Challenges for implementing the Marine Strategy Framework Directive in a climate of macroecological change

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Unprecedented basin-scale ecological changes are occurring in our seas. As temperature and carbon dioxide concentrations increase, the extent of sea ice is decreasing, stratification and nutrient regimes are changing and pH is decreasing. These unparalleled changes present new challenges for managing our seas, as we are only just beginning to understand the ecological manifestations of these climate alterations. The Marine Strategy Framework Directive requires all European Member States to achieve good environmental status (GES) in their seas by 2020; this means management towards GES will take place against a background of climate-driven macroecological change. Each Member State must set environmental targets to achieve GES; however, in order to do so, an understanding of large-scale ecological change in the marine ecosystem is necessary. Much of our knowledge of macroecological change in the North Atlantic is a result of research using data gathered by the Continuous Plankton Recorder (CPR) survey, a near-surface plankton monitoring programme that has been sampling in the North Atlantic since 1931. CPR data indicate that North Atlantic and North Sea plankton dynamics are responding to both climate and human-induced changes, presenting challenges to the development of pelagic targets for achievement of GES in European Seas. Thus, the continuation of long-term ecological time series such as the CPR survey is crucial for informing and supporting the sustainable management of European seas through policy mechanisms.

Keywords: Marine Strategy Framework Directive; plankton; climate change 15; ocean acidification; biodiversity; Continuous Plankton Recorder

1. Introduction

Owing to the range, extent of occurrence and interactions between anthropogenic and climatic pressures, managing marine waters is a complex task. Historically, European marine management has focused on discrete aspects of anthropogenic pressures or ecosystem components. For example, at the European level, nutrients are managed by the Nitrates and Urban Waste Water Treatment directives [1,2], coastal eutrophication by the Water Framework directive [3], commercial fishing by the Common Fisheries Policy (CFP) [4] and conservation by the Habitats
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directive [5]. While these directives all address management of specialized elements of the marine system, lack of political integration has resulted in inefficiencies, gaps and even conflicts in management. For example, the objective of the CFP is to deliver economically, environmentally and socially sustainable fisheries [4]. From an environmental perspective, the CFP is failing to deliver this goal. Not only is there a recognized issue with wasteful discard practices, 72 per cent of European commercial stocks are overfished [6]. Additionally, the environmental impacts of fishing extend further than just the fish themselves. Trawl fishing is affecting most of the European continental shelf seabed every year, resulting in ongoing destruction of sensitive benthic habitats, destabilization of the sediment, increased turbidity and lowered biological diversity [7–9]. Integration of management mechanisms is clearly needed to halt the degradation of European marine ecosystems.

To sustainably manage European seas in a holistic manner, in 2008 the European Commission passed into force the Marine Strategy Framework Directive (MSFD) [10]. The rationale behind the MSFD is to manage the marine ecosystem to a healthy and productive state (good environmental status; GES) by harmonizing existing policies and filling gaps left by other pieces of legislation. The objective of the MSFD is to achieve GES of Europe’s seas by 2020.

In order to achieve GES by 2020, each European Member State is required to determine by 2012 the characteristics of GES and to establish the targets and associated indicators needed to guide progress towards GES (figure 1). This is a critical step in the MSFD implementation process. Although the MSFD provides qualitative descriptors of GES (table 1), the directive does not explicitly describe the vision of GES for these descriptors. Moreover, the directive itself gives very little guidance advising Member States on how to select indicators, set targets and determine what GES looks like for their waters. The European Commission’s decision of 2010 [12] and additional work by European Task Groups [13] and the OSPAR Commission [14] have provided some further criteria and direction for indicator selection and target setting, but, as with deciding what constitutes GES, the actual development of relevant indicators and setting of targets has been left to the discretion of the Member States.

According to the MSFD, plankton must be monitored towards GES. They also occupy the base of the marine food web, are sensitive to changes in their environment and are crucial to the functioning of the marine ecosystem [15], making them good indicators for environmental change. The Continuous Plankton Recorder (CPR) survey is an ecologically rich and spatially extensive

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**Figure 1. MSFD timeline to implementation (adapted from [11]).**
Table 1. The Marine Strategy Framework Directive’s 11 qualitative descriptors of good environmental status.

