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Incorporating uncertainty associated with habitat data in marine reserve design

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ABSTRACT

One of the most pervasive forms of uncertainty in data used to make conservation decisions is error associated with mapping of conservation features. Whilst conservation planners should consider uncertainty associated with ecological data to make informed decisions, mapping error is rarely, if ever, accommodated in the planning process. Here, we develop a spatial conservation prioritization approach that accounts for the uncertainty inherent in coral reef habitat maps and apply it in the Kubulau District fisheries management area, Fiji. We use accuracy information describing the probability of occurrence of each habitat type, derived from remote sensing data validated by field surveys, to design a marine reserve network that has a high probability of protecting a fixed percentage (10–90%) of every habitat type. We compare the outcomes of our approach to those of standard reserve design approaches, where habitat-mapping errors are not known or ignored. We show that the locations of priority areas change between the standard and probabilistic approaches, with errors of omission and commission likely to occur if reserve design does not accommodate mapping accuracy. Although consideration of habitat mapping accuracy leads to bigger reserve networks, they are unlikely to miss habitat conservation targets. We explore the trade-off between conservation feature representation and reserve network area, with smaller reserve networks possible if we give up on trying to meet targets for habitats mapped with a low accuracy. The approach can be used with any habitat type at any scale to inform more robust and defensible conservation decisions in marine or terrestrial environments.

1. Introduction

In the face of current global failure to stem the rate of biodiversity loss (Butchart et al., 2010), there is an imperative to enhance protection of the world's terrestrial and marine biodiversity. However, numerous uncertainties make conservation decisions difficult. For example, less than half of the world's species have been described (Barnes, 1989; May, 1992) and the distribution of most described species is poorly known (Bini et al., 2006). Limitations also exist in our knowledge of ecological processes because they are dynamic and complex (Davis et al., 1998; Pearson et al., 2006). Despite these knowledge gaps and uncertainties, planners are required to make decisions about what, where, and when to invest in biodiversity conservation, due to limited conservation funds and competing needs for resources.

Protected areas (or reserves) can be one of the most successful management tools for protecting biodiversity (Margules and Pressey, 2000). However uninformed decisions on the location and design of reserves could have serious repercussions for the effectiveness and efficiency of conservation strategies (Possingham et al., 2006). There is a need, therefore, to improve upon current conservation planning practices, such as reserve design, and increase the reliability of conservation decisions. This can be achieved by including measures of uncertainty in the planning process.

A tacit assumption of most conservation planning is that ecological data are certain (Possingham et al., 2009; Wilson et al., 2005). In reality, there is uncertainty inherent in all ecological data. In addition to gaps in our knowledge of biotic systems and processes, we know that there are many facets of risk, error and/or uncertainty in any prediction of species distribution (Regan et al., 2005; Rondinini et al., 2006). These include presence–absence data errors, incomplete species distribution data, measurement or processing errors, erroneous taxonomic attribution, partial system observability, scarce or outdated observational data, and

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population model uncertainties (Drechsler, 2004; McCarthy et al., 2003; Moilanen et al., 2006; Soberon and Peterson, 2004; Wilson et al., 2011). With doubt surrounding our understanding of ecological systems, species distributions, and data integrity, methods used to study them cannot be considered robust unless they account for uncertainty. Despite this, significant gaps still remain in the conservation planning literature, with many aspects of uncertainty not yet accounted for (Halpern et al., 2006; Langford et al., 2009; Stine and Hunsaker, 2001).

When planning for reserves, conservation planners would ideally have access to distribution information for all aspects of biodiversity. However, such information does not exist for even the most data rich areas in the world as it is difficult and costly to collect (Pressey et al., 1993). To compensate for this lack of data, planners often use habitat maps as surrogates for biodiversity (Cowling and Heijnis, 2001; Margules and Pressey, 2000). While many studies have found that habitat surrogates are far from perfect (Beger et al., 2007; Lindsay et al., 2008; Mumby et al., 2008; Sutcliffe et al., 2012), they are essential if we wish to conserve biodiversity now.

