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Temporal and spatial variability in the cover of deep reef species: Implications for monitoring

Nicholas R. Perkins[a,*], Scott D. Foster[b], Nicole A. Hill[a], Martin P. Marzloff[a], Neville S. Barrett[a]

[a] Institute of Marine and Antarctic Studies, University of Tasmania, Australia
[b] Commonwealth Industrial and Scientific Research Organisation, Hobart, Australia

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ABSTRACT

Imagery collected from Autonomous Underwater Vehicles (AUVs) provides a novel means of monitoring changes in benthic ecosystems over large spatial scales and depth ranges. However, for many benthic ecosystems there is little baseline data to quantify temporal and spatial variance for key indicator species. This information is crucial for isolating background "noise" from long-term "signals". Here we quantify components of variance for five key deep-water sessile invertebrate species across four long-term benthic monitoring sites in a region undergoing strong climate-driven changes. We use linear mixed models to estimate the contribution of sources of spatial and temporal variance in species covers from empirical data. We then combine this information with projected long-term climate-driven changes in the cover of these groups and test the power of various survey designs to detect change through time. Large short-term temporal and spatial variability in the cover of a gorgonian octocoral results in high components of variance that limit the detectability of the projected long-term trend for this species. Conversely, for three of the sponge species high power is achievable with revisits to the four original sites every two years until 2060. By including more sites in the revisit design, high power can be achieved with less frequent revisits. For the fifth species, we find high power is unachievable due to the small trend predicted. Overall, we highlight how examination of components of variance in a system can aid in the selection of suitable indicators and the establishment of effective monitoring programs.

1. Introduction

Marine benthic ecosystems are under increasing pressure from widespread threats such as climate change, over-fishing, pollution and invasive species (Jackson et al., 2001; Halpern et al., 2008; Hoegh-Guldberg and Bruno, 2010). These pressures can induce localised extinctions, changes in the distribution of species, including climate-driven range-shifts, and hence they affect local community composition (Poloczanska et al., 2013). Monitoring programs are essential to quantify the effects of these pressures and to assess the effectiveness of conservation measures such as marine reserves. Studies that cover large spatial scales over long time periods are required to robustly detect ongoing large-scale changes, such as those related to climate change (Brown et al., 2011). However, baseline information on abundance and natural levels of variation in key benthic species is often lacking, in particular for deeper-water marine systems below SCUBA diving depths, which have been historically under-sampled.

Image-based methods provide a non-intrusive approach to sampling natural systems, with modern technologies such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) allowing the routine surveying of deeper benthic communities over large spatial scales. These approaches generate a large volume of imagery that has the potential to greatly enhance our understanding of these environments and our ability to monitor long-term changes. However, image-based underwater surveys have challenges: image scoring is time-consuming, and the effectiveness of AUV survey design (spatial and temporal replicates) to detect long-term changes remain largely untested (but see Ling et al., 2016).

Assessing approaches for appropriate sampling designs, and sub-sampling of acquired imagery, has been an area of recent research (Molloy et al., 2013; Foster et al., 2014; Perkins et al., 2016, 2017). This research has contained important messages regarding the level of within site sampling likely to be required to bring

* Corresponding author at: Institute of Marine and Antarctic Studies, Private Bag 49, University of Tasmania, Hobart 7001, Australia.
E-mail address: Nicholas.Perkins@utas.edu.au (N.R. Perkins).

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uncertainty in percentage cover estimates down to an acceptable level. At a site-level this will involve consideration of the interplay between transect design (or number of transects), the image subsampling approach, the scoring approach for individual images, and the properties of target groups such as their mean cover and spatial distribution (Perkins et al., 2016). Broad-scale long-term ecological monitoring programs will typically deploy a survey design that involves multiple sites nested within regions of interest that are revisited through time (Larsen et al., 2001; Urquhart, 2012). Therefore, there is also a need to take into account variability introduced into the time-series of data that are produced across larger scales. Indeed, spatial and temporal variation in ecological dynamics is typically large for most indicators (Skalski, 2012) and can compromise the ability of monitoring programs to detect long-term trends in group abundance, or community composition (Urquhart and Kincaid, 1999; Larsen et al., 2001).

Monitoring programs generally have two concerns: (i) estimating status; and (ii) estimating trends. Information about status is gained through gathering data on the geographical distribution of biota, whereas information about trend requires repeat visits over time (McDonald, 2003; Urquhart, 2012). The best survey designs for status estimation will cover the spatial extent of the survey area more effectively by including as many sites as is practical within budgetary constraints. On the other hand, designs with the highest power for detecting trends include planned revisits to sites across the entire survey period (Urquhart and Kincaid, 1999). Under a restricted budget, program designers need to balance the trade-off between spatial replication and temporal revisits. Various designs, termed panel designs, exist that aim to provide a balance between increasing the spatial extent of surveys for status estimation, and the benefit of revisits to sites for trend estimation (Duncan and Kalton, 1987). A panel in this sense is a set of selected units, such as sites, that enter and leave the sample at the same time, for example by being visited in the same year (for a review of different designs see McDonald, 2003). Regardless of the panel design employed, understanding the components of variance across the system and the influence they can have on survey outcomes is an essential element in order to effectively design the monitoring program (Elston et al., 2011).