<table>
<thead>
<tr>
<th>Descriptor</th>
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<tbody>
<tr>
<td>1. biological diversity must be maintained</td>
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<td>2. non-indigenous species are at levels that do not adversely alter the ecosystem</td>
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<tr>
<td>3. commercial fish populations are within safe biological limits</td>
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<tr>
<td>4. marine food webs are intact and functioning</td>
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<td>5. anthropogenic eutrophication is minimized</td>
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<td>6. sea-floor integrity is structurally and functionally sound</td>
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<tr>
<td>7. hydrographic alterations do not adversely affect marine ecosystems</td>
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<tr>
<td>8. contaminant concentrations do not give rise to pollution effects</td>
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<tr>
<td>9. seafood contamination is at safe levels</td>
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<tr>
<td>10. marine litter does not harm the environment</td>
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<tr>
<td>11. anthropogenically caused energy and noise do not adversely affect the marine environment</td>
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near-surface plankton-monitoring programme that has been collecting plankton data in the North Atlantic and North Sea for eight decades. The aim of this study was to show that the response of plankton dynamics to both climate and anthropogenic drivers presents challenges to the development of pelagic targets and the determination of GES in European seas, and that the continuation of such long-term time-series datasets as the CPR survey is imperative to understand and sustainably manage our seas.

2. Challenges for managing European seas

(a) The need for long-term data

The MSFD states that GES should be achieved by using an ecosystem-based approach. A key characteristic of the ecosystem approach is that humans are included as a part of the natural ecosystem and that human activities must be managed so that they are sustainable in the long term, and do not compromise any ecosystem components that contribute to the overall ecosystem’s structural and functional integrity [16]. Implementing this management approach is complicated, as the ecosystem must be managed holistically, considering all aspects (ecological, physical, chemical and human) simultaneously. Ecosystem management is data intensive and requires an understanding of ecosystem structure and functioning. To successfully implement the MSFD, long-term biological datasets are crucial for informing indicators, constructing environmental targets and defining GES.

There is a recognized global paucity in long-term ecological datasets available to support management and decision-making [17,18]. Funding constraints often limit the frequency of sampling, spatial area covered or length of time series of datasets, factors that are important for monitoring regional-scale change over time, particularly when the marine environment is responding to climate change [18]. The CPR survey is an exception, collecting approximately 1 million plankton samples in the North Sea/North Atlantic during the past eight
decades, using cost-effective voluntary ‘ships of opportunity’. The CPR survey is operated by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS), an internationally funded charity located in the UK. The survey, which routinely identifies approximately 500 plankton taxa, most to species level, has had a virtually unchanged methodology since 1931, making it the world’s longest and most spatially extensive macroecological marine dataset (see [19,20] for detail on CPR data collection and use). The CPR survey has evolved in response to policy needs and so has been used to develop applied indicators that routinely inform UK, European and basin-scale policy and management mechanisms [18]. Owing to the long time series, expansive spatial coverage, ecologically rich dataset and policy-motivated development of the survey, the CPR survey provides critical data and expertise to support decision-making and help meet the challenges faced by Member States during this first phase of MSFD implementation.

(b) Dealing with climate variability

During the past five decades, there have been significant climate-driven changes in plankton community composition and dynamics in the North Sea and Northeast Atlantic. Phytoplankton biomass has increased [21], phytoplankton functional group dominance has changed [22], biogeographical shifts have increased the population of warm-water taxa in the North Sea and North Atlantic [23,24] and Arctic sea ice decline has allowed the establishment of a species extinct from the Northeast Atlantic for the past 800000 years [25]. Although contemporary anthropogenic pressures such as fishing and eutrophication can be managed, the changes in climate that are being observed at the moment are a response to previous carbon emissions, and so cannot be managed. Management measures may be taken to decrease future emissions and mitigate and adapt to climate change, but ecosystems will continue to respond to past emissions. In fact, if carbon emissions were immediately halted at the global scale, our planet would still experience anthropogenic climate change, including global warming, for decades to centuries [26]. Ecosystem responses to climate change must therefore be considered and accounted for when defining GES and setting targets for the MSFD. Throughout this study, the term ‘anthropogenic’ will be used to reference and describe manageable pressures such as fishing and eutrophication, and the term ‘climate change’ will be used to reference and describe ecosystem changes and pressures resulting from alterations in climate, which, though anthropogenically driven, are unmanageable at decadal time scales.

