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Research article

Trade-offs between data resolution, accuracy, and cost when choosing information to plan reserves for coral reef ecosystems

Vivitskaia J. Tulloch [a, *], Carissa J. Klein [b], Stacy D. Jupiter [c], Ayesha I.T. Tulloch [b, d], Chris Roelfsema [e], Hugh P. Possingham [a]

[a] ARC Centre of Excellence for Environmental Decisions, School of Biological Sciences, University of Queensland, St Lucia, QLD 4072, Australia
[b] School of Geography, Planning, and Environmental Management, University of Queensland, St Lucia, QLD 4072, Australia
[c] Wildlife Conservation Society, Melanesia Program, 11 Ma'afu St, Suva, Fiji
[d] Fenner School of Environment, Australian National University, Canberra, ACT, Australia
[e] Biophysical Remote Sensing Group, University of Queensland, Brisbane 4072, Australia

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A B S T R A C T

Conservation planners must reconcile trade-offs associated with using biodiversity data of differing qualities to make decisions. Coarse habitat classifications are commonly used as surrogates to design marine reserve networks when fine-scale biodiversity data are incomplete or unavailable. Although finely-classified habitat maps provide more detail, they may have more misclassification errors, a common problem when remotely-sensed imagery is used. Despite these issues, planners rarely consider the effects of errors when choosing data for spatially explicit conservation prioritizations. Here we evaluate trade-offs between accuracy and resolution of hierarchical coral reef habitat data (geomorphology and benthic substrate) derived from remote sensing, in spatial planning for Kubulau District, Fiji. For both, we use accuracy information describing the probability that a mapped habitat classification is correct to design marine reserve networks that achieve habitat conservation targets, and demonstrate inadequacies of using habitat maps without accuracy data. We show that using more detailed habitat information ensures better representation of biogenic habitats (i.e. coral and seagrass), but leads to larger and more costly reserves, because these data have more misclassification errors, and are also more expensive to obtain. Reduced impacts on fishers are possible using coarsely-classified data, which are also more cost-effective for planning reserves if we account for data collection costs, but using these data may under-represent reef habitats that are important for fisheries and biodiversity, due to the maps low thematic resolution. Finally, we show that explicitly accounting for accuracy information in decisions maximizes the chance of successful conservation outcomes by reducing the risk of missing conservation representation targets, particularly when using finely classified data.

1. Introduction

Through a systematic conservation-planning framework, planners can maximize the chance that reserves are located in areas that will protect desired proportions of biodiversity (Margules and Pressey, 2000). However, trade-offs are inevitable in any planning situation. Although the location of marine reserves should be informed by high quality information on the distribution of biodiversity (Cabeza and Moilanen, 2001), often such data are incomplete or inaccurate, with scarce financial resources and time limiting additional data collection (Grantham et al., 2008). Habitat maps can be cost-effective data options for informing spatial management decisions, but all maps have errors (Wilson, 2010). Furthermore, their ability to represent biodiversity varies considerably depending on the features mapped (Mumby et al., 2008). A prevalent problem in marine spatial planning is using maps without understanding their classification accuracy (Tulloch et al., 2013). Knowing and accounting for differences in the accuracy of feature data used to plan reserves is crucial to ensure planning goals are achieved.

Remote sensing is rapidly becoming the most common method used to map marine habitats cost-effectively at a broad scale

* Corresponding author.
E-mail address: v.tulloch@uq.edu.au (V.J. Tulloch).

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(Mumby et al., 1999; Hamel and Andréfouët, 2010). However remotely-sensed habitat maps differ substantially in quality, depending on the types and pixel grain of satellite images used, the classification method and desired resolution of the final data, as well as the nature of features to be identified (e.g. geomorphology versus benthic habitat), and their spatial heterogeneity (Mumby et al., 2004; Goodman et al., 2013). Challenges exist in obtaining up-to-date accurate data for coral reefs due to their dynamic nature, as well as spectral similarities of certain reef cover types (Phinn et al., 2012). Because of this, errors and uncertainty in coral reef habitat map classification can be high (Phinn et al., 2008; Roelfsema and Phinn, 2013). This uncertainty invariably propagates through the decision-making process (Grand et al., 2007; Moilanen et al., 2006). In the past, many conservation plans using habitat maps have not accounted for their classification accuracy, often because it was not available, or hard to obtain. One recent example is the Great Barrier Reef Marine Park Rezoning (Fernandes et al., 2005), which used bioregional maps and assumed these were representative of a range of coral reef habitats without any accuracy information. Management decisions can be prone to errors of omission (when a feature is mistakenly thought to be absent) or commission (when a feature is mistakenly thought to be present) if inaccurate spatial data are used (Rondinini et al., 2006; Beech et al., 2008).

