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A hierarchical framework for classifying seabed biodiversity with application to planning and managing Australia's marine biological resources

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ABSTRACT

A conceptual hierarchical framework for classifying marine biodiversity on the sea floor, used successfully for continental-scale bioregionalisation and adopted to guide marine resource planning and management in Australia, has wider application at a global scale. It differs from existing schemes for classifying marine biota by explicitly recognizing the overarching influence of large-scale biodiversity patterns at realm (ocean basin and tectonic), provincial (palaeohistorical) and bathomic (depth-related) levels. The classification consists of 10 nested levels within realms, of which the first seven are primarily spatially nested and ecosystem based, and the lowest levels represent units of taxonomic inheritance: 1 – provinces, 2 – bathomes, 3 – geomorphological units, 4 – primary biotopes, 5 – secondary biotopes, 6 – biological facies, 7 – micro-communities, 8 – species, 9 – populations, and 10 – genes. According to this scheme, marine biodiversity is characterised in a systematic way that captures the scale-dependence and hierarchical organization of the biota. Levels are defined with respect to their functional roles and spatial scales, in a manner that directly supports the incorporation of biodiversity information in regional-scale planning by highlighting centres of endemism, biodiversity richness and priority information needs. Whereas species are the fundamental units of biodiversity, biological facies are the smallest practical unit for conservation management at regional scales. In applying the framework we make extensive use of biological and physical surrogates because marine data sets, particularly those of the deep sea, are usually sparse and discontinuous. At each level of the hierarchy, attributes and surrogates are defined to reflect the scale and range of biogeographic and ecological processes that determine the spatial and temporal distribution of marine biodiversity. The Australian experience in applying this framework suggests that it provides a workable systematic basis for defining, managing and conserving biodiversity in the sea.
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1. Introduction

Studies of marine biodiversity have focused almost exclusively on local-scale processes which are typically less informative than biogeographic processes for understanding species richness patterns (Gray, 2001). While ecosystem-based management (EBM) of marine systems aims to manage biota at continental and broad regional scales, knowledge of large-scale biodiversity is usually poor. In such circumstances, biodiversity surrogates, based on more easily mapped geophysical variables, are an attractive option for representing biological patterns (Zacharias and Roff, 2000). However, the use of physical surrogates in isolation has often meant that the relevance of, and context provided by, mega-scale biodiversity have been overlooked. When the geographic scale of a bioregion includes a whole continent, knowledge of the fundamental aspects of biodiversity, such as its biogeographic structure, is essential for management planning. Nevertheless, incorporating the biogeography of marine biodiversity at national scales has not been approached systematically (Roff, 2005).

The classification of biodiversity into hierarchical units is not new (Noss, 1990; Soberon et al., 2000). Various hierarchical ecological approaches have been proposed to conserve terrestrial (Noss, 1990) and marine biodiversity (Zacharias and Roff, 2000). However, most approaches focus on the lower and middle levels of biodiversity (i.e., genes, populations, species and communities) and rarely deal with larger, meso- and mega-scale units (i.e., realms based on ocean basin tectonics, biogeographic provinces based on evolution, and bathymetric associations based on depth) that encapsulate historical patterns in biodiversity and the processes driving its distribution. Harding (1997) provided a four tier, mega-scale classification of marine biodiversity but did not attempt to link his hierarchy to lower (biocoenotic) levels. Spalding et al. (2007) have since summarised existing national regionalisations to produce an amalgamated set of realms, provinces and ecoregions, covering all coastal and shelf waters of the world. The maps were derived through qualitative reinterpretations of existing national regionalisations, based on three principles: "that

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it should have a strong biogeographic basis, offer practical utility, and be characterised by parsimony". Their hierarchy was chosen to be parsimonious with apical elements of a preliminary framework which formed the basis of an Australian provincial regionalisation reported in IMCRA (1998), but developed in an earlier scientific analysis (Anon, 1996a). Our framework was constructed to integrate all of these levels, focusing on improving their utility for managing biodiversity at continental-scales. A top-down approach was used to classify biodiversity within a sequence of nested levels (below the scale of realms) that reflect the processes that drive/determine each level. In the absence of a complete regional coverage of biological data, biodiversity surrogates were used to appropriately assign biological, geological and physical information to each level. This approach allowed us to deal with biogeographic complexity and to selectively reduce entropy by appropriately combining biological and geophysical information.

Biodiversity, with both biotic and abiotic components, includes the variation of life at all levels of biological organization (Gaston and Spicer, 2004). However, it can and has been interpreted in many ways (Noss, 1990; Ray, 1996), often reflecting disciplinary biases and confusion of the issues of scale and context. For example, ecologists and mangers concerned with processes typically focus on mid-levels of biodiversity, whereas biogeographers focus more on larger regional scales, and taxonomists and molecular biologists focus mainly on the basal levels of biodiversity – the species. In practical terms, these levels form part of a natural hierarchy being either fully or partially nested in levels above and providing quite different information in a biodiversity management context. Consequently, discussions about biodiversity are often incoherent because participants, focusing on different levels of the hierarchy, are often at cross-purposes.

