Ecosystem Services 20 (2016) 69–81

Contents lists available at ScienceDirect

Ecosystem Services

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

A conceptual framework for assessing the ecosystem service of waste remediation: In the marine environment

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ARTICLE INFO

Article history:
Received 6 May 2015
Received in revised form
24 June 2016
Accepted 28 June 2016
Available online 21 July 2016

Keywords:
Ecosystem services
Waste remediation
Marine, Shelf-seas
Human wellbeing

ABSTRACT

In the marine environment, the ecosystem service of Waste Remediation (WR) enables humans to utilise the natural functioning of ecosystems to process and detoxify a large number of waste products and therefore avoid harmful effects on human wellbeing and the environment. Despite its importance, to date the service has been poorly defined in ecosystem service classifications and rarely valued or quantified. This paper therefore addresses a gap in the literature regarding the application of this key, but poorly documented ecosystem service. Here we present a conceptual framework by which the ecosystem service of WR can be identified, placed into context within current ecosystem classifications and assessed. A working definition of WR in the marine context is provided as is an overview of the different waste types entering the marine environment. Processes influencing the provisioning of WR are categorised according to how they influence the input, cycling/detoxification, sequestration/storage and export of wastes, with operational indicators for these processes discussed. Finally a discussion of the wider significance of the service of WR is given, including how we can maximise the benefits received from it. It is noted that many methods used in the assessment, quantification and valuation of the service are currently hampered due to the benefits of the service often not being tangible assets set in the market and/or due to a lack of information surrounding the processes providing the service. Conclusively this review finds WR to be an under researched but critically important ecosystem service and provides a first attempt at providing operational guidance on the long term sustainable use of WR in marine environments.

Contents

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http://dx.doi.org/10.1016/j.ecoser.2016.06.011

1. Introduction

Of the many definitions of Ecosystem Services (ES) Fisher et al. (2009) produced a widely used formulation of "the aspects of ecosystems utilised (actively or passively) to produce human well-being". This paradigm of ES is an increasingly prevalent concept, but one poorly defined ES is the service of Waste Remediation (WR). In the marine environment, the ES of WR enables humans to utilise the natural functioning of ecosystems to process wastes, potentially without detrimental effect. Without this service humans would either have to process all wastes on land or suffer serious health implications of wastes remaining in a toxic and available state. This would not only impact human wellbeing directly, but would also impact the overall ecological health of marine ecosystems. Whilst preserving the ES of WR is vital in its own right, it is also important for ensuring the provision of a whole host of additional marine ES and benefits that the service provides including: food security, raw materials, recreational amenity, shoreline protection, sequestration of carbon and an equable environment. The sustainable exploitation of benefits provided by WR depends on our ability to manage waste inputs in relation to the capacity of ecosystems to remediate wastes. This no-damage limit or "capacity for assimilation" is highly variable depending on the ecosystem, waste types, and other pressures on the given environment (Islam andTanaka., 2004; Nellemann et al., 2008). There is also an added complication that loading limits are dependent on human judgments as to what is an acceptable level of human health risk or structural change to an ecosystem. While it is in society's interest to ensure that discharges of waste into the ocean are minimal (and in turn reduce the need for the service of WR), in an increasingly human dominated planet there is a growing necessity to utilise and value all aspects of the natural environment to improve health and well-being.

Previously the ES of WR has been defined by the Millennium Ecosystem Assessment (MA) as the service of "Water purification and waste treatment" but as "Water quality regulation" by the UK's National Ecosystem Assessment classification (NEA); and more recently as "Mediation of waste, toxics and other nuisances" by the Common International Classification of Ecosystem Services (CICES). While many of these classifications are remarkably similar, having been built using the same principles, and are frequently referenced in the literature they are often poorly understood and rarely quantified (Beaumont et al., 2008). It is considered that one of the causes of this is that there are so many classifications available causing confusion and creating an illusion of complexity. More specifically in the case of WR there has also been a lack of application of these sub-classifications in terms of assessing, quantifying and valuing the contribution WR has on the wider marine environment, due to a lack of information surrounding the processes providing the service. This is a fundamental problem for environmental practitioners with the service of WR often being undervalued in policy design and implementation and is therefore at risk of being ignored in future policy decisions.

As a central component to communicating any subject is a readily understandable terminology that is applied consistently, this paper aims to clarify some of the potential confusion surrounding the application of the service of WR and provide a provide a utilitarian guide for academics and policy makers who wish to understand and utilise the ES of WR in the marine environment. Whilst there is always a risk of simply developing another classification, there are obvious benefits of combining the knowledge inherent within different classification systems to develop a more comprehensive understanding of a particular service. This review therefore begins by giving abroad overview to the different waste types present in the marine environment to ensure consistency of understanding. This is followed by drawing on the current literature and previous analyses of ecosystem services frameworks to provide a coherent definition WR in the context of marine ecosystems. Following classification, the mechanisms and ecosystem processes involved in the provision of the WR alongside suitable indicators and methods of assessment are then detailed and discussed. Finally a general discussion of the wider significance of the service of WR is given, including how we can maximise the benefits received from it, and possible future research directions for managing it sustainably. Overall as the decision-making context will differ substantially from place to place, issue to issue, and over time, the framework is designed to be sufficiently general to ensure that it can be applied across a wide range of situations, and flexible enough to encourage the user to develop and adjust the classification as required, for example by adding new components if required, and potentially repositioning components within the classification as required. This will result in a situation specific classification of WR that can be developed according to the purpose of the ecosystem service assessment (Costanza, 2008; Fisher et al., 2009; Johnston and Russell, 2011).

While WR occurs in all marine environments; from estuaries to the continental shelf, pelagic, demersal and deep sea habitats the focus of this paper will be on continental shelf ecosystems and their associated sea-beds with the rationale that many of the ecosystem benefits provided directly or indirectly by the service (e.g. clean water, recreational amenity, shoreline protection, fish and shellfish (food)) will be realised by humans on land or in areas surrounding the continental shelf margins (Pauly and Christensen, 1995; Martínez et al., 2007). Equally, there is extensive evidence that specific habitats found in brackish and coastal water habitats (e.g. saltmarshes and mangroves) can provide an important bioremediation function, (Agunbiade et al., 2009; Santos et al., 2011; Mucha et al., 2011; Ockenden et al., 2012; Wu et al., 2014 Ribeiro et al., 2014). While these habitats will not be discussed in detail here (as they are well-referenced elsewhere), the fundamental principles considered in this paper can still be applied to these habitats.

