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Viewpoint

Force majeure: Will climate change affect our ability to attain Good Environmental Status for marine biodiversity?

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ABSTRACT

The EU Marine Strategy Framework Directive (MSFD) requires that Good Environmental Status (GEnS), is achieved for European seas by 2020. These may deviate from GEnS, its 11 Descriptors, targets and baselines, due to *endogenic managed pressures* (from activities within an area) and externally due to *exogenic unmanaged pressures* (e.g. climate change). Conceptual models detail the likely or perceived changes expected on marine biodiversity and GEnS Descriptors in the light of climate change. We emphasise that marine management has to accommodate '*shifting baselines*' caused by climate change particularly during GEnS monitoring, assessment and management and '*unbounded boundaries*' given the migration and dispersal of highly-mobile species. We suggest climate change may prevent GEnS being met, but Member States may rebut legal challenges by claiming that this is outside its control, *force majeure* or due to 'natural causes' (Article 14 of the MSFD). The analysis is relevant to management of other global seas.

1. Introduction

Integrated marine management, conservation and protection must maintain and protect the natural structure and functioning while at the same time ensure that the seas deliver the benefits required by society (Elliott, 2011). This should accommodate many local activities and pressures, those emanating from inside the sea area being managed, and wider pressures, such as global climate change, emanating from outside the area. The European Marine Strategy Framework Directive (MSFD, 2008/56/EC; European Commission, 2008) aims to ensure that through the measures and monitoring performed by the EU Member States, that Good Environmental Status (GEnS) will be achieved for European seas by 2020 (e.g. Borja et al., 2013a) (NB, the acronym GEnS is used here following Mee et al., 2008 and Borja et al., 2010a, to be differentiated from Good Ecological Status (GEcS) *à la* the EU Water Framework Directive, WFD 2000/60/EC; European Commission, 2000). GEnS is defined according to a set of 11 Descriptors (as different components of environmental status, Tables S1 and S2 (Supplementary Material)) and their component 29 Criteria (Table S1). The Descriptors and Criteria will then be deemed to have been met according to a set of 56 indicators and whether these achieve a set of targets (i.e. quality objectives, or reference conditions), selected by the European Commission (2010) (see also Borja et al., 2013b and Cardoso et al., 2010).

Borja et al. (2013a) propose the operational definition that: '*GEnS is achieved when physico-chemical (including contaminants, litter and noise) and hydrographical conditions are maintained at a level where the structuring components of the ecosystem are present and functioning, enabling the system to be resistant (ability to withstand stress) and resilient (ability to recover after a stressor) to harmful effects of human pressures/activities/impacts, where they maintain and provide the ecosystem services that deliver societal benefits in a sustainable way (i.e. that pressures associated with uses cumulatively do not hinder the ecosystem components in order to retain their natural diversity, productivity and dynamic ecological processes, and where recovery is rapid and sustained if a use ceases)*'.

All regional seas, their catchments and the adjacent areas will be affected by climate change (Cheung et al., 2013a, 2013b; Poloczanska et al., 2013; Stocker et al., 2013; Frost et al., in press), one of many stressors in a wider typology of marine hazards and risks (Elliott et al., 2014). Conceptual models derived here show the dominant pathways, causes and consequences of climate

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change on the marine system and their link to the MSFD elements used to assess environmental status and functioning. These indicate the ways in which climate change could compromise achieving GEnS for the Descriptors which are referred to throughout by their numbers: (1) Biological diversity; (2) non-indigenous species; (3) exploited fish and shellfish; (4) food webs; (5) human-induced eutrophication; (6) seafloor integrity; (7) hydrographical integrity; (8) contaminants; (9) contaminants in seafood; (10) litter and (11) energy and noise. Each Descriptor except D7 was the subject of an international Task-team: D1 – Cochrane et al. (2010); D2 – Olenin et al. (2010); D3 – Piet et al. (2010); D4 – Rogers et al. (2010); D5 – Ferreira et al. (2010); D6 – Rice et al. (2010); D8 – Law et al. (2010); D9 – Swartenbroux et al. (2010); D10 – Galgani et al. (2010); D11 – Tasker et al. (2010). Given their interlinked nature, this review considers all Descriptors but focuses on the biodiversity Descriptors (1, 2, 4 and 6), although it is argued that if the Descriptor 1 is satisfactory then, by definition, so will be the other Descriptors and vice versa (Borja et al. (2010a). By considering all Descriptors, the aim here is to show the predominant effect of climate change on the biodiversity ones.

The MSFD process includes a set of steps (Fig. 1, inner circle, created here using the MSFD, Claussen et al., 2011, and CEC, 2014): defining the main vision, giving a current assessment of their seas, develop a set of indicators against the Descriptors and Criteria needed to define GEnS (by 2012) (see Borja et al., 2010a, 2013a,), indicate the monitoring needed (by 2014) and a programme of measures (by 2015) and implement strategies (by 2016) to reach GEnS by 2020 (with a six-years review). Successful management then requires targets, trends (qualitative or quantitative), baseline values and thresholds, i.e. precise values of metrics or indices against which the monitoring is carried out and which then should act as triggers for the measures to be implemented (e.g. Teixeira et al., 2014). The indices or metrics must be SMART, i.e. Specific, Measurable, Achievable, Realistic and Time-bounded so that monitoring can determine compliance and management measures if GEnS is not achieved (Elliott, 2011).

This review shows how climate change influences or inhibits the MSFD implementation and the ability to detect GEnS; this follows the DAPSI(W)R Risk Assessment and Risk Management framework where the causes of change (the **D**rivers, **A**ctivities and **P**ressures) lead to **S**tate changes on the natural system and then to **I**mpacts on societal **W**elfare (Atkins et al., 2011; Cormier et al., 2013; Elliott, 2014). Finally, adverse S and I(W), the non-achievement of GEnS, then require a societal **R**esponse (including monitoring and measures) aimed at ensuring GEnS is reached and thus that Member States fulfil the legal obligation of this and all EU Directives (Boyes and Elliott, 2014). Thus the legal repercussions of not meeting GEnS due to climate change are addressed especially when the spatial overlaps of the associated EU Directives require some marine areas to reach GEnS under the MSFD, Good Ecological and Chemical Status under the Water Framework Directive, and Favourable Conservation Status (FCS) for the biodiversity conservation objectives under the Wild Birds and Habitats Directives (2009/147/EC; 92/43/EEC) (Frost et al., in press).

Climate change was not explicitly included in the MSFD and indeed is mentioned only twice. Elsewhere it is mentioned as a major pressure (CEC, 2014) but unusually was given greater prominence in the proposed Directive (CEC, 2005) compared to the final MSFD. Climate change is implicit in the list of characteristics, pressures and impacts (Annex III) but, for example, ocean acidification is listed as a characteristic rather than a pressure. It is of note that in the proposed MSFD (CEC, 2005), the highly variable nature of

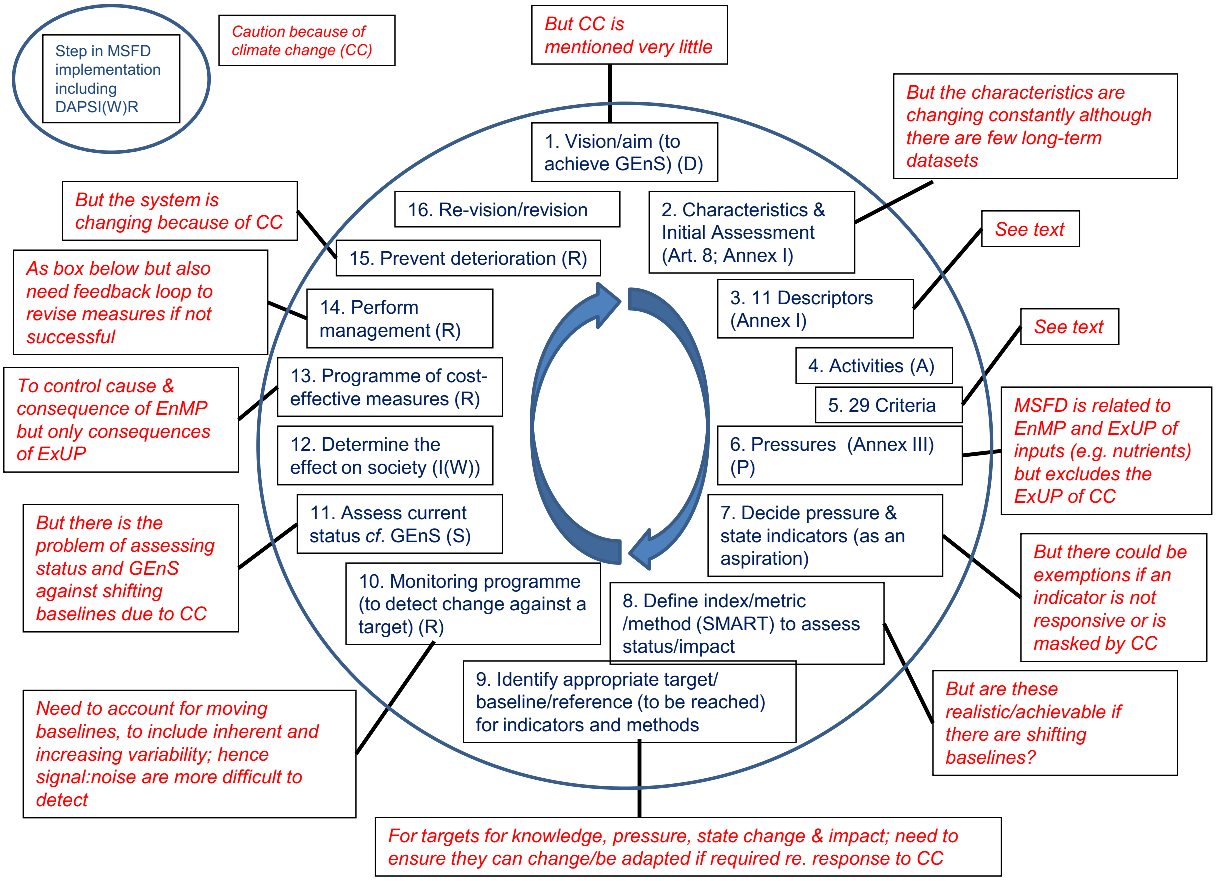

Fig. 1. A conceptual model of the implementation of the MSFD (inner blue circle) together with the areas for caution as the result of global climate change (red boxes) (see text).

marine ecosystems and the changes over time in human activities and pressures, were cited as the reasons for having an adaptive, flexible and dynamic definition of GEnS. The wording had then changed in the final Directive to: '*In view of the dynamic nature of marine ecosystems and their natural variability, and given that the pressures and impacts on them may vary with the evolvement of different patterns of human activity and the impact of climate change, it is essential to recognise that the determination of good environmental status may have to be adapted over time.*'

Biodiversity is threatened by the spatial extent, temporal duration and severity of pressures and the repercussions differ with area (CEC, 2013). Lethal and sub-lethal changes occur at cellular, individual and population levels due to hazardous inputs from physical (e.g. noise), chemical (contaminants) and biological (non-indigenous species) stressors. Overfishing affects the communities and ecosystem as does physical disturbance and loss of habitat. These are included in the MSFD as pressure-related Descriptors (No. 2, 5, 7, 8, 9, 10 and 11) and so global climate change needs to be judged against a background of these locally and regionally managed pressures (Elliott, 2011, 2014).

