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Remote sensing for studies of the spatial distribution of coral reef fishes

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Abstract. Reef fish biodiversity is influenced by habitat, including such variables as coral cover, depth, rugosity, and the distance to the reef edge. Commercially available satellite imagery can be used to map these habitat variables, and fish biodiversity can be estimated using the resulting habitat maps. We present a case study from two reefs in Zanzibar, Tanzania, based on IKONOS imagery acquired concurrently with habitat and fish surveys. The influence of some habitat variables, difficult or impossible to measure in-situ but mappable using satellite imagery, such as habitat diversity and depth variability at a range of spatial scales, are also explored. We illustrate how well each habitat variable can be estimated using remote sensing, and how accurately a variety of models can predict the spatial distribution of reef fish biodiversity. High-resolution satellite imagery can map species richness with a Residual Standard Error of <5 species at the study site. Future refinement of habitat maps and of predictive models is expected to reduce prediction error.

Key words: Remote sensing, Habitat mapping, Reef fish biodiversity, Predictive models.

Introduction

The influence of habitat on reef fish diversity has been demonstrated in experimental and observational studies (Roberts and Ormond 1987; Friedlander and Parrish 1998; Gratwicke and Speight 2005). Habitat variables found to influence fish diversity typically include live coral cover (henceforth: coral cover), depth, rugosity, and habitat heterogeneity (Huston 1994; Chabanet et al. 1997; Jones et al. 2004). The predictive strength of these variables, individually or combined, has varied between studies (Jones and Syms 1998; Knudby et al. 2007). It is therefore prudent that any relationships be establish locally before they feed into management decisions, e.g. designation of 'high-diversity habitat' as protected.

We established habitat-fish relationships using in-situ data on a range of habitat and fish diversity variables, from two reefs in Zanzibar, one protected (Chumbe) and one un-protected (Bawe) (Fig. 1). We then assessed the feasibility of predicting spatial variation in fish diversity using remotely sensed estimations of the most important habitat variables.

Material and Methods

Three data sets were used for this study. Fish point counts were made at 93 sites on Chumbe and 51 sites on Bawe. Sites were located at a random number of fin kicks, in a random direction, from the previous site. Habitat data were also collected at these sites, as well as at 347 additional sites on Chumbe and 56 sites on Bawe, covering all major habitat types. IKONOS satellite data, from 2007 for Chumbe and 2005 for Bawe, covered both reefs.

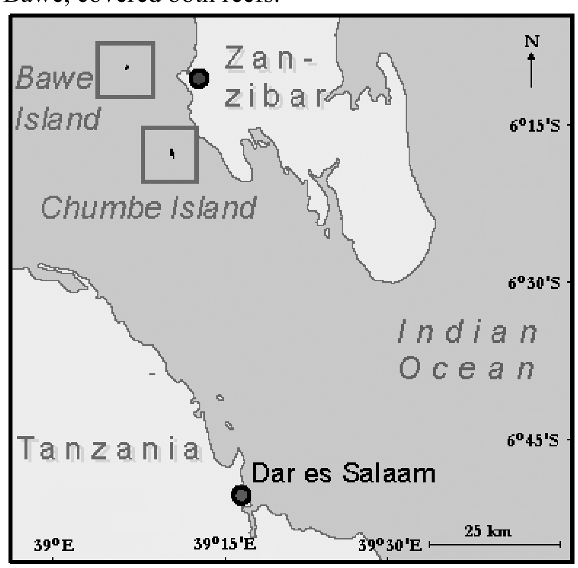

Figure 1: Study sites. The reef around Chumbe Island is effectively protected from direct human damage; the reef around Bawe Island is fished and used for dive and snorkel tourism.

Fish point counts

Fish point counts were carried out in 5m radius circles according to Bohnsack and Bannerot (1986). The location of each site was found by snorkeling in a random direction for a random number of fin-kicks from the previous site. Abundance and average length of all species were recorded.

