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Viewpoint

"And DPSIR begat DAPSI(W)R(M)!" - A unifying framework for marine environmental management

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ABSTRACT

The marine environment is a complex system formed by interactions between ecological structure and functioning, physico-chemical processes and socio-economic systems. An increase in competing marine uses and users requires a holistic approach to marine management which considers the environmental, economic and societal impacts of all activities. If managed sustainably, the marine environment will deliver a range of ecosystem services which lead to benefits for society. In order to understand the complexity of the system, the DPSIR (Driver-Pressure-State-Impact-Response) approach has long been a valuable problem-structuring framework used to assess the causes, consequences and responses to change in a holistic way. Despite DPSIR being used for a long time, there is still confusion over the definition of its terms and so to be appropriate for current marine management, we contend that this confusion needs to be addressed. Our viewpoint advocates that DPSIR should be extended to DAPSI(W)R(M) (pronounced *dap-see-worm*) in which **D**rivers of basic human needs require **A**ctivities which lead to **P**ressures. The **P**ressures are the mechanisms of **S**tate change on the natural system which then leads to **I**mpacts (on human **W**elfare). Those then require **R**esponses (as **M**easures). Furthermore, because of the complexity of any managed sea area in terms of multiple Activities, there is the need for a linked-DAPSI(W)R(M) framework, and then the connectivity between marine ecosystems and ecosystems in the catchment and further at sea, requires an interlinked, nested-DAPSI(W)R(M) framework to reflect the continuum between adjacent ecosystems. Finally, the unifying framework for integrated marine management is completed by encompassing ecosystem structure and functioning, ecosystem services and societal benefits. Hence, DAPSI(W)R(M) links the socio-ecological system of the effects of changes to the natural system on the human uses and benefits of the marine system. However, to deliver these sustainably in the light of human activities requires a Risk Assessment and Risk Management framework; the ISO-compliant Bow-Tie method is used here as an example. Finally, to secure ecosystem health and economic benefits such as Blue Growth, successful, adaptive and sustainable marine management Responses (as Measures) are delivered using the 10-tenets, a set of facets covering all management disciplines and approaches.

1. Introduction

The marine environment is a complex system of interactions between morphological and physical structures, continuously varying physico-chemical processes and varying ecological structure and functioning (Fig. 1). It is the composite set of interrelationships whereby the environment influences the biota (e.g. sandbanks supporting burrowing sandeels), the biota modifies itself (e.g. predator-prey relationships) and the biota also modifies the environment (e.g. burrowing worms causing physical and biogeochemical changes in sediments) – respectively termed the *environment-biology*, *biology-biology* and *biology-environment* links (Gray and Elliott, 2009) (Fig. 1). Superimposed on this dynamic ecosystem, the intensity of anthropogenic activities both varies and is increasing, and pressures from these activities may affect the natural environment and subsequently this may have a knock-on effect on society (Burdon, 2016). Management of the marine environment therefore requires a holistic approach that recognises the complexity of the system and accommodates the diverse range of uses and users (de Jonge et al., 2003; Atkins et al., 2011; Pinto et al., 2014; Turner and Schaafsma, 2015). This is particularly the case as there is only one major idea in marine environmental management – *to maintain and protect the ecological structure and functioning while at the same time ensure that it maintains ecosystem services from which society can obtain*

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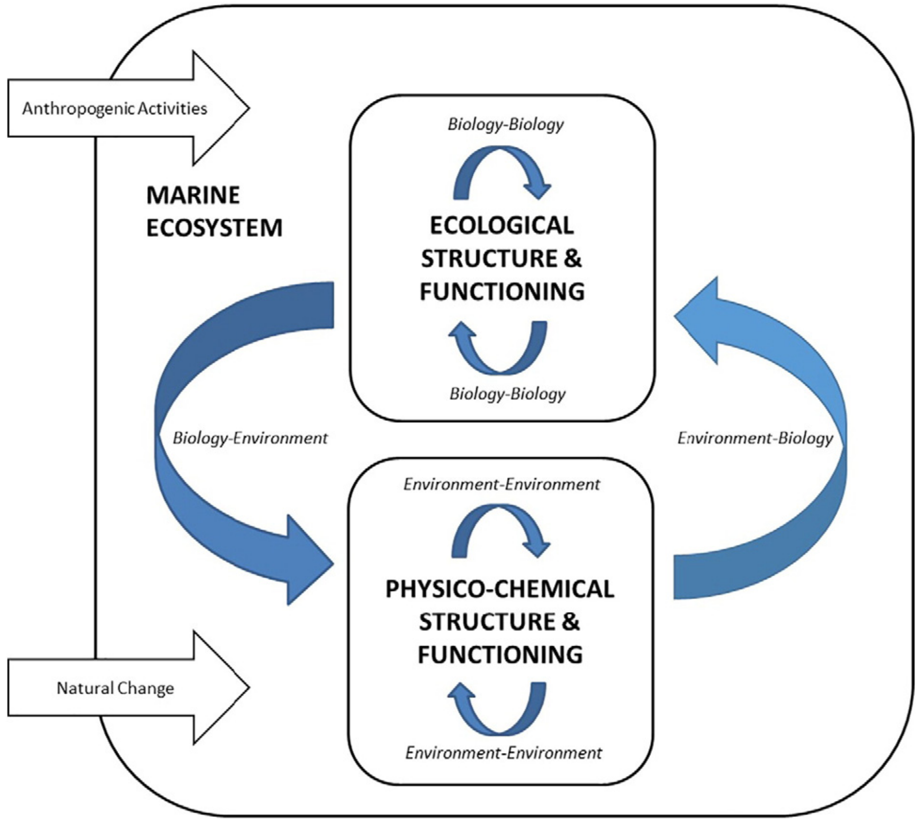


Fig. 1. A conceptual model indicating the linking and feedback between abiotic and biotic attributes of the marine ecosystem (Burdon, 2016).

benefits (Elliott, 2011). As such, integrated marine management needs to consider the environmental, economic and societal impacts of all activities (see de Jonge et al., 2012; Puente-Rodríguez et al., 2015). The Ecosystem Approach, enshrined in 12 principles by the UN Convention on Biological Diversity (CBD, 2000), provides the guiding principles for such an integrated management (Elliott, 2011).

It is argued here that in order to fully achieve the Ecosystem Approach in marine management then an interdisciplinary approach is required which bridges the divide between the natural environment and society (Borja et al., 2016a, 2016b; Burdon, 2016; Turner and Schaafsma, 2015). As implied by such a complex system, the approach requires a large level of detail (de Jonge and Giebels, 2015) as well as to be fully linked to an operational policy life cycle to ensure that measures reflect societal goals and objectives (Cormier et al., 2017). It is recognised, however, that effective marine management requires the complexity of the marine system and the links between the environment and society to be firstly understood by managers, policymakers and stakeholders (Beaumont et al., 2007) and secondly carried out with their involvement (Newton and Elliott, 2016).

The DPSIR (Drivers-Pressures-State-Impact-Response) approach is an accepted, valuable and holistic problem-structuring framework which can be used to assess the causes, consequences and responses to change (Atkins et al., 2011; de Jonge et al., 2012; Gregory et al., 2013; Pinto et al., 2013). As a concept, it has long been used to integrate and provide structure to the management of environmental systems (Atkins et al., 2011; Patrício et al., 2016). From its origins in the unpublished report by Rapport and Friend (1979), it was further developed from an 'Organisation for Economic Co-operation and Development' (OECD) approach which aimed to link anthropogenic Pressures with State changes and Impacts (OECD, 1994), and has since been often used within an environmental context (EEA, 1995; Turner et al., 1998; Elliott, 2002; Atkins et al., 2011; Gari et al., 2015; Smyth et al., 2015; Smith et al., 2016).

A key strength of the DPSIR framework is that it captures simply the key relationships in environmental management (Svarstad et al., 2008; de Jonge et al., 2012). DPSIR models have been applied to many systems in which the boundary of the management system depends on the issue of interest and its conceptualisation (Atkins et al., 2011). Feedback loops between the management Responses and the Drivers and Pressures are also of importance, as are the effects of natural change on the system (Fig. 2). Within a marine context, applying the DPSIR framework to marine management is therefore consistent with the Ecosystem Approach (Karageorgis et al., 2006; de Jonge et al., 2012; Cooper et al., 2013).

Despite its strengths, the DPSIR framework has been criticised within the literature (e.g. Berger and Hodge, 1998; Rapport et al., 1998; Rekolainen et al., 2003; Gregory et al., 2013) and there appears to be confusion surrounding the terminology of the various elements. In particular, confusion exists between definitions of Drivers and Pressures and also in the distinctions between State and State change and between these and Impacts, the latter often being regarded as impacts on the natural system, the human system or both. Several recent reviews have specifically focussed on applications of DPSIR (and its derivatives) in the coastal and marine environment (e.g. Gari et al., 2015; Smith et al., 2016; Lewison et al., 2016; Patrício et al., 2016). This paper does not replicate those reviews, but aims to focus specifically on the confusions in the DPSIR terminology as justification for improving the framework for practicable management purposes. The confusion between the DPSIR components is illustrated in Table 1 together with suggestions for potential solutions to address these anomalies/queries. To be valuable for management purposes and to provide clarity to science regarding the advice needed, we advocate that this confusion needs to be removed. Therefore, we track the evolution of the various approaches while presenting a solution to the anomalies using an integrated model for marine management and for differing spatial scales of management.

