From DPSIR the DAPSI(W) R(M) Emerges… a Butterfly – '*protecting the natural stuff and delivering the human stuff*'

Michael Elliott and Timothy G. O'Higgins

Abstract The complexity of interactions and feedbacks between human activities and ecosystems can make the analysis of such social-ecological systems intractable. In order to provide a common means to understand and analyse the links between social and ecological process within these systems, a range of analytical frameworks have been developed and adopted. Following decades of practical experience in implementation, the Driver Pressure State Impact Response (DPSIR) conceptual framework has been adapted and re-developed to become the D(A)PSI(W)R(M). This paper describes in detail the D(A)PSI(W)R(M) and its development from the original DPSIR conceptual frame. Despite its diverse application and demonstrated utility, a number of inherent shortcomings are identified. In particular the DPSIR model family tend to be best suited to individual environmental pressures and human activities and their resulting environmental problems, having a limited focus on the supply and demand of benefits from nature. We present a derived framework, the "Butterfly", a more holistic approach designed to expand the concept. The "Butterfly" model, moves away from the centralised accounting framework approach while more-fully incorporating the complexity of social and ecological systems, and the supply and demand of ecosystem services, which are central to human-environment interactions.

M. Elliott (✉)
Department of Biological & Marine Sciences, University of Hull, Hull, UK

International Estuarine & Coastal Specialists Ltd., Leven, UK
e-mail: Mike.Elliott@hull.ac.uk

T. G. O'Higgins
MaREI Center for Marine and Renewable Energy Ireland, Environmental Research Institute, University College Cork, Cork, Ireland
e-mail: tim.ohiggins@ucc.ie

T. G. O'Higgins et al. (eds.), *Ecosystem-Based Management, Ecosystem Services and Aquatic Biodiversity*, https://doi.org/10.1007/978-3-030-45843-0_4

1 Introduction

There is only one big idea in environmental management, especially that for aquatic ecosystem, that is '*how to maintain and protect the natural ecological structure and functioning and the resultant ecosystem services while delivering the societal goods and benefits*' (Elliott 2011). This is exemplified in Ecosystem-Based Management (EBM) which seeks to "integrate the connections between land air water and all living things including human beings and their institutions" (Mee et al. 2015) and to manage complex adaptive systems towards particular goals and targets. In essence, this is a risk assessment and risk management approach which requires monitoring to determine whether management actions have worked (Cormier et al. 2019). Hence in order to assess whether specific policy decisions are effective management efforts need to agree measurable targets on pre-defined indicators. Yet the complexity of interactions and feedbacks between human activities and ecosystems can make the analysis of such systems intractable and so we need an underlying accepted framework to link together the causes and consequences of change and their management. Systematic methods of accounting for socio-ecological interactions are required to assess the effectiveness of management in such complex adaptive systems. Here we follow environmental accounting as the process of systematically organising and presenting information relating to interactions between the economy and the environment in a standardised way in order to support policy making (UNSD 2012).

While there are many legal instruments which are required to manage the environment, and so fulfil the 'big idea' above (Boyes and Elliott 2014), in Europe there are two major framework environmental policies relating to aquatic environments: the Water Framework Directive (WFD) (European Commission 2000) and the Marine Strategy Framework Directive (MSFD) which both promote an ecosystem approach to freshwater, estuarine, coastal and marine management (see O'Hagan 2020, and Borja et al. 2010 and references therein for detailed accounts). These policies seek to apply common standards, equally, to the conservation of aquatic environments across the European Union Member States (European Commission 2008). This results in a particular need for standardised methodologies because each Member State has its own unique geographic and environmental conditions, as well as traditions of monitoring the environment based on indicators. For example, Teixeira et al. (2016) generated a catalogue of 611 indicators of biodiversity proposed or in use for monitoring European marine environments. Under these conditions, accounting frameworks enable the intercomparison of different Member State efforts and activities. This should enable assessment on a continental scale of whether environmental policies are reaching their objectives and whether EU member states are complying with these and other Directives. Experiences in the implementation of these directives have been instrumental in developing the state-of the art science addressing socio-ecological systems in Europe and has led to many valuable insights into Ecosystem-Based Management.

One environmental accounting framework, which has developed in parallel with the application of European aquatic environmental law is the Driver Pressure State

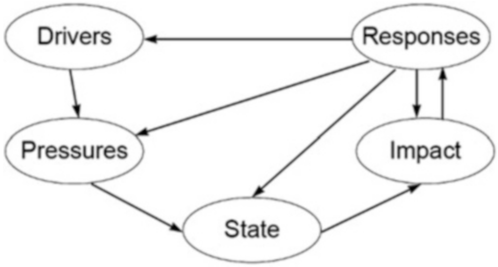

Fig. 1 Original depiction of the DPSIR framework. Source: European Environment Agency (1999)

Impact Response (DPSIR) framework (EEA 1999) which developed from the earlier PSI framework adopted by the OECD in the early 1990s. In brief, human activities or *Drivers* place *Pressures* on the environment resulting in changes to the environmental *State* and *Impacts* which result in a management *Response*. This causal chain in Fig. 1 uses the original diagram of the European Environment Agency (EEA 1999). DPSIR is a conceptual framework for analysing socio-ecological systems which encapsulates the interactions between anthropogenic and natural components of socio-ecological systems (Turner and Schaafsma 2015) where each element in the cause-consequence-management chain can be described by an indicator (see below). As a conceptual framework, the DPSIR is used to compartmentalise and thereby simplify and analyse socio-ecological systems.

With origins in the field of environmental risk assessment and accounting (Rapport and Friend 1979), the DPSIR was first formally published in 1999 (EEA 1999) prior to adopting the WFD (European Commission 2000) and has widely been used and adapted over the intervening 20 years (Patrício et al. 2016). The Web of Science indicates DPSIR has been the subject of 577 peer-reviewed papers, principally in the fields of environmental science ($n = 406$), water resources (88) and ecology (66). As an overarching conceptual frame, the DPSIR has been employed to analyse a broad variety of environmental problems in diverse environments and geographic settings from the study of water scarcity in Oman (Al Kalbani et al. 2015) to biodiversity loss (Maxim et al. 2009). Yet the DPSIR has been most commonly used in Europe (Patrício et al. 2016) and the most highly cited/influential DPSIR papers relate to the European aquatic environmental conservation directives, the WFD (Borja et al. 2006) and the MSFD (Atkins et al. 2011).

Early iterations of DPSIR (EEA 1999), did not rigorously define the various information categories, rather it described their interrelationships:

> …social and economic developments [Driving forces] exert Pressure on the environment and, as a consequence, the State of the environment changes, such as the provision of adequate conditions for health, resources availability and biodiversity. Finally, this leads to Impacts on human health, ecosystems and materials that may elicit a societal Response that feeds back on the Driving forces, or on the state or impacts directly, through adaptation or curative action. (EEA 1999)

As a result, through practical application, the DPSIR has been continually refined and redefined in the context of European Marine environments. DPSIR has been applied to the Mediterranean and Baltic Seas (Lundberg 2005; Karageorgis et al.

2005; Skoulikidis 2009). Studies in the Black Sea (Langmead et al. 2009; Knudsen et al. 2010) employed a modified DPSIR (mDPSIR) approach, while, Cooper (2013) made a variety of changes to develop DPSWR (where W is Welfare) which has been used in a variety of geographic contexts from the Black Sea (O'Higgins et al. 2014 to the North East Atlantic (O'Higgins and Gilbert 2014) as well as to explore socio-ecological scale mismatches in marine sectors (O'Higgins et al. 2019) and to explore intertemporal trade-offs in activity and environmental quality (O'Higgins et al. 2014). This evolution of DPSIR is fully detailed by Patrício et al. 2016) which indicated anomalies in the way the concept has been used; this culminated in the development of DAPSI(W)R(M) which incorporated 20 years of the evolution of the concept and attempted to resolve the confusion in the use of the forerunners (as well as being the more pronounceable "*dap- see–worm*") (described in detail in Elliott et al. 2017, but used in their previous papers, e.g. for the Baltic Sea by Scharin et al. 2016 and the Arctic by Lovecraft and Meek 2019).

In this volume, the DPSIR and its variants are critical to many of the case studies. For example, these frameworks form the basis of the linkage framework techniques (Culhane et al. 2020); and were used as an organisational framework for case studies in the Azores (McDonald et al. 2020), the Danube (Funk et al. 2020) and in Lough Erne (O'Higgins et al. 2020). In this paper we first set out the major features of the DAPSI(W)R(M) framework (Elliott et al. 2017). We then consider the broader characteristics of ecosystem-based management (Langahns et al. 2019; Delacamara et al. 2020) and introduce a derivation of the framework which we call "the butterfly". The latter is designed to expand the concept, moving away from the centralised accounting framework approach while more-fully incorporating the complexity of social and ecological systems. We present the butterfly not as a replacement to the DPSIR-family (which has been so successfully applied to the existing marine policy) as a socio-ecological accounting framework, but as a potential tool to enable more fully integrated approaches to the development and application of Ecosystem-Based Management.

