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VECTORS of change in the marine environment: Ecosystem and economic impacts and management implications

1. Introduction

Human use of the European marine environment is increasing and diversifying. This is creating new mechanisms for human induced-changes in marine life which need to be understood and quantified as well as the impact of these changes on ecosystems, their structures (e.g. biodiversity) and functioning (e.g. productivity), and the social and economic consequences that arise. The current and emerging pressures are multiple and interacting, arising, for example, from transport, platforms for renewable and non-renewable energy, exploitation of living and non-living resources, agricultural and industrial discharges, together with wider environmental changes (including climate change). Anticipating the future consequences of these pressures and vectors of change for marine life and of adaptation and mitigation measures (such as the introduction of new technologies and structures, new ballast water practices, ocean and offshore wind energy devices and new fishing strategies) is a prerequisite to the development and implementation of strategies, policies and regulations to manage the marine environment, such as the IMO Convention on ballast water management and the EU Maritime Policy and Marine Strategy Framework Directive.

Recognising the economic and societal importance of marine life and potential consequences of future change, the EU funded a large-scale research project, "VECTORS of Change in Oceans and Seas Marine Life, Impact on Economic Sectors" (VECTORS, www.marine-vectors.eu). The clear aim of VECTORS was to deliver genuinely integrated, interdisciplinary research. The objectives of VECTORS were to:

- Collate understanding of the different current and potential future pressures and vectors of change in the marine environment
- Advance understanding of the mechanisms of changes in marine life and the role of human activity
- Determine the impacts of changes in marine life on ecosystems, their structure and functioning, the services they provide, and the economic and societal implications
- Project the future changes and consequences of multi-sectoral human activity in the marine environment under future possible scenarios of adaptation and mitigation
- Synthesise the derived information into innovative, predictive management tools and strategies targeted to different policy-makers and other stakeholders

Given the complex nature of the marine environment, its multiple stressors and ecosystem responses, it was necessary to focus on specific areas of concern. These areas were:

- Outbreaks of invasive or indigenous species
- Changes in the distribution of marine organisms, such as commercially exploited fish.

The vectors of these changes, and the related impacts on biodiversity and maritime economic sectors were considered as well as the policy and management implications. The approach was to develop generic understanding and test it through three case study regional seas (Western Mediterranean, North Sea and Baltic Sea). The natural contrasts offered by these three regions helped ensure that the VECTORS outputs are relevant and valuable to other regional seas.

The VECTORS project addressed a complex array of sectoral interests: areas of concern for marine life, regional seas, biodiversity, and academic disciplines as well as stakeholder interests. VECTORS aimed to explore, elucidate, and model links between all areas of interest, and then effectively communicate them to the relevant stakeholders. VECTORS was totally focussed on The Ecosystem Approach *sensu stricto* in which humans are an integral part of the ecosystem and the overall aim of marine management is to deliver ecosystem services for the benefit of society while at the same time maintaining, enhancing and protecting the natural capital of the marine environment.

2. Integrative research in an applied context

The VECTORS project developed integrated, multidisciplinary, research-based understanding that contributed towards the information and knowledge required for addressing forthcoming requirements, policies and regulations across multiple sectors. An integrative research approach was emphasised from the beginning of the VECTORS project and throughout. It was achieved through strong interdependency between the different research strands that often cooperatively addressed the different objectives. For example: through jointly developed scenarios used by different disciplines; through a focus on ecosystem services; through linking natural science and social science outcomes mediated by governance and social drivers as well as global change scenarios; and through development of generic research understanding that was applied and tested in regional sea contexts. A focus was maintained across all of the relevant facets of change in marine life and its consequences for different industry and public sectors in the regional seas of Europe.

VECTORS aimed to provide data, innovative models and decision support tools to relevant stakeholders within the environmental,

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policy and socio-economic spheres. To achieve this it employed a combination of policy and sector analysis, data synthesis, comprehensive statistical analysis, targeted experimentation, social and economic valuation, and ecosystem and economic modelling along with regular and in-depth stakeholder consultation and interaction. VECTORS promoted the application of its tools and knowledge throughout the lifetime of the project and beyond, aiming to seek outcomes from the research as well as outputs, culminating in the production of a synthesis website of the project's findings. More than 230 peer-reviewed papers were produced in association with this project and a representative portion of the research undertaken in VECTORS is collated within this special issue. An overview of these papers is provided here in the context of the scientific objectives of VECTORS.

3. Scientific objectives of VECTORS

The scientific objectives of VECTORS were highly interlinked. The research presented in the special issue and introduced here provides examples of efforts to address most of the scientific objectives:

- *To review understanding of the different current and potential future pressures and vectors of change in the marine environment*

Early and rapid reviews provided the contextual scene for VECTORS and enabled the project, including the papers presented in this special issue, to build upon existing work (Ojaveer et al., 2011; Defew et al., 2012).