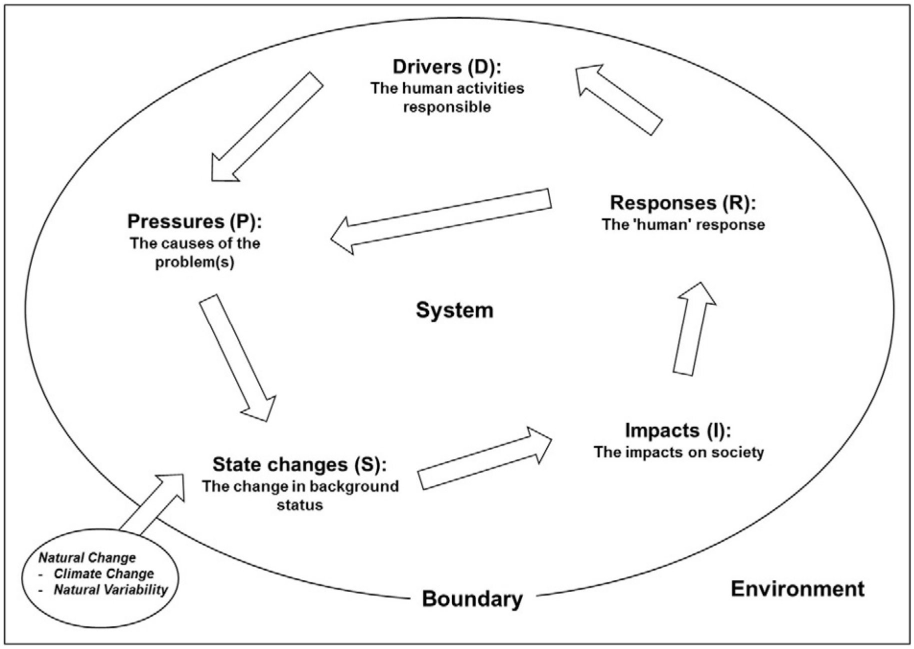


Fig. 2. The DPSIR framework as a cycle and system in the environment (Atkins et al., 2011).

2. Transforming DPSIR into DAPSI(W)R(M)

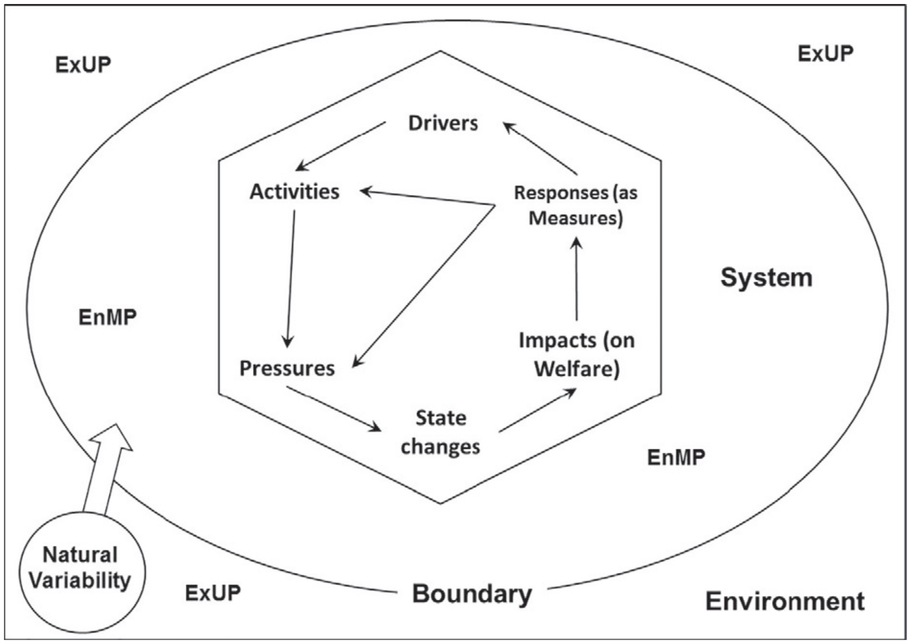
Several studies have attempted to address some of these challenges; for example, Cooper (2013) proposed that DPSIR should be modified to DPSWR (Drivers-Pressures-State-Welfare-Responses), to avoid potential confusion between the impacts on the environment i.e. changes in State, and the impacts on human Welfare, i.e. Impacts in its basic form. Such a distinction was recently made by the UK National Ecosystem Assessment Follow-On (UKNEAFO) project which applied a DPSWR model for the coastal and marine environment (Turner et al., 2014, 2015). However, we contend that this element should describe an Impact on human welfare (as an adverse change in the system) rather than Welfare per se. Hence, following Elliott (2014), Smyth et al. (2015) proposed that DPSWR should become DAPSI(W)R (Drivers-Activities-Pressures-State changes-Impacts (on Welfare)-Responses). This recognises that the Pressures are the mechanisms of change, that it is human Activities that cause Pressures not the Drivers themselves, and that Impacts are on human Welfare. This modified DAPSI(W)R framework was applied in the context of the UK offshore wind energy development sector, with the focus on decommissioning as a management Response (Smyth et al., 2015). Finally, but without explaining the rationale in detail, Wolanski and Elliott (2015) proposed that the framework should be further extended to incorporate Responses (as Measures) and thus keep it within the wording of marine governance such as European Directives (e.g. Water Framework Directive (WFD, 2000/60/EC), and Marine Strategy Framework Directive (MSFD, 2008/58/EC) (Borja et al., 2010)). These require Member States to enact measures, such as economic and legal instruments, new technologies and stakeholder consultation, to fulfil the obligations of such Directives (Fig. 3). Taking all these changes together produces the new acronym of the DAPSI(W)R(M) framework (pronounced *dap-see-worm*).

By extending the DPSIR scoping framework to DAPSI(W)R(M), it is possible to identify more holistic management strategies that are capable of addressing the linkages between different environmental problems and their Drivers and Pressures (Atkins et al., 2011; de Jonge et al., 2012; Cooper et al., 2013). Within this framework, we consider that the main societal Drivers are related to basic human needs such as the need for food, energy, space, movement of goods, security or recreation. Each of these can then be achieved through human Activities. The Activities, as the human interventions (see below), then create the mechanisms of change termed Pressures, for example sediment re-suspension by trawling and dredging or increased polluting inputs (see below).

Each of those Pressures in turn lead to several State changes, as an altered natural system, which in turn can have an Impact on societal Welfare. For example, we obtain food by fishing and harvesting the fish populations providing the available stock will ultimately impact the catching ability of the fishing sector. Accordingly, those Pressures, State changes and Impacts (on Welfare) require a societal Response using Measures (e.g. fishing quotas). If the Measures are successful

Table 1
Anomalies and solutions of the DPSIR approach.

DPSIR component	Anomaly/query	Solution
Drivers	Unclear, these could be the activities or the sectors giving rise to the marine use	Need to define exactly what is a Driver and to ensure it differs from a Sector, an Activity and/or a Pressure
Pressures	Could be the mechanisms of change or the activities or even the sectors	Need to define what is a Pressure and where it comes from
States or state changes	Could be the characteristics of the environment (natural scientists) or the change in the characteristics of the natural environment (social scientists)	Need to determine exactly the term and its meaning in a way acceptable to all users irrespective of discipline
Impacts	Could be the impact of the pressures on the state (natural scientists) or the resulting effect of the state change (social scientists); has confusion between state change and impact	Need to determine exactly the term and its meaning in a way acceptable to all users irrespective of discipline
Responses	The actions performed to prevent human uses leading to adverse changes	Need to determine exactly the term and its meaning in a way acceptable to all users; to be clear what constitutes a response



Key: ExUP = Exogenic Unmanaged Pressures; EnMP = Endogenic Managed Pressures (see text for explanation)

Fig. 3. The DAPSI(W)R(M) problem structuring framework. Key: ExUP = Exogenic Unmanaged Pressures; EnMP = Endogenic Managed Pressures (see text for explanation).

they will ultimately prevent the Drivers and Pressures from causing State changes and Impacts (on Welfare), or ameliorate the negative impacts (Atkins et al., 2011; Wolanski and Elliott, 2015).

The Responses (as Measures) include prevention, mitigation and compensation initiatives which are required to cover many aspects, the so-called 10-tenets; amongst others, these include the legal, economic and administrative instruments, and suitable techniques and technologies (Elliott, 2013; Barnard and Elliott, 2015). Most importantly, it is axiomatic that while we assess, measure and monitor the Pressures, State changes and Impacts (on Welfare), we act on and manage the Drivers and Activities to prevent deleterious effects. Each of these components is further discussed below.