2 The DAPSI(W)R(M) Framework

2.1 Drivers (D)

Previous DPSIR frameworks (e.g. Cooper 2013) had an in-built confusion as the Drivers were often synonymous with activities (what is done in the environment) or sectors (groups of activities such as fisheries) (Patrício et al. 2016). There may also be different interpretations of this between natural and social scientists—for example the former may regard Drivers as activities but social scientists regard them as 'basic human needs'. In order to resolve the confusion, and because the later elements in the framework refer to and separate Activities and Pressures, Elliott et al. (2017) emphasised that the Drivers should refer to Basic Human Needs and thus the work of Maslow (1943) who proposed a five-tier hierarchical structure of such Drivers

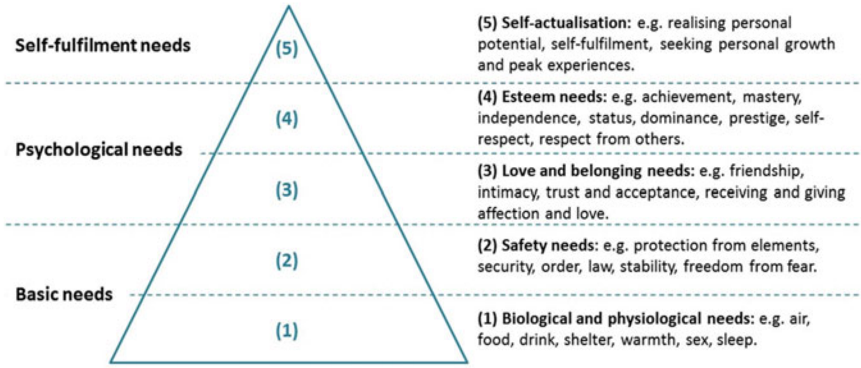

Fig. 2 Maslow's hierarchy of needs and human welfare (adapted from Maslow 1943)

(Fig. 2). At the lowest level these refer to an individual's biological and physiological needs which relate to survival (e.g. oxygen, food, drinking water) and safety and security (e.g. protection from external stressors). At its most simple, we can determine what are our basic human needs and then how do we get those from the natural and human environment.

The intermediate levels of basic human needs then cover psychological and emotional attributes which determine the societal structure and family relationships including love and belonging (e.g. friendship, intimacy, trust and acceptance) and esteem (e.g. prestige, achievement, self-respect). Hence, the lower four levels in Maslow's triangle cover the 'deficiency needs' i.e. what are required to motivate and satisfy people and for which desires and activities increase to satisfy these needs. The fifth and uppermost levels relate to meeting one's emotional fulfilment, such as the personal potential, emotional growth and satisfied experience—these may be regarded as 'growth needs'. Hence, there is the need for both an individual and society to satisfy the lower 'deficit needs' before achieving the higher 'growth needs' (Maslow 1943, 1970a, b). This includes three further intermediate categories of 'cognitive needs' (e.g. knowledge and understanding, curiosity, exploration, need for meaning and predictability—the scientific requirements), 'aesthetic needs' (e.g. appreciation and search for beauty, balance, form, etc. influencing our cultural appreciation) and 'transcendence needs' (e.g. altruistic behaviour helping others to achieve self-actualisation) (Maslow 1970a, b). Many of these needs are directly dependent on ecosystems, the 'basic needs' and safety needs require provisioning ecosystem services, while others for psychological and self-fulfilment needs depend on supply of ecosystem services and societal goods and benefits (Turner and Schaafsma 2015).

All of these basic human needs in turn dictate the way the marine space is used, the competition between individuals, tribes, societies and nations in the way in which the competition now occurs at larger scales from the regional to the global. Satisfying these needs and this competition (the basis of the economy) then leads to Activities inherent, for example, in international marine trade which is needed to deliver increasingly required/desired consumer products and services. All of this shows that the Drivers can ensure both economic benefits as well as high individual (physiological and psychological) and societal well-being and welfare. However, this unchecked growth in Drivers can lead to levels of Activities and Pressures which exceed the carrying and assimilative capacities of a particular system or even of the global system (Rockstrom et al. 2009) resulting in depletion of resources and damage to the natural system. This exceedance then requires measures which aim to minimise conflicts and partition that marine space in order to deliver the human and protect the natural aspects (Elliott et al. 2018).

The aggregate of these human wants and needs (or the urge to maximize utility) are the forces that drive economic development—the Blue Economy or Blue Growth. As set out above, they involve a range of social interactions between humans (e.g. respect from others, intimacy), as well as socio-ecological interactions between humans and the environment (e.g. food, shelter and warmth).

2.2 Activities (A)

As indicated above, there is the need to separate Drivers from Activities and Activities from Pressures. In essence, Activities are what we do in the seas to obtain those basic human basic needs, and the Pressures are the resulting mechanisms of change from those Activities (Elliott et al. 2017). Marine activities can be separated into 15 key marine sectors which then represent many individual, but often interlinked, activities which occur in most if not all seas (Table 1 gives 7 of these sectors). Elliott et al. (2017) lists all the Activities and Pressures and Burdon et al.

Table 1 Examples of sectors and activities in a marine environment (adapted from Elliott et al. 2017)

Sector	Examples of activities
Extraction of living resources	Benthic trawling (e.g. scallop dredging), netting, pelagic trawls, potting/creeling; bait digging, seaweed and harvesting, shellfish gathering
Transport and shipping	Mooring/beaching/launching, shipping, ferry operation, waste disposal.
Navigational dredging	Dredging, removal of substratum, disposal of dredge spoil.
Coastal infrastructure	Construction of artificial reefs and barrages, beach nourishment, laying of communication cables; constriction of transport infrastructure, dock and port facilities, land claim; construction of urban dwellings.
Land-based industry	Treatment and discharge of industrial; discharging particulate waste disposal, desalination effluent, sewage and thermal waste discharge
Agriculture	Animal waste disposal, crop fertilisation, farming, coastal forestry,
Tourism/recreation	Angling, boating/yachting, diving, public beach use, tourist resort and water sports operation, whale watching.
Research and education	Marine research; field education and training, research vessel cruises.

(2018) shows the complexity by giving a detailed breakdown of these relating to one main sector—oil and gas decommissioning. Hence the separation of sectors with nested activities may simplify the scheme. For example, the commercial fishing sector includes many types of fishing activity (trawling, potting, long-lines, etc.) and each produces Pressures which may or may not differ across Activities. This therefore creates operational marine management which is sufficiently specific for targeted problem-solving directed at specific activities (Cormier et al. 2019). Such a framework has to include historical marine activities (e.g. fisheries, oil and gas extraction), and newer offshore technologies (e.g. marine biotechnology, nodule mining) which together reflect the expanding global marine economy with its increasing human pressures (Stojanovic and Farmer 2013). Together this constitutes what may be termed the Blue Economy 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) (European Commission 2012).

As indicated above, as the original DPSIR framework confused Drivers and Pressures, there was the need to separate them within the DAPSI(W)R(M) framework by adding Activities. As an example, the basic Driver is to obtain food and beam trawling is a fishery Activity which then leads to the Pressure of seabed abrasion caused by towed gear. It is then assumed that such abrasion would cause seabed habitat damage (e.g. a State change in the functional traits of the benthic community) which eventually leads to Impacts (on human Welfare) by reducing the fishable resource (see below). In turn, a Response (using management Measures), such as gear modifications or fishing-period limitation is needed to limit the Activities and hence minimise the Pressures.

The confusion between terms was noted in the otherwise important and seminal study by Halpern et al. (2008) giving the global analysis of 'human impact' on many marine ecosystems. This study listed 17 anthropogenic 'drivers' but, using the definitions here, these comprised 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 as defined above. The global analysis of Halpern et al. (2008) appears to map Activities (and possibly Pressures) but terms them 'impacts'—it is emphasised here that this should not be assumed as mitigation measures may stop Activities creating impacts. This also reinforces the point that it may be easier to map Activities, which are often recorded on maps, photographs and databases, than Pressures. The latter requires the need to detect the spatial and temporal effects-footprints of each Activity which are much more difficult to determine (Elliott et al. 2018). Many of the assessment schemes used worldwide focus on Activities instead of Pressures (Borja et al. 2016), presumably because of the difficulty in determining these effects-footprints. Here the linkage Framework methodologies (Culhane et al. 2020) can be valuable in understanding and untangling activities and their resultant pressures.

2.3 Pressures (P)

Each Activity leads to one or more Pressures and each Pressure can result from one or more Activity thereby creating an interlinked matrix of Activities and Pressures (see Culhane et al. 2020 for approaches to analysing such linkages, and Burdon et al. 2018 for a precise example). A Pressure is defined as the mechanism of change, first to the natural system (State changes) and then to the social system (Impacts (on human Welfare)) (see below). Elliott (2011) then separated the pressures affecting a given sea area into Exogenic Unmanaged Pressures (ExUP) and Endogenic Managed Pressures (EnMP) (Fig. 3). In this way, exerting pressures on the ecosystem will reduce ecosystem services and ultimately affect societal goods and benefits.