Further, in previous ES classifications there has been a tendency to limit ES to biotic components, with abiotic outputs often receiving less attention or being addressed inconsistently in ES classification systems (Van der Meulen et al., 2016). However abiotic processes such as fluid advection and photochemical transformations play an important role in the provision of WR both in terms of the introduction of wastes into the marine environment but also in their dilution, degradation and dispersal (Bottrel et al., 2014), allowing wastes to remain in the system but at harmless levels (Hinga et al., 2005). This review therefore highlights how to include abiotic flows as an inherent part of an ecosystem services classification with the hope that in doing so, the application of the WR concept can be made more holistic and consistent and will optimize its integration power for practical planning and decision making.

As the marine environment is fundamentally different to that of the terrestrial especially with respect to the physicochemical environment (Carr et al., 2003), there is also an inherent benefit to developing a specific classification for the service of WR in marine systems. Notable differences between the application of the marine, compared with the terrestrial service, would arise from the greater extent and rate of dispersal of water borne compounds (nutrients, organic wastes, contaminants and organisms) as opposed to those in air (Logan, 1985), as well as from expanded scales of connectivity among near-shore communities in the marine environment (Di Lorenzo, 2015). In addition lateral and vertical advective transport (e.g. currents and upwelling) processes also have the effect of augmenting local primary and secondary production at a much greater magnitude in marine than in terrestrial systems (Duggins et al., 1989) allowing natural remediation to occur at much higher rates. As a consequence, it should be noted that some of the waste remediation strategies and frameworks developed and discussed here with regards to the marine realm may not be directly transferable to terrestrial systems.

2. Key wastes in the marine environment

In recent history the sustainable threshold of use of WR has been exceeded by high waste loading rates in many regions (Levin and Möllmann, 2015). In developing countries the impact of contaminated water from inadequate wastewater management is one of the most important factors undermining world health (Corcoran et al., 2010). Incorrectly managed or unmanaged discharges of wastewater have serious implications on biological diversity, ecological integrity and the ongoing capacity of marine ecosystems to deliver the service of WR (Schwarzenbach et al., 2010; Qadir et al., 2010). Within developed countries one of the most important impacts on the provisioning of WR is the enhanced input of nutrients (eutrophication); mainly nitrogen and phosphorus from agricultural sources into rivers, lakes and oceans (Howarth et al., 2011). The impacts of eutrophication is of major global concern as it affects the functioning of marine ecosystems through the exacerbation and rapid growth of eutrophic deoxygenated zones (Diaz and Rosenberg, 2008). These pressures present a global threat to human health and well-being as well as significant challenges for environmental waste management.

The contributing factor for the amount and types of wastes released into the marine environment ultimately depends on the choices or behaviours of governments, organisations, and individuals. Through the implementation of polices and regulation, efficient waste management strategies can promote the functioning of healthy marine ecosystems (Potts et al., 2014). With the recognition that waste management is highly variable across countries, with waste substances often managed in different ways, by different bodies, there is an increasing need for a holistic approach to ensure environmental protection (Perry et al., 2010). One such approach nominally cited as the 'Ecosystem Approach' follows a growing recognition for the need to evaluate ecological functions and the value of the ES they provide as a whole, so that none are overlooked when management decisions are made (Halpern et al., 2008; Mangi et al., 2011). This increased awareness over the past few decades has led to considerable management efforts to reverse the historical approach of dumping wastes, including nutrients, into the oceans (Halpern et al., 2012; Moore et al., 2013b; Jefferson et al., 2014).

However, to enable such holistic waste management strategies, a comprehensive understanding of all sources of waste and how they enter and move through the marine environment is vital. The term waste is often defined as “substances present in the marine environment which would not otherwise be there in the absence of anthropogenic activity and/or is present at a higher level than typical levels” (Hinga et al., 2005). It includes compounds and materials that might otherwise be useful in a different context, such as oil after an oil spill or nutrients once they are no longer at their site of application. In addition, living organisms in the form of pathogens (e.g. bacteria, viruses, fungi) can be included as biological contaminants or “wastes” (Elliott, 2003). The terms ‘pollution’ or ‘pollutant’ are often used interchangeably with the terms waste or contaminant, but is different in being the point at which the levels become damaging in the environment (Chapman, 2007). As such, the term ‘pollution’ and its derivatives are not generally used here as the focus of this ES assessment is to review the processes supporting the service of WR and not the impacts of wastes on the ecosystem.

Humankind produces a large variety of wastes that are introduced into the marine environment either by accident or by design (see Table 1). Although there is no attempt here to systematically assemble and estimate the damage to humans and ecosystems done by past waste releases, a few examples of the types, issues involved, and magnitude of damages of wastes that exceeded ecosystems' capacity are provided in order to illustrate the importance of managing wastes. Generally, for the purpose of this paper waste types can be divided into three groups:

1) Nutrients & organic matter;
2) Biological wastes/contaminants
3) Persistent contaminants.

A distinction can be made between these three forms of waste in terms of their movement through the marine system and their potential to be broken down by abiotic and biotic processes. The more slowly a waste is cycled or detoxified in the environment (that is the more persistent it is), the greater the chance of it reaching harmful levels in the local or global environment and the greater effects of bioamplification of harmful substances across food chains (Clements, 2000).

For instance, most nutrients and organic matter are normal components of natural ecosystems and will ultimately be completely broken down into their basic components and completely re-cycled by the system (Anderson and Sarmiento, 1994) or can be buried and removed from the normal turnover pathways. Inputs of these wastes often only become detrimental to ecosystem service provision when they reach levels high enough to impair or modify the ability of an ecosystem to function (Woodward et al., 2012). This is often the case in many coastal ecosystems where accelerated flows of anthropogenically-derived organic nutrients, particularly nitrogen and phosphorous compounds from municipal waste and agricultural discharges, provide point and diffuse sources of water quality degradation (Conley et al., 2009; Antón et al., 2011; Sun et al., 2013). Thus the bioavailability of the organic nutrient pool is an important issue in the assessment of this ES if the waste problem in question is a direct result increased nutrients or organic matter for example in the case of eutrophication.

