# Temporal constraints on ecosystem management: definitions and examples from Europe's regional seas

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Temporal constraints on ecosystem management: Definitions and examples from Europe's regional seas

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**Abstract**
Our ability to meet environmental targets is often constrained by processes and events which occur over long timescales and which may not be considered during the planning process. We illustrate with examples and define three major types of temporal scale phenomena of relevance to marine managers: memory and future effects (jointly called legacy effects) and committed behaviours. We examine the role of these effects in achieving marine environmental targets in Europe under the Marine Strategy Framework Directive and the implications for future management indicating the increased importance that these temporal phenomena give to reducing future Pressures.

**Background**
The ecosystem approach to management requires decision makers to set environmental goals for utilising and maintaining ecosystem services and to put in place management measures to achieve these goals. Under the Marine Strategy Framework Directive (MSFD) the environmental target is Good Environmental Status (GEnS) which must be attained for each of eleven descriptors (D1-D11) prescribed in the Directive (EU 2008) and refined in the commission decision on descriptors (EU 2010). The MSFD seta out a strict timetable for initial assessment (both of the state of ecological systems and the social and economic consequences), definition of environmental targets, implementation of a programme of measures and finally achievement of GEnS (EU 2008; O'Higgins & Roth 2010). Implementation of the directive will be an iterative process with an adaptive management cycle for target setting and achievement every 6 years, following the initial cycle which ends in 2020. This represents a major challenge for European marine managers (Mee, 2008; Potts et al., 2012).

For the MSFD in particular and for marine management in general the attainability of goals and targets is dictated by the temporal characteristics of the Drivers, Pressures and environmental State changes relevant to a particular objective (see Cooper, 2012, for an account of the DPSWR approach). The ability to achieve targets depends on social and technical problems, the ability of society to manage the levels of Drivers and the Pressures, as well as ecological properties inherent in a particular environment which dictate how environmental State responds to Pressures. Future environmental State depends not just on societal Response measures and future actions but also on historical and current Drivers and Pressures and environmental State.

At its simplest, a past release of a marine pollutant could affect our ability to achieve GEnS today or in the future if the pollutant is persistent. In such a case historical Driver, Pressure and State alter current and potential future environmental status. The residence time of the particular pollutant in a particular system is dependent on the physical and ecological properties of the system. The combined physical chemical and biological characteristics of the systems work together to impose temporal constraints on rates of ecosystem processes and progress toward management goals. These complex combinations of properties are unique to each sea and variable between systems. For example, in Europe, regional seas (Baltic, Black, North Sea and Mediterranean) flushing times range three orders of magnitude from approximately annual in the North Sea (Rodhe et al., 2006) to millennial in the Black Sea (Murray et al., 1991). Though the physical properties determining flushing times are relatively simple and reasonably well understood, non-linearities in system response to changes in environmental pressures are the rule rather than the exception and these include shifting baselines (Duarte et al., 2009) as well as regime shifts to new stable states which may be the result of either anthropogenic or natural pressures (McQuatters-Gollop et al., 2008; de Young et al., 2008).

Recognition of the constraints on management imposed by temporal characteristics of social-ecological systems is a prerequisite for successful management. Targets for environmental status must be attainable and goals should be adapted to meet these changing constraints. The lack of functional classification of long term effects calls for definition of new concepts and changes in our assessment methodologies to better understand how temporal effects influence ecosystem processes and service provision.

In this paper we identify and formally characterize constraints resulting from Driver activities that are not amenable to Response in the short to medium term, and to provide illustrations and rigorous definitions. We apply these concepts in the analysis of cases studied for the KnowSeas project and discuss the implications for policy and management. We conclude with comments on the operationalization of these concepts and highlight their policy relevance.

**Definitions, classic illustrations and conceptual framework**

Over the period to 2020, the target date for delivery of GEnS the state of marine ecosystems will not simply represent the effect of Drivers and Pressures arising in that period but will also be affected by the legacy of previous activities, in addition the Drivers may be so deeply rooted in human systems that realistically they cannot be materially changed in an intended direction during that period. To formalise and develop these ideas, we define constraints on policy or management response over a prospective (planning) period as system properties or conditions that are not susceptible to response measures in that period. Thus, constraints constitute part of the context within which decisions for a planning period have to be formulated and made.

Effective management must focus on the elements of a social ecological system which are amenable to change through human action. Elements of the system, including irreversible changes which cannot be altered through management measures may be considered exogenous, lying outside the part of the system under the sphere of influence of the manager. The most obvious and widespread example of an exogenous constraint is the inherent variability in natural systems, introducing an exogenous influence on the interactions between human and ecological systems. Natural cyclical forcing of the environment occurs on many timescales. On the millennial timescales (of human evolution and emergence of civilisation) climate is controlled by planetary oscillations, Milankovitch cycles (Milankovitch, 1941). In the short to medium term (annual to decadal timescales) there are many cyclical phenomena forcing environmental processes, a prominent European example is the Atlantic Multidecadal Oscillation (AMO) (Schesinger and Ramankutty, 1994) the effects of which result in naturally changing conditions of the North Atlantic and the North Sea which are observed throughout the entire ecosystem from phytoplankton to marine mammals (Nye et al., 2013). These cycles comprise natural variability forming a baseline for environmental management which should be considered when setting targets but are not manageable through policies or measures.