The cause of Exogenic Unmanaged Pressures, as the name suggests, emanates outside the area, for example sea-level rise as the result of global climate change, and so management inside the area is only treating the consequences (such as building higher sea defences) (Elliott et al. 2016). Management actions to address these pressures therefore has to be at the large scale and even global level (such as the Paris COP meetings). In contrast, Endogenic Managed Pressures, by definition, occur within the management area and so both their causes and consequences need managing and can be managed. For example, increased infrastructure such as a new bridge or power plant in an area will cause pressures whereby the reduction of their consequences need to be incorporated into a management plan. Hence the

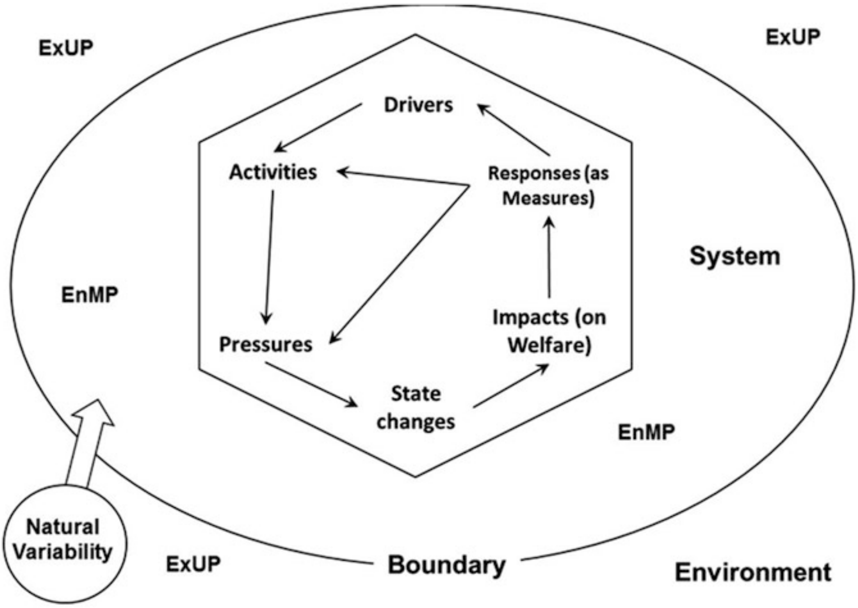

Fig. 3 The DAPSI(W)R(M) problem structuring framework (from Elliott et al. 2017). Key: ExUP = Exogenic Unmanaged Pressures; EnMP = Endogenic Managed Pressures (see text for explanation)

effects-footprints of all the endogenic pressures, both singly and cumulatively, need to be determined and managed in both space and time (Elliott et al. 2018).

2.4 State or State Changes (S)

In the original DPSIR framework, State, State change and Impact were often used interchangeably (Patrício et al. 2016) and often the natural scientists used State as the nature of the natural system and Impact as the change to the natural and social systems. In contrast, social scientists appear to have made the differentiation that State referred to the natural system and Impact referred to the social system. Because of this, the DAPSI(W)R(M) framework has used the term 'State change' (rather than 'State' as we are only interested in anthropogenic changes, i.e. a signal against a background of inherent variability ('noise')) to relate to the natural system (the ecology) due to single or multiple Pressures. This includes both the physico-chemical variables (i.e. sediment type, dissolved oxygen, organic matter, etc.) and biological health at all levels of organisation—the cellular system, individuals, populations, communities and ecosystems. Such changes can be referred to as structural characteristics (the features in each level at one time, for example the number of species in a community) or functioning variables (rate processes, such as productivity or ecosystem carbon flow) (Strong et al. 2015; de Jonge et al. 2003, 2012).

This then leads into the recent discussions regarding ecosystem services and societal goods and benefits which are derived from a healthy functioning natural system (Atkins et al. 2011; Turner and Schaafsma 2015). If the natural system has an appropriate structure and functioning then it is creating a healthy environment, for example if the waves, tides, substratum, etc. are appropriate then they will support the prey which sustains fishes (an ecosystem service). In turn, the natural State should provide the intermediate and final ecosystem services (as defined by Fisher et al. 2009, Turner and Schaafsma 2015, and Elliott et al. 2017) and human activities and pressures could then influence (in a positive or negative way) this natural state (i.e. State change) as well as the underlying marine ecosystem components and processes (Fig. 4, left hand side). The amount and fluxes of physical, chemical and biological materials may be regarded, in economic terms, as marine ecosystem stocks and flows which can be measured and which can have management targets and management measures to achieve those targets (Pinto et al. 2014; Atkins et al. 2015). In essence, the natural system can produce the ecosystem services but it then requires society to input 'human complementary assets' or 'human capital' (such as time, money, energy and skills) to extract societal goods and benefits ('*the sea can produce fish but we need to learn how to catch and cook them*'!) (Elliott et al. 2017).

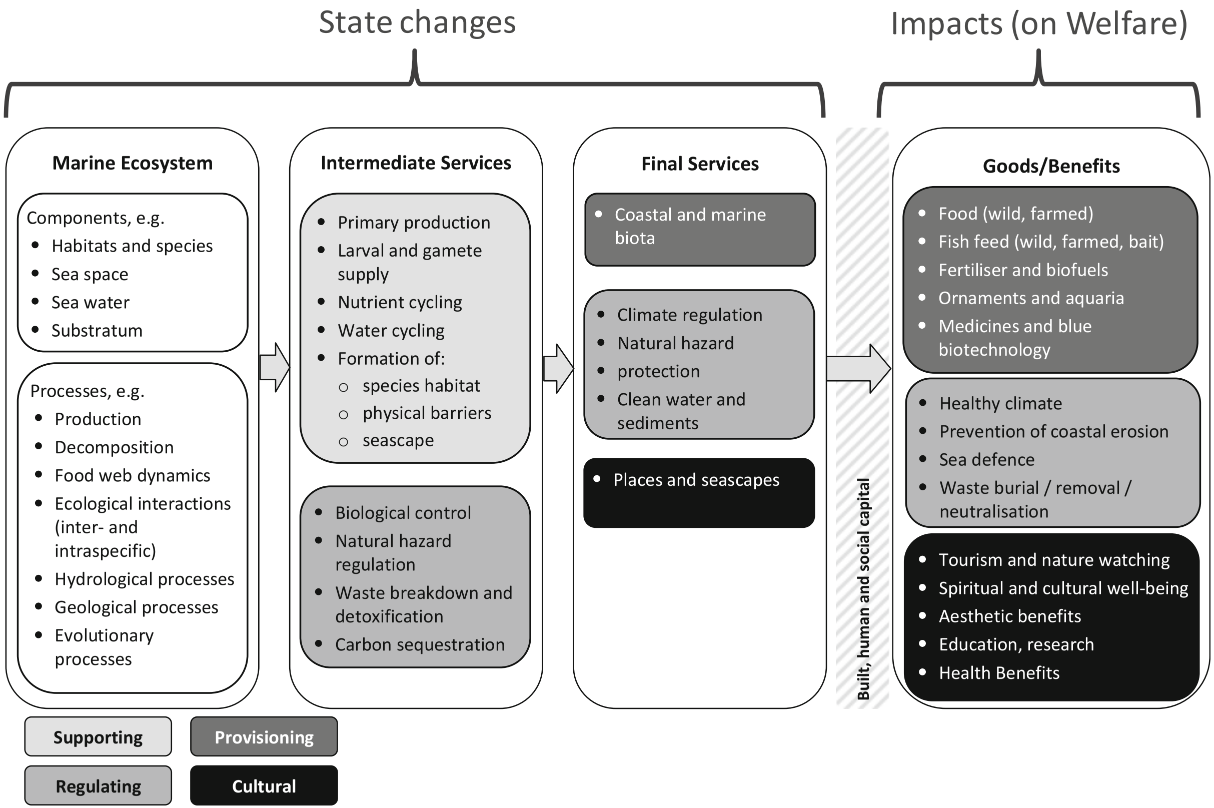

Fig. 4 State changes to the natural system reflected by changes in the marine ecosystem, intermediate and final ecosystem services (left hand side), and Impacts (on human Welfare) reflected by changes to the provision of Societal goods and benefits (right hand side) (modified and expanded from Turner et al. 2015)

2.5 Impact (I) (on Human Welfare)

Once the natural physico-chemical and ecological state has been changed by human activities and pressures then this could eventually influence the marine goods and benefits obtained by society. In DAPSI(W)R(M), this then is reflected as Impacts (on human Welfare). While Cooper (2013) changed the term 'Impact' to 'Welfare' this created a further confusion as it is the Impact *on* our Welfare that is of concern rather than Welfare *per se* (hence the use of parentheses). Hence, those Impacts (on Welfare) reflect the negative or even positive changes in the system providing societal goods and benefits (as defined by Turner et al. 2015, see below). Accordingly, it is necessary to derive and use quantitative indicators to detect and explain such changes in societal welfare (Fig. 5, right hand side). As indicated, societal goods and benefits are obtained by applying human complementary capital (social, human and human-made or built capital) to the natural environment (intermediate and final ecosystem services) (Atkins et al. 2011; Elliott et al. 2017). Therefore, any adverse Impacts on human Welfare are manifest as an inability of the marine system to provide those societal goods and benefits. For example, a healthy natural system is required to create natural places and seascapes which then influence our cultural appreciation of the sea. Society will then spend time and money to enjoy those benefits and, linking back to Maslow's work, this relies on us being sentient beings to appreciate the benefits—'*we need to expend energy to appreciate a blue whale even if we have never seen one*'!