2. Integrated conceptual models and the evidence-base for the ecosystem effects of climate change

The repercussions of climate change on the ability to meet GEnS and to determine whether marine ecosystems are experiencing variability or direct climate change effects are grouped here as linked conceptual models and main topics (Figs. 2–10; Sections 2.1–2.8 below). Fig. 2 cross-refers to Figs. 3–10 onto which are superimposed the numbered main MSFD Descriptors likely to be affected by climate change and its consequences. Table 1 gives examples of the main literature base for the conclusions. The diagnosis of the state of the oceans and future prognoses for the trajectories of change are detailed in the recent Inter-Governmental Panel on Climate Change reports (Pörtner and Karl, 2014; Wong and Losada, 2014).

2.1. Altered temperature regime – species re-distribution and community response

Species distributions are changing, as temperature regime changes, in relation to their thermal tolerances, ability to adapt, extend their range or become extinct (Table 1, Fig. 3). The degree to which temperature increases and its seasonal timing may vary between regions. For example, annual mean temperatures in Europe are likely to increase more than the global mean with winter temperatures in northern Europe being notably higher and summer temperatures increasing significantly in the Mediterranean region (Christensen et al., 2007). As such, poleward extension, southerly contraction and depth changes cannot be assumed to be uniform among species (Table 3).

The increase of southern species into northern areas, loss of northern species with migrations, increased probability of Non-indigenous Species (NIS) influx and successful colonisation if the vector of transfer is not controlled, and a colonisation pathway is available will all prevent achieving GEnS for D2 (Occhipinti-Ambrogi, 2007; Hellmann et al., 2008). This depends on the physiological tolerances and competitive abilities of the individual species and the suitability of receiving conditions.

A biogeographical shift has occurred since the mid-20th C in the NE Atlantic, e.g. calanoid copepods experienced a 1000 km northward shift (Beaugrand et al., 2002; Beaugrand, 2009; Brown et al., 2011) and a switch in congeneric *Calanus* species (Beaugrand, 2003; Reid et al., 2003). As these species reflect climate patterns and have a key role in the North Sea food-web (Kirby and Beaugrand, 2009), achieving GEnS for Descriptor 4 will be more difficult. Similarly, a climate-driven regime shift, decline in North Sea total copepod abundance (O'Brien et al., 2013), increase in phytoplankton biomass (Reid et al., 1998; McQuatters-Gollop et al., 2011), but decrease in diatoms and dinoflagellates (O'Brien et al., 2012) have resulted in trophic mismatches (Beaugrand, 2004; Edwards et al., 2002; Edwards and Richardson, 2004), again reducing achieving GEnS for Descriptor 4. However, as an example of equivocal evidence, at regional and European levels, a projected sea surface warming of 2.29 ± 0.05 °C may reduce zooplankton and phytoplankton biomasses by 11% and 6%, respectively (Chust et al., 2014a, 2014b); the resultant influence in nutrient use and bloom-forming species will affect GEnS for Descriptor 5.

Several MSFD Descriptors are influenced by two thirds of North Sea fish shifting or retracting northwards or deeper, in line with increasing sea surface temperature (SST), and replacement by southerly species (e.g. red mullet, anchovy, sardine, and John Dory) (Dulvy et al., 2008). Given the warming and increasing availability of shallow water winter habitats, any indicators reliant on

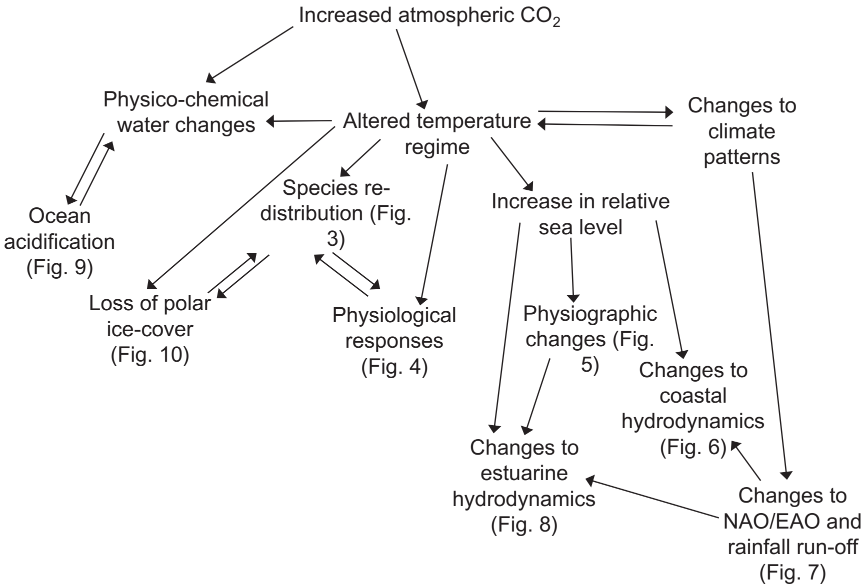

Fig. 2. Primary drivers and consequences of marine global climate change (cross-referring to other figures).

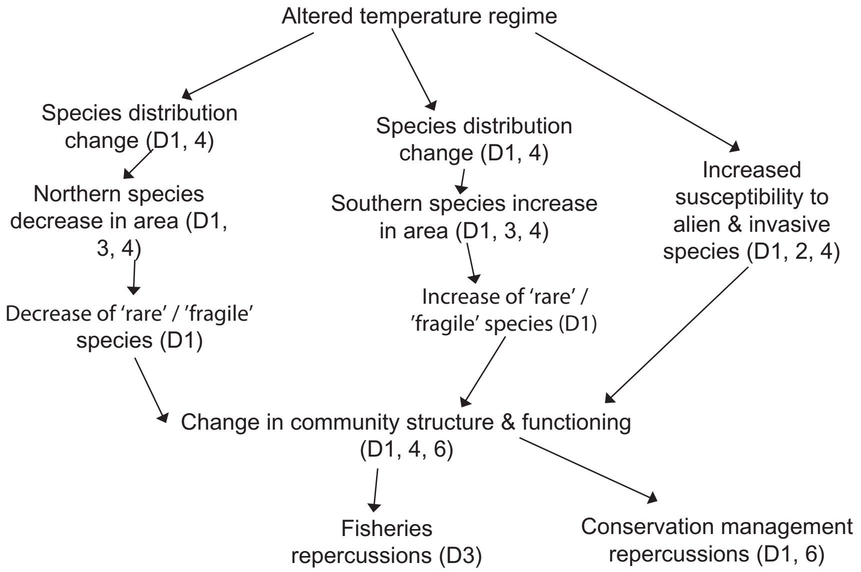

Fig. 3. Species re-distribution and community response due to altered temperature regime (MSFD Descriptor denoted in brackets, see text).

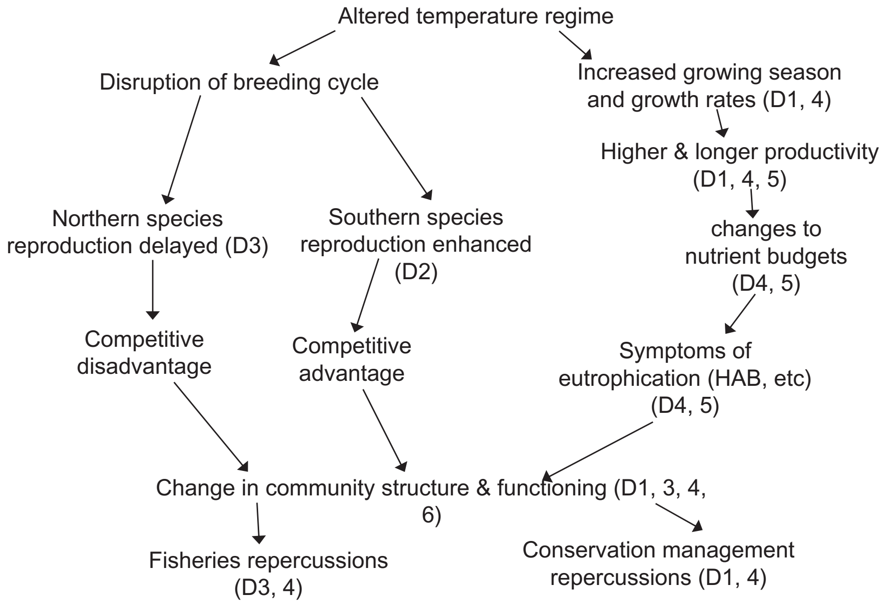

Fig. 4. Physiological and phonological responses due to an altered temperature regime leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

community structure and population dynamics and their effects on fisheries and predator–prey relationships will affect GEnS indicators for D3 and 4. For example, plaice and sole have migrated northwards 142 and 93 km since 1913 (Engelhard et al., 2011). Plaice have generally moved northeast and into deeper waters (a depth change of approx. 20 m) whilst sole are more prevalent south-eastwards in shallower waters of <10 m. This may be due to physiological differences between plaice which prefers cooler waters compared to sole which prefers warmer waters (Engelhard et al., 2011). However, the extent to which this will affect GEnS for the fisheries Descriptors cannot yet be predicted (Pörtner and Peck, 2010).

In influencing several GEnS Descriptors, Nicolas et al. (2014) directly linked the recent increase in SST to the decrease in *Calanus* biomass and a significant decline in adult and juvenile cod density (despite decreased fishing pressure) in the southern North Sea. Higher temperatures in early spring compromised cod recruitment due to reduced spawning success, earlier egg hatching, faster rapid larval development, a mismatch between prey availability and requirement and changes in primary production. This directly depleted cod rather than producing a marked northward migration and suggests that management measures to achieve GEnS for Descriptor 3 (fisheries) are unlikely to be effective against further decline. This also suggests that the mechanisms behind changing species distributions are more complex than simple latitudinal migration.

