Available online at www.sciencedirect.com
ScienceDirect
Deep-Sea Research I 54 (2007) 385–402
DEEP-SEA RESEARCH PART I
www.elsevier.com/locate/dsri

Adaptive classification of marine ecosystems: Identifying biologically meaningful regions in the marine environment

Edward J. Gregr*, Karin M. Bodtker

Marine Mammal Research Unit, Fisheries Centre, University of British Columbia, 6248 Biological Sciences Road, Vancouver, BC, Canada V6T 1Z4

Received 26 April 2005; received in revised form 21 November 2006; accepted 30 November 2006
Available online 2 February 2007

Abstract

The move to ecosystem-based management of marine fisheries and endangered species would be greatly facilitated by a quantitative method for identifying marine ecosystems that captures temporal dynamics at meso-scale (10s or 100s of kilometers) resolutions. Understanding the dynamics of ecosystem boundaries, which may differ according to the species of interest or the management objectives, is a fundamental challenge of ecosystem-based management. We present an adaptive ecosystem classification that begins to address these challenges. To demonstrate the approach, we quantitatively bounded distinct, biologically meaningful marine regions in the North Pacific Ocean based on physical oceanography. We identified the regions by applying image classification algorithms to a comprehensive description of the ocean's surface, derived from an oceanographic circulation model. Our resulting maps illustrate 15 distinct marine regions. The size and location of these regions related well to previously described water masses in the North Pacific. We investigated seasonal and long-term changes in the pattern of regions and their boundaries by dividing the oceanographic data into four seasons and two 10-year time periods, one on either side of the 1976–1977 North Pacific Ocean climate regime shift. We compared our results for each season across the regime shift and for sequential seasons within regimes using the Kappa Index of Agreement and the index of Average Mutual Information. Seasonal patterns were more similar between regimes than from one season to the next within a regime, while the magnitude of seasonal transitions appeared to differ before and after the regime shift. We assessed the biological relevance of the identified regions using seasonal maps derived from remotely sensed chlorophyll-*a* concentrations ([chl-a]). We used Kruskal–Wallis and Wilcoxon rank sum tests to evaluate the correspondence between the [chl-a] maps and our post-regime shift regions. There was a significant difference in [chl-a] among the regions in all seasons. We found that the number of regions with distinct chlorophyll signatures, and the associations between different regions, varied by season. The overall pattern of association between the regions was suggestive of observed, broad-scale patterns in the seasonal development and distribution of primary production in the North Pacific. This demonstrated that regions with different biological properties can be delineated using only physical variables. The flexibility of our approach will enable researchers to visualize the geographic extents of regions with similar physical conditions, providing insight into ocean dynamics and changes in marine ecosystems. It will also provide resource managers with a powerful tool for broad application in ecosystem-based management and conservation of marine resources.

Keywords: Ecoregion; Biogeography; Ecosystem management; Habitat modeling; Ecosystem models; Habitat classification; North Pacific

*Corresponding author.
E-mail address: gregr@zoology.ubc.ca (E.J. Gregr).

0967-0637/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.dsr.2006.11.004

1. Introduction

Studies at the ecosystem level are relevant to both fisheries management and protected areas definition. Fisheries managers are increasingly required to take ecosystem considerations into account when assessing commercially exploited stocks, while conservation efforts are increasingly focused on delineating areas that will protect habitats of species at risk at all life stages. The determination of habitat boundaries (e.g., essential or critical habitat) for both endangered and commercial marine species has been a legal requirement in the United States for decades under both the Endangered Species Act (1973) and the Magnuson-Stevenson Fisheries Conservation and Management Act (1996). In Canada, similar legislation is now in place in the form of the Species at Risk Act (2002). This increasing focus on ecosystem-based management, first advocated at least 70 years ago (Allee, 1934), presents significant challenges, including the mapping of marine ecosystems in space and time.

Ecosystem mapping—the characterization of a physical environment and its associated biota—is complex. Even in terrestrial ecology, commonly described as being decades ahead of marine ecology in terms of ecosystem classification, there is no single, general non-taxonomic classification system for ecological units beyond the species level (Morrison et al., 1998). Instead, terrestrial regions are often delineated based on biological, geographic, and climatic characteristics (e.g., biogeoclimatic zones). This works well as an operational definition of terrestrial ecosystems because the biological component (i.e., flora) is relatively immobile. It is only an operational definition because it does not include the more mobile components of the terrestrial ecosystem (e.g., insects, birds, ungulates). Biogeoclimatic zones thus provide landscape ecologists a bio-physical pattern, a spatial context, in which the more mobile components of the terrestrial ecosystem exist.

There has been limited success in applying the methods of landscape ecology to the oceans. While even a cursory examination reveals physical and biological patterns in the oceans at a range of spatial and temporal scales (e.g., Bakun, 1996; Mann and Lazier, 1996), the patterns are ephemeral and manifest themselves differently across spatial scales. In contrast to the landscape, marine primary production (phytoplankton) is patchy, ephemeral, and quickly consumed by higher trophic levels. The processes responsible for creating the patterns in phytoplankton distribution are largely a function of physical forcing and the associated biological response (Platt and Sathyendranath, 1999). The overall biogeographic patterns (ecosystems) thus represent a combination of environmental structure, species behavior, and population dynamics (MacArthur, 1972).

Variability in physical forcing results in physical patterns with different spatial and temporal scales that provide the environmental structure for the overlying biology. However observations of these biological patterns and their integration into the classification can be complicated by species at various trophic levels, operating at different spatio-temporal scales (Steele, 1989). Given the dynamic nature of the marine environment and the mobility of the species of interest (marine mammals and commercial fishes), methods for delineating ecological marine boundaries must be adaptable to a range of spatial and temporal scales. The delineation and mapping of a dynamic geo-physical context has the potential to be as useful to marine ecology as biogeoclimatic zones are to terrestrial ecology.

In this study, our objective was to apply image classification techniques to the marine environment as a method for classifying this environmental structure. We hypothesized that regions of similarity identified by a classification based solely on physical parameters would have both physical and biological significance, and consequently assessed the resulting maps in terms of both physical and biological relevance. Since we are undertaking the task of mapping ocean regions that are both physically and biologically meaningful, a brief look at previous efforts to classify the marine environment into meaningful regions is warranted.

1.1. Existing classification systems

Marine ecosystems have commonly been defined in one of four ways (Laevastu et al., 1996): the nature of the dominant organisms (e.g., planktonic ecosystems); specific physical features (e.g., reef and benthic ecosystems); geographic locations (e.g., Bering Sea ecosystem); or some combination of these. Classification systems have been developed to describe such boundaries. A shared characteristic of most classification schemes is that they operate on a single spatial and temporal scale. Generally, these scales tend to be large (coarse resolution) and have no temporal