- *To elucidate mechanisms causing outbreaks of indigenous species and the spread of invasive species by transport or via other transfer vectors*

VECTORS increased understanding of the ecological frames in which outbreaks are more likely to occur or invasions more likely to impact on native communities, with cascading effects on diversity and ecosystem functioning. A prerequisite to achieve this was the creation and compilation of databases such as the online information system on aquatic non-indigenous and cryptogenic species (AquaNIS, www.corpi.ku.lt/databases/index.php/aquanis). This database was designed to assemble, store and disseminate comprehensive data on organisms introduced to marine, brackish and coastal environments of Europe and neighbouring regions, and hence assist the evaluation of the progress made towards achieving biological invasion management goals (Olenin et al., 2013). The paper by Galil et al. (2018) contributed to that database for the Mediterranean Sea, identifying 726 multicellular non indigenous species (NIS), their patterns of introduction, and discussing the implications for management (including monitoring) and policy. Cardeccia et al. (2018) analysed the biological traits of sixty-eight widespread multicellular non-indigenous species identifying the traits commonly associated with these species and the functional groups that describe most of them. These 'most widespread' species comprise a wide range of taxa and biological trait profiles and a clear "identikit of a perfect invader" for marine and brackish environments is difficult to define.

Pelagia noctiluca (Forskål, 1775) (Scyphozoa) is recognised as the predominant outbreaking jellyfish species in the Western and Central Mediterranean Sea. Milisenda et al. (2018) have investigated its sexual reproduction elucidating some of its mechanisms and patterns of outbreaks formation. In the North Sea, the settlement of planula larvae of two commonly encountered jellyfish species was investigated using a combination of laboratory experiments and hydrodynamic modelling approaches. Gambill et al. (2018) found that projected warming of the North Sea will not impede the settlement of planula larvae of these species. Further application of the approaches used will improve understanding and prediction of climate-dependent changes in the production of scyphozoans and other gelatinous plankton.

- *To distinguish between those mechanisms of changes in fish distribution and productivity that are caused by environmental and human-induced changes*

Four broad categories of spatially-explicit modelling approaches currently used to understand and project changes in the distribution and productivity of living marine resources were reviewed and compared by Peck et al. (2018). These include: 1) statistical species distribution models, 2) physiology-based, biophysical models of single life stages or the whole life cycle of species, 3) food web models, and 4) end-to-end models. Teal et al. (2018) examine in greater detail two approaches for developing physiology-based models to characterize fish habitat suitability considering their strengths and limitations.

Research in VECTORS focussed on combined effects of broad scale and local drivers of change on fish distribution and productivity, particularly in the case study areas. Kanstinger et al. (2018) exemplifies this as it considers how the massive reduction in submerged macrophytes observed in recent decades in the southwest Baltic Sea, thought to have been caused by eutrophication, has affected a key location for spawning with potential ramifications for an important herring stock. Experimental and modelling approaches used by Illing et al. (2018) demonstrate that adaptive behavioural and physiological responses are tightly linked to prey match-mismatch dynamics in larval herring and that these responses can be included in models to better explore how bottom-up processes regulate larval fish growth and survival. Archambault and Le Pape et al. (2018) used a life-cycle modelling approach to examine the effect of different stressors: climate variability, habitat availability and fisheries on the Eastern English Channel (EEC) population of the common sole (*Solea solea*). Their spatially structured age-and stage-based hierarchical Bayesian model, integrating various aspects of ecological knowledge, data sources and expert knowledge, indicated that all of these stressors can interact in important ways to influence population renewal.

- *To develop a modelling framework aiming at predicting the impact of area-based restrictions on key sectors of activity*

VECTORS analysed the determinants of human activities focussing particularly on the spatial interactions between fishing activities and other human uses (e.g. maritime traffic, offshore wind farms, aggregate extractions), but also the behaviour of non-fishing sectors of activity (Bastardie et al., 2013 & 2015; Marchal et al., 2014a; b; Girardin et al., 2015; Tidd et al., 2015). VECTORS research analysed fishing decision-making processes based on existing data and then made forecasts building on scenarios. Models developed, refined and applied in VECTORS indicated that traditions (reflected by past effort allocation) and economic opportunism remain more important in driving effort allocation than spatial interactions/competition with other fishing fleets, maritime traffic, aggregate extraction, wind farms and closed areas. Model results were largely confirmed by interviews with stakeholders from different sectors of activity. Many of these studies are reviewed by Janβen et al. (2018) within the context of examining the challenges associated with the integration of fisheries into marine spatial planning. Techniques exist to analyse areas most frequently utilized by fishers, to assess the drivers for fisher's behaviour, to examine the effects of spatial competition on fisheries