Given the key role of the benthos in the functioning of hard and soft substrata, climate change affects the likelihood to achieve GEnS for several Descriptors, especially the biodiversity ones (Fig. 3). The intertidal community has responded more quickly to climate driven warming for species close to their physiological tolerance limits. For example, the abundances of the two co-occurring intertidal Lusitanian barnacles *Chthamalus montagui* and *C. stellatus* have markedly increased since the mid-1900s in the British Isles

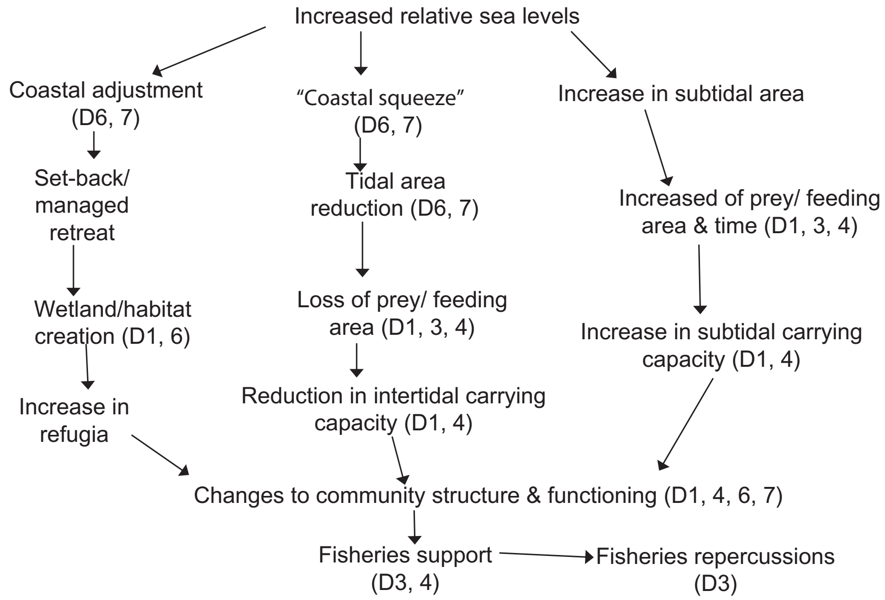

Fig. 5. Physiographic changes due to increased relative sea level leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

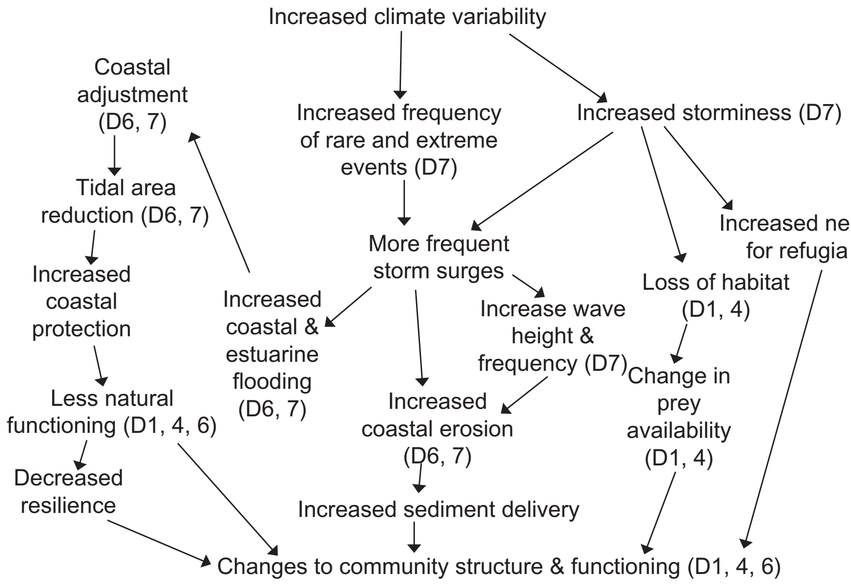

Fig. 6. Coastal hydrodynamic changes due to increased climate variability leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

whereas the Boreal *Semibalanus balanoides* proliferated during cooler periods but declined significantly due to temperature-driven competition (Birchenough et al., 2013; Mieszkowska et al., 2006, 2014). In soft sediments, the bivalve *Macoma balthica* has moved several 100s of km north in the Wadden Sea (Beukema et al., 2009). In contrast, there is less evidence for shifts in subtidal benthic communities which appear more buffered to increasing temperature than intertidal communities, plankton or fish (Hinz et al., 2011). Distributions of several warmer water species recorded in the English Channel in the late 1950s now remain largely unchanged. Despite this, Rombouts et al. (2012) predicted that, with continued warming, several key (ecologically or commercially important) species may be displaced northwards from the English Channel by 2100, due to increasingly unsuitable habitat. This ultimately reduces the possibility of achieving GEnS for the biodiversity and fisheries elements but shows the importance of the indicators chosen. As an indication of the importance of the offshore limits for GEnS, and what may be regarded as unbounded boundaries, Hinz et al. (2011) also suggested that depth changes may be more apparent than latitudinal ones since shallow coastal waters are more susceptible to temperature change.

Species, such as the Horse mussel *Modiolus modiolus*, which reach their southerly limit around the British Isles and are vulnerable but have a key role in benthic productivity and a high associated biodiversity (Gormley et al., 2013). Its loss or northward migration would have a significant, negative impact on marine habitat functioning and thus achieving GEnS for the biodiversity and fisheries Descriptors. A progressive loss of suitable habitat and progressive spawning and recruitment failure at sub-optimum temperatures, will cause overall long-term decline.

As a dominant indicator for D4 (food-webs, Tasker et al., 2010), recent warming-induced declines or migrations in overwintering distributions of many coastal wading birds will again reduce

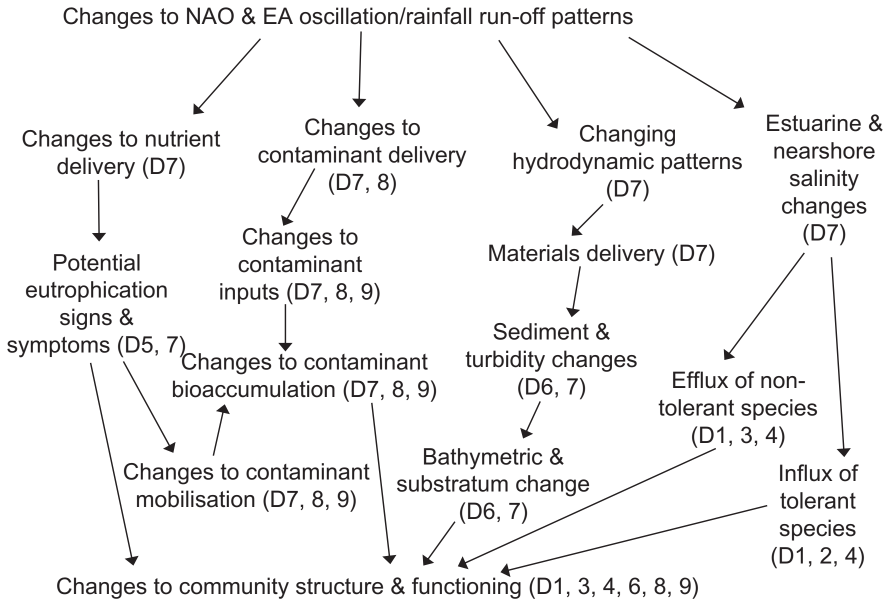

Fig. 7. Land-based discharges and run-off due to regional climate perturbations leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

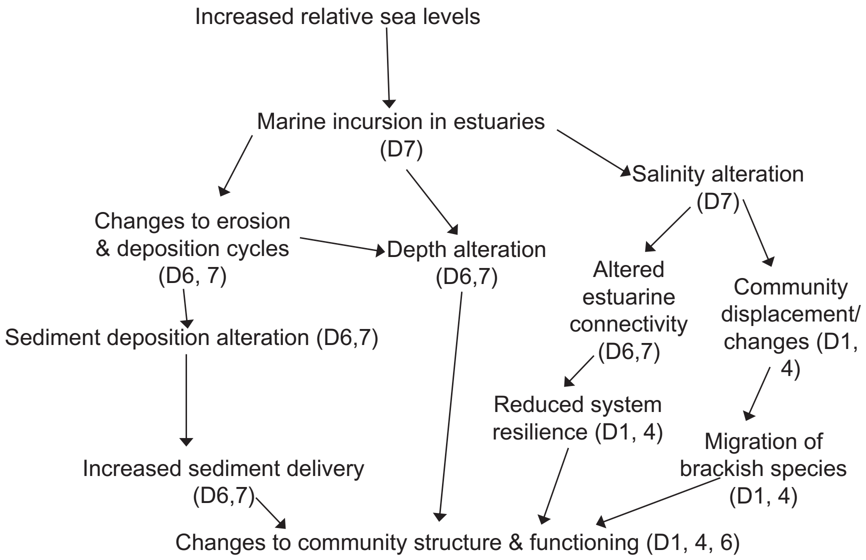

Fig. 8. Estuarine hydrodynamic changes due to increased relative sea levels leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

GEnS being attained for D1 and D4. These changes may have resulted from redistributing individuals rather than changes in survival, either due to cold-weather movements or changing juvenile recruitment patterns, for example, by seaducks taking advantage of ice-free conditions in the Baltic Sea, and in coastal waterfowl changing estuarine overwintering use again indicating changing baselines in GEnS determination. Hence, any reliance on GEnS indicators relating to dominant piscivorous seabirds (as proposed by the HELCOM and OSPAR Regional Seas Conventions) will be affected.

Recent models predict both warming-induced increasing and decreasing abundance of many wintering wader and waterbird populations in the UK. This may reduce the possibility not only of achieving GEnS but also Favourable Conservation Status under the EU Birds and Habitats Directives. While most current Special Protected Areas (Frost et al., in press) are likely to continue to support internationally important numbers of wintering waterbirds, even under a high-emissions 2080 scenario, there could be large overall changes to biodiversity.

Distributional shifts in response to climate change are not uniform between species and are not necessarily a simple, linear, change in depth distribution, poleward migration and/or contraction at the distribution edges (Richardson et al., 2012). Furthermore, species ranges may fluctuate with harsh and mild periods (Parmesan, 2006), again increasing variability in the system and making GEnS for many Descriptors difficult to judge or baselines difficult to define. The availability of new, suitable habitat (in terms of temperature regime) does not necessarily mean that species will expand into it especially as hydrodynamic conditions, the biology of the newly colonising species compared to that of the established species and barriers to dispersal all influence the ability of a species to migrate (Hiscock et al., 2004). Thermally-induced changes in parasite distribution may occur; for example, the protist *Perkinsus marinus* (which infects oysters) extended its range

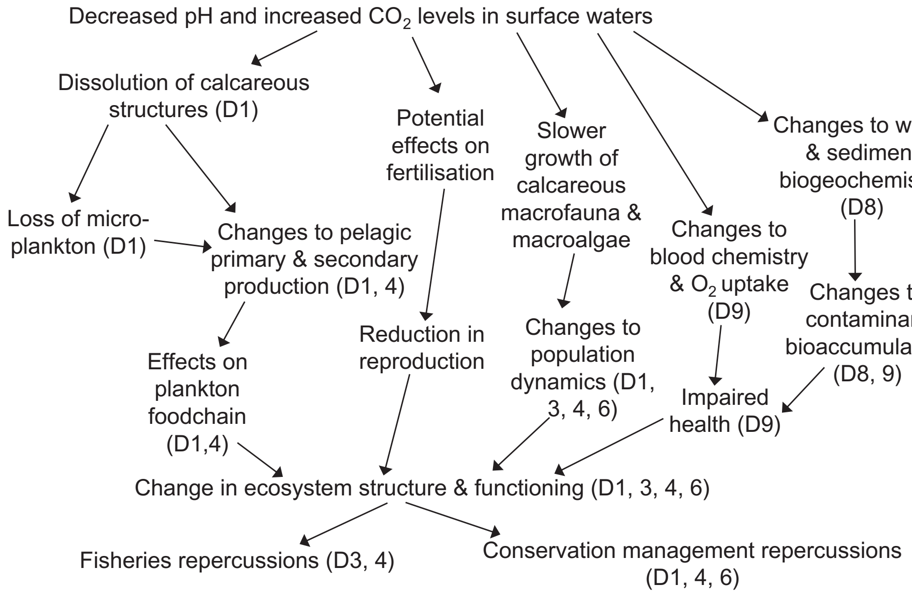

Fig. 9. Physico-chemical water changes due to decreased pH and increased CO_2 levels leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

