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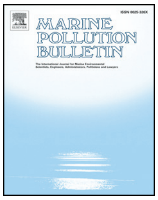

Pollution exposure on marine protected areas: A global assessment

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ABSTRACT

Marine protected areas (MPAs) face many challenges in their aim to effectively conserve marine ecosystems. In this study we analyze the extent of pollution exposure on the global fleet of MPAs. This includes indicators for current and future pollution and the implications for regionally clustered groups of MPAs with similar biophysical characteristics. To cluster MPAs into characteristic signature groups, their bathymetry, baseline biodiversity, distance from shore, mean sea surface temperature and mean sea surface salinity were used. We assess the extent at which each signature group is facing exposure from multiple pollution types. MPA groups experience similar pollution exposure on a regional level. We highlight how the challenges that MPAs face can be addressed through governance at the appropriate scale and design considerations for integrated terrestrial and marine management approaches within regional level networks. Furthermore, we present diagnostic social-ecological indicators for addressing the challenges facing unsuccessful MPAs with practical applications.

1. Introduction

Marine ecosystems are increasingly degraded from human pollution impacts on a global scale (Halpern et al., 2008; Worm et al., 2006). Marine ecosystems provide essential ecosystem services from local-scale provisioning to large-scale processes that support human welfare and ecosystem stability (Burt et al., 2014; Potts et al., 2014). The aggregation of human pollution impacts is now undermining the ability of marine environments to provide key ecosystem services that support the foundations of global climate stability (Hughes et al., 2013), biological integrity (Magris et al., 2014), coastal livelihoods and economic stability (Villasante et al., 2013).

Marine protected areas (MPAs) have become a part of normative marine management and spatial planning policy to mitigate anthropogenic pressure on marine ecosystems (Halpern et al., 2008) and to sustain marine resource economies and livelihoods (Bennett and Dearden, 2014). MPAs with full protection status now cover approximately 2% of global oceans, and the Convention on Biological Diversity has agreed that this should increase to 10% by 2020 (Bennett and Dearden, 2014; Halpern, 2014). However, currently no coherent definition of an MPA exists (Costello, 2014). MPAs and marine spatial planning have evolved out of and largely followed historied terrestrial approaches, although there are clear differences between marine and terrestrial ecosystems as well as the institutional processes needed to manage them more effectively (Álvarez-Romero et al., 2011; Schlüter et al., 2013; Weber de Morais et al., 2015). Most normative MPA implementation has currently focused on mitigating resource extraction such as overfishing, to protect against habitat loss and to promote species conservation (Green et al., 2014; Le Cornu et al., 2014).

Within the current setting MPAs may be considered successful if they achieve their marine spatial planning goal, buffering the intended anthropogenic pressure that they were implemented for and sustaining socio-economic benefits; however, less than 10% of MPAs globally are considered successful (Batista et al., 2014; Edgar et al., 2014). More specifically the success of an MPA can be measured by its ability to fulfill its ecological potential when referenced against a baseline control site, as well as its implications for socio-economic sustainability within contextual settings. Maintaining the provision of ecosystem services to surrounding communities and economies is playing an increasing role in the perceptions and implications for MPA success (Bennett and Dearden, 2014).

Key factors that have been considered as important characteristics for successful MPAs included enforcement, large size, old age, isolation (relative location) and full protection (Edgar et al., 2014). While the mentioned factors may be essential for effective MPAs, there are many additional factors which encompass a more holistic array of considerations affecting success that are multi-scalar and multi-purpose. MPA networks should integrate into broader spatial planning networks, interlink with effectively managed terrestrial areas, and consider the

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proximity to land-based pollution sources (Green et al., 2014). Among other recommendations, there are considerations for how MPAs can be effectively designed to address local contextual challenges, integrate within regional land–sea networks, and be part of a global agenda for maintaining marine ecosystem resilience (The Nature Conservancy, 2012).

Despite the scientific recognition that MPAs exist within complex social-ecological systems, the purpose of many MPAs is often singular in focus, such as to restore ecosystems or maintain a fisheries economy. A lack of holistic considerations for the interlinked social-ecological system interactions and externalities can cause undesired outcomes for MPAs (Fox et al., 2014). This has led many MPAs to be considered ‘paper parks’, existing primarily as a part of a theoretical agenda rather than a practical mitigation, socio-economic enhancing or conservation-enabling entity (Bennett and Dearden, 2014; Halpern, 2014). Better informing management to understand the many social-ecological system interlinkages incurred on MPAs is necessary through compiling and analyzing existing data. However, there is a lack of large-scale data synthesis in this respect (Caldow et al., 2015; Shucksmith et al., 2014). To achieve this goal, there have been recommendations for the collection and synthesis of data on linkages within and between regional marine ecosystems, the physical and ecological characteristics of a marine planning area, and the vulnerability to human pressures (Caldow et al., 2015; Magris et al., 2014).