2.1. Drivers

Previous DPSIR papers either did not define Drivers or confused them with activities or sectors (see Patrício et al., 2016) but it is considered logical here to avoid such confusion by referring to them as 'basic human needs'. The early work of Maslow (1943) proposed a range of basic human needs for an individual as a five-tier hierarchical structure and it is proposed here that such needs reflect the Drivers within the DAPSI(W)R(M) framework (Fig. 4). Firstly, there are the basic human needs relating to an individual's survival and include both physiological requirements (e.g. food, air, drinking water) and safety (e.g. protection from elements and hazards) in order to maintain our physiological requirements.

Following on from the basic level, the next stages up the pyramid relate to psychological needs including love and belonging (e.g. friendship, intimacy, trust and acceptance) and esteem (e.g. prestige, achievement, self-respect). The first four levels are often referred to as the 'deficiency needs' i.e. those needs which motivate people when they are not satisfied and for which desire grows stronger when they are not fulfilled. The fifth and final level relates to self-fulfillment or self-actualisation needs (e.g. realising personal potential, seeking personal growth and peak experiences) and these needs are often referred to as 'growth needs'. Maslow (1943, 1970a) suggests that one must

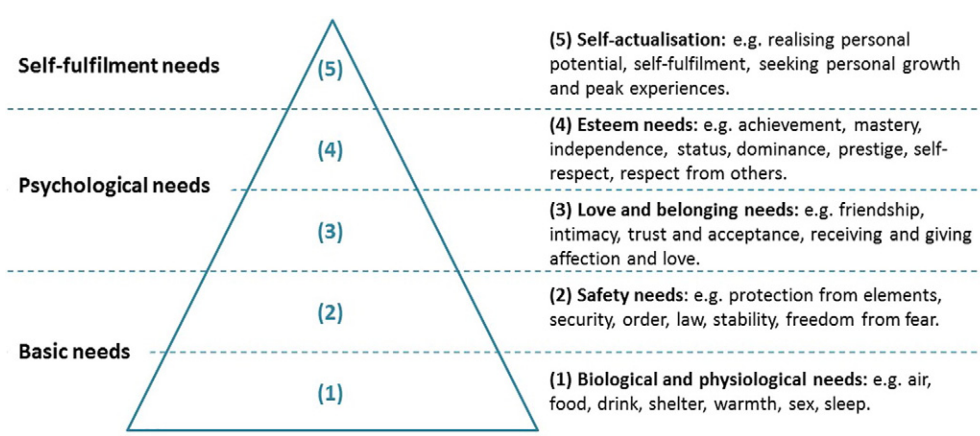


Fig. 4. Maslow's hierarchy of needs and human welfare.
(Adapted from Maslow, 1943).

satisfy the lower level 'deficit needs' before progressing on to meet higher level 'growth needs'. Subsequently, the author went on to propose three further categories which include Cognitive needs (e.g. knowledge and understanding, curiosity, exploration, need for meaning and predictability), Aesthetic needs (e.g. appreciation and search for beauty, balance, form, etc.) (Maslow, 1970a) and Transcendence needs (e.g. helping others to achieve self-actualisation) (Maslow, 1970b). These three additional needs would be located at position (5), (6) and (8) respectively within the hierarchical pyramid, with self-actualisation moving to (7).

Globalisation and international trade, so dependent on the marine space, has also resulted in an ever increasing set of drivers related to the satisfaction of human wants usually in the form of consumer products/services. The satisfaction of wants through market-based mechanisms can result in Maslow's scheme to a blockage part of the way up the pyramid, as higher order needs are not satisfied by ever increasing want satisfaction (the Easterlin Paradox - Easterlin, 1974). The Easterlin paradox proposes that increasing income does not necessarily translate into increased well-being/happiness. Accordingly, the DAPSI(W)R(M) framework needs to accommodate both economic welfare and physiological and psychological well-being.

2.2. Activities

Human activities in the marine environment can be grouped into 15 key marine sectors, each of which then encompasses many activities (Table 2). These activities are generic for all seas although for management purposes using the term 'sector' is considered here to be too ambiguous. For example, within the commercial fishing sector there are many types of fishing activity (trawling, potting, long-lines, etc.) which each result in different Pressures, State changes and Impacts on Welfare and as such may require very different management Responses. Therefore, for operational marine management we propose that it is more appropriate to identify individual Activities rather than sectors, as they are more specific with respect to their resulting Pressures, State changes and Impacts (on Welfare) and thus can be subject to more specific management Responses (as Measures). In addition to the historically important marine activities such as fisheries and oil and gas extraction, recent offshore technological developments and an expanding global economy are increasing pressures from human activities (Stojanovic and Farmer, 2013). This reflects the increasing exploitation of the Blue Economy which can be defined as '*smart, sustainable and inclusive economic and employment growth from oceans, seas and coasts*' (e.g. marine energy extraction, aquaculture, maritime, coastal and cruise tourism, marine mineral resources, blue biotechnology) (EC, 2012).

There has historically been much confusion between Activities and Pressures (Patrício et al., 2016), hence the reason for separating them within the DAPSI(W)R(M) framework. We emphasise that Activities do not necessarily automatically lead to Pressures on the system if prevention, mitigation or compensation mechanisms are put in place, as reflected by management Responses (as Measures). For example, in the case of management of a fishery, beam trawling would be categorised as the Activity whereas abrasion caused by the towing of gear across the seabed would represent a Pressure. If not managed correctly, abrasion may result in damage to the seabed habitats and thus result in a State change (e.g. a change in the functional traits of the benthic community) that may even approach the level of irreversibility. However, if mitigation measures, such as gear modifications or closure periods, are put in place then the Pressure is minimised or mitigated.

The lack of consistency in the terms was illustrated, for example, in Halpern et al. (2008) who produced a global map of 'human impact' on 20 marine ecosystems. Their very important and valuable study acknowledged that the management and conservation of the oceans requires an assessment of the distribution and intensity of human activities and an understanding of the overlap of their impacts. However, in the context of DAPSI(W)R(M), their list of 17 anthropogenic 'drivers' comprised a range of seven Activities (including various forms of fishing, shipping and commercial activity) and 10 Pressures (including organic and inorganic pollutants, benthic structures, invasive species, sea temperature and ocean acidification) with none of the categories relating to Drivers per se. Their study highlights the potential for confusion in terms related to Drivers, Activities, Pressures and Impacts. However, given the global focus of their study, and the data sets available, then we consider that it may be more practicable to map the Activities, from databases where society operates, rather than to detect the spatial and temporal footprints of Pressures; however, more clarity is required in relation to what is actually being mapped. There is now an increasing number of assessment approaches worldwide for the marine environment but again many of these by necessity assess Activities rather than Pressures (Borja et al., 2016a).

2.3. Pressures

Pressures, as a result of one or more Activities, reflect the mechanisms of change and can result in changes to the natural system (State

Table 2
Main activities in the coastal and marine environment.
(Adapted from Smith et al., 2016).

Sector	Examples of activities
Aquaculture	Culture of fin-fish, macro-algae, predator control, shellfisheries
Extraction of living resources	Benthic trawling (e.g. scallop dredging), discharging fishery wastes, netting (e.g. fixed nets), pelagic trawls, potting/creeling, suction (hydraulic) dredging, bait digging, seaweed and saltmarsh vegetation harvesting, bird egg and shellfish hand collecting, curio collecting
Transport and shipping	Ejecting litter and debris, mooring/beaching/launching, shipping, producing shipping wastes, operating ferries
Renewable energy	Building and operating for devices for renewable (tide/wave/wind) power generation
Non-renewable (fossil fuel) energy	Building and operating oil and gas installations, power stations, discharging thermal wastes (cooling water), marine fracking
Non-renewable (nuclear) energy	Nuclear effluent discharge, nuclear power construction and operation, thermal discharge (cooling water)
Extraction of non-living resources	Water abstraction and operating desalination plants, mining for inorganic and particulate materials, non-living maerl, rock/minerals extraction by coastal quarrying, sand/gravel (aggregates) extraction, water for salt extraction
Navigational dredging	Capital and maintenance dredging, removal of substratum, dredged material disposal
Coastal infrastructure	Artificial reefs and barrage building, beach replenishment, communication infrastructure (cables); culverting lagoons, building dock/port facilities, groynes, land claim, marinas, pipelines; removal of space and substrata, constructing sea walls/breakwaters, urban dwellings, i.e. housing and other, buildings.
Land-based industry	Industrial effluent treatment and discharge, industrial/urban emissions (air), discharging particulate waste, desalination effluent, sewage and thermal discharge
Agriculture	Agricultural waste production, coastal farming, coastal forestry, operating land/waterfront drainage
Tourism/recreation	Angling, boating/yachting, diving/dive site operation, litter and debris production, public beach use, tourist resort and water sports operation
Military	Disposal areas operation, infrastructure building, munitions testing and use; warfare
Research and education	Animal sanctuaries, marine archaeology, marine research; engaging in field education and training
Carbon capture and storage	Exploration, construction, operation of carbon capture and storage

Table 3
Examples of Exogenic Unmanaged Pressures (ExUP).
(Modified from Smith et al., 2016).