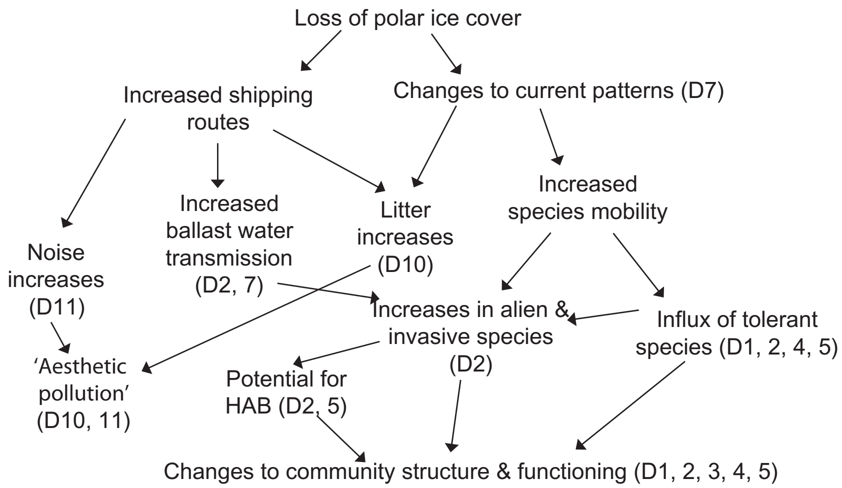

Fig. 10. Global transport repercussions due to loss of polar ice-cover leading to ecosystem effects (MSFD Descriptor denoted in brackets, see text).

by over 500 km per year in the US (Parmesan, 2006). However, this may be exacerbated by relaying of shellfish in aquaculture. In addition to the increase in NIS, proliferation of such parasites may weaken populations at the edges of their ranges thus preventing achieving GEnS for, amongst others, D2 (Non-indigenous species) and the resulting effects on fisheries (D3).

Species distribution changes can bring together species that have not previously interacted (Staudinger et al., 2013; Albouy et al., 2014). Species with long generation times, low fecundity, low mobility, poor dispersal ability and populations living near the extremes of their physiological tolerances, and species with little phenotypic plasticity will be most vulnerable whilst those with high dispersal potential and phenotypic plasticity, which can adjust to and thrive in changing environments, will be favoured by climate change. However, the ability of a migrating, warm-adapted species to become established will depend on its competitive ability and the many interlinked responses (Fig. 3) means that the repercussions for GEnS are almost impossible to predict. For example, contrary to a general assumption, species with broad ranges can be susceptible to extinction through climate change when species typically adapted to cooler environments persist under warming, preventing poleward expansion (Atkins and Travis, 2010; Staudinger et al., 2013). In contrast, the amphipod *Echinogammarus marinus* is highly temperature sensitive and has retracted by 5°N at its European southerly edge (Guerra et al., 2014). Thus a challenge for policy implementation is that the response of species to climate change may contradict expectation, making it difficult to disentangle localised human activities from those caused by climate change and, hence, manage changes in GEnS. Furthermore, species entering an area due to changes in the environmental conditions, may be at the edges of their distributions and hence could be rare and fragile, and thus of wider marine conservation interest.

2.2. Altered temperature regime – individual physiological/ phenological response

Temperature-induced physiological changes ultimately determine ecosystem composition, spatial structure and functioning (e.g. Pörtner and Karl, 2014) and thus many indicators of GEnS

Table 1

Biodiversity-related qualitative Marine Strategy Framework Directive Descriptors and indicators which may be affected by climate change, together with the cause, evidence, precise examples and references.

Descriptor	Criteria	Indicator	Cause of change and impact	Precise example	References
1. Biological diversity	1.1. Species distribution	1.1.1. Distributional range	Shift of species distribution, especially at the margins of its distributional range (i.e. change of area occupied by a species)	*Zostera noltii* northward distributional will shift of 888 km in the suitable habitat of the species, and a retreat of southernmost populations (Valle et al., 2014)	Alcock (2003), Chust et al. (2013b), Duarte et al. (2013), Nicolas et al. (2011), Poloczanska et al. (2013), Reid and Valdés (2011), Rombouts et al. (2012), Tasker (2008) and Valle et al. (2014)
		1.1.2. Distributional pattern within the latter	Boreal species can be refuge in deeper waters, temperate species can extend to deeper waters	In the North Sea six fish species, including plaice (*Pleuronectes platessa*) and cuckoo ray (*Leucoraja naevus*), moved deeper with warming but did not change in latitude (Perry et al., 2005)	Cheung et al. (2013a,b), Poloczanska et al. (2013) and Reid and Valdés (2011)
		1.1.3. Area covered by the species (for sessile/benthic species)	Reduction of the area for boreal species, increase for temperate and subtropical	Reduction in *Calanus finmarchicus* available overwintering habitat northwest of Scotland (Beaugrand, 2009)	Birchenough et al. (2011), García et al. (2013), Poloczanska et al. (2013) and Valle et al. (2013)
	1.2. Population size	1.2.1. Population abundance and/or biomass	Described increases and decreases, depending on the resilience of the species, and are generally non-linear reduction in population size if characteristics of the area becomes sub-optimal	Reduction in abundance and biomass of fish in lower latitudes, increase of biomass at high latitudes (Cheung et al., 2013a, b), reduction in zooplankton and phytoplankton biomasses of 11% and 6%, respectively (Chust et al., 2014a).	Chust et al. (2013a), Finney et al. (2010), Hemery et al. (2008), Munday et al. (2013), Nye et al. (2009), Poloczanska et al. (2013), Reid and Valdés (2011) and Tasker (2008)
	1.3. Population condition	1.3.1. Population demographic characteristics	Early signal of climate change, since it affects first to individual demography Changes to recruitment patterns due to temperature threshold changes; reduction in juvenile stages; changes to spawning thresholds due to temperature change		Albouy et al. (2014), Poloczanska et al. (2013) and Tasker (2008)
		1.3.2. Population genetic structure	Better or worst adaptation to change Inflow of sibling species; genetic changes due to aquaculture changes,		Chust et al. (2013a)
	1.4. Habitat distribution	1.4.1. Distributional range	Shift of habitat (both bed and water column) distribution	Important habitat distributional range shift for macroalgae *Pelvetia canaliculata* (Neiva et al., 2014)	Martinez et al. (2012), Duarte et al. (2013), Reid and Valdés (2011) and Valle et al. (2014)
		1.4.2. Distributional pattern	Boreal habitats can be refuge in deeper waters, temperate habitats can extend to deeper waters	Changes in macroalgae (Lima et al., 2007)	Reid and Valdés (2011)
	1.5. Habitat extent	1.5.1. Habitat area	Reduction of the area for boreal species, increase for temperate and subtropical	Reduction >80 habitat extent in intertidal pools and boulders (Thorner et al., 2014)	Duarte et al. (2013), Reid and Valdés (2011) and Valle et al. (2013)
		1.5.2. Habitat volume, where relevant	No information; habitat volume as a water mass affected by changes to thermohaline conditions changing through climate change		
	1.6. Habitat condition	1.6.1. Condition of the typical species and communities	Reduction of habitat-forming species Change to community composition (but not necessarily guilds and traits represented)	The shift to small bodied, shallow burrowers with opportunistic life histories could caused a reduction or loss of habitat forming species and those that create habitat heterogeneity (Caswell and Frid, 2013)	Hoegh-Guldberg and Bruno (2010)
		1.6.2. Relative abundance and/or biomass, as appropriate	Increase of dominance (by number or biomass) change due to changing species distributions and relative proportion in the community		

Table 1 (*continued*)

Descriptor	Criteria	Indicator	Cause of change and impact	Precise example	References
		1.6.3. Physical, hydrological and chemical conditions	Many evidences of sea temperature increase, acidification increase, and sea-level rise Changes to temperature regime, storminess, salinity changes due to run-off		Stocker et al. (2013)
	1.7. Ecosystem structure	1.7.1. Composition and relative proportions of ecosystem components (habitats, species)	Important changes in structure and function Changes to relative amounts of different communities in the ecosystem; changes to bentho-pelagic coupling	Significant changes in structure and lower diversity in response to reduced pH and increasing temperature. Molluscs are the most affected and annelids the less (Hale et al., 2011)	Hoegh-Guldberg and Bruno (2010), Reid and Valdés (2011), Sydeman and Bograd (2009), Tomczak et al. (2013) and Yamanaka et al. (2013)
2. Non-indigenous species	2.1. Abundance and state of non-indigenous species, in particular invasive species	2.1.1. Trends in abundance, temporal occurrence and spatial distribution of non-indigenous species	Increase of abundance for invasive species; increase in migration of species from outside the area	There is high confidence in which invasive subtropical species will increase at temperate latitudes (Wong and Losada, 2014)	Bremner (2008), Dutertre et al. (2010), Hellmann et al. (2008), Lejeusne et al. (2010), Mendoza-González et al. (2013), Occhipinti-Ambrogi (2007), Otero et al. (2013) and Tasker (2008)
	2.2. Environmental impact of invasive non-indigenous sp.	2.2.1. Ratio between invasive non-indigenous species and native species	Ratio will increase; increasing naturalisation of non-native species	Introductions and shift are faster in marine than in terrestrial systems (Sorte et al., 2010), this likely producing increasing ratios	Occhipinti-Ambrogi (2007) and Otero et al. (2013))
		2.2.2. Impacts of non-indigenous invasive species at the level of species, habitats and ecosystem	Increase of vulnerability of species and habitats, impacts on ecosystem functionality, changes due to bio-engineer properties of invasive species		Birchenough et al., 2011; Bremner, 2008; Occhipinti-Ambrogi, 2007; Ramirez-Llodra et al., 2011
3. Food webs	3.1. Productivity of key species or trophic groups	3.1.1. Performance of key predator species using their production per unit biomass	Key top-predator species will be more vulnerable (e.g. cod, cetaceans, seabirds) Changes to energetic of certain species as shown by P/B ratios, result of physiological changes due to temperature changes		Albouy et al. (2014), Jennings and Brander (2010), Niiranen et al. (2013) and Ottersen et al. (2010)
	3.2. Proportion of selected species at the top of food webs	3.2.1. Large fish (by weight)	Lower size, loss of many large fish; results of bioenergetic changes	Fish will have smaller body weight and local extinction/decreased abundance of larger-bodied species (Cheung et al., 2013a,b)	Albouy et al. (2014), Jennings and Brander (2010) and Ottersen et al. (2010)
	3.3. Abundance/distribution of key trophic groups/species	3.3.1. Abundance trends of functionally important selected groups/species	Loss of feeding links, simplification of food webs, changes in the up and down control of the food webs, change from phytoplankton to bacteria-based food webs		Albouy et al. (2014), Cury et al. (2008), Defeo and Castilla (2012), Drinkwater et al. (2010), Eriksson Wiklund et al. (2009), Hoegh-Guldberg and Bruno (2010), Niiranen et al. (2013), Ottersen et al. (2010), Rombouts et al. (2013) and Travers et al. (2007)
4. Seafloor integrity	4.1. Physical damage, having regard to substrate characteristics	4.1.1. Type, abundance, biomass and areal extent of relevant biogenic substrate	Interactions between human pressures and climate change, increasing damage or reducing resilience		Borja et al. (2013b), Hewitt and Thrush (2010) and Wernberg et al. (2011)
		4.1.2. Extent of the seabed significantly affected by human activities for the different substrate types	Interactions between human pressures and climate change, increasing damage or reducing resilience	Exploited macroalgae beds or beds affected by discharges are less resilient to climate change than unaffected macroalgae (Borja et al., 2013b)	Borja et al. (2013b), Hewitt and Thrush (2010) and Wernberg et al. (2011)