Habitat surveys
For each site, maximum and minimum depth was measured with a dive computer, a GPS on a float was used for geolocation, coarse-scale rugosity (massive corals, patch reefs and low-frequency depth variation) and fine-scale rugosity (branching and digitate corals) were estimated on visual scales of 0-5 (Wilson et al. 2007), and substrate photos covering the 5m radius circle were processed in CPCe.

Satellite data
IKONOS images of the two reefs were preprocessed through geometric rectification, atmospheric correction with Atcor2, water column correction by calculation of Lyzenga's (1978) depth-invariant index, and sunglint removal (Hedley et al. 2005).

Data analysis
Fish point counts allowed calculation of three quantifications of the fish community: 1) species richness, 2) biomass, 3) Shannon-Weiner diversity. The biomass, based on length-weight conversion provided by FishBase (Froese and Pauly 2008), was used instead of abundance to mitigate bias in diversity calculations, otherwise caused by schools of *Chromis spp.*, often with several hundred individuals.

Depth measurements were used to calculate average depth and depth range (max depth–min depth). The substrate photos from each site were processed in CPCe (Kohler and Gill 2006) to extract percentage cover of substrate types. This also allowed calculation of coral cover, habitat diversity, and distinction between coral growth forms allowed calculation of the number of growth forms present at each site. The two reefs were processed independently.

From these sets of habitat and fish variables, individual correlations were explored. Ordinary least-squares (OLS) linear regression models were then developed to explain variation in each fish variable, and generalized additive models (GAM) were developed to account for non-linear relationships, and compared to OLS models using broken-stick transformed habitat variables. The Bayesian Information Criterion (Schwartz 1978) was used to include/exclude variables from both model types.

The satellite data were used to develop a number of products estimating habitat variables. First, a habitat map was developed, from which the habitat class and geomorphologic zone of each site could be derived. Classes were defined as: Dense coral (>40% cover), Sparse coral (5%-40% cover), Dense seagrass (>250g/m^2), Sparse seagrass (10-250g/m^2), Sand, Pavement, Algae, Deep Water (depth>15m). A linear regression of coral cover was derived from the depth-invariant index at each field site, and applied throughout the areas classified as coral in the habitat map, yielding a map of coral cover. Depth was estimated using the method by Stumpf et al. (2003), and rugosity was subsequently derived at a range of spatial scales (pixel sizes) using NOAA's Benthic Terrain Modeler with calculation from Jenness (2002). Finally the habitat map was used to derive a measure of habitat diversity at a range of spatial scales using NOAA's Diversity Calculator (Buja 2008).

Using only these remotely sensed habitat variables, new OLS and GAM models were derived, to assess the performance of IKONOS satellite imagery in predicting the fish variables.

Results
Correlations between fish variables and individual habitat variables showed several interesting patterns. Strong positive correlations with fish species richness on Chumbe were shown by both depth range (R=0.56) and coarse rugosity (R=0.66), presumably because they quantify the structural complexity of the reef at similar scales. Coral cover showed a similar correlation (R=0.58), as did the number of coral growth forms (R=0.55), with depth slightly less correlated (R=0.38). Similar results were obtained for Bawe, except for depth (R=-0.02).

Broken sticks
Analysis of the individual relationships showed that several were non-linear or piece-wise linear. Coral cover, depth, and coarse rugosity all showed positive (linear) correlations at low values, but reached a breakpoint after which further increase in the habitat variable did not lead to an increase in the fish variable.

Figure 2: Broken stick transformation of the relationship between coral cover and fish species richness on Chumbe. The breakpoint at 40% coral cover was determined visually, but can be optimized to yield the best combined fit of the two segments.

Such a relationship is illustrated in Fig. 2, where additional coral cover beyond 40% doesn't lead to an increase in species richness (data from Chumbe).