Our focus in this paper is on endogenous constraints (effects), those that derive from human systems through Driver activities. We distinguish two broad types of such constraint according to when the relevant driver activities arise in relation to the planning period: legacy effects and committed behaviours. We have identified three important types of temporal effects which determine our ability to manage the seas: (i) memory effects (ii) future effects (jointly termed legacy effects) and (iii) committed behaviours.

The definitions of the different types of legacy effect (memory and future) and of committed behaviours are summarised formally in Figure 1a using a simple notation to indicate the critical DPSWR components and timings. Figure 1b provides a conceptual model presenting these effects in a broader context.

| Time, *t* | Legacy effects *(from past anthropogenic state change)* | | Committed behaviours *(future driver activities)* |
|---|---|---|---|
| | Memory effect *(in marine system)* | Future effect *(in other compartment)* | |
| | $D_{t<0}$ | $D_{t<0}$ | |
| | ↓ | ↓ | |
| | $\Delta S^{M}_{t<0}$ | $\Delta S^{N}_{t<0}$ | |
| | ↓ | ↓ | |
| *t* = 0 | $S^{M}_{t=0}$ | $S^{N}_{t=0}$ | |
| | ↓ | ↓ | $D_{t>0}$ |
| | ↓ | ↓ | ↓ |
| | ↓$\pm P^{M}_{t>0}$ | $P^{M}_{t>0}$ | $P^{M}_{t>0}$ |
| | ↓ | ↓ | ↓ |
| | $\Delta S^{M}_{t>0}$ | $\Delta S^{M}_{t>0}$ | $\Delta S^{M}_{t>0}$ |
| | ↓ | ↓ | ↓ |
| *t* = *T* | $S^{M}_{t=T}$ | $S^{M}_{t=T}$ | $S^{M}_{t=T}$ |

Figure 1a: *t* = 0 represents the time at which a decision is to be made and *t* = *T* the planning horizon, so that the planning period covers the range $0<t\leq T$. This figure adopts a similar approach to summarise the definition of the other class of endogenous constraints: committed behaviours showing causal relationships amongst a specific driver activity (*D*), pressure (*P*) and state (*S*) or state change ($\Delta S$). Where relevant, the superscript denotes the affected ecosystem compartment with *M* = marine system, and *N* = other (non-marine) ecosystem compartments. The subscript indicates the time at which the relationship is manifested relative to the time at which a decision is made (*t* = 0) and the planning horizon (*t* = *T*).

