



Cross-Shelf Habitat Occupancy Probabilities for Juvenile Groupers in the Florida Keys Coral Reef Ecosystem

Authors: Harford, W. J., Smith, S. G., Ault, J. S., and Babcock, E. A.

Source: Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 8(8) : 147-159

Published By: American Fisheries Society

URL: <https://doi.org/10.1080/19425120.2015.1074967>

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

SPECIAL SECTION: SPATIAL ANALYSIS, MAPPING, AND MANAGEMENT OF MARINE FISHERIES

Cross-Shelf Habitat Occupancy Probabilities for Juvenile Groupers in the Florida Keys Coral Reef Ecosystem

W. J. Harford,* S. G. Smith, J. S. Ault, and E. A. Babcock

Rosenstiel School of Marine and Atmospheric Science, University of Miami,
4600 Rickenbacker Causeway, Miami, Florida 33149, USA

Abstract

In the Florida Keys coral reef ecosystem, delineation of reef fish distributions in relationship to habitat patterns is important for improving the design characteristics of fishery-independent surveys. Efficient survey design depends on analysis of fish distribution patterns to inform and improve the precision of future surveys. We used a diver visual survey to quantify occupancy patterns of preexploitation-size Black Grouper *Mycteroperca bonaci* and Red Grouper *Epinephelus morio*. The survey was based on a stratified random sampling design with strata reflecting cross-shelf coral reef habitat types. A multiple spatial scale modeling approach confirmed a cross-shelf occurrence gradient for Red Grouper, with higher nearer-to-shore occupancy probability and lower offshore occupancy probability. Black Grouper occurrence followed a latitudinal gradient, with higher occurrence probabilities in the lower Florida Keys than in the upper Keys. Local habitat characteristics measured within reef strata suggested that occupancy relationships for both species varied according to vertical relief. Our analysis also included multilevel slope coefficients (random effects), which revealed unforeseen variance structure in Black Grouper occurrence probability among cross-shelf reef strata. Our study improves on previous qualitative observations of juvenile grouper distributions in the Florida Keys and highlights the use of multilevel models in revealing variance structures of fish distributions not revealed by fixed-effects models. Our analysis contributes to a discussion about foraging characteristics in producing the observed distributional patterns, and we suggest that examining the links between the distributions of forage fishes and larger predators (i.e., groupers) would be a useful step in improving survey stratification schemes.

In the Florida Keys coral reef ecosystem, delineation of fish and shellfish distribution patterns is critically important for efficient fishery-independent monitoring of reef resources (Ault et al. 1999, 2005a, 2009; Lindeman et al. 2000). The iterative process of designing and implementing fish surveys can capitalize on analyses of fish distributional patterns as a means to inform and improve survey design characteristics (Ault et al. 2005a; Smith et al. 2011a, 2011b). A common approach to delineating distribution patterns is to use resource

selection functions (RSFs; Manly et al. 2002). Although RSFs are used increasingly to address a wide range of ecological questions, their application to marine ecosystems remains relatively rare (Robinson et al. 2011). This apparent underutilization is unfortunate because RSFs hold great potential for addressing a range of ecological concerns, including gauging responses to reef degradation, informing marine reserve design, and improving survey stratification schemes (Meester et al. 2004; Grober-Dunsmore et al. 2006; Smith et al. 2011a).

Subject editor: Carl Walters, University of British Columbia, Vancouver

© W. J. Harford, S. G. Smith, J. S. Ault, and E. A. Babcock

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The moral rights of the named author(s) have been asserted.

*Corresponding author: william.harford@noaa.gov

Received February 23, 2015; accepted July 2, 2015

In this study, we had two objectives aimed at evaluating RSFs for preexploitation-size Red Grouper *Epinephelus morio* (<50 cm) and Black Grouper *Mycteroperca bonaci* (<60 cm) within the Florida Keys reef tract. Our focus on Red and Black groupers was motivated by the fact that descriptions of habitat use have been mainly qualitative for preexploitation or juvenile life stages, whereas statistical analyses have more frequently focused on surveys of adult groupers (Alevizon et al. 1985; Sluka and Sullivan 1996; Sluka et al. 1996, 2001; Newman et al. 1997; Connell and Kingsford 1998; Lopez-Rivera and Sabat 2009). Our first objective was to determine whether grouper distribution patterns varied in relation to cross-shelf habitat characteristics at two spatial scales. In riverine ecosystems, nested spatial hierarchies can be used to describe fish distributions in relation to watershed-scale climate patterns, catchment-scale surface runoff and stream flow, and stream-scale substrate characteristics (Harig and Fausch 2002; Harford and McLaughlin 2007; Tisseuil et al. 2013). In coral reef ecosystems, fish distributions can be described in relation to cross-shelf categorization of reef structures and local habitat characteristics within reef strata (Done 1983; Sluka et al. 1994; Connell and Kingsford 1998; Grober-Dunsmore et al. 2008; Kendall et al. 2011; Pittman and Brown 2011; Yeager et al. 2011).