The term Welfare in this element of DAPSI(W)R(M) also includes human well-being and happiness, two important Drivers in the upper part of Maslow's triangle.

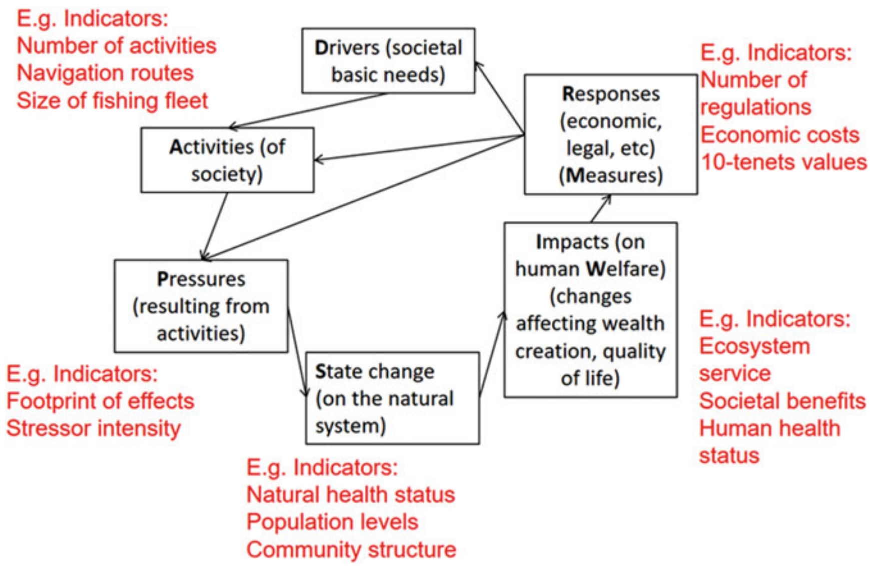

Fig. 5 Examples of indicators for each element of the DAPSI(W)R(M) framework

In addition, given the benefits that we extract from the sea and coastline, this part of the framework as the result of human Activities and Pressures reflects any adverse changes which affect Blue Growth and hence the Blue Economy as defined above. In addition, by adding complementary capital helps to identify the wider human and societal consequences, such as loss or gain in employment. In turn, such employment has a feedback loop to the Activities within the DAPSI(W)R(M) framework. As such, there is the need for operational indicators of the Impacts (on human Welfare) to show the impact of damaging Activities and Pressures assets valued by society (Turner and Schaafsma 2015). Some authors emphasise that changes in Welfare resulting from environmental state changes are the (environmental) costs which need to be traded against the benefits created by the Drivers in Cost-Benefit Analysis (Cooper 2013).

2.6 Response (R) (as Management Measures)

Marine management is dependent on a governance background in which governance relates to the marine policies, politics, administration and legislation (Boyes and Elliott 2014, 2015) as well as other management mechanisms such as economic instruments and technological developments. The management Responses which are required to overcome adverse effects on the natural and social systems (State Change and Impacts on human Welfare respectively) as the result of the Drivers, Activities and Pressures, then should include management Measures. The latter term is used as it appears widely in European Union Directives such as the MSFD and WFD (Borja et al. 2010).

From a regulatory perspective, Responses may be directed at any other element in the DAPSI(W)R(M) cycle but usually we measure the State change and Impacts (on human Welfare) but we use management. Measures to control the Drivers, Activities and Impacts (on human Welfare). A direct response to increasing Drivers might include curtailing economic or population growth. Responses may act on Activities through regulating the levels of activity (e.g. a ban on fishing) or on Pressures by reducing the levels of pressure resulting from a given level of activity (e.g. by modifying the type of fishing gear or employing mitigation and/or compensation). Restoration measures (replanting of saltmarsh, or stocking of fish) are ecoengineering Responses that acts directly on the State of the environment (Elliott et al. 2016). Compensation for environmental damage (for example following an oil spill) is of three types—to compensate the users (e.g. Responses directed at Impacts (on Welfare) of fishermen), the habitat (by habitat creation), or the resource (such as restocking and replanting)—the last two are management responses directed at rectifying State change.

There are many elements involved in defining successful and sustainable adaptive responses. Barnard and Elliott (2015) suggest 10-tenets for successful Measures—that our actions should be *ecologically sustainable, economically viable, technologically feasible, socially desirable/tolerable, administratively achievable, legally* *permissible, politically expedient, ethically defensible (morally correct), culturally inclusive* and *effectively communicated*. While directives and regulations may mandate specific measures and responses to a particular problem, the levels of Response to an environmental problem also depend on social and political perceptions of that problem. For example, increasing awareness of plastics in the marine environment has led to widespread public support, just as the protection of iconic species, the so-called charismatic megafauna, may resonate more easily with the public. However, detecting the problem is only the start of devising management measures (Borja and Elliott 2019).

All of the above relates to the natural and human-derived hazards in the environment and the way in which these become risks when they affect something which we value (Elliott et al. 2014), hence the DAPSI(W)R(M) framework becomes an integral part of a risk assessment and risk management framework (Cormier et al. 2019). However, it has to include adaptive management as in many cases the societal and management response to a particular event is unpredictable. For example the tsunami resulting from the exogenous unmanaged pressure of the 2011 earthquake off Japan and the resulting Fukishima nuclear disaster, resulted in sudden change in attitudes toward nuclear energy in Germany ultimately resulting in the sudden change of German nuclear energy policy (Strunz 2014).

As mentioned above, the elements in DPASI(W)R(M) framework are integral to the management of the seas. It is axiomatic that management cannot be achieved without measurement and that quantitative indicators are needed to determine the amount of each element and to determine whether the management has had the desired effect. Although Teixeira et al. (2016) shows the plethora of marine indicators in existence, Fig. 5 shows the types of indicators adopted for each of the elements.

Learning lessons from the evolution of DAPSI(W)R(M)—the evolving conceptual basis for EBM.

The description of the DAPSI(W)R(M) above illustrates how the simple DPSIR conceptual frame can be expanded, developed and applied to the MSFD. The evolution of DPSIR illustrates how information and concepts from different disciplines have informed the overall approach to analysis, as well as identifying and providing solutions to the problems of disciplinary silos in multidisciplinary research. The DPSIR and its successors (mDPSIR, DPSWR, and now DAPSI(W)R(M)) have for many European scientists and environmental managers been the basis of attempts to integrate our understanding of the ecological and social systems to develop an Ecosystem-Based Approach as mandated by the Directives. This has been a process of "learning by doing" (i.e. adaptive management *per se*) involving iterative improvement and refinement of the conceptual framework such that it now meets the regulatory needs of the Directives, and hence is embedded within the implementation process (European Commission 2017). Following three decades of interdisciplinary research, the framework has now been tailored to meet the requirements of the MSFD, integrating social and ecological information, linking cause-consequence-management, and providing an overarching frame for application and a standardisation of the Directive across European Member States.

The origins of DPSIR as a social environmental accounting framework and its application to a centralised European marine management policy have helped to elucidate, and overcome many of the conceptual difficulties with the practice of socio-ecological system research in the context of Europe-wide marine management. As a Framework Directive, the MSFD seeks to develop an Ecosystem Approach to management while also bringing together existing, more sectoral European marine environmental legislation including the Habitats & Species Directive (European Economic Community 1992) the Water Framework Directive (European Commission 2000) the legislation under the Common Fisheries policy amongst others. Hence while the implementation of the MSFD has developed rapidly since introduced in 2008 (e.g. Boyes et al. 2016), evidence for real improvements to the quality of European marine ecosystems is limited. There is increasing recognition that the sectoral policies for the environment and natural resource management within Europe are failing when it comes to the delivery of biodiversity objectives (Pe'er et al. 2019; O'Higgins 2017; Rouillard et al. 2018) and hence the requirement to develop more holistic approaches to European EBM (Lago et al. 2019). The question then arises, if one were to develop a conceptual framework for EBM *a priori*, what lessons can be learned from the DAPSI(W)R(M).

3 Standing on the Shoulders of Giants

Integration of social and ecological information relevant to stakeholders and managers is an essential component of any efforts which aim to remediate environmental impacts while reaching multiple policy goals. Such goals include those defined under EU Directives and strategies such as the WFD, the MSFD and the EU Biodiversity Strategy to 2020, and globally in the UNCED Sustainable Development Goals and various strategies are incorporated into different conceptual models to support EBM (Ogden 2005; Kelble et al. 2013). The first conceptual models, had a more environmental focus following the OECD pressure-state-impact (PSI). The Response dimension was added subsequently to incorporate policy responses, as in the PSR model (Gentile et al. 2001). In these first linear models, the entire social system was included in the 'Pressure' dimension and the ecological system under 'State'. These models gave little insight into the social processes that result in multiple pressures nor did they describe the entire management cycle. Furthermore, their conceptualisation of ecological systems was limited to the specific structural parameters described by the State term, rather than considering a comprehensive analysis of ecological processes and functions. The evolution of these model into DPSIR and its successors through to the DAPSI(W)R(M) resulted in a number of improvements.