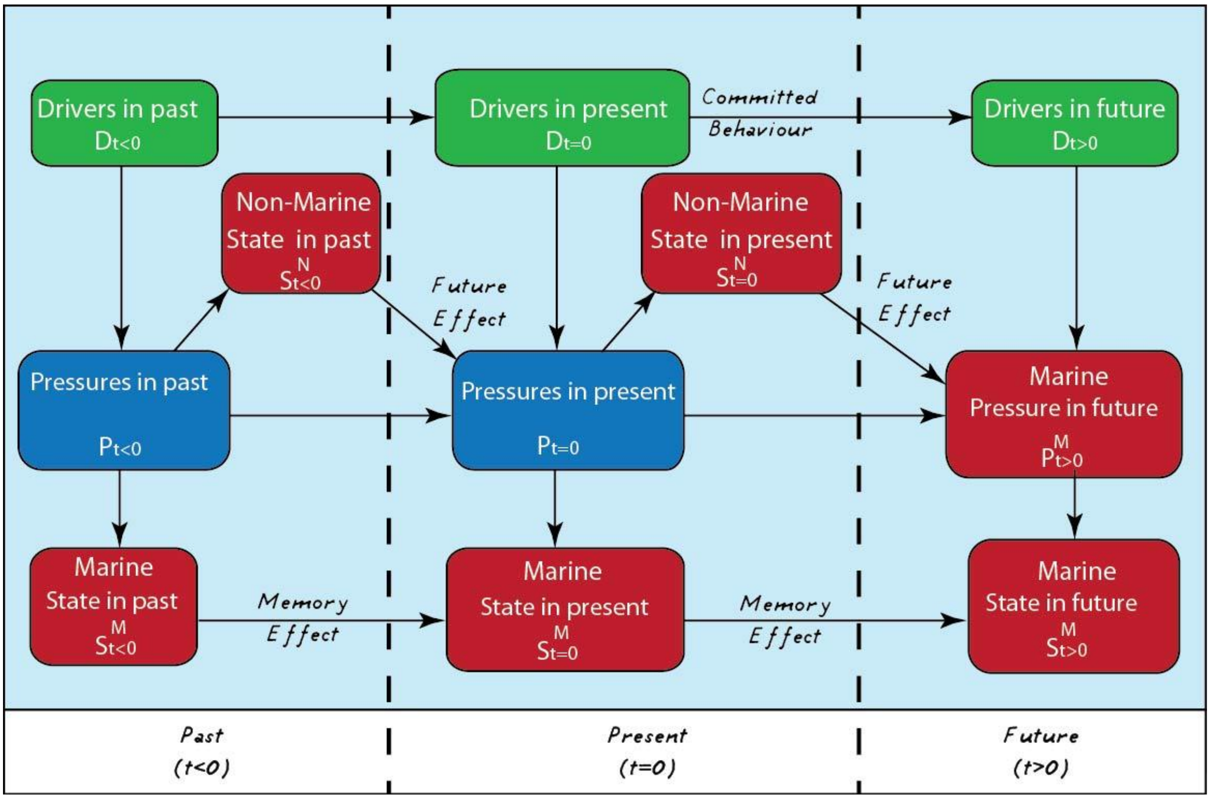


Figure 1b. Schematic diagram of legacy effects and committed behaviours showing Drivers in green Pressures in blue and State in red.

*(i) Memory Effects*

Legacy effects arise from past driver activities, i.e. prior to a planning period, which have altered ecosystems in such a way that they may be instrumental in further state change in marine systems during the planning period. Where the legacy is reflected in the state of marine systems at the start of the planning period, we refer to this as a *memory effect*: in such cases a 'memory' of previous marine system change is carried into the planning period and leads to further state change either naturally (subject to exogenous forcing) or as a result of pressures arising in the planning period.

A striking European example of a memory effect is that of the persistent eutrophication in the Baltic Sea. Large loads of nutrients arising primarily from agricultural and waste water inputs led to a severe eutrophication problem in the 1970s and 1980s characterized by an increase in phytoplankton primary production and increased the sedimentation of organic matter to the seabed. While the total nitrogen and phosphorus inputs to the Baltic since the mid-1990's have been successfully curtailed, the total phosphorus concentrations in the Baltic Sea have shown a general increase (ICES, 2010). This is due to the permanent stratification of the Baltic and limited physical flushing of the system through exchange with the North Sea, the phosphorus concentrations remain high because internal loads of iron bound phosphorus are released from sediments under low oxygen conditions fuelling continued eutrophication (Munkes, 2005) and determining the effects of future management efforts (Österblom et al. 2010).

*(ii) Future effects*

Where the legacy of previous driver activity is carried forward in another (non-marine) ecosystem compartment, we refer to a *future effect*. Such an effect arises where the (non-marine) state change exerts pressure on marine systems during the planning period, i.e. it has the capacity to be translated into a marine system change by constituting or exacerbating a pressure on marine systems in the planning period or in future planning periods.

The issue of ocean acidification (Doney et al., 2009) is a clear example of a future effect. In this case the anthropogenically augmented pool of carbon dioxide currently in the Earth's atmosphere will, over the coming decades, equilibrate with the oceans increasing the acidity of the marine environment and reducing the capacity of many calciferous marine organisms to build shells. Modelling of the effects of potential mitigation policies to limit $CO_2$ emissions indicates that maximum changes in ocean acidity will follow maximum atmospheric $CO_2$ inputs with a time lag in the order of 80 years (Bernie et al., 2010). In the European context this process poses a particular threat to cold water coral species such as *Lophelia pertusa*, found at high latitudes which provide essential fish habitat (Orr et al., 2005). In this way the existing pool of $CO_2$ in the atmosphere poses a predictable and unalterable future threat to marine ecosystems which should be considered when setting management targets. Counteracting ocean acidification requires a global actions and is effectively exogenous at the local to regional scale.

*(iii) Committed Behaviours*

While legacy effects result from human activities in the past which have implications for planning in the present due to the timescales associated with particular ecological processes, the ability of societies to manage the levels of Driver activities within a planning period can also impose constraints on management. Driver activities, the levels of which are not amenable to change in the short to medium term we refer to as, *Committed Behaviours.* Committed behaviours are associated with driver activities in the planning period and can include activities designed to offset existing environmental problems. As such, they may appear superficially to be within human control during the planning period but are only theoretically susceptible to response measures; in reality they are substantially likely to persist and thus are effectively embedded in the trajectory of future driver activities for the planning period. Committed behaviours may be conceptualised as norms and activities which it is not socially or politically feasible to alter in the short to medium term. Committed behaviours may be divided between those resulting from explicit social/ political decisions that have been taken prior to the planning period, and others that are implicit in the operation of economic systems.