(*continued on next page*)

Table 1 (*continued*)

Descriptor	Criteria	Indicator	Cause of change and impact	Precise example	References
	4.2. Condition of benthic community	4.2.1. Presence of particularly sensitive and/or tolerant species	Changes in the presence of sensitive species (especially temperature-sensitive)	Warming induces stratification, oxygen consumption and community shift toward lower species richness and increase of hypoxia-tolerant (Pörtner and Karl, 2014) and opportunistic species (Caswell and Frid, 2013)	Otero et al. (2013) and Tasker (2008)
		4.2.2. Multi-metric indices assessing benthic community condition and functionality, such as species diversity and richness, proportion of opportunistic to sensitive species	Changes in current reference conditions and potential shifts in results from those indices (especially those using structural metrics)	From the previous example, it is expected that the ratio sensitive/opportunistic species will be reduced and, as such, the ecological status will be worst	Nicolas et al. (2011)
		4.2.3. Proportion of biomass or number of individuals in the macrobenthos above specified length/size	Reduction of richness and biomass in some cases		Beukema (2002), Birchenough et al. (2011), Junker et al. (2012) and Yamanaka et al. (2013)
		4.2.4. Parameters describing the characteristics of the size spectrum of the benthic community	Probable changes in body size spectra, towards a reduction	Expected reduction in body size, as shown in palaeo records (Caswell and Frid, 2013)	Levin et al. (2009) and Webb et al. (2009)

(Fig. 4). Demographic changes resulting from alterations to recruitment, growth and survival together with phenological changes (e.g., timing of spawning, migration and spring blooms) lead to potential predator–prey mismatches (Philippart et al., 2003; Dulvy et al., 2008), thus reducing attaining GEnS for D4. Elevated temperature may increase reproductive success and larval survival of species at their northern limits, facilitating their poleward extension, assuming suitable habitat and a lack of physical and hydrological barriers (Rombouts et al., 2012). Hence temperature changes may influence species interactions such as predation and competition, inherent to any indicators used for GEnS for D1, D2, D4 and D6 (Beukema et al., 2009; Somero, 2012).

Temperature thresholds for survival and reproduction (e.g. see Rasmussen, 1973) indicate that climate change will induce summer, warm-adapted spawners to have earlier and/or longer spawning, a longer growing season and greater productivity whereas winter spawners will have later and shorter spawning periods (Guerra et al., 2014) (Fig. 4). Temperature and salinity influence on the metabolic rate of organisms ultimately affects reproductive output and moulting. The advance of spring events such as spawning and migration has been recorded worldwide (Parmesan, 2006) thus again indicating moving baselines and reducing the ability to attain GEnS for several functional indicators and Descriptors.

As an example, thermal-induced early migration to spawning grounds occurs in flounder (*Platichthys flesus*) and veined squid (*Loligo forbesi*) amongst other species (Philippart et al., 2003; Southward et al., 2005; Teal et al., 2008, 2012; Jansen and Gislason, 2011; Fincham et al., 2013). Flounder spawning has advanced by 1.5 weeks yr^{-1} since 1970 due to increasing temperature in the eastern English Channel and in the central and southern North Sea but not in areas of more stable temperatures (e.g. Bristol Channel) (Fincham et al., 2013). Earlier spawning in North Sea mackerel (Jansen and Gislason, 2011) and early maturation of herring and sole (Fincham et al., 2013) has been due to increased temperature although accelerated maturation in sole may be an evolutionary response to commercial fishing (Mollet et al., 2007). Such interactions conflate the responses due to different pressures, such as over-fishing and climate change, in turn making it difficult to determine the influence on achieving GEnS across D1 and D3 (Perry et al., 2010; Pörtner and Peck, 2010; Griffith et al., 2012). Teal et al. (2012) found an increased growth rate with higher summer temperatures in the warm-adapted sole and a positive correlation between size at the end of the first year and temperature whereas this was less in the cooler-adapted plaice, thus further advantaging sole and disadvantaging plaice (Dulvy et al., 2008; Engelhard et al., 2011; Teal et al., 2012), again influencing stock production (Fincham et al., 2013) and thus GEnS for D3.

Temperature-related early spawning, growth and maturation may benefit some but not all species, e.g. the northern bivalve *M. balthica*, if this results in a mismatch with the spring phytoplankton bloom and so reduced recruitment (Philippart et al., 2003). Furthermore, a negative relationship between *M. balthica* recruitment and temperature produces a low density associated with warm winters (Beukema et al., 2009). Similarly, reduced growth and higher mortality occurs with warm summers and mild winters, to prevent sufficient body condition gained during the summer to counteract autumn/winter weight loss. Given the central role of prey species such as *Macoma*, there is a large influence in certain marginal sea areas on achieving GEnS for D1, D4 and D6 (Fig. 4). Beukema et al. (2009) also found that predation on *M. balthica* by the shrimp *Crangon crangon* explained half of interannual variability in recruitment again influencing GEnS for D4. Somero (2012) similarly found an increase in predation of *Mytilus edulis* by the seastar *Pisaster ochraceus*, correlated with increased temperature and had the potential to alter ecosystem structure and function. Given that *Crangon* and *Mytilus* are important commercial shellfish then any loss will prevent GEnS being achieved especially for D3.

Survival under temperature changes in marine ectotherms is partly due to physiological tolerance and adaptation and/or behavioural response (Hofmann and Todgham, 2010). Unregulated physiological processes may reduce growth and reproductive output and increase mortality, each affecting indicators of GEnS for several Descriptors. As yet, there are no indicators of GEnS related to individual functioning but rather to community and population effects, hence the concern regarding integrated effects across levels of biological organisation. Somero (2012) noted an increase in heart rate with increasing body temperature up to a critical point (CT_{max}) in *M. edulis* after which it decreases rapidly, and in the decapod crustacean *Petrolisthes*, lethality occurs at temperatures above CT_{max} with the most warm-adapted species acclimating to higher temperatures, increasing risk from climate change. In fish, limited cardiac performance may compromise migration ability and, thus, reproductive ability. Somero (2012) therefore hypothesised that the latitudinal range was, to some extent, dictated by cardiac function. Given that such changes have a knock-on effect to fisheries populations then there is a resultant adverse effect on GEnS, again for D1 and D3.

In covering species of marine conservation importance, the above changes and their influence on GEnS Descriptors have also been shown in marine angiosperms. There are distribution changes in the intertidal seagrass *Zostera noltii* and decreased photosynthesis and growth with increased temperature even causing mortality (Massa et al., 2009, 2011; Valle et al., 2014). Whilst it would be unusual, but not impossible, particularly as the frequency of extreme weather events increases, for intertidal seagrasses to experience these temperatures in NW Europe, sub-lethal effects on growth occur in the subtidal species *Zostera marina* at 25 °C, 2 °C above the expected summer temperature for SW Europe. However, these experiments involving heat-shock protein expression do not indicate the implications of prolonged, regular exposure to elevated temperatures where there is potential for sublethal effects that may have population level implications. This makes it difficult to determine the long-term effect of such changes on the ability to meet GEnS especially with such moving baselines on decadal scales and where adaptation may occur over tens of generations.

In addition, *Zostera* species are particularly sensitive to habitat conditions and to erosion, increased turbidity, sedimentation and nutrient concentrations, showing the influence on GEnS for D1, D4, D5, D6 and D7 via physico-chemical changes (Figs. 4–8). Through these processes, the increased frequency of storms may cause mortality and loss of seagrasses. Hence, given that recolonisation predominantly occurs through rhizome growth from adjacent vegetated areas (Boese et al., 2009), seagrasses may disappear rather than change distribution. This will affect the ability to attain thresholds for indicators of GEnS that reflect such distributional and associated foodweb changes. Habitat change such as a loss of vegetation cover may also limit behavioural thermoregulation in some species. In contrast, habitats which retain their structural complexity under climate change may continue to provide shelter for the resident organisms which may respond more slowly to increased temperature than might be expected (Staudinger et al., 2013). This reinforces the need to study habitat resilience in relation to changing environmental conditions and thus the ability to meet GEnS.

2.3. Increased relative sea-level rise – physiographic changes

Physical changes ultimately affects indicators of biodiversity and ecological functioning and so changes due to climate change (Fig. 5) reduce or change habitat such as a loss of productive intertidal area and a gain in less-productive subtidal systems, and a potential reduction in productivity and carrying capacity (Gray and Elliott, 2009). Loss of habitat requires either compensation and/or mitigation measures as any such loss of carrying capacity impinges on achieving GEnS for several of the Descriptors.

A global sea-level rise (SLR) of 0.2–0.6 m is predicted by 2100 and possibly 1–2 m if glacial meltwater is included (Katselidis et al., 2014). Intertidal areas with a fixed high-water mark will experience coastal squeeze where the wetland, estuarine and high-shore habitats are prevented from migrating landward (Elliott et al., 2014) although habitat loss will be variable due to shore type, sediment composition, habitat type, topography, exposure to erosive forces and inundation patterns (Pontee, 2013). Coastal squeeze may also create shore steepening due to the low water mark retreating landward more rapidly than the high water mark, which may be fixed or where it has advanced towards a retreating low water mark (Taylor et al., 2004).