Advances resulted from adding the basic human needs (anthropogenic 'Drivers') as the ultimate causes of ecosystem use and ecosystem change, incorporate a better understanding of the *raison d'etre* and functioning of the social system. Adding the

'Impact on (human Welfare)' dimension helped to provide deeper understanding of the consequences of human pressures on ecosystems (Sekowski et al. 2012). Finally, by incorporating the Response (using management Measures) these models have become important tools in the assessment of terrestrial, freshwater and marine ecosystems (e.g. Atkins et al. 2011; Tscherning et al. 2012; Kelble et al. 2013; Scharin et al. 2016).

This family of conceptual models has supported particular progress in the understanding and mainstreaming of impact pathways through which human activities affect the natural environment, both positively and negatively. However, many previous applications of the DPSIR have focussed on the single, pressures in a particular ecosystem. They are in danger of neglecting the simultaneously effects of multiple interacting pressures (Judd et al. 2015) and only rarely address the complexity associated with the assessment of multiple nested DPSIR causal chains running simultaneously (e.g. Atkins et al. 2011; Culhane et al. 2020). Burdon et al. (2018) shows the multiple links within these chains and the level of detail of the activities and pressures required by managers, in this case for oil and gas decommissioning. Hence there is the need for cumulative effects assessments which can accommodate the multiple activities, pressures, state changes and impacts on human welfare (Lonsdale et al. 2020).

All human activities occur within and are (directly or indirectly) entirely dependent on ecosystems (Boumans et al. 2002). The DPSIR models include information on the importance of nature for human welfare, i.e. integrating the linkage between ecosystem functions and ecosystem services and societal goods and benefits. Ecosystem services and societal goods and benefits are implicit in Maslow's (1943) hierarchy of needs. Within DAPSI(W)R(M), the link between ecosystem state change and human welfare is explicitly and negatively represented (generally by the costs, as economic externalities, in the cost-benefit analysis) (Fig. 3). While the importance of ecosystem services in assessing the human impacts of state changes has been recognised during the evolution of these models (see Fig. 4), it is not fully integrated within the model itself. Similarly, many of the indicators mentioned in Fig. 5 can be given monetary or other means of valuation.

As an extension of this, the 'Bow-tie' risk assessment and risk-management framework (Cormier et al. 2019) (Fig. 6) can then be merged with the DAPSI(W) R(M) framework. This shows that the central environmental concern (the red circle, a State change and/or Impact (on human Welfare)) has causes (the left-hand blue rectangles—the Drivers, Activities and Pressures) which in turn lead to consequences (the right-hand red boxes, also State changes and/or Impacts (on human Welfare)). The prevention, mitigation, compensation and adaptation controls then represent the Responses (using management Measures) (inserted between the causes and the consequences). In this sense, the model implicitly represents the centrality of the ecosystem in the production of human welfare and hence this aspect needs to be expanded to fully reflect EBM.

As a result, approaches based on the DPSIR need to incorporate feedback loops and cumulative forward and backward processes, hence favouring responses that are reactive and remedial rather than proactive and pre-emptive. Because of this, they

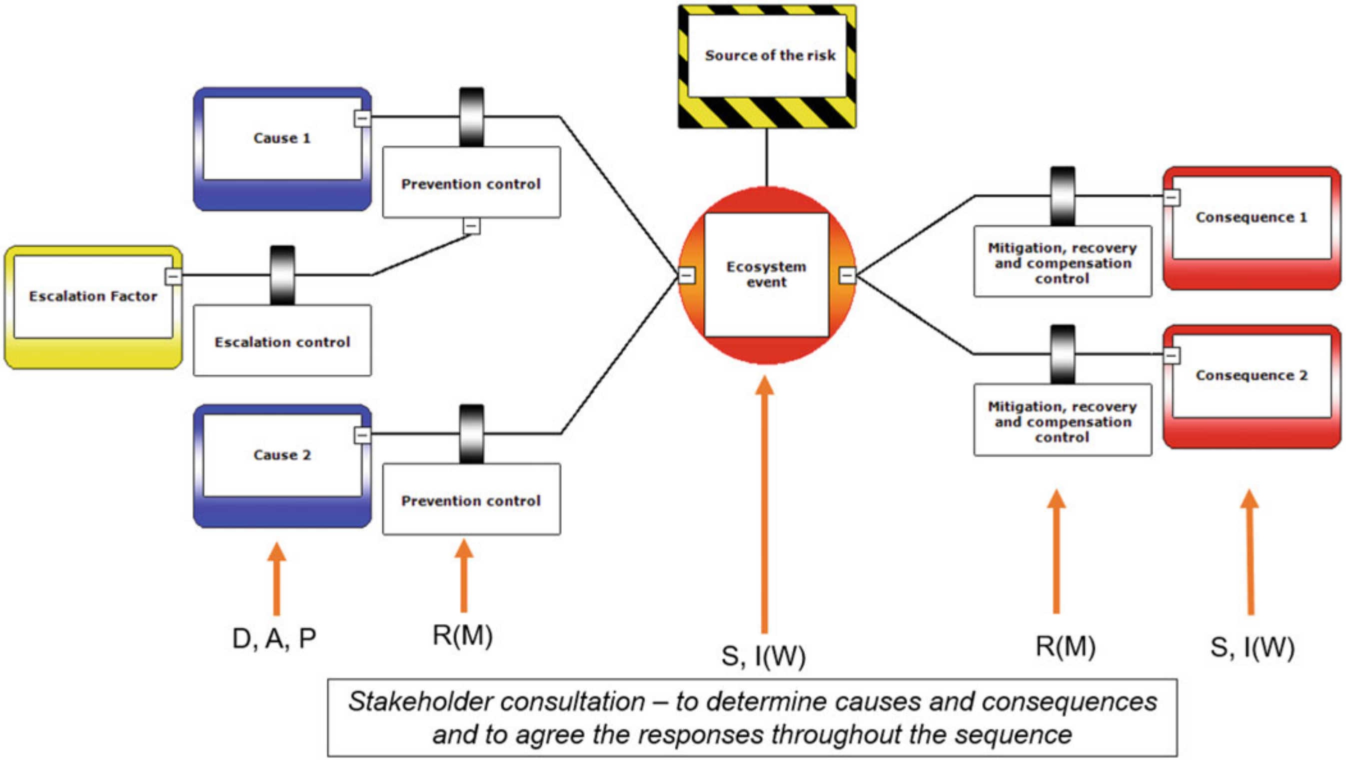

Fig. 6 A Bow-tie diagram (from Cormier et al. 2019, see text for explanation)

may be better suited to assess responses that reduce or modify pressures, regardless of how the socio-economic system and stakeholders adapt their decisions and behaviour and the drivers themselves of ecosystem change. Despite their adaptation to incorporate more fully social-ecological interactions, the causal chains of DAPSI (W)R(M) still reflect their origin in the field of environmental risk assessment. A geographic area and its management will thus need overlapping and interlinked DAPSI(W)R(M) cycles which also may need to be linked to similar cycles outside the immediate management area (see Elliott et al. 2017).

With the advent of the Ecosystem Approach in the 1990s, starting from the global Convention for Biological Diversity (see Enright and Boetler 2020 for a history of the term), the analysis of ecosystem services and their importance for human welfare and societal goods and benefits (Constanza et al. 1997; MEA 2003) shifted the perspective from "*what have we done to nature?*" towards "*what does nature do for us?*". This recognises the centrality of nature and ecosystems services in human well-being, a defining feature of EBM (Tallis et al. 2010). The ecosystem services approach led to a more comprehensive framework including economic perspectives and it called for more effective social action. This has led to new perspectives based upon the potential of ecosystems to provide society with the valuable goods and services they demand and to new conceptual frameworks to integrate these new concepts based on the previous DPSIR (Turner 2000; Cheong 2008; Weinstein 2009) leading to the DAPSI(W)R(M) described above. Ecosystem services and the resulting societal goods and benefits provided the missing analytical block to proceed from the biophysical to the human dimensions of science. Ecosystem services and the resulting societal goods and benefits are the main and most welfare-relevant outcomes from the interaction of social and ecological systems. Therefore, linking ecological and social systems to human welfare (and the goods and benefits it demands) through the notion of ecosystem services is essential to understand and assess the multiple trade-offs involved in individual and collective decisions in a clear and consistent manner and to the development of an EBM conceptual framework.

Ecosystem services and societal goods and benefits are the key emerging outcomes of the interaction between ecological and socio-economic systems (Biggs et al. 2012). They are ‘produced’ and delivered by ecosystems but are also continually shaped by their interaction with socio-economic systems and, in the case of societal goods and benefits, require an input of human capital in order to be realised. They may also favour detrimental, transformative or restorative processes (Biggs et al. 2015). Human actions and institutions shape ecosystem structures, processes and services in landscapes or seascapes by management and uses/users, which in turn shape human behaviour and institutional settings.

The integration of both traditions, impact pathway analysis and the ecosystem services/societal goods and benefits approach, has fostered the emergence of a growing number of alternative socio-ecological system analytical frameworks (Binder et al. 2013). Nevertheless, their success and their capacity for the smooth integration of knowledge may have been impaired by the mismatch resulting from mixing pieces created from slightly different conceptual directions and for different purposes. To some extent, both approaches share the drawbacks of common practice and may only offer a partial view of the complex links between the relevant and important parts of social and ecological systems.

