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Viewpoint

The value of remote sensing techniques in supporting effective extrapolation across multiple marine spatial scales

James Asa Strong *, Michael Elliott

The Institute of Estuarine and Coastal Studies, University of Hull, Hull HU6 7RX, UK

A R T I C L E I N F O

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A B S T R A C T

The reporting of ecological phenomena and environmental status routinely required point observations, collected with traditional sampling approaches to be extrapolated to larger reporting scales. This process encompasses difficulties that can quickly entrain significant errors. Remote sensing techniques offer insights and exceptional spatial coverage for observing the marine environment. This review provides guidance on (i) the structures and discontinuities inherent within the extrapolative process, (ii) how to extrapolate effectively across multiple spatial scales, and (iii) remote sensing techniques and data sets that can facilitate this process. This evaluation illustrates that remote sensing techniques are a critical component in extrapolation and likely to underpin the production of high-quality assessments of ecological phenomena and the regional reporting of environmental status. Ultimately, is it hoped that this guidance will aid the production of robust and consistent extrapolations that also make full use of the techniques and data sets that expedite this process.

1. Introduction

Traditional methods of sampling typically provide point observations with a high information content, i.e. the characteristics of the seabed at one place. For logistic reasons, these observations typically cannot provide continuous data surfaces over large spatial areas (Gray and Elliott, 2009). Consequently, they are poorly suited for detecting the detailed structure within broad-scale gradients (e.g. salinity, depth and propagule dispersal) and representing spatial heterogeneity (e.g. substratum patchiness). Although ecological phenomena occur at various spatial scales (Fig. 1), those occurring at broader spatial scales are currently the target of greater attention e.g. species loss, environmental health and climate change impacts (Box 1). This means there is a growing discrepancy between the spatial scales associated with the sampling and reporting of variables (Urban et al., 1987) – this is especially true for observations from traditional sampling techniques.

The assessment and reporting of these broad-scale phenomena therefore requires that observations, sampled at smaller spatial scales, are ‘scaled-up’ (Miller et al., 2004; Peters et al., 2008; Aertsen et al., 2012) or spatially extrapolated (Fig. 2). Although undertaken routinely, the extrapolative process is complex (Levin, 1992; Wu and David, 2002) and may introduce substantial errors if not undertaken correctly (Miller et al., 2004; Denny and Benedetti-Cecchi, 2012). Of potentially value for extrapolation are the technological developments, often from military and medical sectors, that have generated many remote sensing techniques (i.e. techniques that use sound or light to quantify variables or surrogates of interest) suitable for the marine environment (Solan et al., 2003). The greater spatial coverage captured by many imaging techniques is more closely aligned with the domains of scale (Fig. 1) apparent in marine ecology and required by the current suite of international legislation.

Datasets covering multiple spatial scales, such as those provided by remote sensing techniques, are particularly informative about processes and properties occurring at various spatial scales and especially larger and more ecologically relevant scales. Accordingly, here we examine the complexities inherent within the extrapolative process and the information, provided by remote sensing techniques, that can address these difficulties. Specific objectives are:

1. explain the difficulties in producing robust extrapolations;
2. describe the process of spatial extrapolation used within ecology;
3. develop a framework that combines remote sensing datasets within the extrapolation process (provided with examples); and
4. describe remote sensing techniques and indicate their value, in terms of coverage and thematic focus, and limitations.

1.1. Obstacles to effective extrapolation

The requirement to traverse between many spatial scales (i.e. domains of scale) and account for the localised sources of heterogeneity within each scale complicates the process of extrapolation. Environmental or ecological observations and phenomena (e.g. sampling events, environmental impacts, ecological phenomena and areas for

* Corresponding author.
E-mail address: j.strong@hull.ac.uk (J.A. Strong).

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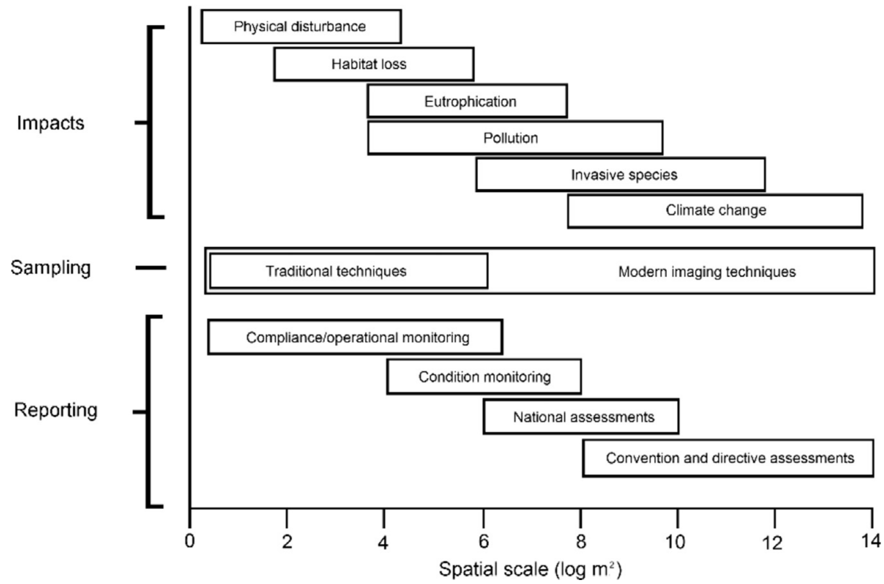

