research on marine pollution. This, however, eludes a transformative shift. The lack of research on deep leverage points is not uncommon (Dorninger et al., 2020) as technocratic approaches have a longstanding history in science and are currently being critically scrutinised (Bäckstrand, 2003; Rametsteiner et al., 2011). An intentional integration of deep systemic transformation is needed (Meadows, 1999). Interventions that were classified as deeper leverage points are related to, for example, a change towards a low-impact (Ehrenfeld, 2005; Liu et al., 2012) or circular economic paradigm (Löhr et al., 2017; Penca, 2018) and a strengthening of the precautionary principle (Liu et al., 2012; Udovyk and Gilek, 2013). These proposed interventions are not bound to one pollutant or pollution source and instead focus on transforming the underlying intent of the system which generates pollution towards more sustainability. Another example of a deep leverage point in relation to nutrients from agriculture is the suggestion to change agricultural practices (McLellan et al., 2015). This entails political changes from global (e.g. curbing the increasingly distant supply chains, Khoury

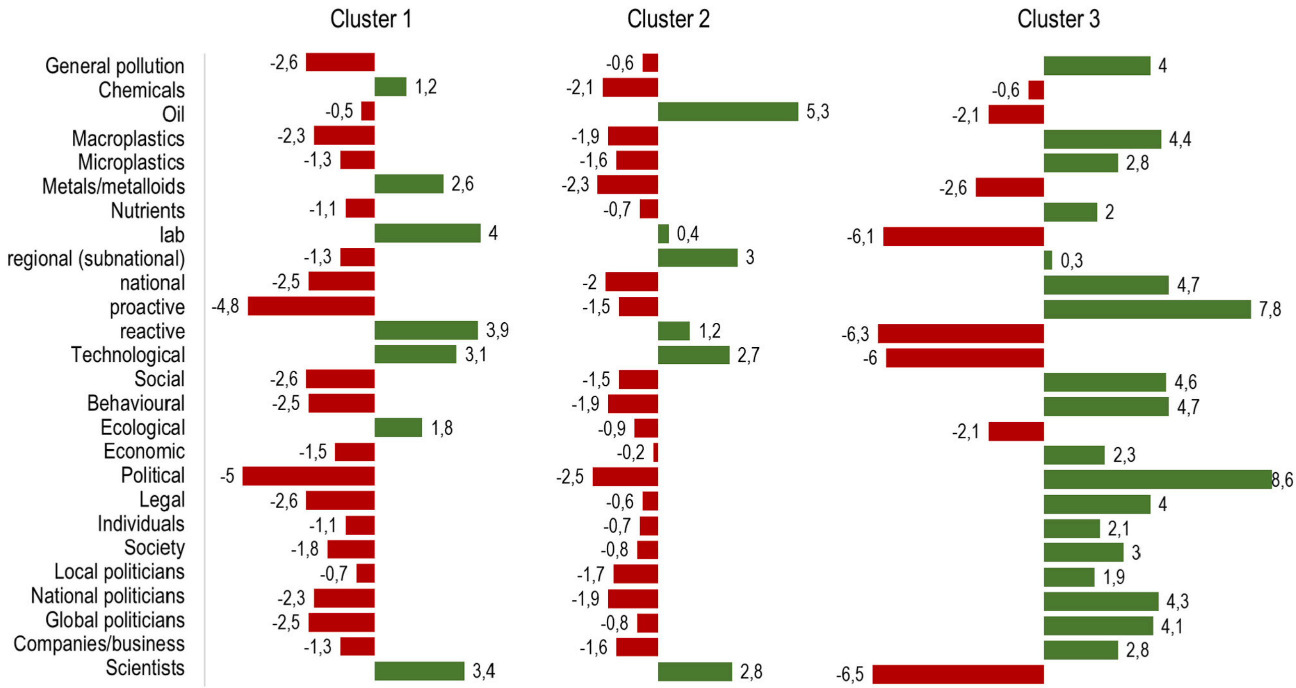

Fig. 5. Results from the HCA of 740 papers. Only correlations with $p = 0{,}000$ are shown. Bars show the standardised residuals of each correlation; negative residuals are shown in red, positive residuals are shown in green. Cluster 1 = Parameters, Cluster 2 = Feedbacks, Cluster 3 = Design and Intent. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2014) to local levels (e.g. supporting organic farmers, Loizidou et al., 2017).