In addition to organic wastes, biological wastes in the form of harmful bacteria, viruses, fungi and some parasites (e.g. Elliott, 2003, 2011; Olenin et al., 2011) are an increasing problem in

Table 1
Overview of the major categories of wastes in the marine environment.

Waste category	Character of source	Waste types/examples	Impacts and consequences	Potential for cycling/detoxification/export/ sequestration/storage	Timescale to remediation	Relevant management initiatives
Nutrients and organic matter	Point and/or diffuse sources	N, P, Si, Sewage both human and agricultural, Atmospheric deposition.	In excess eutrophication, Harmful algal blooms, Anoxic conditions.	Organic matter can usually be completely broken down into its basic components and in the form of nutrients can be used by the biological components of a system. May also be sequestered and stored in the sediment.	Dependent on the form: Nutrients (minutes to hours) in the presence of acceptable conditions. Organics (hours to days) for readily degradable waste and (months to years) for resistant materials.	Control the release of sewage wastes. Control fertiliser application. Enforcement of emission standards.
Biological wastes/ contaminants Pathogens	Point and/or diffuse sources	Herpes virus, Typhoid fever, Dysentery and Cholera	Human health, Mortality, Malnutrition, Loss of viable fisheries.	Endemic and non-endemic pathogens may lose viability in an environment or may be utilised as food for other organisms.	Dependent on lifecycle. Non-endemics typically (hours to days). Endemics may live within or on their host for (hours to years)	Reduction of agricultural inputs to waterways Improving sanitation, hygiene and safe drinking water.
Persistent contaminants Persistent organic pollutants (POPS)	Point and/or diffuse sources	Herbicides, fungicides, insecticides, petroleum products, TBT PCBs, OCPs, HCHs, DDTs, PAHs.	Bioamplification in food chain, Diverse health effects.	Likely to be photodegraded and degraded by microbes and fungi completely destroying the inherent toxicity of the waste. Many have a high affinity to adsorb onto particles and may be stored in the seabed.	Lighter compounds such as hydrocarbons can degrade within (hours to days). Heavier and more persistent compounds are typically (decades to centauries) or indefinitely under anaerobic conditions.	Control of organic chemical runoff from agricultural land, and pesticide misuse. Good industrial manufacturing practices. Monitoring of the global shipping trade. Phase out existing POPs, confine existing sources, and prevent use of new POPs.
Toxic trace metals	Point and/or diffuse sources	Arsenic, cadmium copper, lead, mercury.	Bioamplification in food chain, Metal remobilization, Acute toxicity, Chronic neurotoxicity	Cannot be degraded. May be bound to other material (e.g. Organics). Must be diluted, stored or exported from the environment.	Dependent on environmental setting, such as rates of dilution or precipitation processes. Often (decades to centauries)	Metal neutralization or Removal. Introducing effective nontoxic reagents
Radio-nuclides	Point and/or diffuse sources	^{3}H,^{14}C,^{85}Kr,^{90}Sr,^{99}Tc,^{125}Sb,^{129}I,^{134}Cs,^{137}Cs^{54}Mn,^{55}Fe,^{103}Ru,^{106}Ru.	Radioactive exposure both internal and external from the food web and the sediment.	Natural radioactive decay to stable isotopes – some half lives may be very long 14C over 1000 years. May be sequestered to organic material. Likely to be diluted or stored in the seabed.	Half-lives of medical-use radionuclides range from (hours to weeks). Half-lives of radioactive wastes from nuclear reactors range from (decades to millennia).	Containment of radionucliotides and monitoring of mitigation processes including natural attenuation.
Plastics	Point and/or diffuse sources	Macroplastics, microplastics, nanoplastics.	Ingestion or phagocytic uptake. Leaching or dissociation of toxic contaminants from the plastics.	Will degrade under the influence of many abiotic processes including: photo, thermal, oxidative and hydrolytic degradation pathways. This is often followed by remineralisation by microbes.	Degradation generally classified according to the process causing it. Plastics exposed to a range of environmental degradation mechanisms (years to centauries) while those buried or in anaerobic conditions can last indefinitely.	Quantifying the input of plastics to the marine environment. Management actions to reduce terrestrial and shipping inputs.
Emerging and novel wastes	Point and/or diffuse sources	Nanoparticles, flame retardants, oestrogens, pharmaceuticals, endocrine disruptors.	Largely unknown. May interfere in the normal functioning of organisms.	Ecosystems may be very ineffective At detoxifying novel chemicals. Many are resistant to abiotic and biodegradation processes.	Half-lives are still unquantified for many of the emerging wastes. Some of the better studied compounds e.g. pharmaceuticals are thought to have short half-lives (days to years).	Active monitoring and stringent regulation on novel chemicals discharged in wastewater, agriculture and industry.

marine coastal waters. Many pathogens constitute a pressure emanating from outside a system often as a result of human activities such as unregulated sewage disposal or dumping of ballast water. Many of these biological wastes entering the marine environment lose viability, under the relatively harsh conditions and may be ingested and utilised for food (therefore being remineralised) by other organisms in the environment without detrimental effects. However under favourable environmental conditions vector-borne pathogens may be maintained at unsustainable levels within hosts or in the environment altering ecosystem functioning and degrading human health.

Many natural and synthetic wastes such as pesticides, fertilizers, petroleum products, metals, plastics, and other manufactured goods, are also becoming ever more prevalent in the marine environment (Fleming et al., 2006; Knott et al., 2009; Naser, 2013) and are a serious threat to environmental health due to their persistence, toxicity and ability to accumulate through food chains (Schwarzenbach et al., 2010). This is largely a consequence of increasing agricultural and industrial processes, either intentionally or as by-products (Halpern et al., 2003) but some compounds, such as petroleum-derived compounds, are also naturally formed and are considered persistent contaminants when added to the ocean in excess such as from oil spills. As many these wastes are persistent against biotic and abiotic degradation processes they are often considered to follow pathways to export and are effectively removed from the immediate environment, although may be partially refined to a less toxic state (Jones and De Voogt, 1999). While metals cannot be degraded to harmless materials, they can be bond organically essentially storing them and rendering them unavailable.