An example of an explicit social decision made at the political level lies in the UK's licensing of areas of the North Sea within its Exclusive Economic Zone (EEZ) for future development of offshore wind farms (Crown Estate, 2012), paving the way for future driver activities in the form of turbine installation and operation. As in this example, explicit social decisions generally relate to specified activities with a specific spatial and temporal scope.

Another prominent example of explicit committed behaviours in Europe come from the capture fisheries sector. EU fishing fleet capacity adjustment is supported under the structural policy of the Common Fisheries Policy (CFP) (through a measure previously known as the "Multi-Annual Guidance Programme", MGAP). This was designed to address the excess fishing capacity which underpins the ecological and economic overfishing of European stocks. It is evident that the policy of subsidised voluntary withdrawals has failed to meet its objective. As the Parliament observed in 2002, commenting on the Commission's Annual reports to the Council and to the European Parliament on the results of the multi-annual guidance programmes for the fishing fleets at the end of 1997 (EC, 1999) and 1999 (EC, 2000a) the measures "*have not brought about the desired balance between stocks and their exploitation largely owing to the failure of the majority of the Member States to comply with the MAGP*" (EC, 200b). However, there was still a strong debate during the 2012 CFP reform process, regarding the retention of withdrawal subsidies, resulting in the European Council deciding to retain them until 2017. Even if the will to change had become evident earlier, it is doubtful that the CFP commitment to a 10 year policy cycle would have allowed substantive reform in the interim period. Following the recent vote (EU 2013) agreeing reforms to the common fisheries policy (EU 2011) it remains to be seen whether future actions will be more subject to the same committed behaviours.

By contrast, behaviours implicit in continuing operation of the economy cover a range of activities that are spatially and temporally pervasive, primarily driven by market dynamics. Figure 1 provides an illustration of this type of relationship in the case of maritime freight transport with the level of general economic activity in Europe (note, for example, how a decline in shipping activity tracks the decline in GDP following the recent economic crisis). Thus, even if the global distribution of manufacturing and consumption sites remains static, in the absence of some radical development of a more cost-effective technology for the international transportation of goods, it is to be expected that this use of the sea will continue to track general economic activity.

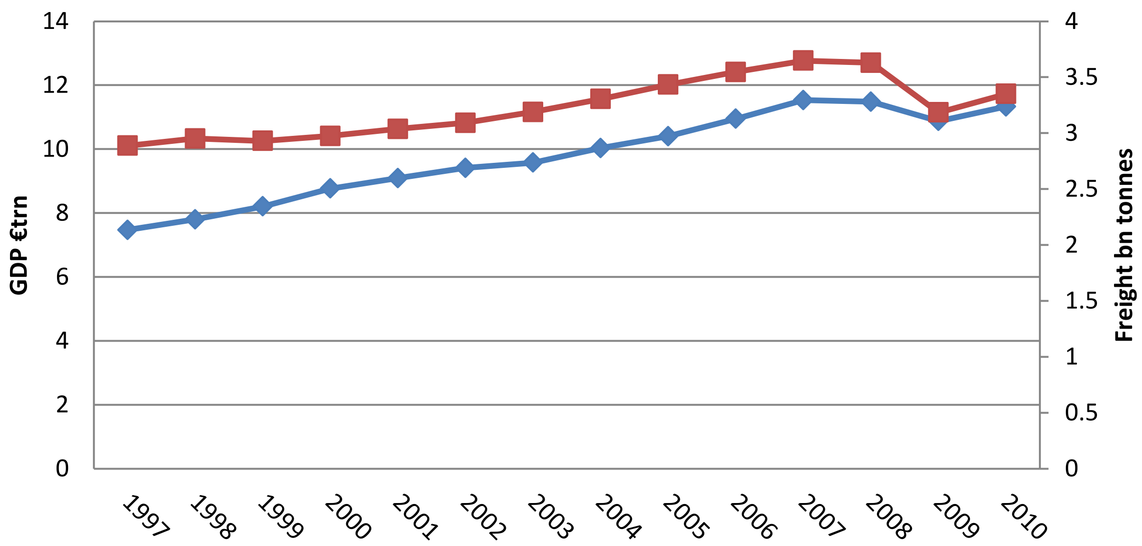


Figure 1 Economic activity (blue) and maritime freight (red) in the EU15 countries. *Sources of data:* Eurostat (2012) datasets *nama_gdp_c* (GDP at market prices) and *mar_mg_aa_cwh* (gross weight of goods handled in all ports in billion tonnes). The Pearson correlation coefficient between the two variables across the years in this sample is 0.913. For reasons of data availability, weight of goods handled is treated as a proxy for the number of trips and size of vessels, which are more likely to be relevant measures of the driver activity

## Results

## Legacy effects and committed behaviour in Europe's Seas

Based on the case studies of the KnowSeas project, we developed a matrix of memory and future effects and Marine Strategy Framework Directive (MSFD) Descriptors of Good Environmental Status (GEnS) for Europe's regional seas. Table 1 indicates the prevalence of legacy and future effects in the case studies considered.

