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Fine-scale benthic biodiversity patterns inferred from image processing

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ABSTRACT

Despite potentially considerable advantages over traditional sampling techniques, image-derived indices of habitat complexity have rarely been used to predict patterns in marine biodiversity. Advantages include increased speed and coverage of sampling, avoidance of destructive sampling, and substantially reduced processing time compared to traditional taxonomic approaches, thus providing a starting point for more detailed analysis if warranted. In this study, we test the idea that the mean information gain (MIG) and mean mutual information (MMI), two indices of image heterogeneity that we derived from photographs of marine benthic assemblages, represent good preliminary predictors of biodiversity patterns for 133 benthic invertebrate and algal taxa on jetty pylons in Gulf St Vincent, South Australia. Both MIG and MMI were spatially structured, with evidence of among-site differences that were also evident in the benthic data. When combined with information on the spatial structure within the dataset (site and depth), MIG and MMI explained ~35% of deviance in invertebrate species richness, ~43% in Shannon's evenness and up to 50% of dissimilarity in species composition. This explanatory power is of a similar magnitude to many other, less readily available, surrogate measures of biodiversity. These results corroborate the idea that indices of image heterogeneity can provide useful and cost-effective complements to traditional methods used for describing (or predicting) marine epibiota biodiversity patterns. This approach can be applied to many case studies for which photographic data are available, and has the potential to result in substantial time and cost savings.

1. Introduction

The importance of being able to do rapid assessments of marine biodiversity cannot be understated. Today only a little over 2% of the oceans fall under some sort of protection (Moffitt et al., 2015). An inherent assumption of marine conservation planning is that maximising the representation of species diversity begets higher ecosystem resilience (McCann, 2000; Ives and Carpenter, 2007; Moilanen et al., 2009), because higher species richness and greater niche partitioning lead to weaker biotic interactions, increased species co-existence and greater functional redundancy (Walker, 1992; Shurin, 2007; Thibaut et al., 2012). Moreover, species richness and niche partitioning tend to be higher in more complex environments (Hutchinson, 1957), leading to the idea that an environment's 'complexity' – measured indirectly as some index of diversity, or more directly based on measures of habitat heterogeneity – can be used as a proxy to predict an ecosystem's resilience to perturbation and environmental change (McCann, 2000; Ives and Carpenter, 2007).

Compared to sampling in terrestrial ecosystems, the relative difficulty, high cost and intensity of sampling marine biota sufficiently to answer ecological and conservation questions (Richardson and Poloczanska, 2008) demands the development of more efficient and meaningful biodiversity approaches and proxies (Mellin et al., 2011, 2012). Combined with difficulties in species identification (including the increasing rarity of specialist taxonomists – Hopkins and Freckleton, 2002), the large number

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of undescribed marine species, and the variable success of using 'surrogates' (Rodrigues and Brooks, 2007) to infer marine biodiversity distributions (Poore and Wilson, 1993; Ward et al., 1999; Beger et al., 2003; Mellin et al., 2011), simple, efficient and cost-effective methods for assessing plot-based biodiversity are surprisingly rare in marine science.

One particularly promising avenue of methodological development to combat these difficulties is in the application and analysis of video and still photographic images. Baited and unbaited underwater video cameras have been used for some time, and to great effect, to estimate fish abundance and diversity (e.g. Watson et al., 2005; Harvey et al., 2007; Field et al., 2009). While still photographs have been used for over half a century (e.g. Connell et al., 2004), they have traditionally been analysed manually, with individual species identified by relevant taxonomic experts. The automated analysis of still photographs of marine habitats and biota at various scales has only recently been recognised as a potentially efficient biodiversity assessment tool (Mellin et al., 2012; Lambert et al., 2013).

Automated or semi-automated image analysis of still photographs in the context of biodiversity assessment relies on the following assumptions: (*i*) that structurally complex environments provide, on average, more niches for species (Huston, 1979; Levin, 1999; Bolam et al., 2002), such that direct measurements of species richness (including its variants) should be higher in more spatially complex sampling units; (*ii*) that for any given spatial scale, structural complexity is by definition greater when the species present are arranged in more spatially complex patterns than in simple patterns (so for example, a chess board is more complex than a board with one half painted white, and the other half painted black); (iii) that two-dimensional photographic images can capture this structural complexity (Proulx and Parrott, 2008, 2009) such that (*iv*) simple metrics of image heterogeneity are positively correlated with the biodiversity present at the sampling site (Mellin et al., 2012). While the first assumption has been validated using physical descriptors for coral reefs (Luckhurst and Luckhurst, 1978; Friedlander and Parrish, 1998; Attrill et al., 2000), only recently has it been tested using image analysis (Mellin et al., 2012; Lambert et al., 2013). Mellin et al. (2012) found that habitat complexity of coral reefs derived from image analysis at scales of 1–20 km explained up to 29–33% of variation in fish abundance, richness and community structure. Lambert et al. (2013) applied the approach to images of the seafloor substrate at finer spatial scales (0.14 m^2), and concluded that it was not as effective at predicting epifaunal density as laser line techniques used to measure sea floor rugosity. Earlier work in freshwater lakes showed that a simpler technique, optical intensity, provided an index that was highly correlated to rugosity, and that it was a good predictor of fish richness, diversity and abundance at a scale of 25 m^2 (Shumway et al., 2007). These techniques have also been applied successfully in a variety of terrestrial systems (St-Louis et al., 2006; Bellis et al., 2008; Estes et al., 2008; Proulx and Parrott, 2008, 2009; Oldeland et al., 2010).