When such relationships were evident, breakpoints were selected from a scatter plot, and broken stick transformations of the habitat variables were carried out. This improved individual correlation for depth range (R=0.71), coarse rugosity (R=0.73), coral cover (R=0.64) and depth (R=0.50). Variables showing linear relationships were not transformed.

In-situ model comparison

OLS models generally included variables with high individual correlations, with a few notable exceptions. Two OLS models for Chumbe included habitat diversity, which had low (non-significant) individual correlations with these variables (R=0.12 for species richness, R=0.15 for diversity). The model for biomass on Bawe included coral cover, but also three specific coral growth forms (digitate, massive and encrusting corals). All three had positive individual correlation coefficients, but negative coefficients in the OLS model. Model summaries, including GAM models and OLS models using the broken-stick transformed variables, are provided in Table 1. As expected, the GAM models produced the lowest residual standard errors (RSE) due to their flexibility.

Dependent fish variable	**OLS**	**GAM**	**OLS BROKEN STICK**
Chumbe: Adj. R^2 / Residual Standard Error			
Species richness (species)	0.550/5.42	0.651/**3.58**	0.648/4.79
Biomass (g/100m^2)	0.348/3354	0.453/**1963**	0.453/3070
Diversity (Shannon Index)	0.538/0.57	0.562/**0.38**	0.532/0.52
Bawe: Adj. R^2 / Residual Standard Error			
Species richness (species)	0.538/4.77	0.619/**3.27**	0.684/3.95
Biomass (g/100m^2)	0.472/995	0.621/**536**	0.507/962
Diversity (Shannon Index)	0.404/0.70	0.534/**0.47**	0.620/0.56

Table 1: OLS, GAM, and OLS broken stick models for Chumbe and Bawe. Lowest RSE values in **bold**.

Remote sensing of habitat variables

The remotely estimated habitat variables were limited to the following: coral cover, depth, rugosity, and habitat diversity.

Coral cover on Chumbe was estimated on a per-pixel basis with an RSE of 19.71 percentage points (p.p.) (R=0.66), with a non-significant improvement gained from applying a 3x3 smoothing filter to the coral cover layer (RSE=19.38p.p., R=0.67). Further smoothing degraded the correlation. Similar results were obtained from Bawe (RSE=19.72p.p., R=0.59 with 3x3 smoothing filter). Coral cover varied between 0-92% on Chumbe, and 0-83% on Bawe.

Depth was estimated to within 1m on Chumbe (RSE=1.00m) and 1.5m on Bawe (RSE=1.52m). Depth varied between 2.6-11.3m on Chumbe, and 0.6-8.9m on Bawe.

Of the two rugosity variables, only the coarse rugosity was estimated from the satellite data. This was estimated better on Chumbe (R=0.46) than on Bawe (R=0.17). On Chumbe, the correlation degraded significantly with a coarsening of the spatial scale to pixel sizes of 8 and 12m, but then improved again with pixel sizes of 20 and 50m. On Bawe, the trend was toward lower correlations with increased pixel size.

Habitat diversity was estimated very poorly, with the highest correlations R=0.14 on both reefs.

Remotely sensed coral cover and fish

The correlations that remotely sensed coral cover obtained with the fish variables is much weaker than that obtained by in-situ observed coral cover. The influence of scale reflects the accuracy of the prediction of in-situ coral cover values, peaking at a 15 meter radius (Fig. 3).

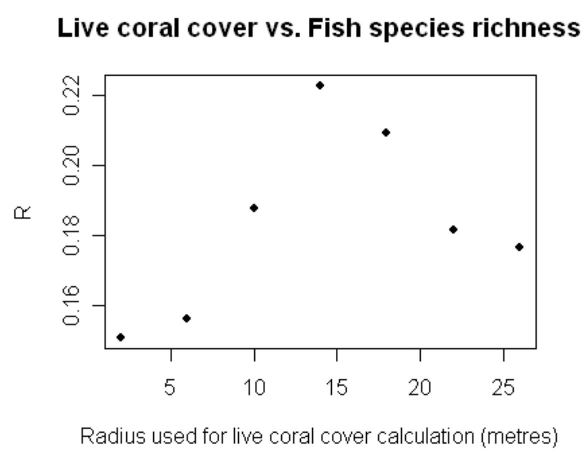

Figure 3: Correlations between fish species richness and remotely sensed coral cover at different spatial scales. Correlation with coral cover observed in-situ: R=0.58. Data from Chumbe. Optimum radius is 15 meters at Bawe, with similar correlation coefficients.