Table 1: Examples of the occurrence of Memory (M) and Future (F) effects in European Regional Seas with respect to the MSFD descriptors. Footnotes indicate the specific topics covered and relevant literature for each case study.

| | Black Sea† | Baltic Sea‡ | North East Atlantic/North Sea | Med |
|---|---|---|---|---|
| 1. Biodiversity | - | - | F§ | - |
| 2. Non-indigenous species | M | - | - | M¶ |
| 3. Commercial species | M | M | F§ | - |
| 4. Food Webs | M | M | - | - |
| 5. Eutrophication | M/F | M | - | - |
| 6. Seafloor integrity | M†† | - | | - |
| 7. Alterations to hydrography | - | - | M\| | - |
| 8. Contaminants | - | - | - | M/F# |
| 9. Contaminants in seafood | - | - | - | F# |
| 10. Energy and noise | - | - | - | - |
| 11. Litter | - | - | M§ | - |

† Regime shift in the Black Sea (Llope et al. 2011; Daskalov et al. 2012)

†† Rapana venosa (Black Sea Commission, 2008; Knudsen and Koçak 2011)

‡Cod and Eutrophication in the Baltic Sea (O'Higgins & Roth 2010, Österblom et al., 2010)

§ Cold water corals (Söffker et al 2011; Tittensor et al., 2010; Hall-Spencer et al., 2009)

| North Sea Windfarms (Busch et al 2012)

¶Caulerpa taxifola introduction to the Mediterranean(Perez-Ruzafa et al., 2012)

#Contaminants in the Meditteranean(Gomez-Gutierrez et al., 2007 a,b; Albaiges, 2005)

Memory and Future effects are widespread phenomena in Europe's regional seas. All of the case studies considered in table one were subject to memory or/and future effects affecting at least one but more commonly several of the GEnS descriptors. Memory effects relate directly to D2 of the MSFD in the case studies of non-native alga *Caulerpa taxifolia* in the Mediterranean (Perez-Rufaza et al., 2012) and of predatory whelk *Rapana venosa* and the comb jelly *Mnemiopsis leydii* in the Black Sea (Daskalov et al., 2007). The comb jelly Memiopsis also results in memory effects on descriptor 3, through competition with juveniles of commercial species and descriptor 5 through predation on grazing zooplankton while the whelk Rapana diminishes sea-floor integrity by predation on native mussel reefs (Black Sea Commission, 2008). Memory effects are also associated with commercial species in the Black and Baltic Seas through historical overfishing as well as through the effects of eutrophication persistent pools of nutrients in the Baltic Sea. In the North Sea memory effects in the form of alterations to hydrography occur and will increase with the construction of offshore windfarms. The memory effect caused by the persistence of marine litter caught in cold water coral reefs is illustrated in Plate 1.

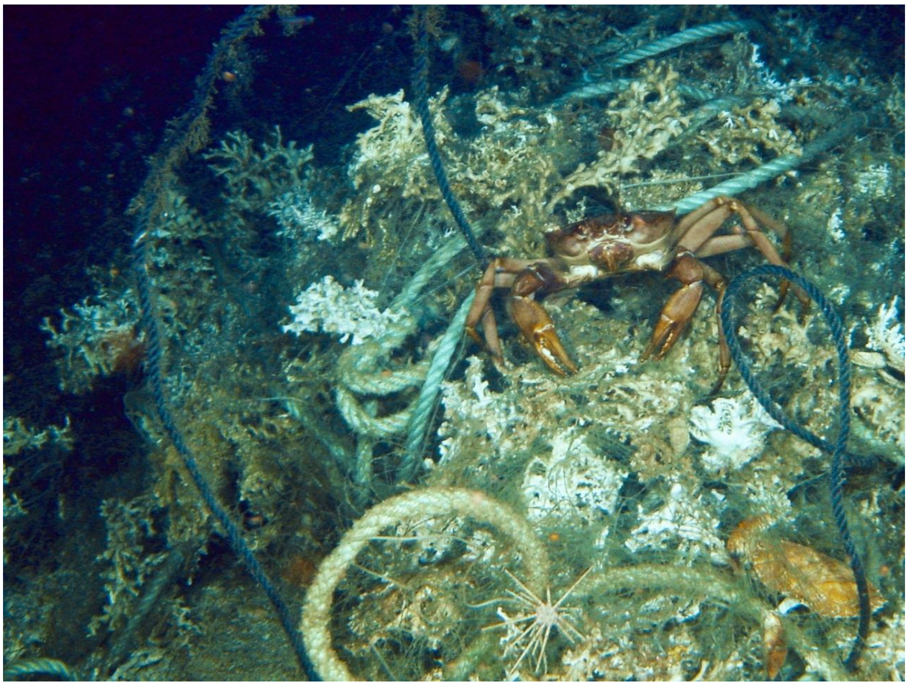

Plate 1: Cold water coral reef with entangled fishing gear indicating the memory effect of marine litter relevant to descriptor 11 of the Marine Strategy Framework Directive. From Söffker et al. (2011) No-biodegradable ropes are likely to remain entangled in the reefs for decades at the least.).