The decision to represent certain conservation features in a reserve is constrained by budget limitations and data availability (Possingham et al., 2001). Remotely-sensed maps of abiotic coral reef features at coarse thematic resolutions (e.g. geomorphic zones) are useful surrogates in spatial planning, as they enable identification of priority areas when more detailed information about species distributions is lacking or too costly to obtain (Heyman and Wright, 2011; Sutcliffe et al., 2015). Geomorphic maps can be very accurate due to the ease of delineating geomorphology at relatively large spatial scales (tens to hundreds of meters) directly from remote-sensing imagery (Andréfouët et al., 2006), but structural complexity and heterogeneity can be lost if the thematic scale of the classification is too coarse (Boyce, 2006). Finer habitat classifications are more difficult to delineate using remotely sensed images alone, but integration of field calibration data can help identify small-scale biotic habitats (e.g. coral, algae). Although some researchers advocate the use of geomorphic features as surrogates for ecological processes and biota (Heyman and Wright, 2011), others recommend using finer-resolution information describing coral reef habitats, as the higher thematic complexity provides a better proxy for associated species, ecological functions, and ecosystem services (Mumby et al., 2008; Dalleau et al., 2010). However, increasing the thematic resolution in a habitat map typically also increases classification error (Andréfouët, 2008; Roelfsema and Phinn, 2010). The sensitivity of conservation plans to increasingly complex habitat data, and the value of these data in representing true biodiversity, is of growing concern (e.g., Van Wynsberge et al., 2012; Deas et al., 2014). Despite this, error associated with increasingly complex features is rarely accounted for in spatial planning.

There are important trade-offs to consider when accounting for error and uncertainties in conservation planning. Approaches incorporating uncertainty typically result in larger (and therefore more costly) reserve systems to have a reasonable certainty of meeting targets (Allison et al., 2003; Tulloch et al., 2013). This is not always practical when management goals aim to balance economic (e.g., impact to fishers) and conservation objectives. Although accounting for socio-economic costs of implementing management is common practice in marine reserve design (Mills et al., 2010), there are other costs to consider for efficient conservation decisions. Collecting fine-resolution field and image data is expensive (Roelfsema and Phinn, 2010). Given a limited budget for marine conservation and the urgency of conservation problems, evaluating the benefits of collecting more detailed feature data against the costs of collection is crucial but rare (see Hermoso et al., 2013; Tulloch et al., 2014).

Here we examine the sensitivity of marine reserve network design to habitat maps of increasing spatial and thematic resolution, and their associated classification accuracies, using a case study of the Kubulau District fisheries management area in Fiji. We explore how conservation prioritization outcomes change given finer classifications, addressing three questions relevant to reserve planning globally:

1. How do priority conservation areas change when habitat data of increasingly fine resolution, and different accuracies, are used to plan reserves?
2. How well do reserves designed using mapped habitat data of differing resolution and accuracy represent biotic habitats, and does this differ when using standard approaches compared to those that consider classification accuracy?
3. What are the trade-offs between habitat representation, accuracy and cost when we move from using maps describing coarse reef data to more detailed benthic habitat data, and consider mapping accuracy during the decision-making process?

We use our results to explore the surrogacy value of different input data in conserving coral reef habitats. We then evaluate the effect of incorporating socio-economic cost data on the prioritization outcomes, and perform a cost-effectiveness analysis to compare the value of developing and using coarse or fine coral reef data in reserve design. We use this information to investigate an applied conservation management question for the Kubulau District fisheries management area in Fiji, where the reserve network was recently reconfigured using habitat maps without accuracy data (Weeks and Jupiter, 2013). We evaluate the adequacy of existing marine reserve networks at protecting targeted biodiversity, and identify how the existing marine network might differ if accuracy information had been used to minimize the risk that habitats were not adequately represented. We identify trade-offs associated with the use of more readily available data versus more risky and expensive options derived from further data collection. In doing so, we demonstrate ways to make more informed decisions about choosing data for reserve design to address issues of scale and find priority areas that are robust to uncertainty.

2. Material and methods

2.1. Study area

Our study area is the Kubulau District fisheries management area (*qoliqoli)* situated in southwest Vanua Levu, Fiji, covering 261.6 km^2 (Fig. 1, inset) (WCS, 2009). This area was chosen because hierarchical habitat data at increasingly spatial and thematic resolution are available. The area includes a diverse array of relatively pristine coral reef, seagrass beds, soft bottom lagoons, and deep channels (Knudby et al., 2011).

2.2. Data

We divided the region into 22,815 planning units (each 5000 m^2). Hierarchical habitat maps of the Kubulau *qoliqoli* have previously been developed using object-based image analysis (Blaschke, 2010) from high resolution satellite data (IKONOS, 2006; QuickBird, 2007), at four scales of increasing thematic and spatial