Overall, combined with source, timescales of bioavailability of all wastes should be considered as an important assessment criterion when implementing this service. Wastes are likely to partition into two ‘pools’: a labile pool, that can be utilised in time frames relevant to water quality processes of interest in the receiving water, and a refractory pool, that is decomposed very slowly and essentially.

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3. Defining the ecosystem service waste remediation in the marine environment

The Millennium Ecosystem Assessment (MA) is the most widely accepted ES classification for assessing the benefits derived from marine ecosystems. The MA (2005) classification system has been criticised because it confuses services (means) and benefits (ends) (Boyd and Banzhaf, 2007; Wallace, 2008) and supporting services with ecosystem functions (T. E. E. B., 2010); which in economic terms may lead to double counting of services. To overcome this there are now a multitude of more precise ES classifications, including; The Economics of Ecosystems and Biodiversity classification (T. E. E. B., 2010), the UK's National Ecosystem Assessment classification (NEA, 2011), The Common International Classification of Ecosystem Services (Haines-Young and Potschin, 2013), Fisher et al. (2009), Haines-Young and Potschin (2010), Atkins et al. (2011), and Beaumont et al. (2007, 2008). Despite these extensive theoretical developments, the practical application of these ES classifications remains limited (Daily et al., 2009; Naidoo et al., 2008). This section aims to clarify some of the potential confusion and provide a guide to the future application of the ecosystem service of WR in the marine environment.

With regards to terminology and in line with the MA and NEA frameworks, the ES of WR is classified here as a regulating service. Further, building on the classifications of the service outlined in the MA, TEEB, NEA, CICES and the outline of the service in Beaumont et al. (2007) “the removal of pollutants through storage, burial and recycling”, the service of “Waste Remediation” is defined here as:

> *“The removal of waste products from a given environment by ecosystem processes that act to reduce concentrations of wastes by the mechanisms of cycling/detoxification, sequestration/storage and export”.*

The mechanisms responsible for removing or degrading waste through an associated suite of ecosystem processes are outlined as follows:

1. ***Cycling/Detoxification***: *Processes that act to change wastes into harmless or less toxic compounds.*
2. ***Sequestration* (*storage*)**: *Processes that sequester waste in the environment in such a way that they are not biologically available and do not exhibit toxicity. Essentially stored sequestration may be reversible if conditions are altered, with the wastes returned to harmful forms.*
3. ***Export*:** *Processes that transport waste from a given bounded system, including atmospheric, benthic and lateral export.*

Each set of ecosystem processes are fundamental transformations which occur in the natural environment driven by physical and chemical reactions, both biotic and abiotic, which may include surface, solute or cellular processes (Paterson et al., 2012; De Groot et al., 2010). Many of these processes occur at very small scales but cumulatively combine to produce a transfer of energy or material often recognised as ecosystem functioning and resulting in the flow of ES (Paterson et al., 2011). In terms of WR, humans can utilise these biophysical processes to remediate wastes which otherwise would need to treated or stored in order to avoid health implications. There is however the consideration that the definition outlined may be context dependent (Langenheder, 2010); with different processes becoming services depending on environmental and management conditions. For example, some export processes may also concentrate wastes into localised ‘hot spots’ of relatively high waste concentrations potentially acting as an ecosystem disservice in the affected area.

As a consequence, WR also warrants more detailed investigation as human activities and wider global changes have, and continue to, significantly impact all marine ecosystems (Harley et al., 2006; Hoegh-Guldberg and Bruno, 2010). In turn, these impacts affect the capacity of the marine environment to remediate our wastes. To understand how the WR service will be affected by these continuing impacts it is necessary to understand the mechanisms and processes supporting the provision of this service. Understanding these processes will also enable the sustainable utilisation and management of this service, and also maximise benefit received from it.

4. Identifying processes and indicators to measure the ecosystem service of waste remediation

While many managers strive for instantaneous information to enable mitigation of harmful wastes entering the marine environment, measurements at high levels of organisation (e.g. community and ecosystem levels) are often slow to obtain and difficult to interpret. This difficulty is attributed to a lack of knowledge with respect to specific elements of the ecosystem structure and processes (Börger et al., 2014). Therefore, to understand the potential WR capacity of an ecosystem, and how to sustainably manage this ES, it is essential to understand the processes which support its provision including identifying indicators that can be used to measure these processes. To aid this, we discuss the ecosystem processes influencing the provisioning of WR and finish with a short discussion of different quantitative indicators of this service with suggestions for their measurement.

Each of the compartments outlined in the waste pathways (Fig. 1) describe the transport and fate of a given waste in a marine environment and are provided by a group of associated ecosystem processes (Table 2) which may amplify or reduce concentrations of substances entering a marine environment. This list is not exhaustive, but was derived during an interdisciplinary expert workshop (UKOA project, http://www.oceanacidification.org.uk) by combining the processes listed in other ecosystem service classifications (e.g. MA, NEA, TEEB, CICES) regarding the service of WR. Alongside are suggested practical guidelines for selecting indicators relevant to the service of WR derived from Hattam et al. (2015). As viewing the ecosystem as a series of steps allows discussion to focus on individual compartments of the specific system in question and how each compartment, rather than individual processes can be regulated, each of the steps involved in the remediation of wastes is discussed in more detail below.

4.1. *Ecosystem processes responsible for inputs of wastes into the marine environment (Steps 1–3)*

4.1.1. *Step 1 atmospheric input*

On a global scale marine ecosystems contribute to air quality by removing waste products from the atmosphere via atmospheric exchanges (O'Driscoll et al., 2013). This exchange of gases and volatile organic compounds across the sea surface interface **(step 1)** represents an important pathway in transport of volatile wastes into the marine ecosystem and is controlled by abiotic physico-chemical transport processes (Wurl and Obbard, 2004). These interactions are complex with the direction of exchange – water to air or vice versa – relative to the concentrations of the compounds in each phase and their relative solubility or volatility. In the case of persistent chemicals, nutrients and organic wastes such as POP's (Moore et al., 2013a), the main pathway through which they reach the marine environment is via 3 major processes: 1. Dry deposition of particle-bound pollutants, 2. Diffusive gas exchange between the atmosphere and surface ocean, 3. Wet deposition (rain) (Gioia et al., 2011).