In order to effectively manage the ecosystem, it must first be determined which ecosystem changes are anthropogenically induced, and can therefore be managed through regulation of pressures, and which changes are unmanageable, such as those caused by natural climate variability and climate change resulting from past carbon emissions. This is a key scientific challenge that profoundly impacts all aspects of indicator and target selection and ultimately the management of marine ecosystems. Comparing changes observed in coastal waters, which are normally more severely impacted by land-based anthropogenic activities, with changes (or lack of changes) observed in less impacted open waters is one such method that can be used to separate the two signals [27], but time-series data that are spatially appropriate are needed first.
During the 1970s, 1980s and 1990s, increased phytoplankton biomass, increased flagellate abundance and elevated numbers of harmful algal bloom taxa were observed in some coastal regions of the North Sea [22,27,28]. Initially, these changes were attributed to anthropogenic eutrophication caused by increasing concentrations of nutrients from land-based sources [29–32]. Examination of offshore CPR data revealed that the changes occurring in coastal waters were also observed in the less anthropogenically impacted open North Sea [27], suggesting that phytoplankton dynamics were being driven not by nutrients but by large-scale climatic drivers [27,28,33]. The importance of climatic drivers to North Sea plankton does not mean that eutrophication is not a problem in some localized areas of the coastal North Sea, but instead indicates that climate is influencing the whole North Sea system at a regional scale and may actually be a more important driver of phytoplankton dynamics in much of the coastal North Sea than are nutrients [27,33]. This suggests that climate change may exacerbate eutrophication in the North Sea; although nutrient concentrations have decreased in coastal waters, increased water clarity and sea-surface temperature have extended the growing season, enabling phytoplankton to make better use of lower concentrations of nutrients [27]. In other words, climate change may increase the sensitivity of coastal waters to eutrophication, complicating the target-setting process. Because of this, separating the manageable anthropogenic and unmanageable climate signals is especially important and targets must be constructed in a way that accommodates climate-driven changes but triggers management action when they fail because of anthropogenic activity. With its extensive spatial coverage and long time series, the CPR dataset provides an open sea perspective that can be used to interpret changes occurring in coastal plankton dynamics, facilitating separation of plankton responses to climate from those driven by anthropogenic nutrients.

Gradual climate-driven changes require special accommodation when setting political targets. During the last 50 years, a biogeographical shift has occurred in the distribution of some marine taxa with calanoid copepods, a key zooplankton indicator group, experiencing a 1000 km northward shift [24,34]. The presence of warm water/subtropical plankton species has progressively increased in the more temperate areas of the Northeast Atlantic, while cold water taxa have retreated poleward (figure 2). As a result, *Calanus helgolandicus*, a warm water copepod species, is replacing *Calanus finmarchicus*, a cold water species, in the North Sea [23]. Although *C. helgolandicus* is increasing in abundance, it is not replacing its sister species in the same numbers, leading to an overall decline in *Calanus* abundance in the North Sea [35]. The change in distribution of these two copepods, regularly used as indicators because of their tight link with climate, is significant because of their key place in the North Sea food web (figure 3). This instance of remarkable yet gradual climate-driven change must somehow be dealt with when selecting indicators and setting targets for the MSFD. If any species or group of species is designated as an MSFD indicator, the fact that its abundance is shifting owing to climate must be incorporated into any target that is set. It may not be practical, however ecologically or economically important a taxon is, to set a target for it at the limits of its distributional range if that taxon may soon not be found there as a result of climate-driven biogeographical shifts. Therefore, it may make more sense to set a qualitative or trend-based target, rather than a target for absolute abundance, for indicators undergoing progressive changes.
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<table>
<thead>
<tr>
<th>warm temperate species</th>
<th>temperate species</th>
<th>cold temperate species</th>
<th>subarctic species</th>
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<tr>
<td>60° N</td>
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<tr>
<th>mean no. species per CPR sample per assemblage</th>
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<tr>
<td>0 0.04 0.08</td>
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<tr>
<td>0 0.4 0.8</td>
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Figure 2. Biogeographical changes in calanoid copepod assemblages spanning five decades. Cold water plankton (e.g. subarctic species) are moving poleward out of the North Sea, and are being replaced by warm water plankton (e.g. warm temperate species) (adapted from [34]).