Pressure	Description
Thermal regime change	Temperature change (average, range, variability) due to climate change (large scale)
Salinity regime change	Salinity and freshwater run-off change (average, range, variability) due to climate change (large scale)
Emergence regime change	Change in natural sea level (mean, variation, range) due to climate change (large scale) and isostatic rebound
Water flow rate changes	Change in currents (speed, direction, variability) due to climate change (large scale)
pH changes	Change in pH (mean, variation, range) due to climate change (large scale), volcanic activity (local)
Change in wave exposure	Change in size, number, distribution and/or periodicity of waves along a coast due to climate change (large scale)

changes) and subsequently the social system (Impacts on human Welfare); the latter two facets are further discussed below. Following Elliott (2011), we can consider that pressures can be separated spatially into both Exogenic Unmanaged Pressures (ExUP) and Endogenic Managed Pressures (EnMP) on the system (Fig. 3). The former (ExUP) are those pressures emanating from outside the sea area being managed and whose causes cannot be managed in that particular area, but for which we have to respond to the consequences of the pressure, such as climate change (Elliott et al., 2015) (Table 3). The EnMP are those occurring within the management area boundary and whose causes and consequences need managing and which can be managed, for example the activity and impacts of a particular sector such as commercial fisheries (Table 4). In order to manage endogenic pressures, it is essential to determine all the effects, often termed the 'footprint' of the pressures, both singly and cumulatively, over both space and time.

2.4. State changes

Within the DAPSI(W)R(M) framework, State changes relate to changes in the natural environmental system as a result of a single or multiple Pressures, especially changes in physico-chemical variables (i.e. dissolved oxygen, organic matter, etc.) and changes to the health of all levels of biological organisation – the individuals, populations, communities and ecosystems. Changes in those levels can be assessed in their structure, the characteristics at one time, and their functioning as rate processes (Strong et al., 2015) including, for example, carbon flow through ecosystems (de Jonge et al., 2003, 2012). By definition, flows of ecosystem services result from a healthy functioning natural system (Atkins et al., 2011; Turner and Schaafsma, 2015) and therefore within the context of the DAPSI(W)R(M) framework it is argued here that State changes (positive or negative) should include those relating to the provision of intermediate and final ecosystem services (as defined by Fisher et al., 2009, and Turner et al., 2015) as well as the underlying marine ecosystem components and processes (Fig. 5, left hand side). In order to identify changes to marine ecosystem stocks and flows, a practicable set of ecosystem service indicators could be applied to identify the state, behaviour and trajectory of marine ecosystem components and processes and intermediate and final ecosystem services; those indicators are needed to make the ecosystem services approach operational for marine managers, for example in the context of marine fisheries, aquaculture and carbon sequestration (Pinto et al., 2014; Atkins et al., 2015).

2.5. Impacts (on Welfare)

Following the above, Impacts (on Welfare) within the context of DAPSI(W)R(M), result from changes in the natural system, but which have consequences for societal Welfare (see Cooper, 2013). As such, it is argued here that Impacts (on Welfare) reflect changes (positive or negative) to the provision of goods and benefits for society (as defined by Turner et al., 2015, see below) and therefore it would again be appropriate to apply a practicable set of indicators to detect such changes in societal welfare (Fig. 5, right hand side). Societal welfare then relies on the delivery of societal goods and benefits which result from applying complementary capital (social, human and man-made or built capital) to the natural environment (intermediate and final ecosystem services) (Atkins et al., 2011). For example, the cultural ecosystem service 'places and seascapes', affected by or reflecting State changes, may

Table 4
Examples of Endogenic Managed Pressures (EnMP) (Smith et al., 2016).

Pressure	Description
Smothering	By man-made structures/disposal at sea
Substratum loss	Sealing by permanent construction (coastal defences/wind turbines), change in substratum due to loss of key physical/biological features, replacement of natural substratum by another type (e.g. sand/gravel to mud)
Changes in siltation	Change in concentration of suspended solids in the water column (dredging/run-off)
Abrasion	Physical interaction of human activities with the seafloor/seabed flora and fauna causing physical damage (e.g. trawling)
Selective extraction of non-living resources (habitat removal)	Aggregate extraction/removal of surface substrata
Underwater noise	Shipping/acoustic surveys
Litter	Waste products disposed of inappropriately into the marine environment
Thermal regime change	Temperature change (average, range, variability) due to thermal discharge (local)
Salinity regime change	Temperature change (average, range, variability) due to thermal constructions affecting water flow (local)
Introduction of synthetic compounds	Pesticides, anti-foulants, pharmaceuticals
Introduction of non-synthetic compounds	Heavy metals, hydrocarbons
Introduction of radionuclides	Radionuclides
Introduction of other substances	Solids, liquids or gases not classed as synthetic/non-synthetic compounds or radionuclides
Nitrogen and phosphorus enrichment	Input of nitrogen and phosphorus (e.g. fertiliser, sewage)
Input of organic matter	Input of organic matter (industrial/sewage effluent, agricultural run-off, aquaculture, discards etc.)
Introduction of microbial pathogens	Introduction of microbial pathogens
Introduction of non-indigenous species and translocations	Through fishing activity/netting/aquaculture/shipping
Selective extraction of species	Removal and mortality of target (e.g. fishing) and non-target (e.g. by catch, cooling water intake) species
Death or injury by collision	Caused by impact with moving parts of a human activity (ships, propellers, wind turbines)
Barrier to species movement	Obstructions preventing natural movement of mobile species. Barrages, causeways, wind turbines etc. along migration routes.
Emergence regime change	Change in natural sea level (mean, variation, range) due to man-made structures (local)
Water flow rate changes	Change in currents (speed, direction, variability) due to man-made structures (local)
pH changes	Change in pH (mean, variation, range) due to run-off/change in freshwater flow etc. (local)
Electromagnetic changes	Change in the amount and/or distribution and/or periodicity of electromagnetic energy from electrical sources (e.g. underwater cables)
Change in wave exposure	Change in size, number, distribution and/or periodicity of waves along a coast due to man-made structures (local) or climate change (large scale).

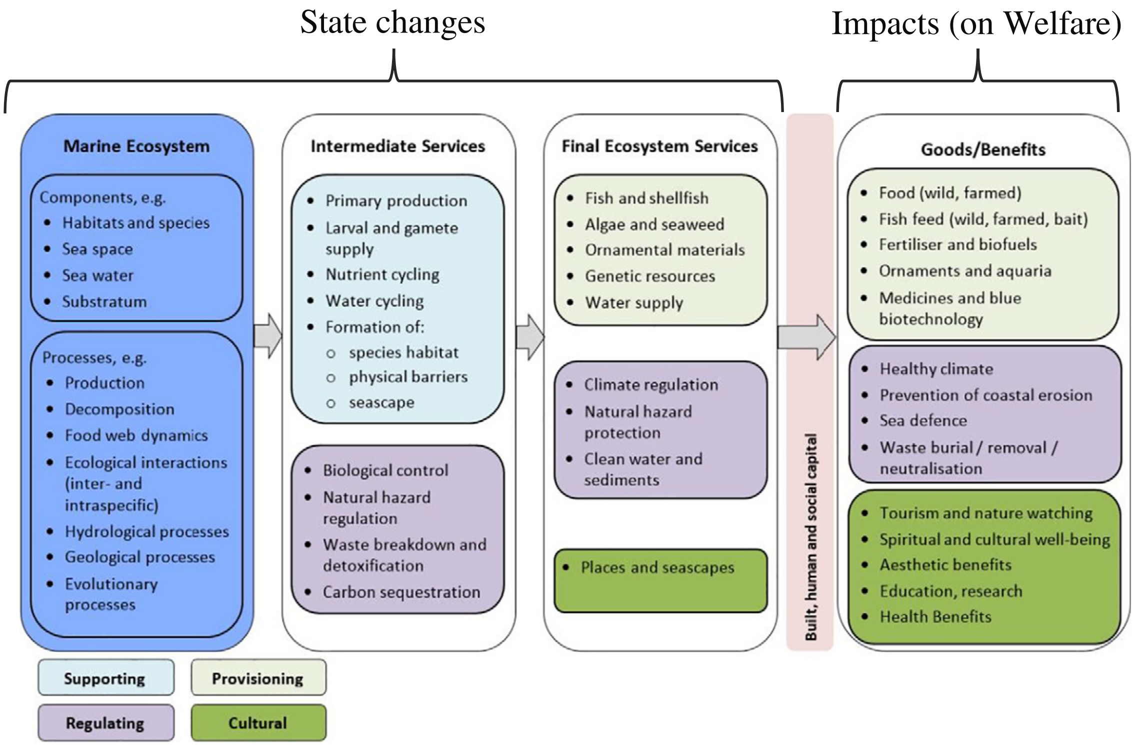


Fig. 5. State changes to the natural system reflected by changes in the marine ecosystem, intermediate and final ecosystem services (left hand side), and Impacts (on human Welfare) reflected by changes to the provision of Societal goods and benefits (right hand side).
(Modified and expanded from Turner et al., 2015).

provide spiritual and cultural welfare when people *invest* time and other resources to acquire such benefits. Thus, it is also emphasised that the term Welfare also by definition encompasses human *well-being and happiness*, again cross-referring to the upper levels of Maslow's hierarchy. Most importantly, it is this element that relates to any deterioration in the marine system to provide Blue Growth and contribute to the Blue Economy as defined above. It is also through recognition of the role of complementary capital that the wider human consequences, such as loss of employment, can be realised. This is also implied, at least in part, through the explicit inclusion of the Activities within the DAPSI(W)R(M) framework. Therefore, we also emphasise the need for operational indicators of the Impacts on human Welfare for communicating adverse effects on assets valued by society (Turner and Schaafsma, 2015).