The MSFD D7 (hydrographical conditions) and D6 (seafloor integrity) address physical effects of climate change. Coastal erosion, linked to global warming and sea level rise, may impact most sandy beaches globally (Feagin et al., 2005) and coastal infrastructure and/or sea defences or areas backed by natural barriers (Katselidis et al., 2014) confine beaches to unnaturally narrow strips devoid of typical plant and animal communities. Increasing erosion due to SLR (Feagin et al., 2005; Poulter et al., 2009; Katselidis et al., 2014) is largely assumed to be associated with soft sediment habitats, although rocky areas are also potentially vulnerable (Jackson and McIlvenny, 2011). Many beaches are erosional and a small increase in sea level will cause a large increase in erosion rates in the 19th and 20thC, especially in areas with hard engineering structures (Zhang et al., 2004; Hanley et al., 2014).

Dune plant communities, important in conservation, will be altered through confinement, fragmentation of communities, breakdown of succession, lack of species for stabilisation and the presence of remnant populations superimposed on erosion and physical barriers (Feagin et al., 2005). Agricultural development, urbanisation, tourism and recreation combined with climate change now threatens remaining dunes (Hanley et al., 2014).

Habitat and biodiversity loss through coastal squeeze and coastal erosion/deposition may occur progressively whilst storm surges or periods of extreme weather (e.g. high winds and high rainfall) may cause rapid and significant geomorphological changes (Elliott et al., 2014). Storm surges are linked to erosion, are increasing in frequency and severity, and cause significant damage (Zhang et al., 2004; Hanley et al., 2014; Pörtner and Karl, 2014) sufficient to prevent achieving GEnS, particularly in terms of D1, D3, D4 and D6.

Finally, erosional changes in topography or shore profile induce sediment and habitat structure changes and hence biological community structure and ultimately D1 and D4 (Snelgrove and Butman, 1994). SLR is of concern as some MSFD indicators relate to the large and charismatic, conservation important species, e.g. to reduce nesting habitat for loggerhead turtles, especially where there are physical barriers to landward migration (Katselidis et al., 2014). Similarly, Galbraith et al. (2002) and Erwin et al. (2006) highlighted that although increased inundation may benefit waterfowl, it removes nesting and feeding habitat for many waterbirds. Similarly, North Sea plaice nursery grounds may be adversely affected by climate change with temperature-induced changes in currents, leading to reduced connectivity between spawning and nursery grounds (Hufnagl et al., 2013). Hence the likely difficulty in attaining indicators of the Biodiversity Descriptors for GEnS which especially include those higher level and charismatic species such as fish, birds and sea turtles.

2.4. Increased climate variability effects on coastal hydrodynamics

Climate change will increase the variability and determine the trajectory of the over-riding influence of physical forcing factors on the structure and functioning of the marine system (e.g. Gray and Elliott, 2009) (Fig. 6). This will remove coastal habitats and their prey populations, and require new refuge areas; hydrodynamic-induced erosion will remove some habitats but may supply sediment and change bathymetric patterns to secure new habitats especially in sheltered areas. For example, long-term variation in shallow coastal soft sediment communities follows substratum changes, hence increased storminess associated with climate change may reduce structure and function (Davoult et al., 1998; Smits et al., 2005; Weisse et al., 2005). While such communities may recover from severe physical disturbance, little is known about the impact of recurring events acting on communities that are partially recovering (Allan, 2006). This predominant effect on D6 and D7 then ultimately affects the seabed and nektonic components. However, the change is storminess changes with geographical area if at all (Muschinski and Katz, 2013) giving equivocal evidence despite the high control by coastal hydrodynamic features on ecological structure and processes (Scavia et al., 2002). Furthermore, even with such changes, the ability of coastal populations, which are adapted and hence resilient to high wave conditions, to be adversely affected by such hydromorphological changes is unknown. For example, benthic communities especially in highly-mobile sediments already are adapted to substratum changes such that they may be resilient to climate-induced variability (Gray and Elliott, 2009; Duarte et al., in press). Similarly, it is not possible to predict the result of ocean current pattern changes on larval transport with population and community level consequences (Harley et al., 2006), which affect many Descriptors and indicators. Therefore, the ability to achieve GEnS, especially for the Biodiversity Descriptors and D6 and D7, cannot be reliably predicted given that any knock-on effects from the coupled hydrophysical-ecological response are buffered by inherent variability and resilience.

2.5. Changes to large scale climatic patterns due to land run-off

Large scale climatic patterns influence catchment run-off, including nutrients and contaminants, into semi-enclosed seas, hence showing interlinked responses (Fig. 7). In Europe, the most influential patterns are the Atlantic Multidecadal Oscillation (AMO) (Kerr, 2000), the NAO (Hurrell, 1995), and the East Atlantic (EA) Oscillation (Barnston and Livezey, 1987). Their impacts on biodiversity and ecosystems are well-known e.g. for the AMO (Drinkwater et al., 2014; Gnanadesikan et al., 2014; Harris et al., 2014; Mieszkowska et al., 2014; Nye et al., 2014) and NAO (Ottersen et al., 2001; Ji et al., 2010; Henderson et al., 2011; Kröncke et al., 2011; David et al., 2012; Henson et al., 2012; Beaugrand et al., 2014), but less for EA (Borja et al., 2008; Chaalali et al., 2013).

Arguably the greatest challenge in predicting the effects of climate change on the hydrodynamics of a catchment and hence the nutrient inputs to, and response in, enclosed coastal seas is the ability to understand these interlinked relationships (Meier et al., 2011). In particular, nutrient run-off will create the adverse consequences of eutrophication (i.e. D5) but this is difficult to predict against a background of inherent variability due to changes in land-use patterns. Similarly, the influence of nutrients entering from the Northern Atlantic into the northern European seas due to NAO conditions (Frigstad et al., 2013) gives effects over and above the influence of agricultural nutrients and industrial contaminants. Hence, there is the possibility of not meeting GEnS due to NAO irrespective of anthropogenic influences on land and again Member States may consider that such changes are outside their control.

As an indication of the influence of land-based climate patterns on the adjacent coastal and marine areas, modelling has shown the trajectory of recent (decadal) changes and indicated the overall future patterns in salinity and temperature (Andersen, 2012). For example, for the Baltic Sea, climate change may create a warmer and less saline sea than seen in records since 1850, and climate-induced effects will occur earlier than previously thought (Meier et al., 2012a, 2012b). This results in adaptations by the food webs (Niiranen et al., 2013) thus reducing the ability to meet GEnS for D4 or at least requiring the revision of the baseline and target values for this Descriptor.

2.6. Increased relative sea-level rise changing estuarine hydrodynamics

Tidal wetlands may be included within the MSFD if it is applied up to the high-water mark. As estuaries and other transitional waters are tidal then it is possible, but as yet undecided in all Member States, that they will be included in the MSFD. However, some countries, including the UK, have decided that estuaries will be excluded and that the MSFD will be applied from Mean High Water on the coast and seawards from the 'Bay closing lines' across the mouths of estuaries. Because of this, estuarine characteristics are included here briefly and only for comparison and completeness (Fig. 8).

Climate change repercussions on the hydrogeomorphology of estuaries, such as SLR, increased salinity incursion and current pattern changes ultimately alter the fundamental characteristics of estuaries and their biodiversity (see Elliott and Whitfield, 2011), especially as most species distributions reflect salinity tolerances (Whitfield et al., 2012). Estuarine water budget changes, such as those caused by changed tidal and NAO patterns, also alter the salinity balance in estuaries and hence the distribution of brackish-tolerant species (e.g. Scavia et al., 2002). However, the net effect of increased seawater influx as the result of SLR and the changes to catchment water balance and freshwater delivery into estuaries are unknown although the upper estuarine fauna may change with increased seawater incursion (Little, 2012).

As most sediment inputs in estuaries are from marine sources, estuarine bathymetry is influenced if marine incursion is increased and sea-level rises. This may impact wintering waterbird communities, especially where coastal defences are maintained. Similarly, any significant warming will reduce the Arctic and subarctic breeding ranges of wintering waterbirds and so despite improving winter conditions in the British Isles, wintering populations of many species here may decline due to the habitats necessary outside the area. Therefore, again, any GEnS high-level indicators focusing on waders and seabirds will be influenced by climate change and conditions well outside areas controlled by a Member State.

Given these overall changes, climate changes will adversely influence the GEnS Descriptors for biodiversity (D1), foodwebs (D4) and hydrophysical (D6) characteristics of the water column and substratum. Despite this, the ability of estuarine communities to withstand a larger variability while already being adapted to a high inherent variability (Elliott and Quintino, 2007) will make climate change responses difficult to detect.

2.7. Increased ocean acidification and seawater physico-chemical changes

The central conceptual model proposed here (Fig. 2) centres on the direct and indirect effects of elevated atmospheric CO_2 inducing a 0.3–0.4 unit decrease in pH by 2100, i.e. ocean acidification

(OA) although daily and annual variations compound difficulties in detecting change (Blackford and Gilbert, 2007; Dupont et al., 2013; Williamson et al., 2013; Artioli et al., 2014). Although the vulnerability of marine biodiversity to OA may be minor (Hendriks et al., 2010), detailed meta-analyses, especially on the benthos (macrofauna and macroalgae) and plankton, have highlighted important negative effects (Kroeker et al., 2010) (Fig. 9). This includes changes to physiology, growth and reproduction, loss or reduction of calcareous microplankton and macroalgae, and resultant changes to the planktonic and shore food-webs (Kroeker et al., 2010; Durrieu de Madron et al., 2011; Asnaghi et al., 2013; Wittmann and Pörtner, 2013).

Ocean acidification could increase the toxicity of contaminated sediments due to diagenesis, the mobility of metals in sediment pore water, with increases in the overlying water column and bioaccumulation of metals, in turn producing biological responses such as in clams (Carere et al., 2011). Experimental exposure of metal-rich sediments to different predicted pH concentrations show an increased metal toxicity and resultant effect on crustaceans (Roberts et al., 2013). However, although this may affect many components comprising the GEnS, especially relating to ecological structure and functioning and even contaminant exposure (D8, 9), the timescale of effects, the rate at which the system over many generations can adapt to reduced pH and hence the final ecological consequences are unknown.

The ecological effects of OA based on laboratory and field studies is equivocal, even between different strains of a single species of phytoplankton (Langer et al., 2009) such that it is difficult to predict long-term changes. Declining calcification rates with decreasing pH make coccolithophores particularly vulnerable (Riebesell et al., 2000; Zondervan et al., 2001; Fabry et al., 2008) although their abundance has increased during the past two decades, a likely response to warming sea-surface temperature (Beare et al., 2013; Beaugrand et al., 2013). As a further concern, bivalve shellfisheries and aquaculture may also be affected by pH effects on the young stages especially at a time when aquaculture may be increasing to accommodate reductions in wild fisheries.

The scientific uncertainty shows the need for further study on ecosystem responses to OA as some species will be more susceptible whereas others may tolerate or adapt to the changing conditions. As biotic responses to OA will occur over decadal timescales together with other environmental pressures, genetic variability/selection, phenotypic plasticity and a wider range of ecological interactions (Williamson et al., 2013), then experiments or modelling are needed to interrogate such changes. The cumulative effects of these changes on achieving GEnS cannot as yet be predicted especially on the complex behaviour of Descriptors D1, D5, and D8 and its repercussions.