Remotely sensed rugosity and fish

Similarly, remotely sensed rugosity is correlated much weaker with the fish variables than either coarse rugosity (R=0.40, Bawe) or fine rugosity (R=0.37, Bawe) measured in-situ. Remotely sensed rugosity obtains the highest correlation with fish species richness at small pixel sizes (R=0.22 at 4m pixel size, Bawe), the correlation degrading with increasing pixel size (Fig. 4).

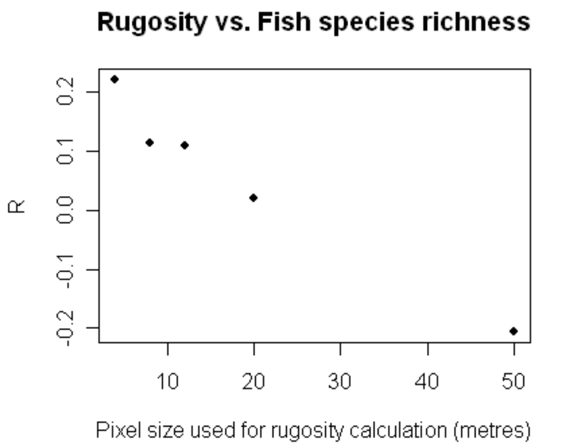

Figure 4: Correlations between fish species richness and remotely sensed rugosity calculated at different spatial scales. Correlations with other fish variables showed similar trends. Data from Bawe.

Remotely sensed habitat diversity and fish

Habitat diversity, however, showed a different trend. The in-situ habitat diversity variable had low correlations with all fish variables (R≤0.14), but when calculated on the basis of classes in the habitat map the correlations improved, reaching a peak at a radius of 30 meters (R≤0.37) (Fig. 5).

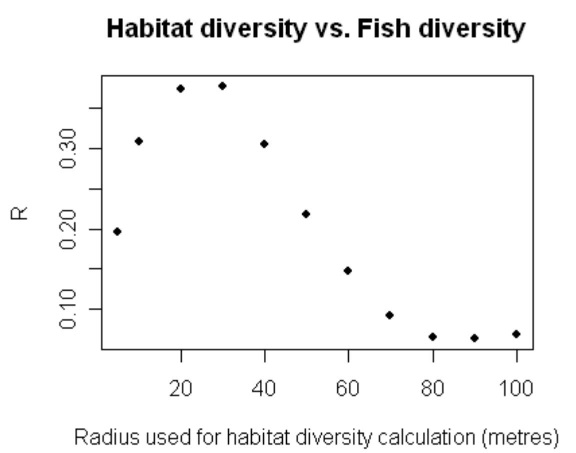

Figure 5: Correlations between fish diversity and remotely sensed habitat diversity calculated at different spatial scales. Correlations with other fish variables showed similar trends. Correlation with habitat diversity calculated on the basis of in-situ data: R=0.14. Data from Chumbe shown, data from Bawe show overall lower correlation coefficients, and two peaks at radii 10 and 50 meters.

Model comparison

The results from the OLS and GAM models, based exclusively on remotely sensed habitat variables, are shown in Table 2. A comparison reveals that models based on in-situ data generally outperform remote sensing-based models slightly, the one exception being diversity on Bawe.