The examples given in Table 1 illustrate three different types of future effect, those related to atmospheric, terrestrial and sedimentary non-marine pools. Anthropogenic sources of carbon dioxide in the atmosphere will result in ocean acidification as discussed above. Warming of the oceans will alter the biogeochemical processes causing the release of accumulated contaminants currently found in sediments back into the marine environment (see Schiedek et al. 2007 for review). The future effects associated with the Black Sea case study are associated with pools of nutrients currently outside the marine environment where reservoirs of silica are bound up in the lakes created by the damming of the River Danube (Humborg et al., 1997).

A second matrix was developed relating sectoral drivers (implicit committed behaviours) and specific practices in a particular sector (eg. dredging, trawling) to the GEnS descriptors. Table 2 shows sectors affecting particular descriptors of GEnS, a more detailed account of the interactions between committed behaviours and descriptors can be found in the online supporting material.

| | 1<br>Biodiversity | 2<br>Non-indigenous species | 3<br>Commercial species | 4<br>Food Webs | 5<br>Eutrophication | 6<br>Seafloor integrity | 7<br>Alterations to hydrography | 8<br>Contaminants | 9<br>Contaminants in seafood | 10<br>Energy and noise | 11<br>Litter |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Shipping | X | X | | | | X | X | X | | X | X |
| Fishing | X | | X | X | X | X | | X | | X | X |
| Aquaculture | X | X | X | X | X | X | X | X | X | X | X |
| Agriculture | X | | | X | X | X | | X | X | | |
| Energy | | | | X | X | X | X | | | X | X |
| Construction and Urban Development | | | | | X | X | X | X | X | X | X |
| Tourism | | X | | | | X | | X | X | X | X |
| Mining | | | | | | X | | X | X | X | |
| Industry | | | | | | | | X | X | | |

Table 2: Examples of the relationship between some implicit committed behaviours and the MSFD descriptors

Each of the sectors presented in table 2 may be considered an implicit committed behaviour, as it is not politically feasible to change these activities in the short to medium term. These drivers exert a range of different Pressures on European Marine ecosystems affecting all of the GEnS descriptors.

Shipping affects biodiversity (D1) through the introduction of non-indigenous species (D2) and fouling organisms. The past use of antifoulants (e.g. TBT) also affected biodiversity (D1) by disrupting the reproduction of gastropods (Alzieu, 2000, Lewis & Ford, 2012). Dredging for maritime transport affects both seafloor integrity (D6) and hydrography (D7) while antifoulants, oils spills and ship emissions contribute to contaminants (D8) that may eventually taint seafood (D9). The noise (D10) and litter (D11) from ships are further effects on descriptors by the maritime sector.

Fishing affects biodiversity (D1), commercial species (D3) and food webs (D4) by the selective removal of certain species, notwithstanding by-catch. There is also a relationship with eutrophication (D5) as fishing exerts pressures further down the food chain by removing top predators. Bottom trawling in particular affects sea floor integrity (D6) and fishing port structures affect hydrography (D7). Antifoulants and ship emissions cause contamination (D8) while noise (D10) and litter (D11) are also a feature of the fishing fleet, as described above for the maritime transport sector.

The aquaculture sector affects biodiversity (D1) by the introduction of non-indigenous species (D2) and the market demand for certain species. Aquaculture may also affect food webs (D4) at a global scale, for example the fish-meal production in Peru and Chile from the anchoveta fisheries but also at a local scale, for example the removal of phytoplankton by filter-feeeding bivalves. Furthermore, this may have an attenuating effect on eutrophication (D5), (Ferreira et al, 2009), whereas feeding caged fish may have an aggravating effect on eutrophication (D5). Digging for bivalves, (e.g. clams) and the construction of aquaculture ponds affect seafloor integrity (D6) as well as hydrography (D7), in coastal areas. The use of contaminants (D8) in intensive aquaculture such as antibiotics, pesticides and colourants can have an effect on seafood (D9). There is also noise (D10) of motor boats for offshore aquaculture and litter (D11) from aquaculture nets, ropes and buoys.

Agriculture mainly affects biodiversity (D1) through the effects of eutrophication (D5) when excess use of fertilisers cause changes in the stoichiometry of nutrients such as N and P that alter the composition of the phytoplankton, the food web (D4) and therefore commercial catches(D3). Dams built to retain water for irrigation alter hydrography (D7) but also retain sediment thereby compromising seafloor integrity (D6). The use of contaminants (D8) in agriculture (pesticides, herbicides) and animal rearing (antibiotics, hormones, pesticides) may eventually contaminate seafood (D9).