2.8. Loss of polar ice cover and global transport repercussions

The 2014 IPCC report (Pörtner and Karl, 2014) highlights the increasing loss of polar ice cover which, together with opening Arctic shipping routes (Verny and Grigentin, 2009), is likely prevent GEnS being reached (Fig. 10). The exchange of NIS via the Arctic occurred previously in warm periods of the Pleistocene (Dodson et al., 2007), but now will be exacerbated by ballast water transport and other vessel vectors (Lewis et al., 2004). These increasing vectors produce hazards and risks associated with NIS (Elliott et al., 2014) although as yet it is unknown whether these become introduced, invasive or nuisance species, and whether they can be prevented or controlled (Olenin et al., 2011). Consequently any D2 indicators of GEnS will be influenced by species either drifting on re-established current systems or via increased vessel transport. Most notably, this is similar to species entering the Mediterranean via the Suez Canal (cf. Galil et al., 2014) but again raises the question of, firstly, whether such vectors can be controlled and, secondly, whether a Member State may be liable for failing to meet GEnS for something out of its control.

There may be repercussions for the other biodiversity Descriptors and eutrophication (D5) given any resulting colonisation. For example, in 1999, a Pacific Ocean diatom species, *Neodenticula seminae*, occurred in the North Atlantic due to the summer of 1997/1998 experiencing the lowest extent of Arctic sea ice, leaving an ice-free passage (Reid et al., 2007). It has become established in the North Atlantic phytoplankton community although as yet there appears to be no adverse effects other than a change to community composition. In addition, the input of fresh water, from Greenland ice melting, may increase nutrient inputs, give significant earlier blooms in the Arctic (Kahru et al., 2011) and allow Atlantic phytoplankton species into the Arctic (Hegseth and Sundfjord, 2008).

Opening these routes also increases regional emissions of greenhouse gases and other hazardous materials (Macdonald et al., 2005) (hence affecting D8, 9, 10) although the new routes could reduce net shipping emissions globally. Furthermore, although not yet quantified, the northern increase of shipping will increase the noise field in the NE Atlantic, thus potentially causing GEnS for D11 to fail, although as yet these changes cannot be quantified in scale, extent or duration.

3. Discussion

3.1. Trajectories of change and meeting baselines for GEnS

The MSFD follows the sequence of descriptor-criteria-indicator-target-monitoring-measures-management (European Commission, 2010) (Fig. 1, inner circle) which aims to address anthropogenic stressors in a region but, as emphasised here, these cannot be separated form changes due to climate change. By definition, detecting GEnS (and also GEcS and FCS) is against the perceived and required status, i.e. a baseline, threshold or reference condition (e.g. Borja et al., 2012) irrespective of whether that status changes due to climate change. In the highly variable marine environment this is made even more challenging due to changing and ill-defined boundaries, what may be termed *moving baselines* and *unbounded-boundaries,* and the status of any component (e.g. mobile species, hydrographic patterns) is influenced not only by activities and pressures in an area but also as the consequences of events at large distances. Hence, there is the challenge of detecting a signal (such as failure to meet GEnS) against a background of inherent variability (the so-called signal-to-noise ratio).

Summarising the MSFD Descriptor entries in Figs. 2–10 in Table 2 shows the dominance of the repercussions for the biodiversity Descriptors (D1, 2, 4 and 6) especially the Biodiversity Descriptor 1 and its Criteria, indicators, metrics, targets and baselines. In particular, marine biodiversity change has to be judged against a defined baseline/reference/threshold value or situation, the essence of the MSFD in determining whether GEnS is or is not met. This requires indicators or indices/metrics to be agreed in relation to monitoring, measures and management (Teixeira et al., 2014). As shown here, wide-ranging climate change effects may prevent many indicators and targets set for achieving GEnS being met. The large empirical and modelling evidence (described above and in Table 1) shows the relative confidence that such changes will occur. However, as yet there is not the ability to extrapolate to quantitative predictions, especially in relation to the GEnS Descriptors.

Managing the marine ecosystem centres on separating the manageable endogenic signal from the effects of exogenic pressures, such as climate change, and from natural variability

Table 2
Main topics relating to the marine consequences of climate change and the way in which they influence the Good Environmental Status Descriptors D1–D11 (cross refer to Figs. 2–10; see text and Tables S1 and S2 for Descriptor titles).

Descriptor	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Topics											
I. Altered temperature regime – species re-distribution and community response	✓	✓	✓	✓		✓					
II. Altered temperature regime – individual physiological/phenological response	✓	✓	✓	✓	✓	✓					
III. Increased relative sea-level rise – physiographic changes	✓		✓	✓		✓	✓				
IV. Increased climate variability effects on coastal hydrodynamics	✓			✓		✓	✓				
V. Changes to large scale climatic patterns due to land run-off	✓		✓	✓	✓	✓	✓	✓	✓		
VI. Increased relative sea-level rise changing estuarine hydrodynamics	✓			✓		✓	✓				
VII. Increased ocean acidification and seawater physico-chemical changes	✓		✓	✓		✓		✓	✓		
VIII. Loss of polar ice cover and global transport repercussions	✓	✓	✓	✓	✓		✓			✓	✓
Sum categories	8	3	6	8	3	7	5	2	2	1	1

Table 3
The rate of change in latitudinal location of representative groups.

Organism	Rate of change	Reference
Phytoplankton	469.9 (±115.3) km dec^{-1}	Poloczanska et al. (2013)
Invertebrate zooplankton	142.1 (±27.8) km dec^{-1}	Poloczanska et al. (2013)
Copepods	≈500 km dec^{-1}	Calculated from Beaugrand et al. (2002)
Intertidal biota	50 km dec^{-1}	Helmuth et al. (2006)
Bony fish	277.5 (±76.9) km dec^{-1}	Poloczanska et al. (2013)
Plaice (North Sea)	−3.96 m (depth) dec^{-1} (1980–2004)	Dulvy et al. (2008)
	142 km NE (1913–2007)	Engelhard et al. (2011)
Sole (North Sea)	+7.64 m (depth) dec^{-1} (1980–2004)	Dulvy et al. (2008)
	93 km SE (1913–2007)	Engelhard et al. (2011)

(Elliott, 2011). Although management resources are limited, the ability to apportion change to endogenous anthropogenic pressures is especially important to setting GEnS targets and identifying management measures (Greenstreet et al., 2012) as is setting baselines against which ecosystem change will be interpreted. Hence the inherent difficulties in the ability to meet GEnS for biodiversity in areas where targets are impaired relies on understanding degradation and recovery of marine systems following the occurrence and removal of stressors (Borja et al., 2010b; Duarte et al., in press; Tett et al., 2013)

As indicated above, North Atlantic marine and coastal species are responding to climate change through distribution and regime shifts (Table 3) and these have repercussions for achieving GEnS for most of the Descriptors. As a species distribution changes due to climate change, its value as an indicator of anthropogenic change is compromised (Beaugrand, 2003). If such a species is designated as an MSFD indicator, its shifting abundance due to climate must be incorporated into any target set. It may not be practical, however ecologically or economically important or well-studied a taxon, to set a target for it at the limits of its distribution if that taxon disappears due to climate-driven biogeographical shifts (McQuatters-Gollop, 2012). Hence, any species whose abundance is governed by exogenous drivers is unlikely to be a good indicator for endogenic anthropogenic pressures. Despite this, species are often designated of conservation importance because of their fragility or rarity which may be due to their occurrence at their geographical limit or a particular set of conditions.

Historical data are valuable in setting baseline conditions but this may not be possible due to climate change, especially as marine areas have changed considerably in the past six decades (Beaugrand et al., 2002; Edwards and Richardson, 2004; McQuatters-Gollop et al., 2011), thus altering regional food-webs and fish stocks (Kirby and Beaugrand, 2009). Compounding this are the effects of combined stressors, for example climate change and overfishing (Damanaki, 2011), hence with repercussions for GEnS for D3 on fisheries exploitation (Perry et al., 2010; Pörtner and Peck, 2010; Greenstreet et al., 2012; Griffith et al., 2012). The interaction of climate change with multiple pressures and their cumulative, synergistic and antagonistic effects is particularly unknown (Brown et al., 2013). Interactions between climate, plankton and fish stocks may indicate that recovery of the latter to their previous levels is not possible, even assuming sustainable management. Thus the challenge then lies in deciding, for example amongst the MSFD indicators, which fish stocks can be regarded as a realistic 'baseline' but also in understanding that these changes may mean that GEnS cannot be either agreed or achieved.

The setting of targets and adequate monitoring is of utmost importance for an accurate assessment and consequently implementing adequate management measures to achieve GEnS. This requires that the science behind the pressure-impact-response sequence is adequate, i.e. that the amount of pressure required to produce an effect and then effect of a management response is well known. This is not the case – for example, as indicated for D5 (eutrophication) the science was inadequate where four ecosystems had different trajectories, ecological tipping points and hysteresis in response to nutrient abatement measures (Duarte et al., 2009, in press).

Similar failures under different pressures (e.g. fishing, aggregate extraction etc.) could be due to broad changes in environmental and climate conditions, all affecting ecosystem dynamics, especially during conservation management in the expected long time of recovery after taking management measures (Borja et al., 2010b). Hence setting reliable management targets in response to multiple shifting baselines under climate change is essential (Duarte et al., 2009, 2013; Andersen, 2012). Ecosystem response thresholds have been also related to marine regime shifts that are characterised by various drivers, scales and potential for management action (Meiner and Reker, 2013). Thus reliable thresholds and targets will need revising with moving baselines, being dynamic instead of static. Thus the increased 'noise' in the system, due to climate change, will require the yet to be defined thresholds (as class limits) which may need to be fuzzy to reflect the moving baselines. Hence given the usual short-term societal response (Swaney et al., 2012), the unpredictability of the changes require adaptive management which is made more challenging if the background involves moving baselines. This is particularly important in the case of the MSFD and its six-year reporting cycles but it remains to be seen whether such cycles can accommodate those moving baselines.

3.2. The repercussions for monitoring and management measures

Across Europe, there are many well-established regular monitoring programmes (Smith et al., 2010; Patrício et al., 2014) for all biodiversity components, which require to be continued but the extensive reduction in monitoring effort is an increasing cause for concern especially given current economic constraints (Borja and Elliott, 2013). These monitoring programmes are designed to assess the main changes resulting from single or multiple pressures but will be required to be spatially and temporally extended to detect further changes arising from climate change in relation to other pressures, such as organic enrichment and fishing (e.g. for benthos: Kröncke and Reiss, 2010). Although as shown here there are good spatial data for some components, there is limited information on the effects of climate change on elements of high conservation importance such as cetaceans and seals (Evans and Bjørge, 2013). Spatial data sets may need combining to give time-series and observations on particular surrogate species (e.g. intertidal organisms) could indicate trends in climate change effects (e.g. Mieszkowska et al., 2006; Nicolas et al., 2011, 2014).