Fig. 1. Domains of scale for examples of marine sampling, anthropogenic pressures and the reporting of environmental status.

the reporting of environmental status) are all associated with specific spatial scales termed 'domains of scale' (Urban et al., 1987). These domains are not spatially exclusive and can overlap (Fig. 1). Changes in ecosystem properties and the dominance of specific processes create discontinuities in the scaling relationship when scaling between domains of scale. For example, sea surface temperature may generally not be expected to vary much 1–1000 m, but will vary, and therefore be influential, over 1–>1000 km. As such, it is important to identify and characterise these domains of scale during extrapolation.

Box 1
Research and policy drivers for effective extrapolation.

As environmental and ecological information and understanding accumulates at a local level, there is a greater interest and ability to examine broad-scale issues. This has also been driven by increased concern regarding regional and global pressures on ecological phenomena and environmental status (e.g. distributional mitigation and climate change, broad-scale habitat loss and the modification of ecosystem goods and services). Unfortunately, this has coincided with a paradox in marine assessments – that an increasing marine governance is dependent on acquiring greater data across larger spatial scales (Borja et al., 2016, b) and yet the bodies responsible for data collection are subject to significant resource limitation (Borja and Elliott, 2013). For example, ambitious legislation, such as the EU Marine Strategy Framework Directive (2008/56/EC) and the US Oceans Act (S.C. 1996), are making greater demands from the assessment process, with the current trends including:
(i) the evaluation of health over large spatial scales; increasingly defendable and repeatable measurements of status;
(ii) responsive to management measures, and
(iii) cost-effective implementation (Borja and Elliott, 2013).
Estimating environmental status over larger spatial scales requires that reliable extrapolation is used. While those assessments have been historically centred on point observations that may or may not have been extrapolated to larger areas, this is now acknowledged to create larger uncertainty in policy implementation. It is now apparent that the most effective extrapolations are those drawing on both high-quality point observations (i.e. traditional sampling) and informative, broad-scale sampling (i.e. remote sensing techniques) to be combined to deliver the best outputs possible.

The environmental or ecological properties and processes associated with each domain will be associated with a particular type and range of variation, termed here 'source(s) of heterogeneity' (SoH). An individual SoH can be either qualitative (comprised of differing classes e.g. broad-scale substratum or habitat classes) or quantitative (gradient of a continuous variable e.g. sea surface temperature) (Fig. 2). Both natural and anthropogenic properties and processes can generate SoH. Due to the 'nesting' of the domains of scale, a SoH can occur within another SoH present within a larger domain of scale. Interactions can occur between nested SoH to generate further heterogeneity. For example, an interaction will occur between substratum patchiness (SoH1 in Fig. 2) and biological dispersal (SoH2 in Fig. 2) if settlement is only possible on one class of substratum. These interactions complicated the aggregation of response surfaces. Combining all of the individual sources of heterogeneity, and the interactions generated between sources, provides the 'total heterogeneity' observed (Fig. 2).

It is therefore apparent that robust extrapolations require information on SoH from several domains of scale. These sources must be represented during extrapolation to avoid scaling errors and provide an accurate spatial representation of the phenomena of interest. Depending of the size of the extrapolation, this may require several sources of information. Of particular value for meeting this requirement are remote sensing techniques that generate continuous data surfaces over large spatial areas.

2. Extrapolation and a framework for integrating remote sensing

2.1. Types of extrapolation in ecology

Observations can be scaled over space, time and ranges of base quantities (Fig. 3). Lumping, extrapolation and explicit integration are the three main methods for scaling (King, 1991). *Lumping* averages observations within an area and creates a mean value assumed to represent a larger area. *Extrapolation* maintains the detail within the observations through creating a small-scale response function, which either project (empirical approach) or model (mechanistic approach) the extrapolated value based on initial observations and predictor variable(s). *Extrapolation by explicit integration* rescales a smaller scale model to create a new, larger scale model with space as an integrating variable (King,