Biodiversity (D1) is affected by the energy sector because offshore structures act as artificial reefs. Hydro-electric dams affect eutrophication (D5) as they change nutrient stoichiometry by retaining Silicon and altering the composition of phytoplankton. Sea floor integrity (D6) is affected by the installation of offshore structures and these alter hydrography (D7) by causing stirring. Noise (D10) is caused by activities around offshore installations that may also contribute to marine litter (D11).

Mining, in particular sand and gravel extraction, affects seafloor integrity (D6) and is a source of noise (D10). Mining may also release metal contaminants (D8) that may accumulate in seafood (D9). This is also true for industrial activities that cause contamination (D8 and D9).

Construction, urban development and tourism affect biodiversity (D1) through changes in coastal land use and especially land reclamation. In addition, coastal cruising may introduce non-indigenous species (D2) through ballast water and fouling organisms. Domestic effluent contributes to eutrophication (D5) which may also contain contaminants (D8) such as hormones, antibiotics, and other lifestyle pollutants that may eventually contaminate seafood (D9). Beach nourishment and coastal defence structures affect seafloor integrity (D6) and disrupt sediment cells as well as hydrography (D7), while large cruise ships re-suspend sediment (D6). Noise (D10) from power boats and jet skis as well as litter (D11) may originate from urban beaches and cruise ships.

*Discussion:*

In this paper we have introduced the concept of legacy as a constraint on policy and management planning but the concept has wider ramifications for the analysis of interactions between human and ecological systems that merit further research. Where legacy effects exist there is a temporal disjuncture between 'historic benefits' and 'future costs' that needs to be factored into cost-benefit analysis but it remains to be seen how far the matching of costs and benefits takes account of this temporal distribution. Furthermore, the idea of system legacy has implications for how changes in natural capital should be valued: there is the risk of over-estimating capital value if legacy effects are not taken into account.

Within the decision context of the MSFD the Environmental assessment, targets and indicators are set on national level. The delimitation of the ecosystem services (the descriptors) focus on the environmental degradation of the natural environment, as does the OSPAR (2010, Quality status report) and HELCOM (2010, Ecosystem Health of the Baltic Sea) assessment reports and does not at present integrate the need for a meaningful and appropriate classification system able to inform the political process, a pre-requisite for the integration of ecosystem services into decision making (Fisher et al., 2009). Alternatively, the assessment should focus on the definitions and characteristics which are necessary to protect or restore future welfare. The policy requirements for decisions on future "Programme of Measures" cannot exclude ecosystem imbalances for the sole reason of Legacy or Commitment, but may wish to adapt to the changes or actively offset the impacts (Welfare effects). The concepts developed in this paper can form the foundation of a meaningful and appropriate classification of ecosystem processes and services which may be used practically in decision making

While 'legacy effects' represent limitations in the capacity of ecosystems to deal with anthropogenic pressures, e.g. through assimilation of pollutants, 'committed behaviours' lie entirely in DPSWR's human domain and are thus more susceptible to social action. However, their likely persistence, as noted above, represents a form of inertia in social systems that is particularly acute in the case of behaviours connected with economic activity. Consequently, the design of responses intended to alter committed behaviours entails recognition of the forces shaping relevant economic activities and the scale at which they operate.

Driver activities ultimately manifest consumption demands and how markets are mobilized to meet those demands, respectively corresponding to the individual and institutional elements. Thus, two broad forms of response measure are highlighted: changing the level or pattern of consumption, e.g. through incentivizing individuals or influencing their preferences for the consumption of animal protein, and changing systems of production, e.g. through technological innovation to limit nutrient inputs. The detail of such responses goes beyond the current scope but these examples illustrate the long-term nature of the changes involved and hence the continuing challenge of social inertia. A challenge that is likely to be exacerbated by the underlying drivers of population growth, increasing affluence and globalization.

The scale of action required to implement social change adds further complexity to the challenge of social change. Although it is argued that environmental resources can be most sustainably managed by locally-devised, adaptive, institutions (Ostrom, 2005, 2009), few social-ecological systems are sufficiently closed at a local scale for this to be possible and certainly in the case of marine ecosystems social-ecological interactions occur at scales beyond conventional political boundaries. Therefore, response is required at the supra-national level, as in the case of the MSFD. At least in this case, it is arguable that the inertia of large institutions has been overcome in the sense of achieving a social decision on an objective. However, it remains to be seen whether the social changes required for its successful achievement can be implemented in the member states by the 2020 deadline. Experience with the Urban Waste Water Treatment Directive suggests that full implementation may take decades to occur (see, for example, Smith, 2000).