Achieving more successful MPA networks will require an understanding of the magnitude and distribution of anthropogenic pollution pressures and their spatially oriented implications for MPAs. The range of potential pollution pressures on marine environments can be categorized as either input-based pollution (e.g. CO_2, nutrients, invasive species) or output-based resource extraction (e.g. commercial fishing, mining). Input-based pollution originates from many different sources on land, in the atmosphere and at sea, and enters marine environments through a variety of direct and indirect mechanisms. Additionally, different pollution types affect marine environments across varying time-scales, with current and future implications (Batista et al., 2014). Pollution can broadly include organic and inorganic chemicals, invasive species, shipping, ocean acidification, increased sea surface temperature, and a variety of others (Crain et al., 2009). The ability of MPAs to buffer the impacts of anthropogenic pollution is largely unknown at a global scale.

Not all MPAs may be affected in the same way by certain types of pollution due to their biophysical characteristics. The social-ecological and physical characteristics that an MPA embodies can fall across a wide spectrum of classification. Due to these considerations, MPAs occupying certain distinctive marine environments may face differing challenges from various pollution types. Consideration for this variability of MPA characteristics into the design and implementation of them may play a role in increasing the success of MPAs going forward.

In this study we analyze the variety of pollution exposure incurred on the biophysical groupings of the global MPA fleet. We analyze the spatial extent in which pollution, categorized by current and future relevant types, is currently having or may potentially have on MPAs with particular characteristic signatures. We grouped MPAs by their characteristics, termed their signature, with indicators including bathymetry, baseline biodiversity, distance from shore, mean sea surface temperature and mean sea surface salinity. We assess the extent at which each signature group is exposed to current pollution intensities and rates of increase for future pollution indicators related to climate change. The discussion highlights how the challenges facing MPAs today can be addressed through design and implementation considerations for more integrated land–sea management approaches within regional level networks. Considerations for the levels and scales of governance that MPAs could address are highlighted. Furthermore, we present diagnostic social-ecological indicators for addressing the challenges facing unsuccessful MPAs.

2. Methods

2.1. Characterizing MPAs into biophysical signature groups

We considered five attributes to be critical in defining an MPA's biophysical signature from a global perspective. These five attributes include the distance from shore, amount of biodiversity (OBIS, 2015), bathymetry, mean sea surface temperature, and mean sea surface salinity (Sbrocco and Barber, 2013). Global scale data on each attribute category was projected as separate layers into ArcMAP 10.2. MPAs were projected as another separate layer, with distinctive shapefiles indicating each MPA's geographic location and spatial extent. The MPA shapefiles were downloaded from Protected Planet (UNEP and IUCN, 2015), and selected from the International Union for Conservation of Nature (IUCN) categories 1a, 1b, II, and IV (UNEP and IUCN, 2015). The IUCN MPA categories used were chosen to select MPAs with a direct conservation oriented purpose, which led to the inclusion of 2,111 MPAs in our analysis. To analyze the characteristic signature of each individual MPA, to be defined by the collective five attributes, the formatted data layers were exported for analysis to R 2.15 (R Core Team, 2013). Zonal statistical calculations were conducted to spatially relate the five attribute data layers to each MPA. With each MPA now attributed data from each of the five categories, a hierarchical cluster analysis was performed using Ward's method (function “agnes”, library “cluster”).

2.2. Assessing current and future pollution pressure

Anthropogenic impacts on marine environments were classified into two input-based pollution categories, current and future impacts. Current impact indicators were assessed through the direct place-based impacts of shipping traffic frequency, organic pollution quantity, inorganic pollution quantity, artisanal fishing rates, the number of invasive species and ocean based pollution. Each pollution type was projected as an individual raster layer in ArcMAP 10.2 and spatially attributed to individual MPAs through zonal statistical calculations performed in R 2.15 (R Core Team, 2013). This data was gathered as secondary data from Halpern et al. (2008), and the dataset displayed by raster values had been log-transformed and normalized to a scale between 0 and 1 for each pollution type. The data is not the result of a model, but rather comparative empirical data showing the rates of increasing intensity of climate change indictors. Future impacts were assessed from three data categories indicating the rates of change for Ultraviolet (UV) light reaching the ocean surface, increases in the ocean acidification rates, and increases in sea surface temperature. The future impact data categories also represent the current rates of change, and do not predict or model rate increase under future conditions (e.g. with increasing greenhouse gases scenarios) but are used as an indication of current empirical trends for increasing pollution pressure from the three future categories going forward. UV light is indicated as the amount of anomaly measurements, when the monthly average exceeded the climatological mean of the first standard deviation. Sea surface temperature was measured similarly as the number of times a measurement exceeded the standard deviation from the mean for each week, this was normalized for variability between regions (Halpern et al., 2008). Acidification was measured as the difference between modeled pre-industrial ASS (aragonite saturation state) values and averages from 2000 to 2009 (Halpern et al., 2008). Future pollution exposure was derived from data presenting the rates of increase of climate change driven indicators from pre-industrial baselines to the present. The data used do not represent modeling predictions, but rates of increase that show the current continuum of increasing pressure from climate change.

3. Results

Five distinctive MPA groups were designated from the hierarchical cluster analysis and plotted on a political map, shown in Fig. 1. All

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