Given the above difficulty of setting baselines and determining whether GEnS has been achieved, a major consideration is the adequacy of monitoring proposed, whether the monitoring cycle will be sufficient and how many monitoring cycles will be needed to accurately detect change. There is still uncertainty regarding the monitoring and measures required and their robustness particularly to enable accurate assessments for complying with the MSFD and other directives (Boyes and Elliott, 2014), to improve the state of the marine environment and to ensure its sustainable development.

The separation of the effects of the local and wider pressures described above and detection of shifting baselines will require high-resolution spatio-temporal data (McQuatters-Gollop et al., 2007; Couvet et al., 2011. However, Patrício et al. (2014) showed that although European monitoring programmes address most biodiversity components and Descriptors (although less so for D6, Seafloor Integrity), the ability to detect variation due to climate change depends on the sampling intensity, frequency, geographical scale of the monitoring, standardisation (over time) of sampling and analysis techniques and data quality rather than on the number of programmes. In addition, Patrício et al. (2014) questioned whether the monitoring programmes are scientifically sound and fit-for-purpose.

The empirical evidence presented of the responses of marine species to climate change will require to be supplemented by spatial modelling (e.g. Rombouts et al., 2012; Gormley et al., 2013) which predict species distributions from habitat information (Monk et al., 2012). However, the often mismatch between observed and expected distributions (see Reiss et al., 2014) emphasises the inadequacy of current monitoring. Therefore, whilst modelling is of value, it has limitations, hence not only are changes to GEnS difficult to predict, they also cannot be detected or have a cause attributed to them especially of climate-driven timescales. Hence the background of climate change will increase the scientific resources needed in the MSFD implementation.

Given the above, climate change will have repercussions at each stage of the MSFD implementation (Fig. 1, outer boxes). It requires the initial assessment to be revised given that ecological and hydrophysical characteristics will change and the pressures list for an area has to be expanded to include external pressures such as climate change; some of the Descriptors, Criteria and indicators, especially those which rely on the distribution of particular species, will have to be revised or even omitted as being unsuitable. Most importantly, climate-affected baselines will have to be constantly revised during the six-year iterative cycle hence requiring extensive spatial and temporal monitoring to detect the signal–noise ratio obscured by climate change. The management measures proposed should address the causes and consequences of the endogenic managed pressures as well as the consequences of exogenic unmanaged pressures emanating from climate change (Elliott, 2011; Field et al., 2014). For example, while a management measure to control the inflow of non-indigenous species in ballast water can be proposed, the separation of these species from those entering via increased polar connectivity will be difficult to detect and to control.

3.3. Climate change, MSFD and the legal repercussions – 'Force majeure or natural causes'

This review emphasises the difficulty of implementing MSFD and achieving GEnS because of climate change. Any Member State not fulfilling a Directive faces infraction proceedings for which there are considerable fines from the European Court of Justice. Article 14 of the MSFD indicates the following special cases for not meeting environmental targets or attaining GEnS: (a) *action or inaction for which the Member State concerned is not responsible*, (b) *natural causes*, (c) *force majeure*, (d) *modifications or alterations to the physical characteristics of marine waters brought about by actions taken for reasons of overriding public interest which outweigh the negative impact on the environment, including any transboundary impact*, (e) *natural conditions which do not allow timely improvement in the status of the marine waters concerned*. Hence in any legal challenge, Member States may claim that climate change is preventing GEnS or its targets and indicators being met or met within the time stated due to clause (a), (b), (c) and/or (e), because of shifting baselines, compromising the use of static reference conditions or targets, or without a return to a previous state of the system after restoration, because of changes in ecosystems due to climate change. The available scientific information, either empirical or modelling, will thus play a predominant role in addressing such a challenge and this will also centre on whether climate change is 'natural' or human-induced.

Article 14 requires Member States to prevent a 'deterioration in environmental status' due to the above causes but it is contended here that this rests on (i) proving that climate change does represent a deterioration rather than merely a change to another ecological state, and (ii) being able to address (mitigate) such a change. Of immediate relevance is that measures to deal with the consequences of Article 14 should be identified to the Commission at the time the overall programme of measures is proposed, i.e. 2015. The Article further advocates Member States take a regional approach to the causes of change but there is a further allowance that any actions requiring disproportionate costs will not be required as long as there is no further deterioration to the environmental status. The final section of the Article implies that Member States have to fully justify their decision to avoid taking steps to counter environmental change but as long as not achieving GEnS is not permanent.

As an example of the impending argument and role of science, global temperature changes will cause local physiological changes in organisms thus impacting bioenergetic rates such as growth and feeding and potentially leading to changes in spawning thresholds (see Rasmussen, 1973; Rijnsdorp et al., 2009). These organism changes will influence various metrics/indicators used to determine GEnS. This then has the potential to prevent GEnS being reached for several Descriptors and thus Member States will be threatened by infraction proceedings and being subject to heavy fines. Hence, a Member State could be penalised as the result of consequences of climate change which are not the result of its own action but rather global patterns. As in previous cases, the Member State would then engage scientific opinion and evidence to counter the claim and demonstrate either that this change is outside its control (*force majeure*), is a natural event and/or the system has not deteriorated but just changed. Hence, Member States should take this into account when designing monitoring networks, in order to quantify natural variability due to climate change. This information should then be used when assessing the status, to determine if the ecosystems experience either an unusual change or they do not return to the previous state when management measures are taken. This information should be used to justify, with appropriate and extensive scientific evidence, why GEnS is not achieved.

4. Concluding remarks and recommendations

As shown here, climate change produces impediments to implementing the MSFD and achieving GEnS and there are repercussions of those impediments:

(1) The science-base is good on conceptual aspects but is required to give precise links between changes in biota and climate features; the 'so-what?' and what-if?' questions cannot yet be answered. New scientific developments may overcome this during several iterations of the MSFD process. At the organismal level, knowledge is needed on how abiotic factors interact to control the vital processes (survival, growth, feeding) of different life stages; this will allow parameterizing models to project the cumulative impacts caused by, for example, warming, reduced dissolved oxygen concentrations and decreased pH values. A mechanistic, cause-and-effect understanding is needed of how key abiotic factors interact to affect vital rates (including optimal and suboptimal limits defining the species fundamental niche) (Pörtner and Peck, 2010). At the population level, additional process knowledge is needed including how extrinsic and intrinsic properties of populations may be linked (e.g. see Planque et al. (2011) for marine fish populations). Species-level responses to habitat change caused by multiple, interacting stressors will probably differ among populations and so ecosystem-level projections must accommodate changes in the strength of species interactions via bottom-up, top-down and intra-guild processes.

(2) Climate change produces '*shifting baselines*' which need to be accommodated in monitoring, particularly during the assessment of GEnS and marine management; actions will have to account for '*unbounded boundaries*' given the ecology and climate change-induced migrations and dispersal of highly-mobile, nekton and plankton species. Hence, long-term and spatially large datasets are essential for signal–noise separation, to identify changes in ecological indicators, detect sudden and gradual ecosystem shifts and regime changes, and provide a baseline against which to interpret future changes. However, given that such datasets do not exist for most components then this may not be achieved. As the MSFD takes the current conditions as the baseline, predictions are required against current values.

(3) More cost-effective spatial and temporal monitoring is required using current (e.g. Continuous Plankton Recorder, FerryBox), semi-autonomous or autonomous (sea gliders and wave gliders, moorings) or remote systems at the ecohydrodynamic rather than geographic scale. However, as monitoring budgets are being reduced, joint monitoring programmes are required across a suite of Descriptors. The absence of empirical data will increase the use of modelling but the error limits on the models may be large, and increase because of climate change, or even be unknown, thus giving poor predictability. Furthermore, existing models are adequate for scenario and semi-quantitative testing but not for detailed quantitative and accurate predictions.

(4) Member States at present are only considering the means of determining GEnS on a Descriptor-by-Descriptor basis but at some stage before 2020 they need to consider aggregating these to give GEnS for a regional or sub-regional area (Borja et al., 2014). Hence while assessing climate change on single Descriptors is the first priority, interactions amongst Descriptors and their changes due to climate change need addressing. Unless GEnS is defined across the Descriptors then ecosystem health (*sensu* Tett et al., 2013), will not be determined. However, it is questioned whether the science is adequate to judge changes in health due to climate change and whether any resulting system is regarded as 'unhealthy' ('deteriorated' *à la* MSFD) or just different.

(5) The challenges for marine monitoring and management result from having climate change superimposed on the effects of local activities and where climate change may either exacerbate or mask anthropogenic changes in the Descriptors. For example, whilst anthropogenic nutrient inputs from its catchment will be controlled by Member States to achieve GEnS for eutrophication, bloom-forming species not otherwise in an area may arrive and cause failure. Detecting change against a greater inherent variability will increase monitoring costs, a challenge in economically difficult times (Borja and Elliott, 2013).

(6) Climate-driven spatial and temporal variation should be interrogated including a potential geographic disparity to achieving GEnS across the marine environment in general and across the regional seas in NE Atlantic in particular. Raised temperature may have greater effects in northern than southern Europe but these are equivocal. Hence, baselines will have to be revised on a site-specific basis although the evidence needs to be extrapolated to show the short, medium and long-term effects and the speed of environmental response. Modelling is required to indicate how quickly communities can reach a new equilibrium but there is now an urgent need to show adaptation (or the lack of it) overs 10–100 s of generation times for marine organisms.

(7) Although not discussed further here, society will place emphasis on the repercussions of non-achieving GEnS for the Ecosystem Services and Societal Benefits obtained from the regional seas (e.g. Atkins et al., 2011). The loss of these due both to managed pressures but also climate change has to be determined and emphasised to environmental managers and policy-makers (Luisetti et al., 2014; Turner et al., 2014).

(8) The failure to meet GEnS because of climate change has wide-ranging legal repercussions and could lead to a Member State being placed in infraction proceedings. A legal challenge will arise not because of the pressures inside the waters of a Member State under which they might have some control (Endogenic managed pressures), but because of the external and non-controlled pressures (Exogenic unmanaged pressures). For example, a NW European Member State may be threatened with legal (infraction) proceedings for failing GEnS for non-indigenous species entering via new Arctic-related vectors over which the Member State has no control (*cf.* the corresponding case for the Suez Canal, Galil et al., 2014). The legal defence, that the failure was the result of third-party actions, natural causes or *force majeure*, would require to be supported by robust science.

(9) These lessons are relevant and applicable not only to European seas and the implementation of the MSFD but also to other global areas, for example during the implementation of the Canada Oceans Act and the US Oceans Act 2000 (US Congress, 2002). While the latter does not give the same degree of detail as the MSFD in achieving healthy and productive seas and it does not mention climate change

in its few pages, determining and managing change due to separating this from other anthropogenic pressures have to be considered.

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Appendix A. Supplementary material

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