1. Awareness

An understanding of memory and future effects is needed by all those involved in marine management. The MSFD requires (Art. 8) an assessment of the status of marine waters. This is more than simply an assessment of a pollutant concentration or size of a fish population, but requires an understanding of how status has changed and likely future projection. Embedded within this assessment, memory effects need to be determined. Is a state change permanent or transient? Would measures to address a pressure cause a state change or not, or over what possible timescale?

Awareness of memory effects is not only essential for the marine manager, but also for communication by marine managers with stakeholders. Stakeholders need to understand the opportunities and limits for change in marine systems due to memory effects and potential timescales for change. Research and modelling are also required to better assess the timeframes for temporal effects.

2. Developing indicators and targets

The MSFD requires the establishment of indicators (Art. 10) to guide the development of measures and monitoring. It is important to understand the implications of memory effects in developing indicators as required by the MSFD, in particular where such indicators are established with respect to a baseline metric. If the baseline includes a memory effect, this might result in a target or indicator which is realistic in management. Alternatively, it may result in an artificial result. For example, if a target is set according to the number of 25 year old cod in the North Sea and the oldest cod in the sea is currently 12 years old, the target could not be met for at least another 13 years.

While a number of memory effects have been identified and some studied in detail, some are only understood in general terms. Therefore, identifying clear indicators and integrating memory effects within monitoring is necessary to move from conceptual understanding to generating sufficient information for practical application.

Similarly in the setting of targets under the MSFD (Art. 9), understanding the role of memory effects is critical in determining the future marine environment that is achievable. Without this targets could be too ambitious (e.g. seeking to remove memory effects) or over-estimate the level of those effects.

3. Inclusion in Programmes of Measures

The actions to be taken forward to achieve the objectives of the MSFD within Marine Strategies are to be set out in programmes of measures (Art. 13). In establishing such measures it is critically important to ensure that memory effects and future effects are understood with respect to the individual marine regions, pressures, etc., so as to identify the adoption of measures which would be most effective at tackling individual pressures and to avoid measures which would be ineffective and result in unnecessary costs.

Furthermore, understanding the interaction between ongoing pressures and legacy effects may change the measures considered appropriate to some pressures (e.g. reflecting a change understanding of the scale of the impact of those pressures). With regard to committed behaviour, measures also need to target the key aspects of decoupling which would most alleviate the pressures resulting from the drivers.

4. Decoupling limits state change externalities (welfare).

While committed behaviours constitute a constraint on policy and management decisions, the extent of their impact needs to be assessed in terms of the Pressures they exert on marine ecosystems. Consequently, the decision-maker should recognise the scope for decoupling between driver activities and the pressures they exert: ultimately it is the extent of Pressure rather than the level of driver activity that leads to change in environmental State and consequent changes in Welfare. For example, more stringent treatment of urban waste water has decreased the nutrient loading to rivers and coastal seas without requiring changes in patterns of consumption by citizens. This potential for decoupling presents opportunities for the decision-maker to implement response measures that will limit the alterations to ecosystem State resulting from committed behaviours. Nevertheless, without complete decoupling the driver activity remains a source of state change in the planning period.

Some future effects are strong and reflect the robustness of certain human activities in delivery social and economic needs. For example, agricultural activity causes a number of impacts on marine systems, but it is not conceivable that this sector, as a driver, be significantly curtailed in Europe. Some major drivers have declined, such as industrial activity, but this has partly been through exporting the activity to other areas of the world (e.g. East Asia), which results in impacts on marine waters there. However, there is now discussion on whether reindustrialisation of Europe is desirable. For committed behaviours the challenge for marine managers (and others) is to decouple the driver activity from the pressure(s) that it causes. Ensuring agricultural productivity can continue with lower fertiliser and pesticide inputs would deliver such decoupling. Similarly, altering fishing behaviour to allow for sustainable catch levels while delivering maximum sustainable yield would also deliver decoupling. Measures under the directive however do not specifically address the innovation required to decouple drivers from pressures.

**Conclusions**

While the importance of spatial considerations in applying an ecosystem approach to marine management has been widely recognised (eg. O'Higgins et al., 2010; Alexander et al., 2011; Jordan et al., 2012) temporal aspects have received less focus. We have described and defined several important and widespread temporal characteristics of social- ecological systems which constrain our ability to manage them, these are legacy effects (and the subcategories of memory and future effects) as well as implicit and explicit committed behaviours. These concepts present a formal analytical framework to allow us to integrate considerations of our past activities, their current and future impacts into decision making providing a basis for addressing intergenerational equity in environmental management. In some cases the costs of environmental remediation may only be justified when offset against benefits which were experienced by a previous generation (O'Higgins & Roth, 2010).

The importance of legacy effects and committed behaviour is not limited to the implementation of the MSFD but has global implications concerning historical and futures costs and benefits, where and when they occur and how they can be efficiently and effectively managed.

Given the nature of committed behaviour, the technological means of decoupling drivers from the pressures they cause in the environment should be a priority for research and for policy.

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