When considering a long-term monitoring program with multiple sites, the components of variance at a minimum include: (i) site-to-site differences (some sites have, on average, higher/lower measurements than others for all measurement times); (ii) temporal variance that is expressed at all sites for example due to a trend; (iii) inter-annual differences, some years are higher/lower than others for reasons not related to trend; and (iv) the residual variance (Larsen et al., 2001). Even for the best sampling schemes, if there is high inter-annual variation in the response that is not driven by the trend, then detecting the trend will be challenging at best (Urquhart and Kincaid, 1999; Larsen et al., 2001; Urquhart, 2012).

Here we use data collected from AUV imagery in the early stages of a long-term deep-water benthic monitoring program in order to quantify the components of variance and their influence on the programs ability to detect climate-change-driven trend. Strong climate-driven ocean changes in SE Australia over recent decades (Ridgeway, 2007) have resulted in a large range of species undergoing a poleward redistribution in the region (Johnson et al., 2011; Robinson et al., 2015; Marzloff et al., 2016a,b). Given forecasts for ongoing warming (Oliver et al., 2014), further range shifts are expected, with populations of sessile benthic invertebrates being no exception. We focus our study on five deep water benthic indicator species with distributions that span at least the extent of the east coast of Tasmania (James et al., 2017). We analyse the results of repeat AUV surveys conducted to date at four deep-water monitoring sites in order to estimate the components of variance for these indicators. We then combine this information with predicted changes in abundance until 2060 (Marzloff et al., 2016b) to examine whether various revisit designs can detect the expected impacts of climate driven trends in abundance. Monitoring designs that vary in both the frequency of revisits and the number of sites included are simulated. Using the example of five key species in our study system, our aim is twofold: (i) to provide a baseline quantification of the components of variance in our system, in particular aspects of temporal variance, and (ii) to examine the power of various revisit designs to detect the declining regional trend in abundance predicted from the SDMs. While our focus is on key species in our study system, these species exhibit attributes common to many benthic taxa, and our approach and results will be informative for researchers aiming to establish benthic monitoring programs elsewhere.

2. Methods

2.1. Overview

The percent cover of five key deep-water invertebrate species was quantified in AUV imagery from repeat transects across four sites on the east coast of Tasmania, Australia (Fig. 1). The combined sessile invertebrate fauna below photic depth in this region often constitutes up to 100% benthic cover, however, few individual species exceed more than 2% of overall cover at any one survey location, and power to detect change is in part, a function of this rarity (Skalski, 2012). The species utilised here are representatives of the most abundant and readily recognised species in eastern Tasmanian surveys. They typify the species that may be monitored in any long-term program examining change in deep reef assemblages through time, and include a gorgonian, erect branching sponge, palmate sponge, massive sponge and a cup sponge species. Data on the percent cover of these species at four sites over two sampling events were analysed with generalised linear mixed models (GLMMs) in order to obtain estimates of the components of variance within this system for each species. Current cover estimates and predicted changes by 2060s derived from regional scale distribution models were combined to simulate scenarios of future changes in cover for our species. A set of monitoring designs were tested where the frequency of surveys and the number of sites revisited in any given panel varied. For each species, power was assessed by testing whether the climate trend induced by the predicted trend could be detected at any given point in time, or with any particular revisit design.

2.2. Data collection

AUV imagery was collected by the Australian government funded Integrated Marine Observing System (IMOS) program, which includes the long-term deployment of an AUV to monitor benthic ecosystems around Australia's coastline (Williams et al., 2012). This program was launched in 2007, with the intent of regular revisits to national reference sites as part of ongoing long-term benthic monitoring. We focussed our study on four sites on the east coast of Tasmania (Fig. 1) where repeat transects have been conducted: the western boundary of the Flinders Commonwealth marine reserve (CMR; $40^0 36'$S, $148^0 35'$E, mean depth 46 m), a deep water reef offshore from Bicheno in the Freycinet CMR ($41^0 54'$S, $148^0 26'$E, mean depth 74 m), a site off the Lanterns on the Tasman Peninsula ($43^0 08'$S, $148^0 00'$E, mean depth 50 m) and a site in the Huon CMR ($43^0 37'$S, $146^0 55'$E, mean depth 62 m). The Flinders site was first surveyed in June 2011, and again in June 2013 (2 years apart); the Bicheno site in June 2011, and again in June 2014 (3 years apart); the Lanterns site in May 2012, and again in June 2014