4.1.2. *Step 2 Land/Estuary/Human Input*

Due to their proximity to human development, estuarine environments act to convey terrestrially derived wastes onto the continental shelf **(step 2)**. Waste inputs derived from terrestrial urban wastewater, agricultural and industrial activities are the major contributors for the majority of the nutrient, pathogen and xenobiotic compounds entering the marine environment (Mason, 2012). This is amplified by natural abiotic transport processes such as leaching and lateral advection often in the form of storms acting as a locus of input for transient wastes into the marine environment (Dagg et al., 2004; Mckee et al., 2004). For example, a number of studies have shown how the high unidirectional flow of estuarine systems drives the movement of plastic debris into the

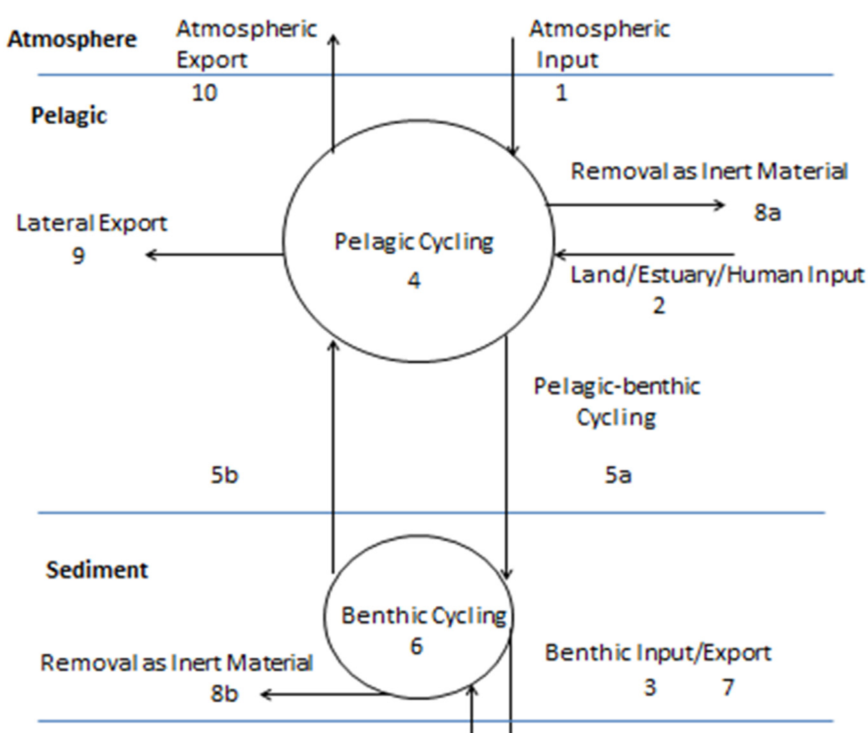

Fig. 1. The processes and flows potentially involved in the transport and fate of a given waste in a marine environment grouped broadly into 3 categories: **Inputs** (steps 1 Atmospheric, 2 Land/Estuary/Human, and 3 Benthic); **Cycling/Detoxification** (steps 4 Pelagic, 5a,b Pelagic-benthic, 6 Benthic); **Sequestration/Storage and Exports** (steps 7 Benthic, 8 Removal from system as inert materials, 9, Lateral export and 10 Atmospheric export.).

Table 2
Ecosystem processes & Indicators relevant to the processing of wastes in the marine system ✓=relevant to a particular numbered step in Fig. 1.

Categories of ecosystem processes	Examples of ecosystem processes	Inputs			Cycling/detoxification			Exports & sequestration (storage)				Description of the processes	Indicators of processes and their measurement (adapted from Hattam et al. (2015))
		1	2	3	4	5a,b	6	7	8a&b	9	10		
Abiotic transformation	Photochemical, hydrolytic, oxidative and thermal degeneration, radioactive decay, redox reactions.				✓	✓	✓	✓	✓			Abiotic processes in the environment that chemically alter wastes. Often leads to a structural change that may not reduce the toxicity of a waste, but it may be a first step toward detoxification and act as a catalyst for many other processes.	Absolute levels of waste in the water column or sediments.
Abiotic Transport	Advection, aerosol formation, chemical partitioning, dilution, dispersion, dry deposition, mixing, precipitation from solution, tidal currents, volatilization, water residence time, wind, wave action, wet deposition.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	How chemicals are moved by abiotic processes in the environment and thus affect the fate and reduce the concentration of the substances in the environment.	Diffusivity and advection flux determined, for example, from hydrodynamic modelling.
Biogeochemical cycling	Biomass production, diagenesis, remineralisation.			✓	✓	✓	✓	✓	✓			The overall cycling of chemicals through the ocean as modified by chemical, physical, and biological processes.	Degradation and mineralisation rates measured as microbial metabolism, concentrations of organic matter over time and space or chemical analysis for contaminants.
Biotic transports	Migration, propagule dispersal, bioamplification (food chain transfer).					✓				✓		Movements of wastes in the ocean by the: uptake of organisms, settling of organic materials and food chain transfers.	Production and biomass at different trophic levels.
Biotic transformation	Bioaccumulation (living), biodilution, biosorption (non living), dehalogenation.				✓	✓	✓		✓			Processes by which organisms, take up the waste substance, transform it and thereby reduce the concentration of the waste substance in the organism and or in the surrounding area.	Body biomass of toxicants.
Biotic habitat modification	Bioturbation biodeposition, bioirrigation.			✓		✓	✓	✓		✓		All transport processes carried out by organisms that directly or indirectly affect sediment matrices. These process a pivotal role in the delivering of the service through the storage and degradation of organic matter, mediating the exchange of gases to the atmosphere, storing, degrading and transforming materials, as well mediating the water and habitat quality.	Bioturbation measures such as: burrow extent, turnover and stability per unit time, sediment accumulation and deposition.

oceans (Browne et al., 2010; Andrady, 2011; Cole et al., 2011; Ballent et al., 2012).