Sudden ecosystem change presents an entirely different challenge when setting targets. During the 1980s, the North Sea and Northeast Atlantic ecosystem experienced a rapid increase in phytoplankton biomass [21,37], changes in copepod diversity and community structure [23,38], changes in plankton phenology resulting in trophic mismatch [28,39] and alterations to benthic communities [40]. The multi-decadal CPR dataset revealed that these significant ecosystem alterations were part of a region-wide climate-driven regime shift, affecting multiple trophic levels [41]. Nonlinearities such as regime shifts are inherently difficult to predict, and therefore are challenging to account for in...
management scenarios. Any sudden change in an ecosystem indicator could invalidate environmental targets. For example, phytoplankton biomass increased by 21 per cent in North Sea coastal waters as a result of the regime shift [27]. If a target is set for phytoplankton biomass as part of the MSFD process, for example as an indicator of eutrophication, such a regime shift could cause the target to fail. This is the case with either a quantitative target (for instance, a coastal annual mean $<4.0 \text{mg m}^{-3}$ chlorophyll) or a qualitative target (for instance, no significantly increasing trend in annual mean chlorophyll); both of these theoretical targets would have been breached as a result of the rapid unmanageable change caused by the regime shift. Although this example is for phytoplankton biomass, these circumstances could apply to other ecosystem indicators as well because regime shifts impact multiple trophic levels. During target development, it is therefore imperative to require the identification of the driver behind the indicator change that causes the target to fail so that a link to a manageable human pressure is ascertained. During the next round of assessment (every 6 years for the MSFD), the target can then be adjusted to reflect the new regime.

Regime shifts are not the only unpredictable climate-driven events whose impacts must be incorporated into management targets. Climate change is creating opportunities for the establishment of organisms in new environments.
where they are now able to survive and flourish in previously unsuitable regions. At times, the introduction of such organisms can be specifically linked to a discrete event, whether climatic or anthropogenic. Instatement of management measures to prevent introduction falls under descriptor 2: non-indigenous species; however, this descriptor addresses only anthropogenically induced introductions. Non-indigenous species, particularly those that carry diseases, are toxic, or become invasive, and can disrupt ecosystems in similar ways regardless of their means of introduction. While many climatically driven introductions occur as a gradual process, such as biogeographical range shifts, some do occur as unpredictable, rapid or sudden events. Multi-decadal times-series datasets rich in ecological information are necessary in order to identify the first appearance of new organisms and any consequent changes to ecosystem structure. In 1999, a Pacific Ocean diatom species, *Neodenticula seminae*, was identified in North Atlantic CPR samples. Although regularly found in Pacific CPR samples, the species had become extinct in the North Atlantic basin 800,000 years previously. Further investigation showed that the summer of 1997/1998 experienced the then lowest extent of Arctic sea ice, leaving an ice-free passage through the Arctic Ocean, through which the diatom performed the first recorded trans-Arctic migration in recent times [25]. Since its introduction, *N. seminae* has become an established member of the North Atlantic phytoplankton community. The extent of *N. seminae*’s impact on the structure and functioning of the Arctic and North Atlantic ecosystems is currently unknown; however, its sudden and unpredictable introduction and incorporation into the ecosystem may signal a potential inundation of new organisms, some of which could be toxic or disruptful to North Atlantic food webs. Regardless of the source of introduction, the potential ecosystem impacts of the appearance and establishment of a non-native species may cause failure of environmental targets for descriptors 1: biodiversity; 4: food webs; or 6: sea-floor integrity. Targets therefore require the flexibility to accommodate introductions and the potential impacts of non-indigenous species through unpredictable, non-anthropogenically driven events.

\( (c) \) Dealing with uncertainty

Despite progress in climate and ecological research, scientists do not fully understand the ecological or physical manifestations of climate change or the mechanisms behind them, the temporal and spatial scales associated with climate change impacts, the interactions between climatic and anthropogenic pressures, or the existence of ecological thresholds and tipping points. Regardless of this uncertainty, it is still necessary to set legally binding targets for the MSFD, which need to account for this lack of understanding yet still ensure sustainable use and achievement of GES. Ocean acidification is a result of anthropogenic climate change and its effects are considered an unmanageable ‘prevailing climatic condition’ by the MSFD. This implies that, like climate change-driven alterations in temperature, the ecological manifestations of ocean acidification must be recognized and understood so that they can be separated from manageable anthropogenically induced ecosystem changes. Although it is generally acknowledged that acidification will affect the plankton, the scientific understanding of ecological effects of decreased pH is often conflicting,
even between different strains of a single species of phytoplankton [42]. Because calcification rates may decline with decreasing pH, coccolithophores (a calcifying phytoplankton taxon) are likely to be particularly vulnerable to ocean acidification [43,44]. Coccolithophores are important primary producers and are also responsible for the production of more than 50 per cent of global open ocean calcium carbonate, playing a key role in the marine carbon cycle [45]. Coccolithophores form calcium carbonate liths, or shell-like plates, in surface waters, which then precipitate to the sea floor; in this way, coccolithophores act as a sink for atmospheric CO$_2$, and changes in their abundance could affect the way the oceans absorb CO$_2$ with major consequences for global warming [44,46,47].