As mentioned earlier, the distinction between relatively shallow and deep leverage points does not mean that interventions, which can be classified as shallow are unnecessary and ineffective. It means rather that certain interventions, while effective for their particular purposes, have little power to fundamentally alter system dynamics and trajectories. Moreover, if research related to marine pollution continues to focus on shallow leverage points, the concomitant public policies developed will be ineffective, avoiding real and necessary transformation. For instance, cleaning up after an oil spill is highly necessary (Beyer et al., 2016; Incardona et al., 2014). Such highly visible spill incidents can lead to a proliferation of research in advancing clean-ups (e.g. Bernabeu et al., 2009; Sueiro et al., 2011) and more effective response categories (Melaku Canu et al., 2015; e.g. Poje et al., 2014; Qin et al., 2017). However, discussions about fundamentally preventing another oil spill through changed, stricter legislation are less prevalent. Hence, we highlight that an intentional focus on deep leverage points and links between leverage points (i.e. addressing both deep and shallow leverage points) is necessary to expand the focus beyond leverage points that are insufficient for systemic change to sustainability. Our cluster analysis showed that interventions addressing the system characteristics of design and intent occur together – yet discussions around the linkages between shallow and deep leverage points remain missing. An example of this from our findings relate to plastics (micro-, meso- and macro-). Our results showed that 15% of interventions focused on system intent (e.g. raising awareness and education), ~55% on system design (e.g. stricter rules and regulations) and ~30% on parameters (e.g. finding more biological-friendly alternatives). Given the rise of research on plastic pollution, this could suggest a potential shift of focus towards a social-ecological perspective which considers links between leverage points.

4.1.2. Causal and teleological focus on interventions

Research on marine pollution is relying on finding principles of causality, as our results point out. This focus on causality has, for example, led to strong predictive models on clean-ups and response efficiency. These interventions use the dominant scientific mode of forecasting, where known causalities are extended into the future. Scientific forecasts, regardless of whether they are on anthropogenic climate change, demographic change or biodiversity loss, are extremely useful tools in decision-making (IPCC, 2018). Taking a leverage points perspective, we underscored that these models and forecasts target parameters and feedback system characteristics. The hierarchy of leverage points proposed by Meadows (1999) and Abson et al. (2017) spans a range of considerations from causal to teleological – providing a place where fundamentally different modes of thinking can be bridged.

We argue that cleaner marine and coastal ecosystems are not only achieved by better predicting when pollution events might happen and how to respond to them. Instead, one should also proactively aim to change the system intent towards healthy and clean marine and coastal ecosystems (such as the "intents" of above named circular economy or the precautionary principle). For instance, this shift could promote the modification of our ways of being in the world, our production and trading systems and the ways in which we relate to each other and to the rest of nature. The system goals and especially the power to transcend the paradigm underpinning a system acknowledge that human agency, its normative direction and thus teleology fundamentally shape outcomes. An example of an approach that lends itself to this kind of research is backcasting. Backcasting is a strategic planning tool, which is designed to envision a desired future (e.g. in 20 years). This vision is the starting point to discuss and design concrete steps to materialise this vision (Dreborg, 1996). Backcasting, hence, includes a focus on the design and intent system characteristics and strengthens the focus on proactive interventions. With the system intent set on healthy and clean marine and coastal ecosystems, the causal relationships will act within these teleological boundaries and serve its overall purpose and goal. There are other methods which include a teleological approach (see e.g. Three Horizon in Sharpe et al., 2016) and we argue that their inclusion can have great merit for transformative action. Such methods can also engage scientists from various disciplines and non-academic actors that rally behind a common vision.

4.1.3. Inter- and transdisciplinary solution-oriented research

Preventing marine pollution is a practice as much as it is a science and hence the scientific approach needs to be more solution-oriented. Three-quarters of the interventions considered in this literature review are only proposed and not (yet) implemented. To develop and implement more effective interventions that address the root causes of marine pollution, we suggest the application of inter- and transdisciplinary approaches, which engage with plural scientific perspectives and a diversity of stakeholders (Riechers et al., 2021). Environmental conservation and management have traditionally been addressed within disciplinary boundaries and on a sectoral basis (Coppolillo et al., 2004; Simberloff, 1998). This fragmentation results in science providing advice, instead of co-producing knowledge between actors (Kirchhoff et al., 2013). Transformative interventions to combat marine pollution cannot be answered from within the natural nor the social sciences alone. Instead, they require inter- and transdisciplinary approaches that facilitate collaboration between a diverse group of scientists and non-academic actors (e.g. industry, policy, affected locals; see Sala and Torchio, 2019 for a discussion on these issues). To jointly develop more transformative interventions, researchers may enter unfamiliar grounds of knowledge co-creation, facing the complexity of the issue on purposive, normative and pragmatic levels of societal problem solving (Hirsch Hadorn et al., 2006). Concomitantly, researchers can engage in a discussion on the role that science, technology, industry, policy and society could play to accomplish the challenge of reducing pollution and its impact on humans and the environment around the globe.