4.1.3. Step 3 Benthic Input

Once in the environment the ultimate fate of many non-buoyant wastes is deposition to the ocean sediments **(step 7)** as mediated by various water column transport processes. Benthic inputs are therefore largely a consequence of the materials previously accumulated or deposited in the sediments. However due to the dynamic nature of these environments it is inevitable that eventually many persistent wastes will be re-circulated back into the environment and become “new” sources of waste **(step 3)** (Perelo, 2010). Sediments may be disturbed by a number of abiotic processes such as across sediment water flows, wave action, tidal currents (e.g. from floods and storms) leading to the re-suspension of contaminants across a range of spatial and temporal scales (Schiedek et al., 2007). In addition, burrowing fauna can significantly influence the stability, mixing, burial and re-suspension of particles and solutes at the sediment-water interface, through the processes of bioturbation and bioirrigation (Richter, 1936; Rhoads, 1974; Volkenborn et al., 2007). These processes modify the ability of the sediment to act as sinks of contaminants and therefore their upward redistribution into the environment (Gilbertson et al., 2012; Mayor et al., 2013). POPs and metals for example are groups of contaminants known to desorb into a dissolved phase from sediments and again enter into the environmental cycle (García-Flor et al., 2009). Consequently, sediments may not be final sinks of persistent contaminants, depending on the presence and activity of burrowing fauna and physics, and on the presence of other interacting stressors like ocean acidification and hypoxia, that can exacerbate contaminant leaching from sediment bonds and their bioavailability (Roberts et al., 2013; Atkinson et al., 2007).

4.2. Ecosystem processes responsible for cycling & detoxification of wastes in the marine environment (Steps 4–6)

4.2.1. Step 4 pelagic cycling & detoxification

Under natural conditions organic wastes entering the pelagic pathway **(step 4)** are often completely degraded at this stage to harmless compounds by biogeochemical cycling processes such as remineralisation by marine microbes and accumulation into biomass (Cunliffe et al., 2011) preventing harmful symptoms such as eutrophication. In coastal shelf-sea environments liable nutrients and high-nutrient content organics are more likely to be rapidly turned over and cycled than in open ocean systems (Proctor et al., 2003), lending to different remediation strategies depending on the environmental context. For more persistent contaminants abiotic transformation processes that occur at the ocean-atmosphere interface such as photochemical, hydrolytic and thermal degeneration reactions act to change the structure and reduce the toxicity of a waste. For many complex wastes such as crude oil, POPs and plastics these processes may be the first step towards remineralisation (Guitart et al., 2010) and complete detoxification. Rates of detoxification by abiotic transformations may vary widely between contaminants even those with similar structural compositions.

4.2.2. Step 5 a,b pelagic – benthic cycling & detoxification

Many of the same biogeochemical cycling and detoxification processes that occur in the upper surface layers also occur in the underlying water column **(step 5 a&b)** but to a much lesser extent. For waste compounds not completely degraded at the surface, bacterial activity along with phytoplankton, zooplankton and fish (Echeveste et al., 2010; Szlinder-Richert et al., 2009) provide much of cycling connectivity between the pelagic and benthic compartments facilitating further decomposition of available wastes on route to the sediment.

4.2.3. Step 6 benthic cycling & detoxification

Once wastes enter the benthic pathway **(step 6)**, bacterial cycling of wastes is facilitated by biogeochemical and physical processes in the sediment (e.g. diagenetic alterations, particle mixing, compaction, redox state reactions). Specifically the process of reductive dehalogenation is an important biodegradation process undertaken by anaerobic microbes and is responsible for making numerous xenobiotic compounds less toxic and more readily degradable (Payne et al., 2011). Combined with hydrolytic degradation, dehalogenation is the most likely degradation pathway followed by remineralisation for many contaminants entering the benthic pathway (Mohn and Tiedje, 1992). In addition, increased rates of transport of particulates and solutes mediated by burrowing fauna through bioturbation and bioirrigation enhance the depth and complexity of redox transition zones (Queirós et al., 2011; Pischedda et al., 2008) promoting remediation. This affects not only the bioavailability of contaminants through changes in the chemical speciation of sediment bound metals (Teal et al., 2009) but also their position in the sediment (Reible et al., 1996). Ultimately this creates a juxtaposition of different biogeochemical niches for bacteria (Bertics et al., 2009), including those necessary for the degradation wastes (Cuny et al., 2007).

4.3. Ecosystem processes responsible for the sequestration (storage) & export of waste in the marine environment

4.3.1. Step 7 benthic sequestration (storage) & export

One particularly important process is that influences the sequestration, storage and export of many persistent aquatic wastes is that of sediment partitioning and scavenging. Often described by the general concentration mechanism known as “solvent switching” (Macdonald et al., 2002) – whereby low-solubility chemicals and metals in the dissolved phase, adsorb to organic particles and/or organisms such as phytoplankton before being removed (or scavenged) from surface waters and delivered to the sediments by sinking particles and vertical animal migration (Fowler and Knauer, 1986; Suedel et al., 1994). In this way both organic matter and persistent contaminants can be sequestered, stored and then exported to the sediments **(step 7)**. Once in the sediment, vertically oriented burrowing fauna can then act to convey organic matter and by association contaminants down into the sediments by the processes of bioturbation and bioirrigation (Shull and Yasuda, 2001; Kristensen et al., 2011) where they may be indefinitely stored (Ciutat and Boudou, 2003). Whilst this process may not directly reduce the toxicity of a waste, essentially the waste material has been utilised in such a manner that the input of waste is no longer evident in the in immediate environment. Aquatic sediments may therefore be among the media with highest concentrations of wastes and depending on the persistence of the waste, the sediments may remain contaminated even if the inputs are stopped.

4.3.2. Step 8a, b removal from system as inert materials

Some waste materials may be sequestered in the environment in such a way that they are not biologically available and do not exhibit toxicity **(step 8a, b)**. The sequestration of certain metals in marine sediments by acid volatile sulphides is one such an example. These metals are bound into a mineral form that is not biologically available and as long as there are sufficient sulphides to bind all the metals, no toxicity is exhibited (Di Toro et al., 1992). Toxic compounds may also be taken up directly by organisms and held within biological tissue. In natural systems a variety of organisms are known to accumulate and bind contaminants which might include industrial and agricultural wastes (Vijayaraghavan and Yun, 2008; Hung et al., 2014). Biosorption and bioaccumulation are physiochemical processes, which involve interactions and concentration of toxic xenobiotic contaminants in the biomass, of either living (bioaccumulation) or non-living (biosorption) matter (Gadd, 2009). Both these processes play an important role in natural storage and export of wastes in the marine environment and occur in virtually all biological wastewater treatment processes and in all bioremediation technologies (Rehman et al., 2006; Kan, 2013).