Some laboratory studies have found that coccolithophores experience compromised lith formation when exposed to an acidic environment [43,48]. This might suggest that, as ocean acidification escalates, abundance of coccolithophores in the sea may decrease. While this may be the case in the future, long-term monitoring data from the CPR survey show the opposite: the frequency of occurrence of coccolithophores on CPR samples has increased during the past two decades [49] (figure 4), a likely response to warming sea-surface temperature [21,50]. This is a clear example of a gap in our knowledge of marine ecosystem response to ocean acidification. Despite scientific uncertainty, Member States must use the best available expertise to inform the target-setting process. Maintenance of long-term ecological time series such as the CPR survey is crucial in order to provide an essential baseline from which to observe future changes in vulnerable organisms. As scientific understanding evolves, the CPR time series can be used to recognize and interpret ecological changes, identifying links to drivers, and informing the revision of MSFD targets during each assessment period.

(d) Trophic complexity

Not only are anthropogenic pressures and climate acting on our marine ecosystem, complex trophic interactions between components of the marine food web also exist, compounding the difficulty of managing the marine ecosystem. Linkages between ecosystem components therefore must be identified and
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Figure 5. Long-term changes in cod (solid line) recruitment (1 year olds, 1 year lag) significantly covaried positively with changes in plankton (dashed line) (dominated by cold water copepod *Calanus finmarchicus*) (adapted from [52]).

considered along with climate forcing and human impact when setting management targets and determining GES. Because changes in the plankton resonate upwards through the food web, an understanding of plankton-relevant trophic linkages can aid and inform the management of other non-plankton ecosystem components.

An ecosystem’s past reference (unimpacted) conditions may be thought of as its most desirable state, which, once allowing for sustainable use, could be designated as GES. However, once changes in the food web are considered, it may not be realistic, or even possible, to arrive at this historical vision of GES, regardless of management measures instated. North Sea cod are severely overfished, experiencing a 70 per cent decline in catch over the past decade [51]. Research using CPR data indicates that both the decline in standing stock biomass [52] (figure 5) and poor recruitment success of North Sea cod [53] are linked to decreasing *C. finmarchicus* abundance, a key prey species (figure 3). Furthermore, there is increasing evidence suggesting that jellyfish numbers are rising as a result of warming seas and anthropogenic pressures [54]. This is an additional pressure on North Sea cod as jellyfish not only compete with larval fish for zooplankton prey, but also prey on larval fish themselves [36,54] (figure 3). Because of the strong influence of climate on the North Sea food web, it may be impossible for North Sea cod stocks to recover to their previous levels, even if the fishery was sustainably and holistically managed. The CPR time series can be used here to compare historical and current food webs, thereby determining the appropriateness of using past reference conditions to shape the vision for GES for cod and to ensure that ecological targets set for the fishery are achievable and realistic under current ecological conditions.

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Although jellyfish act as a pressure on some aspects of the food web, jellyfish also serve as a key prey item for the leatherback turtle, Dermochelys coriacea [55]. In a study by Witt et al. [56], jellyfish data from the CPR survey were used to identify likely foraging areas for turtles in the North Atlantic. CPR data can help improve our understanding of the relationship between jellyfish and sea turtles, helping inform management and conservation efforts, and possibly contributing to the determination of the placement of marine protected areas or areas where turtle-endangering fishing gear might be restricted. In this way, data from the CPR survey regarding lower trophic levels can play a role in managing higher components of the marine food web.