Dependent fish variable	**OLS**	**GAM**	**OLS BROKEN STICK**
Chumbe: Adj. R^2 / Residual Standard Error			
Species richness (species)	0.491/5.76	0.458/**4.40**	0.502/5.70
Biomass ($g/100m^2$)	0.385/3255	0.375/**2109**	No trans.
Diversity (Shannon Index)	0.401/0.59	0.381/**0.43**	0.272/0.65
Bawe: Adj. R^2/ Residual Standard Error			
Species richness (species)	0.397/5.45	0.472/**3.72**	0.465/5.13
Biomass ($g/100m^2$)	0.141/1269	0.248/**763**	No trans.
Diversity (Shannon Index)	0.395/0.70	0.521/**0.44**	No trans.

Table 2: Summary of OLS, GAM and broken stick models based on remotely sensed habitat variables. "No trans." indicates that none of the variables were transformed, and results therefore similar to the ordinary OLS models. Note that the "broken stick" OLS model for diversity on Chumbe performs worse than the ordinary OLS model.

Discussion

This study provides a detailed investigation of habitat-fish relationships. The non-linear nature of several of the relationships provides interesting insights into the effects of habitat variables, e.g. showing how increasing coral cover is associated with increasing species richness, but only up to a 40% cover. For modeling purposes these non-linear relationships render linear models inappropriate, and suggest the use of GAM or other non-linear models.

Remote sensing, based on IKONOS data, was able to map both coral cover and depth fairly accurately. Depth mapping with IKONOS data has been investigated in many studies, but mapping of coral cover has remained difficult with multispectral data. We assume that the very low cover of algae on the two studied reefs has contributed to coral cover being mapped with high accuracy (<20 p.p. RSE).

Our IKONOS data were unable to map rugosity and habitat diversity accurately at the spatial scales at which these variables are observed in-situ. For rugosity, the scales mappable by IKONOS (pixel size 4 meters) have weaker correlations with fish biodiversity variables than visual in-situ estimates.

Inspection of rugosity maps illustrated that beyond the smallest spatial scales, rugosity values were overwhelmingly influences by their proximity to the reef edge, which may be the reason for the improved correlations of rugosity calculated with pixel sizes of 20 and 50 meters. In addition, the image from Bawe suffered from high-frequency noise that reduced the quality of the depth estimation, and hence the rugosity calculation.

Similar to rugosity, we were unable to accurately estimate the habitat diversity as measured in-situ, using the satellite data. However, when measured at scales accessible to remote sensing, but not to in-situ observation, habitat diversity showed improved correlations with the fish variables. This highlights an important use of remote sensing in reef studies: measuring ecologically relevant variables, such as habitat diversity, at their most meaningful spatial scale, which may be inaccessible to traditional field studies.

Optimum spatial scales

Our results are somewhat similar to those reported by Purkis et al. (2008) from Diego Garcia, who found that rugosity was most strongly related to the fish community when measured at radii ≤20 meters, and habitat diversity (quantified as evenness) most strongly related at radii 40-80 meters. Pittman et al. (2007), working in Puerto Rico, similarly found rugosity most strongly related to fish species richness at scales of 42.5 and 22.5 meters (half side lengths of square window). It thus seems that the optimum scales are fairly constant between locations, suggesting that these spatial scales have an ecological basis that is similar for the fish communities studied at these three locations.

Future study directions

The influence of habitat variables will be studied in relation to the presence/absence of individual species or the abundance of families or functional groups. This may yield greater insights into their ecological meaningfulness, which is not revealed by studying their influence on aggregate biodiversity measures as presented in this paper. The analysis of spatial scales will be included in this work, in order to attempt to explain the ecological basis for the optimum scales observed in this and other studies. Regression trees will be explored as a way to deal with the non-linear relationships between habitat and fish variables. The trees will be tested against the described models, and cross-validation applied to ensure robustness of all models.

Finally, the models will be applied to prediction of biodiversity variables in other protected and unprotected areas in Zanzibar.

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