Here, we examine the potential of the automated image analysis techniques described by Mellin et al. (2012) and Lambert et al. (2013) to assess the relationship between habitat complexity and benthic epibiota richness and evenness at small spatial scales (0.04 m^2). While the previous studies examined the relationship between habitat complexity and the diversity and/or abundance of species not necessarily in the image, here we examine the relationship between image heterogeneity and the diversity of species that are present in the image. The ultimate goal is to establish an automated technique for image analysis that provides a reliable preliminary index of marine epibiota biodiversity without the need for comprehensive and time-consuming manual data extraction and species identification typical of processing images of marine benthos. Instead, the method automatically computes metrics describing the heterogeneity (texture) of the entire image for each of its colour components, and uses these as a multivariate index of image, and by proxy habitat, complexity. If reliable, such a technique would be particularly valuable for monitoring benthic epibiota, for example as part of an impact assessment study or for performance assessment of marine protected areas. A particular advantage is that it could be used to provide a rapid initial assessment of changes in biodiversity, which if detected, could be followed up by more time-consuming, traditional analysis of the photographs to determine in more detail what changes have occurred, and to ensure that putative changes are real and not related to changes in environmental conditions that influence the image but not the assemblage (e.g., light availability at the time of the survey).

2. Materials and methods

2.1. Study area and data collection

As part of the Transects for Environmental Monitoring and Decision Making network (TREND; www.trendsa.org.au), we photographically examined spatial and temporal variation in benthic assemblages on jetty pylons at five locations (Rapid Bay, Outer Harbour [Adelaide], Ardrossan, Klein Point and Stenhouse Bay) in Gulf St Vincent, South Australia (Fig. 1). Here we use the images from one survey as a case study for the use of image derived indices to predict biodiversity. We chose locations where jetty pylons extended to a sufficient depth ($\geq$7 m at lowest astronomical tide) on which we could establish sampling quadrats at three depths: $\sim$2, 4 and 6 m at lowest astronomical tide. At Stenhouse Bay, Klein Point and Outer Harbour, we surveyed only a single site, whereas at Rapid Bay and Ardrossan, the jetty structure allowed us to survey two separate sites, each site being an individual dolphin (group of pylons), thus allowing an examination of within-jetty variation. We chose 10 pylons at each site on which we set 20 cm $\times$ 20 cm sampling quadrats (with one quadrat per pylon and depth level, i.e., 30 quadrats/site). Pylons were mostly square or I-shaped of approximately 25 cm $\times$ 25 cm dimensions, but with round pylons of approximately 30-cm radius at Klein Point.

For all quadrats at each site we took photographs (Fig. 2) with a Panasonic Lumix (DMC-FT2) digital camera set on auto and Inon UWL100-28AD lens, using a frame that ensured they were taken from an equal distance (28 cm) from the pylon and with 2 Inon D180 strobes attached at fixed distances and angles. All photographs were taken in February 2012. Of the 210 quadrats photographed, 12 images at Outer Harbour and 1 at Klein Point were of poor quality due to high turbidity, and <50% of randomly selected points (see below) within the image could be assigned to a taxon. We deleted these photographs from the dataset. For the remaining 197 photographs, we calculated percent cover only on the points that could be assigned to a taxon (there was no bare substratum in any of these plots).

We subsequently cropped each photograph to retain only the area inside the quadrat frame, and then analysed them using two different techniques. First, a benthic invertebrate specialist scored them, with the aid of an algal specialist, to determine percent cover of all taxa present from 50 stratified random points per image using the software package photoQuad (Trygonis and Sini, 2012). While some taxa could be unambiguously identified to species from the photographs (with the aid of specimen collections), most could only be identified to genus, and some to higher levels such as family (see Supplementary Table A1 for a full list of taxa). To retain maximum information in the analysis, taxa were analysed at the lowest common level at which they could be identified (i.e., they were not pooled to the lowest common level of phylum). Secondly,