(e) Enhancing the evidence base for decision-making

The setting of environmental targets and defining of GES inherently comprises a degree of subjectivity. For example, biodiversity is usually considered beneficial to an ecosystem, particularly when it comes to supporting ecosystem resilience, stability and services [57], and the MSFD’s descriptor 1 calls for the maintenance of biodiversity. This tenet assumes that biodiversity at all levels is ‘good’ for European seas, but deciding whether biodiversity is ‘good’ or ‘bad’ is a value judgement, a societal choice that depends on what we (society) want from our seas [58]. CPR data indicate that a latitudinal increase in plankton biodiversity has occurred in the extratropical North Atlantic during the past five decades [59]. This temperature-driven increase in diversity has corresponded to a reorganization of the planktonic ecosystem towards dominance by smaller individuals, with the smallest size fractions of the plankton community becoming more important to production [59]. However, increasing planktonic biodiversity may be detrimental to higher latitude fisheries, such as those of the North Atlantic [59]. Cold temperate food webs are generally simpler and lower in diversity than those found in warm waters; these systems are also characterized by large populations of exploitable fish species, such as cod. As the North Atlantic warms and plankton biodiversity increases, historical cold temperate fisheries that are dependent on large fish will have to leave the area or adapt to exploit the more abundant smaller sized fish, for instance anchovy or mullet [60,61]. This shift in the size structure of the pelagic ecosystem from larger sized organisms to smaller ones is likely to decrease the availability of large fish as well as the overall value of temperate fisheries [61]. Therefore, in this case, the high biodiversity of an ecosystem element (plankton) may be viewed as negative because it will probably result in a reduction in the availability of traditionally desirable large fish as well as negatively impact the fishery economically.

Socio-economic techniques, such as cost–benefit analysis, can be used to value benefits and costs to society of both marine ecosystem degradation and conservation management measures, but scientific data and ecological understanding are needed to inform analyses [62]. For the above example, a cost–benefit analysis could indicate that immediately partially adapting North Atlantic fisheries to catch smaller warm water fish will decrease pressure on the large fish fishery, which may extend the life of the fishery at a reduced capacity. Knowledge-based Sustainable Management for European Seas (KnowSeas), a European Framework 7 research project with 31 partners from 16 countries, is working to provide practical guidance for the application of
the ecosystem approach to the sustainable development of Europe’s regional seas (www.knowseas.com). KnowSeas is using the CPR time series, as well as other ecological and climatic datasets, to inform social–ecological systems models, anticipating possible changes to ecosystem services based on climate and development scenarios [63]. The outcomes will then be used to formulate potential management options for European marine ecosystems, allowing the exploration of trade-offs between conservation and use. The results will provide decision-makers with tools to analyse future scenarios for GES, enabling them to interpret these with respect to societal values. In this way, CPR data serve to increase the evidence base available for analysis and to facilitate the practical implementation of the ecosystem approach.

3. Conclusions

The initial phase of the MSFD implementation process has been challenging, with a central difficulty arising from the fact that marine ecosystems are responding to both climatic and anthropogenic drivers, affecting indicator selection, target setting and determination of GES. Using the example of the CPR, this work illustrates the importance of long-term ecological datasets in addressing this issue (summarized in table 2), facilitating decision-makers in delivery of the ecosystem approach to sustainable management of European seas.

The most fundamental value of long-term datasets lies in the fact that multi-decadal time series of data best inform the advancement of our understanding of change in marine ecosystems, reducing scientific uncertainty and ultimately increasing the robustness of management decisions. For example, the separation of climatic and anthropogenic signals in marine ecosystems remains a basic scientific research question as well as a challenge to selecting indicators and setting environmental targets. The correct assignation of ecosystem responses to anthropogenic or climatic drivers is crucial in order to identify appropriate indicators, set attainable environmental targets, construct a realistic vision of GES and ultimately help decision-makers allocate management resources most effectively. Long-term datasets are key to signal separation and can help identify changes in ecological indicators, detect sudden and gradual ecosystem shifts, and provide a baseline against which to interpret future changes.

Climate drivers operate over long time scales and can only be understood by data collected over comparable temporal extents [18]. Without the proper historical context, changes in indicators may be incorrectly interpreted as responses to anthropogenic pressures rather than as the result of anthropogenic climate change (examples in [22,27]). Additionally, ecological systems are naturally variable, with interannual changes superimposed over long-term trends [18,64]. Multi-decadal ecological datasets with continuous measurements not only enable the detection of long-term changes in the marine environment but also aid the separation of natural short-term variability from overall trends. Monitoring programmes sampling on sporadic or infrequent time scales may only capture periodic snapshots of ecosystem state, facilitating the misinterpretation of variation in data as trends, and possibly even missing long-term trends in ecosystem change. Multi-decadal datasets allow the setting of and monitoring towards trend-based targets that capture progressive changes rather than just natural variability.