In attempting to define a conceptual framework specifically for the analysis and design of EBM, there is a clear need to reflect the central nature of ecosystem services, the resulting delivery of societal goods and benefits and the costs and benefits of enhancing natural assets or ecosystems to improve resilience and adaptability. Hence there is the need conceptually to represent how ecosystems function in connection with the socio-economic system, delivering ecosystem services and contributing to social goods, benefits and welfare.

4 The Butterfly

Taking the valuable lessons learned through the application of the DPSIR/DAPSI(W)R(M) framework, we seek to develop a transferable framework with the aim of developing, a-priori, a more holistic methodological approach to implementing Ecosystem-Based Management. This is illustrated in the 'Butterfly' diagram (Fig. 7) (see Gómez et al. 2016 for the full explanation).

Two sets of relationships between humans and nature are implicit in the cyclic DAPSI(W)R(M). Drivers are dependent on the supply of ecosystem services and societal goods and benefits (see Maslow's hierarchy of Basic Human Needs above). In turn, these Drivers (through human Activities) cause Pressures and changes in environmental State altering the supply of ecosystems services. In turn, those State changes influence the Impacts (on human Welfare). These links can readily be conceptualised as supply (from nature) and demand (by humans) for ecosystem services and societal goods and benefits.

The supply side (Fig. 7, shown in blue) involves the links between ecosystems and human Welfare. In DAPSI(W)R(M), this is conceptualised as the (cost-benefit) feedback between Impacts on human Welfare and Drivers. The second set of relationships, 'the demand side' (Fig. 7, shown in yellow), refers to how social systems shape and change ecosystems (the links between Drivers and Activities to Pressures and then State changes). These are connected to each other through complex adaptive processes taking place in ecological and social systems.

The supply-side relationship goes from the ecological to the social system. It represents the potential of ecosystems to supply and effectively deliver ecosystem services to the social system, from which it gets goods and benefits. It includes the capacity of the social system to transform those services delivered into benefits for society through human built, financial and social capital (Fig. 3). This is all contingent on the ecosystem structure and on those processes/functioning taking place in the biophysical system from which ecosystem services lead to the most socially relevant outcomes.

The demand-side relationship goes from the social to the ecological system. It represents and explains the demand and the effective use of ecosystem services and

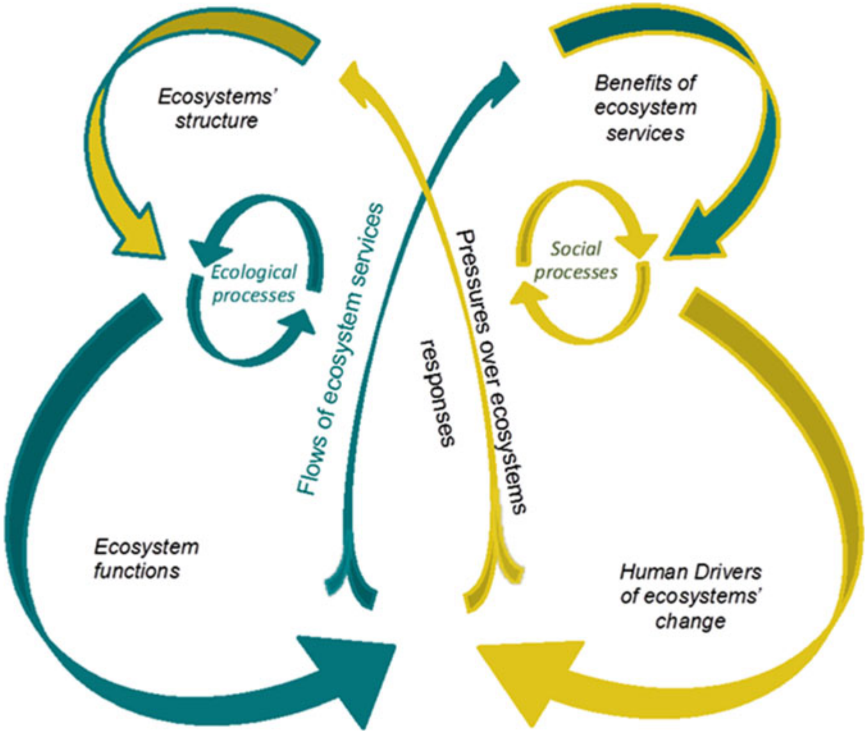

Fig. 7 The butterfly diagram, a new model for the assessment and design of Ecosystem-Based Management. Supply side is shown in blue, demand side is shown in yellow

the impacts on ecosystems. The demand for ecosystem services (and in turn goods and benefits) depends on income, tastes, technology, institutions, and other social and economic factors. Beyond pressures on ecosystems, this demand-side relationship also considers social and individual decisions towards protecting and restoring ecosystems in order to preserve their benefits depending on the governance institutions in place. Hence the need for the ten-tenets of sustainable ecosystem management which can incorporate all the facets of that management, both the natural and the societal. These more fully represent the variety of social processes by which society adapts to manage specific environmental and social conditions (Ostrom 1990) including new types of social innovation (Schor and Thomson 2014), going beyond Responses (and management Measures). This may be best suited to governance or economic instruments, best available technologies, cultural demands, etc. as summarised by the 10-tenets (Barnard and Elliott 2015).

5 Conclusions

Here we present the DAPSI(W)R(M) framework, the latest iteration of the well-known and widely-applied DPSIR framework, as an environmental risk management tool. We draw on advances over the past 3 decades in the analysis of socio-ecological systems, and now include elements such as ecosystem services and societal goods and benefits as well as more a holistic conception of Drivers. However, we emphasise that the causal chain mechanism (of cause-consequence-management) needs to be ideally suited to the cyclical application of adaptive management required under the framework of European environmental directives. The derived system has to fully incorporate the wealth of social and ecological process that result in the dynamics of supply and demand for ecosystem services and the resulting societally goods and benefits, the most socially relevant outputs from ecosystems. The Butterfly enhances the inherited conceptual framework of DAPSI (W)R(M). The Butterfly conceptual framework has been systematically tested through a suite of case studies in aquatic biodiversity management from freshwater rivers (Domisch et al. 2019) and lakes to estuarine and marine systems, some examples of which are presented in this volume (Piet et al. 2020, O'Higgins et al. 2020; Lillebø et al. 2020; Funk et al. 2020).

The ability to meet the predominant aim of satisfying Ecosystem-Based Management, covering both natural and social systems, requires the analysis of socio-ecological systems enabled by the cause-consequence-response chain, and the relationship to European (and other) environmental policies. The widely acknowledged biodiversity and climate crises requires holistic management approaches such as EBM which can then be translated into the supply and demand for ecosystem services and societal goods and benefits at the centre of the Butterfly conceptual framework.

References

Al Kalbani, M. S., Price, M. F., O'Higgins, T., Ahmed, M., & Abahussain, A. (2015). Integrated environmental assessment to explores water resources management in Al Jabla Al Akhdar, Sultanate of Oman. *Regional Environmental Change, 5*, 1345–1361.

Atkins, J. P., Burdon, D., Elliott, M., & Gregory, A. J. (2011). Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Marine Pollution Bulletin, 62*, 215–226.

Atkins, J. P., Burdon, D., & Elliott, M. (2015). Identification of a practicable set of ecosystem indicators for coastal and marine ecosystem services. In R. K. Turner & M. Schaafsma (Eds.), *Coastal zones ecosystem services: From science to values and decision making*. Cham: Springer.

Barnard, S., & Elliott, M. (2015). The 10-tenets of adaptive management and sustainability – Applying an holistic framework for understanding and managing the socio-ecological system. *Environmental Science & Policy, 51*, 181–191.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., Dakos, V., et al. (2012). Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources, 37*(1), 421–448.

Biggs, R., Schlüter, M., & Schoon, M. L. (2015). An introduction to resilience approach and principles to sustain ecosystem services. In *Principles for building resilience. Sustaining ecosystem services in social-ecological systems* (pp. 1–31). Cambrige University Press.

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society, 18*(4), 26.

Borja, A., Galparsoro, I., Solaun, O., Muxika, I., Tello, E. M., Uriarte, A., & Valencia, V. (2006). The European Water Framework Directive and the DPSIR, a methodological approach to assess the risk of failing to achieve good ecological status. *Estuarine, Coastal and Shelf Science, 66*, 84–96.

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A.-S., & van de Bund, W. (2010). Marine management – Towards an integrated implementation of the European Marine strategy framework and the water framework directives. *Marine Pollution Bulletin, 60*, 2175–2186.

Borja, A., Elliott, M., Snelgraove, P. V. R., Austen, M. C. V., Berg, T., Cochrane, S., Cartensen, J., Danovaro, R., Greenstreet, S., Heiskannen, A.-S., Lynam, C. P., Mea, M., Newton, A., Particio, J., Uusitalo, L., Uyarra, M. C., & Wilson, C. (2016). Bridgin the gap between policy and science in assessing the health status of marine ecosystems. *Froniers in Marine Science*. https://doi.org/10.3389/fmars.2016.00175.

Borja, A., & Elliott, M. (2019). Editorial – So when will we have enough papers on microplastics and ocean litter? *Marine Pollution Bulletin, 146*, 312–316.