2.6. Responses (as Measures)

Many marine management responses emanate from a governance background which relates to the political landscape and marine policies and administration (Boyes and Elliott, 2015) and the large amount of legislation required to manage all marine activities (Boyes and Elliott, 2014). The expansion of management Responses to include '(as Measures)' enables the DAPSI(W)R(M) approach to become more harmonised with the terminology used within European Union Directives such as the MSFD and the WFD (Borja et al., 2010). Hence we emphasise that to be successful, management Responses (as Measures) to changes resulting from Drivers, Activities and Pressures should follow the 10-tenets approach for adaptive management and sustainability (Barnard and Elliott, 2015) and as such each tenet requires its own Measures (Table 5) although one Measure may cover several tenets and any one tenet requires several Measures. As an example, Table 6 illustrates Measures required to address the 'ecologically sustainable' tenet, by creating the physical, chemical and biological conditions thus restoring the natural system (as illustrated in Fig. 1). In addition to these Measures, Measures would also be required which relate to the feasibility of technology, the viability of the economic situation based on marginal social cost and benefit comparisons, and so on in order to successfully manage the marine environment.

3. Applying the DAPSI(W)R(M) framework

As described above, the DAPSI(W)R(M) framework is a cycle which relates to a particular human need and accompanying activities, for

Table 5
The 10-tenets framework for examples of management responses.
(Expanded from Elliott, 2013; Barnard and Elliott, 2015).

To be successful, management Responses (as Measures) to changes resulting from human activities should be:	Examples of measures
Ecologically sustainable	See Table 6
Technologically feasible	Building treatment works, remediation habitats
Economically viable	Sufficient funding for the measure, acceptable cost-benefit analysis/ratio
Socially desirable/tolerable	Stakeholder agreement based on consultation
Legally permissible	Compliance with laws and regulations; licence compliance for waste disposal
Administratively achievable	Agreement from administrative and statutory bodies such as an Environmental Protection Agency
Politically expedient	Agreement with the manifesto commitments of the ruling party
Ethically defensible (morally correct)	Funding mechanisms are not a burden on future generations, discounting mechanisms are not a liability
Culturally inclusive	Protection of culturally and aesthetically important areas, no interference of indigenous human population areas
Effectively communicable	Agreement by consultation, advertised decision-making

Table 6
Description of measure categories.
(Modified from Dr. K Wolfstein et al., unpubl.)

Objective/class	Measure category
Biology/ecology/other	Measure to develop and/or protect specific habitats
	Measure to develop and/or protect specific species
	Measure to prevent introduction of or to control/eradicate invasive species
	Measure to develop natural gradients and processes, transition and connection
	Measure for direct human benefit
Hydrology/morphology	Measure to restore longitudinal connectivity
	Measure to restore lateral connectivity (flooding dynamics, floodplains and off-channel habitats)
	Measure to restore water flow - quantity
	Measure to restore sediment flow - quantity
	Measure to restore water flow - dynamics
	Measure to restore morphological quality (structure and substratum)
	Measure to restore morphological diversity (depth and width variation)
	Measure to restore riparian zone
	Measure to restore tidal energy dynamics, range, asymmetry and pumping effects
	Other measures to improve morphological or hydrological conditions
Physical/chemical quality	Measure to reduce pollutant loading (point and diffuse sources)
	Measure to reduce nutrient loading (point and diffuse sources)
	Measure to improve oxygen conditions
	Measure to reduce physical loading (e.g. heat input)
	Other measure to improve self-purifying power

example to obtain food through wild fishing. However, of course, each sea area contains many Drivers and Activities, each with their own set of Pressures, State changes etc. Therefore, as described below, there is the need to expand and apply the concept and framework for holistic marine management, including nested-DAPSI(W)R(M)s, integrating nested-DAPSI(W)R(M)s, and the integration of the DAPSI(W)R(M) approach with risk assessment and management frameworks and integrated socio-ecological frameworks.

3.1. Nested-DAPSI(W)R(M)

Building on Atkins et al. (2011), a spatially-interlinked nested-DAPSI(W)R(M) framework can provide the integrated management of the marine environment (Figs. 6 and 7). For example, in any sea area to be managed there could be wild fisheries, aquaculture, navigation, recreation, etc., each of which requires its own DAPSI(W)R(M) cycle (and colloquially termed DAPSI(W)R(M) 'petals' due to the flower-like pattern!). This emphasises the importance of the relationships between competing uses of the marine environment, represented by the Activities, and their associated Pressures within each DAPSI(W)R(M) cycle. Interlinked or nested-DAPSI(W)R(M) frameworks thus truly reflect the complexity of the marine system.

Fig. 6 shows that a moderate number of Drivers gives rise to many Activities. As some of the Activities have similar Pressures then there could be an overlapping set of Pressures; for example bed trawling and seabed sand extraction will create similar Pressures. Similarly, the management Responses (as Measures) will each tackle several adverse changes in the system. Furthermore, elements in one 'petal' can affect those in others, for example, a loss of fish populations due to wild fisheries can affect the need for aquaculture and its source of feed. Although not shown in Fig. 5, to prevent further complication, the importance of feedback loops should be recognised between management Responses (as Measures) to particular Drivers, Activities and Pressures, and between other elements within the same DAPSI(W)R(M) cycle. An example of the second case may be a feedback loop existing between society realising an Impact (on Welfare) in the form of fish catch, where the smaller the fish population the greater the Impact (on Welfare), at least in the short term; this implies a backward loop between the Impact and the State change. In turn, this may lead to a larger sandeel population (as a key prey species for fish and birds), implying a horizontal loop to this State change, which may result in a larger piscivorous bird (e.g. Kittiwake) population (a horizontal loop between two State change elements), and then the larger the potential Impact associated with tourism in relation to nature watching (implying a forward loop to Impact on Welfare).

Nested-DAPSI(W)R(M) cycles can be rotated to put any single element at their centre, depending on the context being considered. For example, if the focus is on ecological change and status then it would be

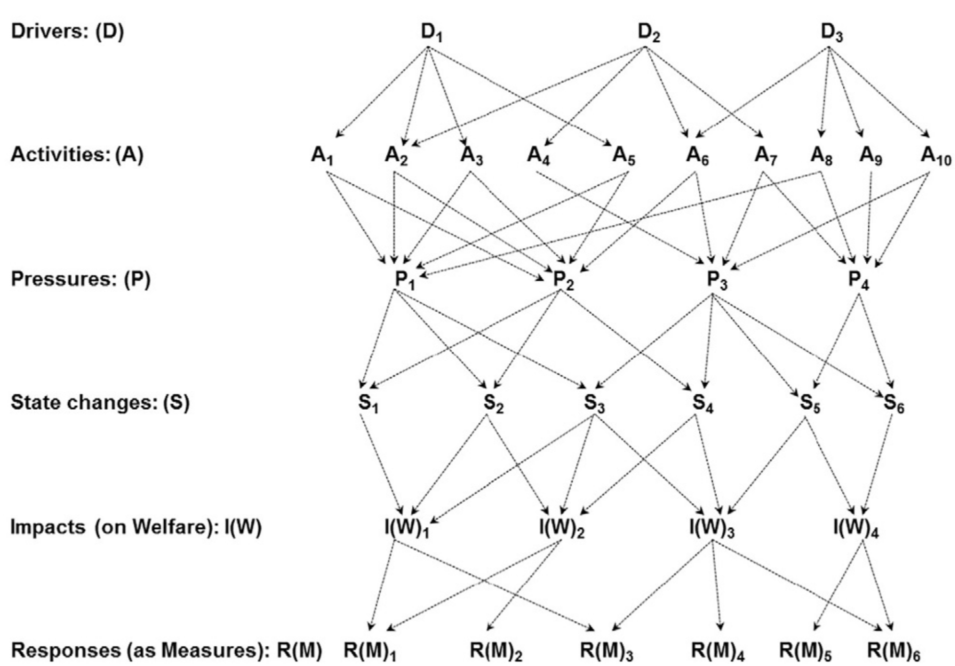


Fig. 6. An illustration of the multiple interactions within the DAPSI(W)R(M) framework.