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Table 2. Summary table of challenges to MSFD implementation and recommendations for the role of CPR data in meeting those challenges.

<table>
<thead>
<tr>
<th>Challenge to Implementation</th>
<th>Recommendation</th>
<th>Role of CPR Data</th>
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<tbody>
<tr>
<td>Ecologically/economically important taxa may be at the limits of their distributional ranges owing to climate-driven changes</td>
<td>Set qualitative or trend-based targets for taxa, rather than absolute abundance targets</td>
<td>Provides information on long-term changes in spatial distribution and abundance linked to climatic drivers</td>
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<tr>
<td>Sudden climate-driven regime shifts could cause targets to fail</td>
<td>Target to require identification of driver behind indicator change as climatic or anthropogenic; reassessment of targets for next reporting period, accounting for new regime</td>
<td>Multi-decadal time series enables identification of regime shifts</td>
</tr>
<tr>
<td>Unpredictable climate-driven events create opportunities for establishment of organisms in new environments, potentially impacting composition and food webs</td>
<td>Targets require flexibility to accommodate introduction and potential impacts of non-indigenous species through unpredictable non-anthropogenically driven events</td>
<td>Long time series and extensive spatial coverage allow identification of the first appearance of new organisms; ecologically rich dataset allows identification of potential changes in community structure</td>
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<tr>
<td>It is often unclear whether the ecosystem is responding to climate, anthropogenic pressure or a combination of the two</td>
<td>Separate climatic and anthropogenic signals in order to focus resources on manageable anthropogenic pressures; targets must be flexible enough to accommodate climate change, but still fail if the change is caused by anthropogenic pressure</td>
<td>Provides a decadal and regional perspective, which can be used to interpret local changes, allowing the separation of climatic from anthropogenic drivers</td>
</tr>
<tr>
<td>Member States must set targets, despite scientific uncertainty</td>
<td>Maintenance of long-term ecological time series enables identification and interpretation of changes; as understanding progresses update MSFD targets during each assessment period</td>
<td>The CPR provides a baseline from which to observe future changes in ecological indicators</td>
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</table>

By supporting and progressing scientific advancement, long-term datasets provide the evidence base to inform socio-economic analyses. The robustness of the environmental component of such analyses is partially dependent on the quantity and quality of data populating it and on the scientific understanding of underlying ecosystem processes and how these relate to the human component.
Table 2. (Continued.)

<table>
<thead>
<tr>
<th>Challenge to implementation</th>
<th>Recommendation</th>
<th>Role of CPR data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjectivity inherent in setting targets and defining GES</td>
<td>Socio-economic techniques, can be used to value benefits and costs to society of both marine ecosystem degradation and conservation management measures, but scientific data and ecological understanding are needed to inform analyses</td>
<td>CPR data increase the evidence base available for socio-economic analysis, thereby facilitating the practical implementation of the ecosystem approach</td>
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<tr>
<td>Current ecosystem state may prevent achievement of GES if targets are set based on historical conditions; state of one food web component has trophic repercussions on other components</td>
<td>Trophic linkages and changes in food web must be identified and accounted for when determining GES and setting targets</td>
<td>CPR time series can be used to: identify changes in multiple trophic levels; determine the appropriateness of using past reference conditions to determine the vision for GES; ensure that ecological targets for higher trophic levels are achievable and realistic under current conditions</td>
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Models supported by good science based on reliable data will enable the most robust valuations of costs and benefits, and aid the setting of meaningful targets and the defining of GES based on societal values.