4.3.3. Step 9 lateral export

Hydrological connections **(step 9)** provide important export pathways for many persistent and non-degradable wastes such as metals, which can be transported horizontally to other bio-geophysical compartments and in the long term 'off-shelf' and effectively removed from the immediate ecosystem. Reduction of waste concentrations in a single body of water is best understood as a result of two abiotic transport processes: dispersion (dilution by mixing into larger volumes of water) and advection (water moving downstream). Both of these processes reduce the concentration of the waste at its point of entry in the ecosystem and facilitate the lateral export of wastes between bio-geophysical compartments. Wastes removed by currents or diluted into larger bodies of water may in turn support other services such as the regulation of pathogens and the reduction of contaminants in seafood (Keeley et al., 2013). Fast flowing or dynamic ecosystems will increase the rate of waste dilution and mobilisation from sources (Johnson and Roberts, 2009) while slow flowing systems will likely lead to areas of relatively high waste concentrations. However this capacity for waste transfer is finite and under the influence of high waste-loading rates the intrinsic capacity of the ecosystem may be overwhelmed such that wastes build up locally or even across whole regions.

4.3.4. Step 10 atmospheric export

For more volatile contaminants atmospheric export is an important export pathway from the water column **(step 10)**. Some chemicals such as POPs and hydrocarbons present as dissolved gases in the surface ocean can build up to supersaturated concentrations in surface waters and can be lost to the atmosphere by the process of negative dry deposition (McVeety and Hites, 1988; Palm et al., 2004). In the case of petroleum compounds, most of the violate fractions evaporate into the atmosphere shortly after they have been released into the environment. While atmospheric and lateral exports are fundamental processes in the provisioning of the service many wastes that are inputted into the entire ocean and atmosphere of the planet have reached concentrations above acceptable levels, thus reducing the ability of organisms to detoxify them.

4.4. Developing Quantitative Indicators of WR

Regardless of the source, the management of waste inputs and the processes driving them is an important function of human societies and is essential to understand all potential sources of wastes if we are to safeguard human well-being into the future. However with such a complex array of factors influencing the fate of a waste, it is not a simple matter to predict the persistence of a waste in the wider environment. Under the guidelines provided by Hattam et al. (2015), evidence and success of the service in action may be observed directly from physiochemical observations such as environmental degradation and mineralisation rates measured as bacteria metabolism, concentrations of organic matter over time and space, chemical analysis for contaminants or by diffusivity and advection flux (see Table 2).

In the absence of physiochemical data, specific responses by living organisms can act as indicators or biomarkers in response to exposure to waste, acting as retrospective and predictive signals of change within an environment (Au, 2004). Biomarkers can be general or specific, reflecting the general stress or relative environmental disturbance of a system and may indicate capacity for waste assimilation if waste inputs are known. Further by using different bio-monitoring indices, effects can be measured at different levels of biological organisation, from the molecular to the ecosystem level. For example microbes, algae, mussels, oysters and other sensitive benthic species are often used as sentinel organisms in bio-monitoring and ecosystem modelling studies (e.g. Schubert et al., 2013; Keeley et al., 2013). Success of many cycling and detoxification processes can be suggested by the presence of resilient and healthy communities indicated for example by: biodiversity levels or numbers of sensitive species. However how to use these indicators to demonstrate avoided change, such as the avoided impacts of a waste incident, still remains a challenge. Therefore, future development of indictors within the context of assessing W*R* is a greatly needed research area. Evaluating what waste compounds are present (**steps 1–3**), their possible rate of degradation (**steps 4–6**) and the likelihood of persistence in the environment (**steps 7–10**) is an important element of this ES assessment and when combined with biological monitoring data will enable the development of qualitative indicators of the service of WR that can be compared over time and space to denote change in the system.

5. Discussion

In summary, the service of WR is of critical importance on many levels, providing an important function for human societies and is essential in the promotion of human well-being. The WR service provided by the marine environment is a pure public good in terms of its use for the disposal and eventual remediation of waste. This has direct implications for the waste management of companies and other businesses that derive benefits from the service at the local level. At the same time, that same use may have implications for the user community with interests in recreation and tourism at the local and regional level, and in the conservation of marine biodiversity at the local through to the global level, depending on the particular site characteristics. Deciding on a safe or acceptable level of utilising the service is not usually a simple matter, as is clear from the complex set of processes and the wide array of possible waste types described in this paper. It is recognised, however, that to successfully manage the service of WR it is essential to include all abiotic processes alongside biotic processes when applying this ES classification in a policy or decision-making context.

Insufficient regulatory management often leads to human health impairment, economic loss, or ecosystem degradation with excessive use in certain areas meaning further use of this service is not possible. This has resulted in many ecosystem functions that act to provide the service of WR being overwhelmed locally and globally well beyond levels that can be sustained under current demands, much less future ones (Hooper et al., 2012). A lack of capacity to manage the service of WR not only compromises the ability of the marine environment to process our waste but also causes a loss of an array of benefits that we often take for granted.

The future sustainable utilisation of WR will depend on our ability to understand the properties of possible wastes interacting within marine ecosystems combined with the mechanisms and processes supporting the provision of this service (as outlined in Section 4). By understanding these processes, and the inter-linkages between them, we will begin to understand how this service is provided and how we can enable the management of this service, maximise benefit received from it, and furthermore, help us consider the vulnerability of this service to over-exploitation and broader impacts. The previous discussion defines WR to be primarily a result of those processes involved in cycling/detoxifying, sequestrating/storing and exporting waste and as such it is these processes we should seek to influence if we wish to maximise the removal of waste from a system.

Understanding of the relative permanence of storage and timescale for waste degradation is essential when determining the benefit of the service of WR. Most notable are wastes that cannot be detoxified, safely stored or cycled and any input will result in a continual decline in environmental quality (often without notice until it affects human health), and therefore provision of this ES. Given sufficient time, a change in water column conditions may bring about the release of stored wastes back to the environment. Therefore the premise of storage of contaminants in biomaterials and sediment is often a short term environmental solution to the problem of toxic wastes. Specifically in the case of non-degradable compounds such as metals, these wastes will continue to persist in the environment unless physically exported out of that system by natural or human means. As such, an important consideration in terms of the “point of entry” versus the location of the environment is most likely to lead to efficient sequestration and storage of all waste types. One such growing international example of humans maximising the service is through the use of marine waste bioextraction (Kim et al., 2014). In USA, Sweden and other European countries the commercial practice of farming organisms that cycle, detoxify and store waste products and then harvesting (exporting) marine organisms out of the system is being considered as a cost effective solution to mitigate excess waste and compliment traditional wastewater treatment programs.