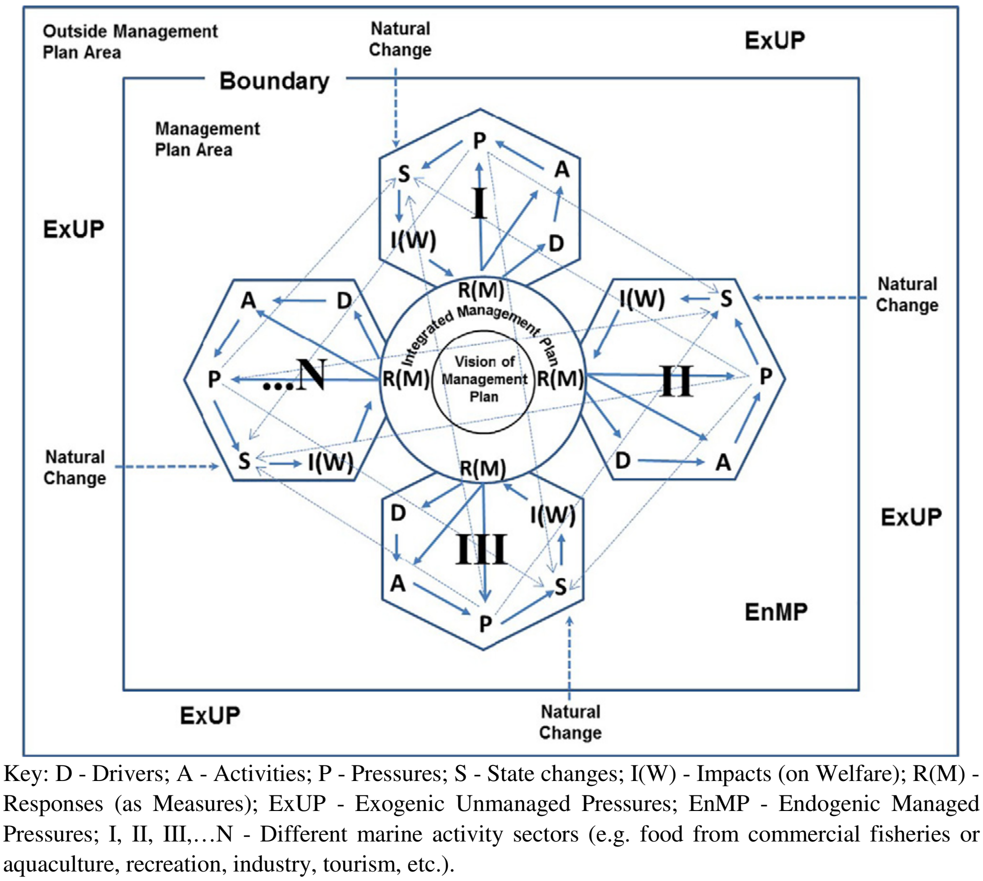


Fig. 7. A nested-DAPSI(W)R(M) framework for the integrated management of a hypothetical marine area. Key: D - Drivers; A - Activities; P - Pressures; S - State changes; I(W) - Impacts (on Welfare); R(M) - Responses (as Measures); ExUP - Exogenic Unmanaged Pressures; EnMP - Endogenic Managed Pressures; I, II, III, …N - different marine activity sectors (e.g. food from commercial fisheries or aquaculture, recreation, industry, tourism, etc.).

most appropriate to focus the nested-DAPSI(W)R(M) framework with State changes at the centre. As another example, and as shown in Fig. 7, all the Responses (as Measures) could be at the centre when the focus is to create an integrated coastal management system. This demonstrates that in order to manage the system in a holistic manner, all management Responses (as Measures) aimed at the range of Activities (e.g. fisheries, aquaculture, tourism) taking place within the boundary of the system to be managed must be integrated in order to ensure that the Pressures on the system are mitigated, resulting in a better (or at least a 'less-bad') State change in the natural system and, possibly, conserving or enhancing the flow of ecosystem services and societal benefits from the system. In practice, the complexity of the marine system will likely lead to a range of consequences, for example, some of which will be unintended and others not apparent until some threshold state has been reached. This emphasises the importance of integrated management plans (e.g. European Marine Site Management Plans), which contain a number of Activity-specific management Responses, but which can be integrated in a truly holistic way to increase the likelihood that the marine ecosystem remains healthy (Tett et al., 2013) and delivers the ecosystem services and benefits of interest to society (Elliott, 2011). This approach was shown for the management of the Baltic Sea by Scharin et al. (2016) by focussing on its major current environmental challenge, eutrophication.

Given the relationships between the delivery of ecosystem services and societal goods and benefits, respectively representing the State changes to Impacts (on Welfare) links of the DAPSI(W)R(M) framework, then systems can be managed in order to deliver a particular ecosystem service, good or benefit. By applying a nested-DAPSI(W)R(M) approach, with for example State changes as its central focus, it is possible to mitigate a number of Pressures (e.g. increased nutrient loads, fishing effort) to ensure that the marine system is healthy and is functioning appropriately to deliver the required ecosystem services and societal goods and benefits. As shown in Fig. 6, mitigating a particular Pressure may have a positive effect in a greater number of State changes, thus emphasising the importance of holistic management of the system based on management strategic planning that includes operational controls to reach strategic goals. The management Responses, through a suite of Measures applied to the Drivers, Activities and Pressures, needs to be integrated given the interaction and additive effects on the system state (Scharin et al., 2016).

3.2. Catchment-linked (networked) DAPSI(W)R(M) models

Gibbs and Cole (2008), Atkins et al. (2011) and Gregory et al. (2013) emphasise that the marine environment could be considered to be a Complex Adaptive System which is formed through the interconnection between natural systems (such as terrestrial, freshwater, estuarine, coastal and oceanic), designed systems (such as extractive industries, tourism, transport and power generation) and social systems (such as environmental activist groups, fishing communities etc.). Holistic management practices are therefore required which encompass the environment, economy and society (de Jonge et al., 2003; Borja et al., 2016a).

In order to manage interconnected systems (e.g. rivers, estuaries, coasts), there is a need to further develop the idea of linking nested-DAPSI(W)R(M) models between areas and ecosystems. This not only recognises the complexity of relationships between adjacent ecosystems, but recognises the potential effects of anthropogenic Activities on the natural and human system throughout the catchment and at sea. This is demonstrated here for aquatic systems whereby nested-

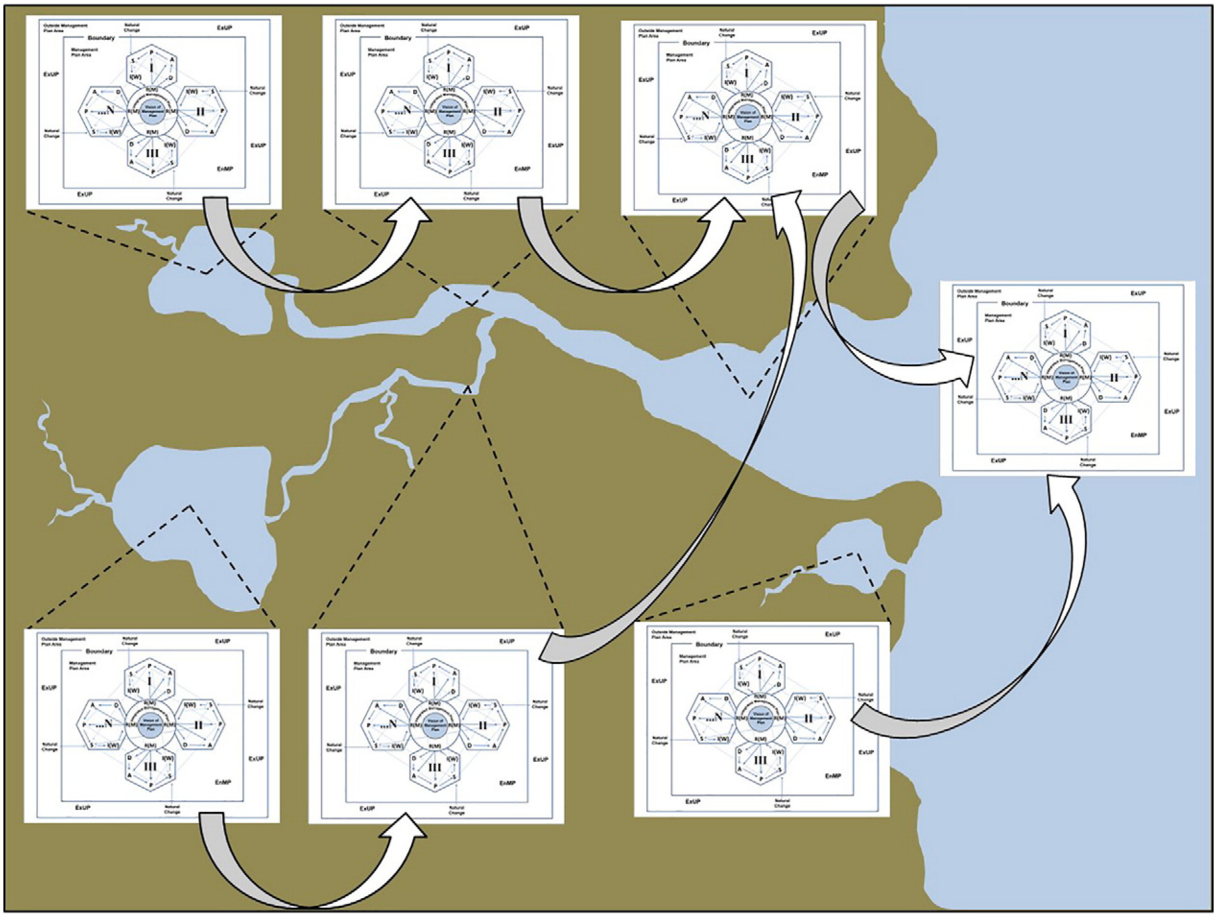


Fig. 8. Catchment linked, networked, nested-DAPSI(W)R(M) models for freshwater lakes and rivers, estuary, coastal lagoon and sea area.