Duarte et al. [17] declared that ‘long-term monitoring programs are, paradoxically, among the shortest projects in marine science: many are initiated, but few survive a decade’. This remains true today with the recognized scarcity of long-term ecological datasets extending to European waters, and particularly to non-coastal regions [18]. The primary reasons for the termination of established monitoring programmes are also the same today as they were 20 years ago—funding is limited and a time lag exists between data collection and scientific yield [17]. Even the CPR survey, an example of a successful long-term monitoring programme, has experienced deficiencies in funding throughout its history, with a near collapse in 1988 [19]. Despite its recognized importance to policy and research [18,65,66], the survey today receives no monitoring funding from the European Union or any EU Member States aside from the UK. The CPR’s funding situation is not unique, but is mirrored in other ecological monitoring datasets that only receive partial national funding and survive by piecing together disparate funding sources and yet are expected to inform the MSFD and other international policy initiatives. Secure EU funding would make datasets such as the CPR survey freely available to all Member States, facilitating integration across monitoring programmes, and increasing the robustness of the data underlying the management decision-making process.
Spatially extensive multi-decadal time series add value by providing a regional perspective with which to interpret local ecological changes over long time scales. This is particularly relevant for the MSFD, which requires a regional sea-scale approach to marine management and monitoring. A spatially expansive monitoring programme provides consistent and comparable data across an ecosystem, progressing scientific understanding of large-scale changes. However, the majority of time series, in Europe and globally, are found in coastal waters, usually near a marine station or laboratory [18]. Uniquely, the CPR survey regularly monitors the open sea environment, providing a comprehensive picture of the pelagic environment at the regional ecosystem scale and complementing coastal time series. In fact, the Global Alliance of CPR Surveys (GACS) provides a near-global picture of the plankton, with CPR surveys sampling in the North Pacific, Southern Ocean, Benguela Current Large Marine Ecosystem, east coast of the USA and Canada, and the seas around Australia, New Zealand and Japan, in addition to the core CPR survey sampling in the North Sea, North Atlantic and Arctic. One of the long-term goals of GACS is to expand CPR sampling to the mid-Atlantic, greater Pacific and Indian Oceans in order to understand plankton dynamics at the global scale. A further European expansion of the CPR survey into the Baltic, Black and Mediterranean Seas would increase the scientific understanding of European plankton communities in the perspective of global changes observed in the wider CPR dataset, and provide a strong evidence base concerning the state of the European marine environment, acting as a framework for marine research and monitoring operations informing policy-making. The CPR survey’s consistent methodology would also allow the direct comparison of plankton dynamics, environmental targets and indicators at the pan-European scale, supporting the international coordinated development of marine strategies as requested by the MSFD.

In addition to the spatial expansion of the CPR survey, increased management and policy application can be achieved by raising the number of environmental variables collected during routine plankton sampling. The SAHFOS North Atlantic/North Sea CPR survey is in the process of augmenting its traditional method of plankton data collection with modern technology. CPRs contain a cargo bay in the rear of the machine, which can be used to carry additional monitoring equipment; in this way, the CPR serves as a bio-oceanographic observing platform, collecting data on both physical and biological measurements to complement its routine plankton sampling. To date, the CPR survey has been instrumented with equipment collecting data on temperature, salinity, depth and chlorophyll [67]; CPR silks also regularly collect microplastic particles that are enumerated during conventional plankton analysis [68]. CPRs on some routes now carry a water and microplankton sampler (WaMS) that collects water samples in plastic bags for supplementary analyses, including flow cytometry, molecular probes and barcoding, and harmful algal bloom microarrays; water samples can also be analysed for dissolved inorganic carbon, nutrients, alkalinity, dissolved oxygen and pCO₂. The WaMS enables CPRs to sample the smallest size fractions of the microbial community, including nano- and pico-plankton, fungi, bacteria and viruses [67]. The microbial community plays an integral role in marine food webs and biogeochemical cycling, but few time series monitoring this ecosystem component exist and there are gaps in the scientific knowledge when it comes to linking microbial dynamics to human pressures [69–71]. Sustained
financial support would enable instrumentation of CPRs with WaMS or physical sensors to routinely collect data complementing the traditional plankton dataset, thereby increasing the scientific evidence base and enabling the development of MSFD indicators and environmental targets for the smallest size fractions of the microbial community.

The MSFD states that ‘the marine environment is a precious heritage that must be protected, preserved and, where practicable, restored with the ultimate aim of maintaining biodiversity and providing diverse and dynamic oceans and seas which are clean, healthy and productive’ [10, L164/19]. This is an ambitious goal, and difficult to achieve with limited ecological data. Support for existing long-term time series such as the CPR survey is imperative to understand and sustainably manage European seas. Funding enabling the expansion of CPR routes throughout European waters as well as the routine instrumentation of the CPR as a bio-oceanographic observing platform for the collection of additional physical and microbial parameters would help to fill scientific knowledge gaps and further increase the robustness of the available evidence base supporting European management decisions.

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