It is noteworthy however, that some management efforts may also negatively affect the ongoing provision of WR itself. Using the same example as above, the same organisms that are introduced to provide the service of WR may also act as an ecosystem ‘disservice’ decreasing human wellbeing by translocating nutrients into the sediment, which facilitates the runaway growth of nuisance benthic algae, and the occurrence of other organisms that may not be involved in the bioremediation of other wastes. Similarly many detoxification and export processes may actually produce more toxic forms of a waste or may export wastes from one area to another more sensitive area with a lesser capacity to remediate that particular waste. Thus the overexploitation of this service can have a negative feedback effect on its provision, as well as on other ecosystem services and should be considered when designing suitable management strategies.

Despite the uncertainties surrounding the application of this service, deferring waste management actions until the problem becomes excessive is not an effective management approach. The costs of trying to reverse damages to waste-degraded ecosystems or remove persistent contaminates from the environment, if possible at all, can be extremely large and burdensome on society (Hinga et al., 2005). Management decisions regarding the service need to be made in the context of the precautionary principle elaborated by US Commission on Ocean Policy (2004) that is, relying on the best information available to reduce potential risks and the need to discharge wastes into the environment while at the same time promoting human well-being.

In this regard, policy makers and environmental regulators have become increasingly interested in the costs and benefits of meeting water quality standards. This follows a growing recognition of the need to evaluate ecological functions and the value of the ES's they provide so that they are not overlooked when management decisions are made (Daw et al., 2015). However, while the service of WR provides a variety of benefits and supports a number of other ES's, there has minimal research undertaken on the valuation of this service. For example, WR was excluded from analysis in the marine economic analysis section of the NEA (Bateman et al., 2011), as – although its importance was noted – there was insufficient long-term monitoring data of ecosystem processes to support its inclusion. It was also noted as important in Costanza et al. (1998) and Beaumont et al. (2008) but excluded from valuation in both marine and coastal ecosystems due to insufficient information. Further, in studies that do evaluate the service, there is often a significant risk of underestimating the value of the service whereby processes that support the service such as nutrient cycling, can be overlooked or considered to be ‘free’ and therefore not considered within management strategies (Braat and de Groot, 2012). Conversely there is also the risk that the service may be overvalued for example when the waste processing capacity of WR is valued (by a replacement cost method), in addition to the benefits of clean water (by a health and/or recreational use metric) in a process often referred to a ‘double counting’ (d'Arge et al., 1997; Fisher et al., 2009; Fu et al., 2011). This lack of a cohesive strategy for valuation may be in part because the benefits of waste processing capacity are not often tangible benefits set in the market and/or due to a lack of perfect information surrounding the processes providing the service. This is a fundamental problem for environmental practitioners with the service of WR often being undervalued in policy design and implementation and is therefore at risk of being ignored in future policy decisions. As a consequence, it seems clear that future research is needed to disentangle the complexity of valuing the service of WR, particularly in light of its socio-economic importance under increased anthropogenic pressures such as increased nutrient loading and global warming. While this task was outwith the remit of this study, it is hoped that the framework provided here will provided a useful basis for more focused work aiming to understand the direct possible human application of utilising the waste processing capacity of the environment to avoid negative impacts on human wellbeing.

6. Conclusions

From a global perspective the service of WR and many of its associated benefits are compromised not only by the unsustainable use of this service, but also through increasing large scale environmental fluctuations such as climate change (Schiedek et al., 2007). While it is difficult to predict on a global scale the effects of climate change on the service of WR it is likely that many ecosystem processes will be altered both in the capacity of the environment to remediate waste products and the susceptibility of organisms to differing waste conditions (Broszeit et al., 2016). For instance changes in large scale water exchange mechanisms, which periodically “flush and clean” continental shelf areas, are likely to be altered being either up-regulated (increasing the turnover of waste material) or down regulated (decreasing the turnover of waste) altering the ability of locations to assimilate wastes (Di Lorenzo, 2015). As a consequence some systems with may allow conditions that continue to process wastes in a non-chronic manner, possibly as a result of greater levels biodiversity and therefore ecosystem resilience (the ability to recover from short-term perturbations), in contrast to other systems where organisms living near their physiological limits may inherit a reduced ability to provide the service into the future. A realistic generalisation is that unless effective waste management efforts can keep pace with the development of nations and the large scale implications of environmental change it is likely that in many regions high waste loading rates will overwhelm the remediation capabilities of systems to the detriment of human health, economic loss, biodiversity and ecosystem functioning. While it is desirable to ensure that discharges of waste into the ocean are as low as can possibly be managed, it should also be our intention to safeguard the many organisms that provide a constellation of other ES's. Making suitable and informed judgments as to the intrinsic capacity of marine and coastal environments to remediate our wastes will help achieve this.

Acknowledgements

This work [NERC Grant Ref: NE/K501244/1] was funded with support from the Biodiversity and Ecosystem Service Sustainability (BESS) programme. BESS is a six-year programme (2011-2017) funded by the UK Natural Environment Research Council (NERC) and the Biotechnology and Biological Sciences Research Council (BBSRC) as part of the UK's Living with Environmental Change (LWEC) programme. The work was also supported by the UK Ocean Acidification (UKOA) research programme (Grant no. NE/H017488/1). The work is based on the outputs of a UKOA workshop held in Plymouth 2011 involving researchers from multiple disciplines (including natural and social sciences and economics) and from subsequent refinements. We thank the participants at that workshop for their contributions specifically: Caroline Hattam, Karen Tait, Jenny Shaw, and Frankie Hopkins. DMP also received funding from the MASTS pooling initiative (The Marine Alliance for Science and Technology for Scotland) and their support is gratefully acknowledged. MASTS is funded by the Scottish Funding Council (grant reference HR09011) and contributing institutions.

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