DAPSI(W)R(M) models are linked between lakes, rivers, estuaries, coastal lagoons and coastal waters (Fig. 8). Furthermore, by its nature these aquatic systems are then linked to the terrestrial system through river run-off and terrestrial inputs, thus giving a surrogate for a whole system analysis.

If an environmental manager is managing one of the ecosystems on Fig. 8, for example the estuary, then all the Pressures in the catchment and further out at sea are defined as exogenic and so management will tackle only the estuarine consequences rather than the external or underlying, root causes. If the estuary is eutrophic then the causes in the catchment have to be managed by much wider-scale initiatives than an estuarine management plan. In contrast, if the environmental manager is charged with managing the whole sea area shown in Fig. 8 then all the Activities and Pressures in the catchment-linked models are endogenic and only global changes, such as climate change, would be exogenic (Elliott et al., 2015). It is of note that catchment and marine management systems, as exemplified by the EU WFD and MSFD and by the US Clean Water Act, treat those larger-scale systems as the management unit – respectively the river basin catchment and the regional sea area (Borja et al., 2010).

3.3. DAPSI(W)R(M) to inform risk assessment and risk management

Many hazards occur within the marine environment, including both natural hazards such as erosion, tsunamis and isostatic rebound, and anthropogenic hazards such as over-exploitation of natural resources, and the input of artificial structures such as harbours, ports or offshore wind turbines (Elliott et al., 2014). If these hazards adversely affect the assets, economy and safety of humans then these hazards become 'risks'. Furthermore, the risk from natural hazards can be exacerbated by human activities, for example the removal of areas of saltmarsh for a port development or mangroves for shrimp ponds, reduces the natural energy absorption function of the saltmarsh and mangrove and thus may result in an increased risk of coastal flooding (Elliott et al., 2016). Unless these hazards and risks are mitigated against, then human Activities may lead to Pressures and subsequent State changes in the natural environment, which then may have knock-on Impacts (on Welfare) and thus require management Responses (as Measures) to address these hazards and risks. For example, a Response Measure creating new wetlands may help to combat internal Pressures such as the loss of intertidal area by land-claim and external Pressures such as increasing sea level (Wolanski and Elliott, 2015; Elliott et al., 2016).

Given the above features, a rigorous risk assessment and management framework is required which can identify the risks, determine their causes and consequences, and accommodate multiple risks individually, cumulatively and in-combination (Cormier et al., 2013). By definition, cumulative threats and pressures emanate from within a single activity, whereas in-combination threats and pressures occur from multiple activities occurring in an area at the same time (Patrício et al., 2016). Because of this, we suggest the further integration of the DAPSI(W)R(M) framework with, for example, the ISO-compliant (International Standards Organisation) Bow-Tie approach for risk assessment and risk management (Fig. 9).

In essence, the Bow-Tie approach is used to identify prevention, mitigation and recovery measures in light of a main event of concern and the causes and consequences of such an event in the presence of a hazard or a source of risk (Elliott et al., 2014). It focuses on a main event of concern (the 'knot' of the Bow-Tie) which is *caused* by the factors at the left hand side and then it results in the *consequences* at the right hand side. The main event occurring can be influenced by inserting

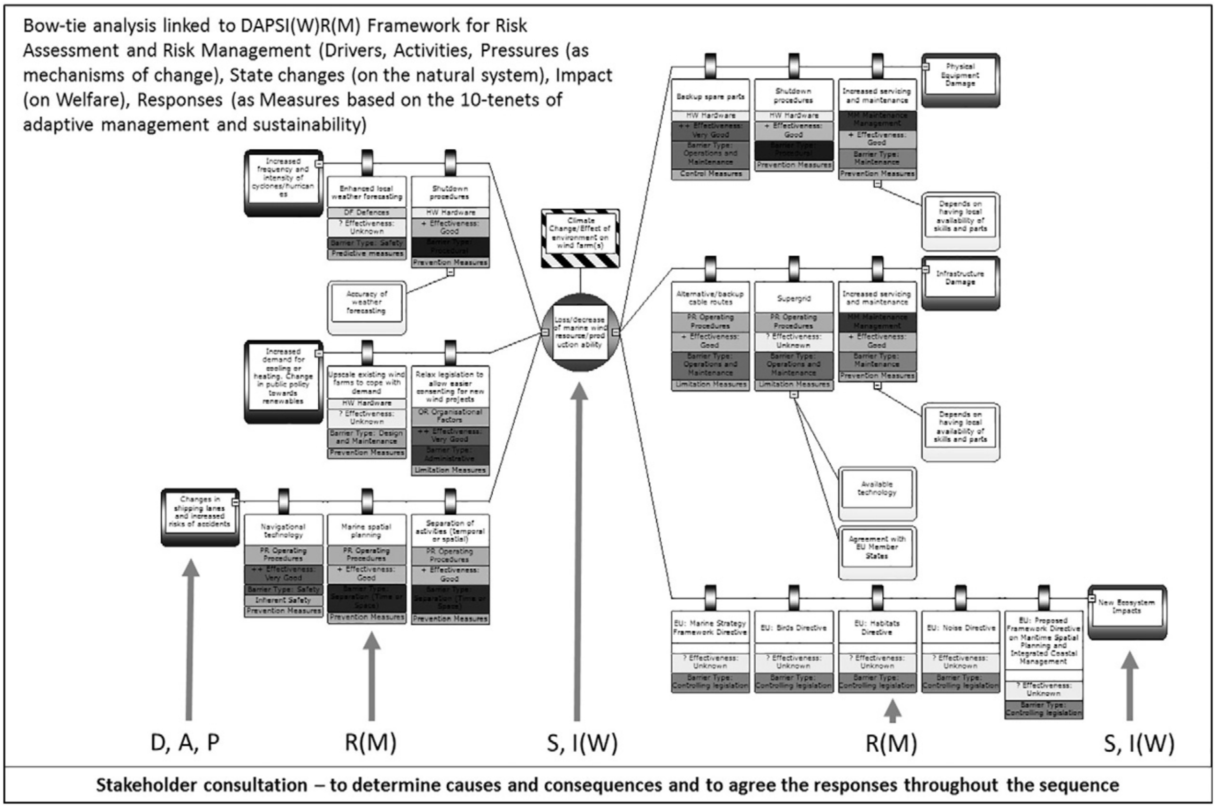


Fig. 9. Examples of causes (left) of the hazard (centre), preventative measures (left of centre), mitigation and compensation measures (right of centre), consequences (right), and escalation factors (hanging boxes). Hazard in this example is climate change resulting in a loss or reduction in the wind power resource (Burdon et al., in press).

prevention mechanisms between it and the causes. If the prevention mechanisms are unsuccessful then mitigation and/or compensation mechanisms can be inserted to prevent the main event leading to consequences. Building on the work of Cormier et al. (2013) and Smyth and Elliott (2014), and linking this method to the DAPSI(W)R(M) framework, enables scoping, identification and analysis of: the Drivers leading to the main events (through Activities and Pressures); anticipatory prevention measures (management Responses as Measures), including those limiting the severity of the main event; the consequences of the events (State changes and Impacts on Welfare), and mitigation and compensation measures (management Responses as Measures) aimed at minimising those consequences. In turn, the Bow-