Such a discussion may also venture into the debate on the values we hold for nature as done in sustainability transformation (Horcea-Milcu et al., 2019). Meadows (1999) highlights 'values' as deep leverage points and current debates highlight the necessity to include the relationship between humans and nature, including relationships between people mediated by nature (Chan et al., 2016; Riechers et al., 2020), as being emphasised by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2015). This discussion of values of the oceans goes beyond instrumental values (Himes and Muraca, 2018), instead aiming for meaningful relationships and responsibilities established between humans and nature through concepts such as stewardship (Bieling et al., 2020; Cockburn et al., 2019; West et al., 2018).

Finally, we recommend that all actors that endeavour to clean our ocean – science, policy and economics – conduct a leverage points assessment of their specific interventions against pollution. Such assessments should collect social-ecological information on a wide range of issues and sources including consideration of the systemic depth of the interventions proposed or implemented and actively engage in the difficult questions concerning the root causes of pollution and how these can be effectively transformed in the long run.

With social-ecological links recognised in the Sustainable Development Goals (UN, 2015) and by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2018), we see great potential to incorporate a leverage points perspective based on social-ecological system thinking into research on marine pollution to move towards a more sustainable trajectory for the marine and coastal ecosystems. Likewise, we see how our recommendation can underpin the objectives set out in the agenda of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) – such as adaptation strategies and science-informed policy responses to global change.

5. Conclusion

By 2025, the Agenda 2030 for Sustainable Development aims to prevent and significantly reduce marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution. Despite existing global efforts, current trends show an ever-increasing marine and coastal pollution. The amount of papers published each year on marine pollution gives a good impression of the astounding level of information achieved already. Humanity, however, has not been able to significantly alter the trajectory on increasing pollution of our marine environment.

Based on the seminal work by Donella Meadows, we use the leverage points perspective, a hitherto under-recognised heuristic and practical tool, for an extensive systematic review to classify different interventions according to their potential for system-wide change and sustainability transformations. Our results highlight (i) that chemical pollution is the most studied area, followed by metals and metalloids and nutrients ($n = 2417$ papers). The most frequently mentioned sources of pollution in the papers were oil spills, industry and wastewater ($n = 741$ papers); (ii) while the amount of papers is increasing, a solution-orientation is limited throughout the years (i.e. around 30% focus on interventions to marine pollution). (iii) These 30% were analysed in depth, showing diverse solutions proposed to minimise marine pollution. More articles focus on reactive interventions, such as cleaning up, instead of proactive, pre-emptive interventions at the source. In this paper, we have shown that deep leverage points related to changing the system's intent and paradigms are rarely addressed. The interventions mentioned to address marine pollution are mostly technological advancements with the agency of intervention in the hands of scientists. A smaller cluster showed a more social-ecological approach with studies done at the national level which identified multiple actors – politicians, society, business – as having roles to intervene in order to foster cleaner oceans. We propose that for initiating system-wide transformative change towards clean and healthy marine and coastal systems, deep leverage points, that is, the goals of a social-ecological system, including its intent and rules, need to be addressed more directly. These priorities, we argue, can provide useful guidance for how to make marine pollution agendas around the world more effective.

CRediT authorship contribution statement

Maraja Riechers: Conceptualization, Writing – review & editing, Investigation, Data curation, Writing – original draft. **Benedikt P. Brunner:** Investigation, Data curation, Writing – original draft. **Jan-Claas Dajka:** Investigation, Data curation, Writing – original draft. **Ioana A. Duşe:** Investigation, Data curation, Writing – original draft. **Hannah M. Lübker:** Investigation, Data curation, Writing – original draft. **Aisa O. Manlosa:** Investigation, Data curation, Writing – original draft. **Juan Emilio Sala:** Investigation, Data curation, Writing – original draft. **Tamara Schaal:** Investigation, Data curation, Writing – original draft. **Sabine Weidlich:** Investigation, Data curation, Writing – original draft.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

We thank Stefan Hilser and Julius Rathgens for their methodological advice. This work was supported by the prolongation of the Leverage points project funded by Volkswagenstiftung and the Niedersächsisches Ministerium für Wissenschaft und Kultur (Grant Number A112269). AOM was funded by a grant from the German Federal Ministry of Education and Research to Achim Schlüter and Anna-Katharina Hornidge.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112263.

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