Boumans, R., Costanza, R., Farley, J., Wilson, M. A., Portela, R., Rotmans, J., Villa, F., & Grasso, M. (2002). Modeling the dynamics of the integrated earth system and the value of global ecosystem services using the GUMBO model. *Ecological Economics, 41*, 529–560.

Boyes, S. J., & Elliott, M. (2015). The excessive complexity of national marine governance systems – Has this decreased in England since the introduction of the Marine and Coastal Access Act 2009? *Marine Policy, 51*, 57–65. https://doi.org/10.1016/j.marpol.2014.07.019.

Boyes, S. J., & Elliott, M. (2014). Marine legislation – The ultimate ‘horrendogram’: International Law, European Directives & National Implementation. *Marine Pollution Bulletin, 86*(1–2), 39–47. https://doi.org/10.1016/j.marpolbul.2014.06.055.

Boyes, S. J., Elliott, M., Murillas-Maza, A., Papadopoulou, N., & Uyarra, M. C. (2016). Is existing legislation fit-for-purpose to achieve good environmental status in European seas? *Marine Pollution Bulletin, 111*, 18–32. https://doi.org/10.1016/j.marpolbul.2016.06.079.

Burdon, D., Barnard, S., Boyes, Elliott, M (2018). Oil and gas infrastructure decommissioning in marine protected areas: System complexity, analysis and challenges. Marine Pollution Bulletin, 135: 739–758.

Cheong, S.-M. (2008). A new direction in coastal management. *Marine Policy, 32*, 1090–1093.

Constanza, R., d’Arge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O’Neill, R. V., Paruelo, J., Raskin, G. R., Sutton, P., & Van den Belt, M. (1997). The value of the world’s ecosystem services and natural capital. *Nature, 387*, 253–260.

Cooper, P. (2013). Socio-ecological accounting: DPSWR, a modified DPSIR framework, and its application to marine ecosystems. *Ecological Economics, 94*, 106–115. https://doi.org/10.1016/j.ecolecon.2013.07.010.

Cormier, R., Elliott, M., & Rice, J. (2019). Putting on a bow-tie to sort out who does what and why in the complex arena of marine policy and management. *Science of the Total Environment, 648*, 293–305. https://doi.org/10.1016/j.scitotenv.2018.08.168.

Culhane, F. E., Robinson, L. A., & Lillebø, A. I. (2020). Approaches for estimating the supply of ecosystem services: concepts for ecosystem-based management in coastal and marine environments. In T. O’Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 105–126). Amsterdam: Springer.

de Jonge, V. N., Kolkman, M. J., Ruijgrok, E. C. M., & de Vries, M. B. (2003). *The need for new paradigms in integrated socio-economic and ecological coastal policy making*. Proceedings of 10th International Wadden Sea Symposium, 247–270, Ministry of Agriculture, Nature Management and Fisheries, Department North, Groningen (272 pp.)

de Jonge, V. N., Pinto, R., & Turner, R. K. (2012). Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' 'ecosystem approach'. *Ocean and Coastal Managagement, 68*(2012), 169–188.

Delacámara, G., O'Higgins, T., Lago, M., & Langhans, S. (2020). Ecosystem-based management: Moving from concept to practice. In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 39–60). Amsterdam: Springer.

Domisch, S., Kakouei, K., Martínez-López, J., Bagstad, K. J., Magrach, A., Balbi, S., Villa, F., et al. (2019). Social equity shapes zone-selection: Balancing aquatic biodiversity conservation and ecosystem services delivery in the transboundary Danube River Basin. *Science of the Total Environment, 656*, 797–807.

EEA. (1999). *Environmental indicators: Typology and overview*. Technical report No. 25, Copenhagen: European Environment Agency.

Elliott, M. (2011). Marine science and management means tackling exogenic unmanaged pressures and endogenic managed pressures – A numbered guide. *Marine Pollution Bulletin, 62*, 651–655.

Elliott, M., Burdon, D., Atkins, J. P., Borja, A., Cormier, R., de Jonge, V. N., & Turner, R. K. (2017). "And DPSIR begat DAPSI(W)R(M)!" – A unifying framework for marine environmental management. *Marine Pollution Bulletin, 118*(1–2), 27–40. https://doi.org/10.1016/j.marpolbul.2017.03.049.

Elliott, M., Cutts, N. D., & Trono, A. (2014). A typology of marine and estuarine hazards and risks as vectors of change: A review for vulnerable coasts and their management. *Ocean & Coastal Management, 93*, 88–99.

Elliott, M., Mander, L., Mazik, K., Simenstad, C., Valesini, F., Whitfield, A., & Wolanski, E. (2016). Ecoengineering with Ecohydrology: Successes and failures in estuarine restoration. *Estuarine, Coastal and Shelf Science, 176*, 12–35. https://doi.org/10.1016/j.ecss.2016.04.003.

Elliott, M., Boyes, S. J., Barnard, S., & Borja, Á. (2018). Using best expert judgement to harmonise marine environmental status assessment and maritime spatial planning. *Marine Pollution Bulletin, 133*, 367–377.

Enright, S. R., & Boetler, B. (2020). The ecosystem approach in international law. In T. O'Higgins, M. Lago and & T.H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 333–352). Amsterdam: Springer.

European Commission. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community actions in the field of water policy. Official Journal of the European Communities L327, 1.22.12.2000.

European Commission. (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for Community actions in the field of marine environmental policy (Marine Strategy Framework Directive). Official Journal of the European Communities L164/19 25.06.2008.

European Commission. (2012). Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. Blue Growth opportunities for marine and maritime sustainable growth. Brussels, 13.9.2012 COM(2012) 494 final.

European Commission. (2017). Commission Directive 2017/845 amending Directive 2008/56/EC of the European Parliament and of the Council as regards the indicative lists of elements to be taken into account for the preparation of marine strategies. L 125/27.

European Economic Community. (1992). Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal of the EEC. 1992; L206/7 1.

Fisher, B., Turner, R. K., & Morling, P. (2009). Defining and classifying ecosystem services for decision making. *Ecological Economics, 68*, 643–653. https://doi.org/10.1016/j.ecolecon.2008.09.014.

Funk, A., O'Higgins, T. G., Borgwardt, F., Trauner, D., & Hein, T. (2020). Ecosystem-based management to support conservation and restoration efforts in the Danube Basin. In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 431–444). Amsterdam: Springer.

Gentile, J. H., Harwell, M. A., Cropper, W., Harwell, C. C., DeAngelis, D., Davies, S., Ogen, J. C., & Lirman, D. (2001). Ecological conceptual models: A framework and case study on ecosystem management for South Florida sustainability. *Science of the Total Environment, 274*, 251–253.

Gómez, C. M., Delacámara, G., Arévalo-Torres, J., Barbière, J., Barbosa, A. L., Boteler, B, Culhane, F., et al. (2016). The AQUACROSS innovative concept. Deliverable 3.1, European Union's Horizon 2020 Framework Programme for Research and Innovation grant agreement No. 642317.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M., Perry, M. T., Selig, E. R., Spalding, M., Steneck, R., & Watson, R. (2008). A global map of human impact on marine ecosystems. *Science, 319*, 948–952.

Judd, A. D., Backhaus, T., & Goodsir, F. (2015). An effective set of principles for practical implementation of marine cumulative effects assessment. *Environmental Science and Policy, 54*, 254–262.

Karageorgis, A. P., Skourtos, M. S., Kapsimalis, V., Kontogianni, A. D., Skoulikidis, N. T., Pagou, K., et al. (2005). An integrated approach to watershed management within the DPSIR framework: Axios River catchment and Thermaikos Gulf. *Regional Environmental Change, 5*, 138–160. https://doi.org/10.1007/s10113-004-0078-7.

Kelble, C. R., Loomis, D. K., Lovelace, S., Nuttle, W. K., Ortner, P. B., Fletcher, P., et al. (2013). The EBM-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. *PLoS One, 8*, e70766. https://doi.org/10.1371/journal.pone.0070766.

Knudsen, S., Zengin, M., & Koçak, M. H. (2010). Identifying drivers for fishing pressure. A multidisciplinary study of trawl and sea snail fisheries in Samsun, Black Sea coast of Turkey. *Ocean and Coastal Management, 53*, 252–269. https://doi.org/10.1016/j.ocecoaman.2010.04.008.

Lago, M., Boteler, B., Rouillard, J., Abhold, K., Jähnig, S. C., Iglesias-Campos, A., et al. (2019). Introducing the H2020 AQUACROSS project: Knowledge, assessment, and management for AQUAtic Biodiversity and Ecosystem Services aCROSS EU policies. *Science of the Total Environment, 652*, 320–329.

Langhans, S. D., Domisch, S., Balbi, S., Delacámara, G., Hermoso, V., Kuemmerlen, M., Martin, R., Martinez-Lopez, J., Vermeiren, P., Villa, F., & Jähnig, S. C. (2019). Combining eight research areas to foster the uptake of ecosystem-based management in fresh waters. *Aquatic Conservation: Marine and Freshwater Ecosystems, 297*, 1161–1173.

Langmead, O., McQuatters-Gollop, A., Mee, L. D., Friedrich, J., Gilbert, A. J., Gomoiu, M.-T., Jackson, E. L., Knudsen, S., Minicheva, G., & Todorova, V. (2009). Recovery or decline of the northwestern Black Sea: A societal choice revealed by socio-ecological modelling. *Ecological Modelling, 220*, 2927–2939. https://doi.org/10.1016/j.ecolmodel.2008.09.011.