The effectiveness of marine resource management practices depends largely on the complexity and knowledge of a region and the strategies employed. An initial step must be to scope the region's biodiversity. In biogeographically complex regions, faunas should be classified initially into smaller, more manageable units to assist with this process. Our framework was designed and tested over more than a decade to produce bioregionalisations of Australian seas, and to assist development of broad-scale regional management plans and strategies for conserving and preserving biodiversity. The continental-scale, Australian marine domain has one of the most diverse biotas on the planet (IMCRA (1998)) so this provided serious challenges. These included describing the province-level biogeographic structure of the region to highlight core features of its biodiversity.

This paper introduces a unified, hierarchical framework for describing the structure of marine biodiversity across all spatial scales from global/oceanic realms to genes. We provide the rationale for this framework and describe key features of the various levels. Its application to the Australian Marine Jurisdiction in the context of Australia's Oceans Policy, including the implementation of bioregional marine plans and a representative system of marine protected areas, is discussed. We highlight issues that require further clarification, in terms of scientific and policy interpretation, and suggest priority areas for further research in terms of the fundamental assumptions underlying the framework. Notwithstanding the need for this additional work, we consider that the framework constitutes a significant step towards EBM of marine systems with broader application in a global context.

2. Bioregionalisation of Australian seas

The "island continent" of Australia is surrounded by marine habitats covering more than 11 million km^2 of seafloor in three oceans (Williams et al., 2009). It has one of the most diverse marine biotas on earth, extending from cool temperate seas in the south to tropical seas in the north. Seabed environments are represented by a rich and diverse array of habitats, and the fauna is a commensurately complex mix of organisms of recent and ancient origins displaying unusually high levels of micro-endemism.

Conservation of Australia's biodiversity is a key environmental responsibility under a suite of strategies and obligations that include the Convention on Biological Diversity (UNEP, 1994), the national strategy for Ecologically Sustainable Development (Anon, 1992b), the national Strategy for the Conservation of Australia's Biological Diversity (Anon, 1996b), and the 2002 World Summit on Sustainable Development. A key expectation of these commitments is the establishment of a National Representative System of Marine Protected Areas (NRSMPA) by 2012. Yet, despite these responsibilities, prior to 1996, knowledge of the large-scale structure and distribution of the biota, required for sound management of biodiversity, was either patchy or lacking. Data gaps are particularly problematic in a large and complex region such as Australia where much of the biota remains undiscovered, or has not been formally identified and named.

The hierarchical framework adopted, starting with large biogeographic scales and working progressively to finer, nested scales, allowed us to define Australia's biogeographic regions as a key input in marine conservation planning and ecosystem management (Commonwealth of Australia, 1998). This approach, whereby biodiversity is classified into nested levels, enabled a complex fauna to be subdivided, sequentially, making use of geophysical surrogates but retaining biological authenticity. A prototype scheme, developed for classifying seabed biodiversity, was originally used for an interim marine bioregionalisation of Australia (Anon, 1996a), and later revised for environmental management planning for northwestern Australia (Lyne et al., 2006). It has been adopted in evolving forms for a variety of similar regional studies (e.g., Butler et al., 2001; Commonwealth of Australia, 2005; Last et al., 2005), but the rationale, application and limitations of the approach have not been formally documented in the primary literature. This approach, which now forms the biological basis of Australia's Bioregional Marine Planning (BRMP) (formerly Regional Marine Planning, RMP), was adopted after critical review by leading federal and local (state) conservation scientists, as well as by an active national marine bioregionalisation committee, overseeing the marine regionalisation process. Considerations in implementing the approach are explained below using selected examples from national regionalisations of Australian seas and a regional investigation of the biodiversity of the continental margin of southeastern Australia.

3. Hierarchical classification of seabed biodiversity

Contemporary marine biotas exhibit distributional patterns based on ancient evolutionary processes (Ricklefs, 2006). Oceanic realms, often recognised as the largest marine geographic subdivisions, have been interpreted as mega-scale evolutionary units (Kauffman, 1973; Briggs, 1995). They differ from Large Marine Ecosystems (LME's) which can be viewed as largely geopolitical units, often lacking a biogeographic basis (Sherman et al., 1995). Various schemes, that equate large-scale, 'apical' biotic units to ocean basins and continental plates, have been proposed (Schmidt, 1954; Briggs, 1974; Pielou, 1979). The Australian continent and its marine domain belong to a large oceanic realm, which includes adjacent geopolitical regions New Zealand and New Guinea, united by their co-occurrence on the eastern sector of the Indian–Australian Plate (Hall, 2001).

Although details of the geophysical evolution of the Indian–Australian Plate remain subject to some debate (e.g., Handayani,

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