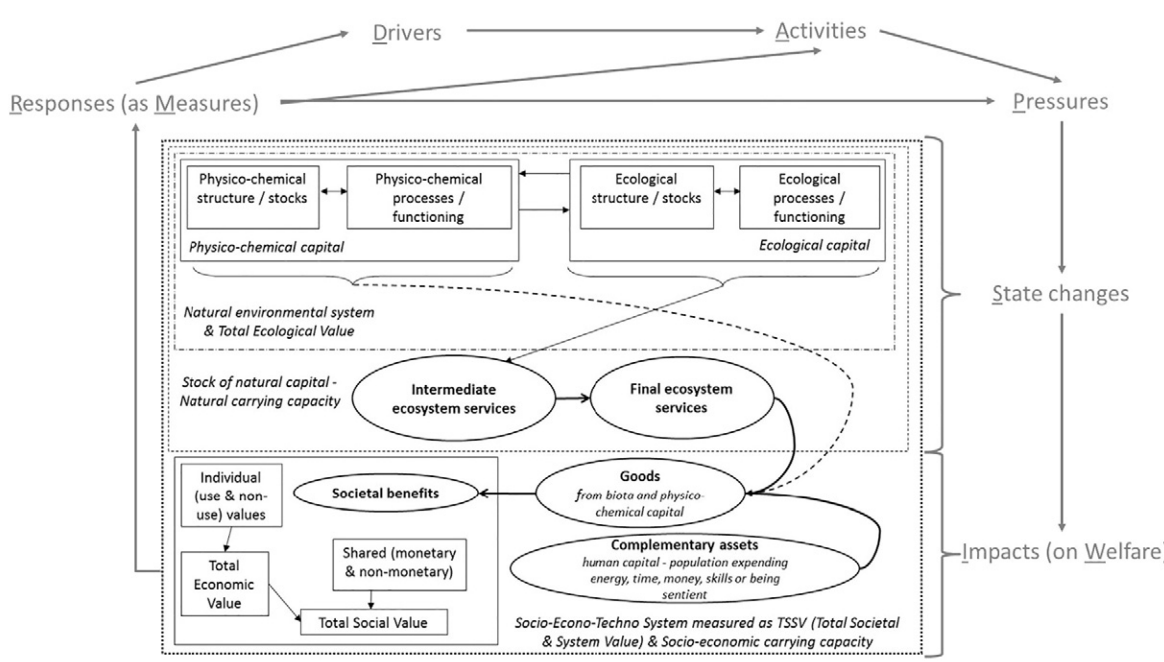


Fig. 10. DAPSI(W)R(M) in the context of an integrated socio-ecological system.
(Modified from Atkins et al., 2014).

Tie approach must also encompass the 10-tenets of adaptive and sustainable management and sustainability (Table 5), for example by incorporating the governance, economic and technological aspects (Barnard and Elliott, 2015).

4. Concluding remarks: DAPSI(W)R(M) as a unifying framework for integrated marine management

The essence of DAPSI(W)R(M) is to link the natural and social systems to deliver the Ecosystem Approach, i.e. to protect and maintain the natural system while supporting ecosystem services which then can help to deliver societal goods and benefits (Elliott, 2014). Therefore, as shown in Atkins et al. (2014) and de Jonge et al. (2003, 2012), the natural (ecological) and social systems can be integrated to recognise the important linkages between the biotic and abiotic components of the natural marine environment. The physical and chemical structure allows the marine processes and physico-chemical functioning to operate which in turn create the niches to be filled by the ecological structure and then the ecological functioning to operate (as shown in the upper part of Fig. 10). Once that ecosystem structure is fully functioning then it creates pathways to provide a range of intermediate and final ecosystem services, and so results in the supply of goods and benefits which are of value to society (the lower half of Fig. 10). This integrated approach also recognises the importance of inputting built, human and social capital to deliver goods and benefits for society. For example, if the water currents and salinity and the sediments can support the fish and their prey then the input of human complementary assets (of skills, time, energy and finance) will allow the fish to be caught and used and thus given an economic value (thus expanding the Blue Economy).

As superimposed on to Fig. 10, the DAPSI(W)R(M) model emphasises the integrated social-ecological framework established by Atkins et al. (2014) and de Jonge et al. (2003, 2012). The underlying assumptions and further explanatory notes of this model are listed in Table 7. The upper half of the socio-ecological model relates to the State changes, which had been adversely affected by the requirement for societal Drivers, the carrying out of Activities and the resultant Pressures. Those State changes in turn cause Impacts (on Welfare) which can be accounted for in monetary or non-monetary terms and which may be positive or negative and which are addressed through management Responses (as Measures).

The essence of integrated marine management is in linking all the relevant aspects, encompassing the natural and social sciences, hence giving and delivering the elements of both the socio-ecological system and the Ecosystem Approach (de Jonge et al., 2012; Burdon, 2016; Borja et al., 2016a). While the approach here can be criticised as deconstructing the marine environment before tackling each aspect, it is emphasised that its complexity requires it to be broken into manageable components. The challenge then is to reassemble the elements for holistic management – we contend that we have all the relevant philosophies and conceptual models but that these still require to be implemented fully for successful and sustainable management.

Our analysis has also indicated the role of different scientific disciplines – for natural sciences (biology, chemistry, hydrology, etc.) to determine the Pressure spatial and temporal footprints, the State changes and the Impacts on human Welfare, especially well-being; for economics and socio-economics to determine the Impacts (on human Welfare) and for many of the 10 tenets (economics, societal interactions and stakeholder engagement, etc.); for engineering, political science, management aspects and economics in the Responses (as Measures), and for the social sciences in determining the Drivers and basic human needs which influence the whole cycle. This emphasises the importance of training new professionals to cope with this diverse landscape.

The approaches here also emphasise the need for policy-informing science and science-informing policy whereby the former allows the prioritisation of the disciplines and the need for each type of analysis and study. The latter (science-informing policy) will be able to identify the limitations in our ability to answer the policy requirements and also it will show the inherent complexity in the marine system. Some of that complexity will require best-judgement approaches rather than very detailed analyses which in the end may only serve to highlight the variability and our inability to show causal links from Activities and Pressures to State changes and Impacts (on Welfare) (de Jonge and Giebels, 2015).

Furthermore, this analysis shows the value of harmonising concepts, from many approaches and disciplines, and allows the framework to be used to tackle real examples. The studies of Scharin et al. (2016), Smyth et al. (2015), and Burdon et al. (in press) have resulted from multidisciplinary projects and had a direct input from the science to the management of sea areas. These studies also show that the integrated approach is a communication tool for allowing stakeholder interaction (Newton and Elliott, 2016). However, the complexity of the integrated approach and of the natural, socio-economic and management aspects of the marine area require stakeholders to be guided through the approach and perhaps only be required to address particular parts of the approach at any one time.

Finally, the approach here builds on recent compendia such as Borja et al. (2017) which show advances in marine science for marine management. It is suggested here that, as a next step, there is the need for a systems-wide or Systems Analysis (Gregory et al., 2013), especially to link the facets of DAPSI(W)R(M) in tackling exogenic and endogenic

Table 7
Underlying assumptions and explanation of the conceptual model in Fig. 9 (Atkins et al., 2014).

The physico-chemical system sets up the framework to support/develop the ecological system but the latter then influences the physico-chemical system (feedback loop);
Functioning relates to rate processes and thus flows whereas structure relates to a commodity at a given time;
The environmental system and (natural) capital is the product of the physico-chemical (natural) capital and the ecological (natural) capital; 'capital' in this case includes both structure and function;
Ecological functioning is created by and in turn creates ecological structure;
Ecological natural capital requires valuing by ecological valuation (which includes rarity, fragility, resilience, vigour, etc.) cf. economic valuation;
Ecological stocks are a subset of ecological structure but are created by and in turn create ecological functioning;
In economic and ecological terms, societal benefits are taken from the stocks without adversely reducing the stocks (c.f. overfishing);
Achieving benefits from services by society requires expenditure of human capital and complementary assets (skills/energy/money/time);
The natural system can have ecosystem services for its own right not linked to societal benefits;
'Intermediate' ecosystem services follow from 'fundamental/basic' ecosystem processes as an economic rather than an ecological construct;
'Carrying-capacity' is the ability of the natural or human system to hold/support the indicated attributes;
The natural and socio-economic systems provide the carrying capacity which then supports the natural and socio-economic capital;
The arrows should be read as something 'leads to' or 'produces' the subsequent box and double arrows denote feedback loops;
'Goods' relates to an entity (cf. structure) whereas 'services' relates to the processes producing that entity;
Human capital is taken to include skills/education/knowledge, entities and ability to use them;
The values concept needs to include 4 dimensions: anthropocentric instrumental value; anthropocentric intrinsic value; non-anthropocentric instrumental value; non-anthropocentric intrinsic value;
By definition 'anthropocentric' means that it can be given a monetary value whereas 'non-anthropocentric' does not (necessarily) have a monetary value;
Whereas the physico-chemical and ecological systems relate to Good (Chemical or Ecological) Status under the EU Water Framework Directive, the physico-chemical, ecological and human systems relate to Good Environmental Status under the EU Marine Strategy Framework Directive.

influences on a marine management area, and a rigorous Decision Support System to guide users through the relevant areas. More than anything, this viewpoint has illustrated an increasingly complex field but we hope it presents an approach that is required to achieve the Ecosystem Approach in managing our seas.

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