Lillebø, A. I., Teixeira, H., Martínez-López, J., Genua-Olmedo, A., Marhubi, A., Delacámara, G., Mattheiß, V., Strosser, P., O'Higgins, T., & Nogueira, A. A. J. (2020). Mitigating negative unintended impacts on biodiversity in the Natura 2000 Vouga estuary (Ria de Aveiro, Portugal). In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 461–498). Amsterdam: Springer.

Lonsdale, J. A., Nicholson, R., Judd, A., Elliott, M., & Clarke, C. (2020). A novel approach for cumulative impacts assessment for marine spatial planning. *Environmental Science & Policy, 106*, 125–135.

Lovecraft, A. L., & Meek, C. L. (2019). Arctic Coastal systems: Evaluating the DAPSI(W)R(M) framework. In E. Wolanski et al. (Eds.), *Coasts and estuaries: The future*. Elsevier. https://doi.org/10.1016/B978-0-12-814003-1.00039-3.

Lundberg, C. (2005). Conceptualizing the Baltic Sea ecosystem: An interdisciplinary tool for environment decision making. *Ambio, 34*, 433–439. https://doi.org/10.1579/0044-7447-34.6.433.

Maslow, A. H. (1943). A theory of human motivation. *Psychological Review, 50*(4), 370–396.

Maslow, A. H. (1970a). *Motivation and personality* (2nd ed.). New York: Harper and Row.

Maslow, A. H. (1970b). *Religions, values, and peak experiences*. New York: Penguin.

Maxim, L., Spangenberg, J. H., & O'Connor, M. (2009). An analysis of risks for biodiversity under the DPSIR framework. *Ecological Economics, 69*, 12–23.

McDonald, H., Hoffman, H., Ressurreição, A., Röschel, L., Gerdes, H., Lago, M., Boetler, B., & McFarland, K. (2020). Ecosystem-based management for more effective and equitable marine protected areas: A case study on the Faial-Pico channel marine protected area, Azores. In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 499–516). Amsterdam: Springer.

Millennium Ecosystem Assessment (MEA). (2003). *Ecosystems and human well-being: A framework for assessment*. Washington, DC: Island Press.

Mee, L., Cooper, P., Kannen, A., Gilbert, A. J., & O'Higgins, T. (2015). Sustaining Europe's seas as coupled social-ecological systems. *Ecology and Society, 20*(1), 1. https://doi.org/10.5751/ES-07143-200101.

Ogden, J. C. (2005). Everglades ridge and slough conceptual ecological model. *Wetlands, 25*, 810–820.

O'Hagan, A. M. (2020). Ecosystem-based management (EBM) and ecosystem services in EU law, policy and governance. In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management and ecosystem services: Theory, tools and practice* (pp. 353–372). Amsterdam: Springer.

O'Higgins, T. G. (2017). You can't eat biodiversity: Agency and irrational norms in European aquatic environmental law. *Challenges in sustainability, 5*, 43–51.

O'Higgins, T. G., & Gilbert, A. J. (2014). Embedding ecosystem services into the Marine Strategy Framework Directive: Illustrated by eutrophication in the North Sea. *Estuarine Coastal and Shelf Science, 140*, 146–152.

O'Higgins, T. G., Cooper, P., Roth, E., Newton, A., Farmer, A., Goulding, I., & Tett, P. (2014). Temporal constraints on ecosystem management: Definitions and examples from Europe's regional seas. *Ecology and Society, 19*(3).

O'Higgins, T. G., Alexander, K. A., & Graziano, M. (2019). Mismatches in spatial scale of supply and demand and their consequences for local welfare in Scottish aquaculture. *Anthropocene Coasts, 2*, 261–278.

O'Higgins, T. G., Culhane, F., O'Dwyer, B., Robinson, L., & Lago, M. (2020). Combining methods to establish potential management measures for invasive species *Elodea nutallii* in Lough Erne Northern Ireland. In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 445–460). Amsterdam: Springer.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge: Cambridge University Press.

Patrício, J., Elliott, M., Mazik, K., Papadopoulou, K.-N., & Smith, C. J. (2016). DPSIR – Two decades of trying to develop a unifying framework for marine environmental management? *Frontiers in Marine Science, 3*, 177. https://doi.org/10.3389/fmars.2016.00177.

Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A., Hansjürgens, B., Lomba, A., Möckel, S., Passoni, G., Schleyer, C., Schmidt, J., & Lakner, S. (2019). A greener path for the EU common agricultural policy. *Science, 365*(6452), 449–451. https://doi.org/10.1126/science.aax3146.

Piet, G., Delacamara, G., Kraan, M., Röckmann, G. C., & Lago, M. (2020). Advancing aquatic ecosystem-based management with full consideration of the social-ecological system. In T. O'Higgins, M. Lago, & T. H. DeWitt (Eds.), *Ecosystem-based management, ecosystem services and aquatic biodiversity: Theory, tools and applications* (pp. 17–38). Amsterdam: Springer.

Pinto, R., da Conceição Cunha, M., Roseata-Palma, C., & Marques, J. C. (2014). Mainstreaming sustainable decision making for ecosystem: Integrating ecological and social-economic targets with a decision support system. *Environmental Processes, 1*, 7–19.

Rapport, D., & Friend, A. (1979). *Towards a comprehensive framework for environmental statistics: A stress-response approach*. Statistics Canada Catalogue 11–510. Ottawa: Minister of Supply and Services Canada.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature, 461*, 472–475.

Rouillard, J., Lago, M., Abhold, K., Roschel, L., Kafaeyke, T., Mattheiss, V., & Klimmek, H. (2018). Protecting aquaticbiodiversity in Europe: How much do EU environmental policies support ecosystem-based management? *Ambio, 47*, 15–24. https://doi.org/10.1007/s13280-017-0928-4.

Scharin, H., Ericsdotter, S., Elliott, M., Turner, R. K., Niiranen, S., Rockström, J., Blenckner, T., Hyytiäinen, K., Ahlvik, L., Heini Ahtiainen, H., Artell, J., Hasselström, L., & Söderqvist, T. (2016). Processes for the sustainable stewardship of marine environments. *Ecological Economics., 128*, 55–67.

Schor, J. B., & Thomson, C. J. (2014). *Sustainable lifestyles and the quest for plentitude* (p. 280). Connetticut: Yale University Press.

Sekowski, I., Newton, A., & Dennison, W. C. (2012). Megacities in the coastal zone: Using a driver-pressure -state-impact-response framework to address complex environmental problems. *Estuarine Coastal and Shelf Science, 96*, 48–59.

Skoulikidis, N. T. (2009). The environmental state of rivers in the Balkans a review within the DPSIR framework. *Science of the Total Environment, 407*, 2501–2516.

Stojanovic, T. A., & Farmer, C. J. Q. (2013). The development of world oceans and coasts and concepts of sustainability. *Marine Policy, 42*, 157–165.

Strong, J. A., Andonegi, E., Bizsel, K. C., Danovaro, R., Elliott, M., Franco, A., Garces, E., Little, S., Mazik, K., Moncheva, S., Papadopoulou, N., Patrício, J., Queirós, A. M., Smith, C., Stefanova, K., & Solaun, O. (2015). Marine biodiversity and ecosystem function relationships: The potential for practical monitoring applications. *Estuarine Coastal Shelf Science, 161*, 46–64.

Strunz, S. (2014). The German energy transition as a regime shift. *Ecological Economics, 100*, 150–158.

Tallis, H., Levin, P. S., Ruckelhaus, M., Lester, S. E., McLeod, K. L., Fluharty, D. L., & Halpern, B. S. (2010). The many faces of ecosystem-based management: Making the process work today in real places. *Marine Policy, 34*(2), 340–348. https://doi.org/10.1016/j.marpol.2009.08.003.

Teixeira, H., Berg, T., Uusuatalo, L., Furhapter, K., Hesikanen, A.-S., Mazik, K., Lynam, C. P., Neville, S., Rodriguez, J. R., Papadopaulou, N., Moncheva, S., Churilova, T., & m Kryvenko, O., Krause-Jensen, D., ZZaiko, A., Verissimo, H., Pantazi, M., Cravalho, S., Particio, J., Uyarra, M.C., and Borja, A. (2016). A catalogue of marine biodiversity indicators. *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2016.00207.

Tscherning, K., Helming, K., Krippner, B., Sieber, S., & Gomez y Paloma, S. (2012). Does research applying the DPSIR framework support decision making? *Land Use Policy, 29*, 102–110. https://doi.org/10.1016/j.landusepol.2011.05.009.

Turner, R. K. (2000). Integrating natural and socio-economic science in coastal management. *Journal of Marine Systems, 25*, 447–460.

Turner, R. K., & Schaafsma, M. (Eds.). (2015). Coastal zones ecosystem services: From science to values and decision making. In *Springer ecological economic series*. London: Springer.

UNSD. (2012). System of environmental-economic accounting, Central Framework. New York: United Nations Statistical Division.

Weinstein, M. P. (2009). The road ahead: The sustainability transition and coastal research. *Estuaries and Coasts, 32*, 1044–1053.