The increasing availability of spatial data obtained through remote sensing has led to the growth of its use in applied marine research worldwide, with innovative new techniques producing habitat maps of high spatial resolution depicting geomorphic and biological structures that could be essential in reserve planning decisions (Andrefouet, 2008; Mumby and Edwards, 2002; Roelfsema and Phinn, 2010). In coral reef environments, remotely sensed satellite imagery is particularly suitable for habitat mapping, however accurate representation of coral reef features are beset by numerous challenges, including: dynamic changes in benthic cover; spatial and temporal variation in water clarity; and interpretation errors often due to spectral similarity of important reef features (Mumby et al., 2004; Phinn et al., 2012). Errors in coral reef maps derived from remote sensing are common, leading to "acceptable" levels of overall map accuracy as low as 50–60% (Phinn et al., 2008). Yet during the planning process there is generally little recognition of the underlying errors created when habitat maps are produced or how the choice of a particular processing technique affects the classification accuracy of each habitat. Furthermore, many of the habitat layers to be used in conservation planning do not contain accuracy assessments or error information. Failure to consider these mapping inaccuracies in conservation planning can lead to poorly informed management decisions as features that support critical species or processes of interest may not be adequately protected (Brooks et al., 2006; Pimm et al., 1995).

To address these problems, Steele (2006) suggests setting high conservation targets – a risk-averse precautionary approach. This is not dissimilar to the approach adopted by Allison et al. (2003), where an insurance factor was created to buffer against the possibility of not achieving conservation targets under a given catastrophe scenario. However, such an approach would lead to errors of commission (where extra habitat other than features of interest are included), wasting valuable conservation resources on large reserve networks that are in many places inefficient or infeasible, especially in areas where fisheries management areas or tenure units are smaller and therefore larger reserves result in substantial opportunity costs (Grand et al., 2007). Conversely, errors of omission (where a reserve does not actually contain the desired conservation features) can occur if one assumes that the maps are accurate, when in fact the mapping process has erroneously under-represented conservation features. Assuming a habitat is present when it is actually absent is the most dangerous error in conservation planning because it increases the risk of under-protecting features in the reserve design (Rondinini et al., 2006). Conservation planning methods that include uncertainty associated with habitat-mapping accuracy can therefore increase reliability and robustness of final conservation solutions by helping us achieve conservation goals efficiently (Moilanen et al., 2006). Despite this, a paucity of research exists that accounts for uncertainty in habitat distributions in reserve design (but see Beech et al., 2008). This may be because habitat mapping accuracy information is often not readily available or accessible to conservation planners. A key issue is not merely to assess whether uncertainty affects the results of a spatial prioritization, but to highlight the value of producing and providing accuracy assessments with any habitat map, so that uncertainty information can be explicitly included in these decision-making processes (Wintle et al., 2011).

Here, we develop an approach to spatial conservation prioritization that can account for inaccuracies in coral reef maps derived from remote sensing image data, using a readily available systematic conservation decision-support tool, and apply it to the Kubulau District fisheries management area in Fiji. Our objective in this study is to demonstrate the value of knowing how accurate our habitat maps are, and show how to explicitly account for these inaccuracies in conservation planning. We design a network of marine reserves using mapped habitat distribution data that aims to maximize the probability of protecting every habitat type by accounting for habitat mapping inaccuracies. We compare the output (i.e. priority areas, costs) of our probabilistic method with that of a more standard approach to reserve design, where mapping accuracy is not considered. Finally we highlight the trade-offs between habitat representation and area of reserve network that occur when habitat mapping accuracy information is or is not available.

2. Methods

2.1. Study region

The study area comprises the Kubulau traditional fishing grounds (*qoliqoli*), centered at 16°51′S and 179°0′E, located in south-west Vanua Levu, Fiji (Fig. 1). The *qoliqoli* extends from the coastline of the district to the outer barrier reefs, including several small islands, covering a total area of 261.6 km^2 (WCS, 2009). With assistance from non-government organizations, Kubulau communities have already initiated marine management projects (Jupiter and Egli, 2011), for which habitat maps were developed (Knudby et al., 2011).

2.2. Habitat data

Coral reef habitat maps were derived for the Kubulau *qoliqoli* by Knudby et al. (2011) using high spatial resolution multi-spectral satellite imagery (QuickBird 2006 and Ikonos 2007). A fine-scale benthic community substrate map with 33 individual classes was derived for the entire study region using object-based image analysis (Roelfsema et al., 2010), which involved image segmentation and classification and integration with field data for training and accuracy assessment (Knudby et al., 2011) (Fig. 1a). Each benthic community class (hereafter "habitat") describes a combination of coral, algal, seagrass, sediment, rubble and reef matrix substrata at a scale between 1 and 10 m. Each benthic habitat was described by the dominant habitat first, followed by sub-dominant, and so on. For example, "sediment rubble" means sediment-dominated substrate with some rubble.

Individual mapped habitat accuracies were obtained from the error matrix produced during the object-based image classification. The error matrix compares reference samples (field data) with image classes to calculate classification accuracy statistics for overall accuracy and the individual map category user and producer accuracies (Congalton and Green, 1999) (Appendix A). The user