Our second objective was to determine whether multilevel models (also known as hierarchical, random-effects, or mixed models) could reveal variation in grouper distribution patterns that would probably remain undetected by simpler fixed-effects models (Kutner et al. 2005; Gelman and Hill 2007). Multilevel linear models allow slope coefficients to vary among cross-shelf reef strata, which could reveal disparate strata-level responses to habitat covariates. Terrestrial applications of multilevel models have been demonstrably beneficial in revealing how habitat use patterns can vary between geographic regions and times of year (Boyce et al. 2002; Gillies et al. 2006; McLoughlin et al. 2010). In revealing whether and how habitat relationships vary spatially, previously unforeseen variance structures can in turn inform stratification schemes that generate cost-effective allocations of sampling effort in future surveys (Xu et al. 2015).

METHODS

Coral reef surveys.—The Florida Keys coral reef extends 400 km southwest along an island archipelago from Key Biscayne near Miami to the Dry Tortugas region 113 km west of Key West (Figure 1). Unique topographic and oceanographic conditions help sustain the highly productive ecosystem (Ault et al. 2005a). The coral reef tract consists of a series of parallel low ridges and connected valleys that are situated parallel to the Florida current and Florida Bay (Hoffmeister 1974). This coastal marine ecosystem consists of estuaries, lagoons, mangrove stands, coral islands, seagrass beds, and coral reefs. The cross-shelf formations of coral reefs

consist of inner-shelf patch reefs that form discontinuous linear clusters or irregularly scattered clusters and outer-shelf fore reefs that occur along the edge of the reef tract (Hoffmeister 1974; Shinn et al. 1977; Lidz et al. 2006; Smith et al. 2011b). Within reef formations, habitats are varied, with dramatic changes in topographic relief, substrate type, coral density, flow patterns, and wave action (Hoffmeister 1974; Geister 1977; Shinn et al. 1977; Smith et al. 2011b).

Since 1979, a multispecies fisheries-independent reef fish survey has been conducted in the Florida Keys coral reef ecosystem (Ault et al. 1998, 2005b; Smith et al. 2011a). We used scuba diver visual observations from these surveys that were conducted in depths <18 m during 2003 and annually between 2005 and 2011 ($n = 2,225$; Smith et al. 2011a). During this time period, divers began collecting detailed habitat measurements within observation plots. Surveys were conducted between May and September in the 885-km² domain of the Florida Keys coral reef tract using a two-stage stratified random sampling design that employed a spatial hierarchy of cross-shelf and site-scale habitat characteristics (Ault et al. 1998; Smith et al. 2011a). Annual allocation of sampling effort among strata was determined using a Neyman allocation to achieve estimates of a desired precision for multispecies reef fish density, abundance at length, and community composition (Smith et al. 2011a).

The two-stage survey design employed primary sampling units (PSUs; 200-m × 200-m mapped grids) and second-stage sampling units (SSUs; 15-m-diameter plots of 177 m²). Within chosen PSUs, two randomly selected SSUs were visited by divers; thus, the sampling design consisted of replicate visits to PSUs in which the observation plots (SSUs) were unique and covered only a small spatial extent of each PSU. At each SSU, closely spaced pairs of scuba divers conducted a standardized observation process that involved listing all observed fish species during 5-min sampling periods before recording abundance and fork length. Cross-shelf reef strata were classified according to reef type, rugosity, and cross-shelf position (Table 1). Because the observed abundances of Red and Black groupers were relatively low at each SSU, we opted to recode the observed counts as binary occurrence indicators (positive = 1 and none-observed = 0). Variables considered as plausible correlates of grouper occurrence (hereafter, habitat variables) were bottom depth (m), maximum vertical relief (m), percent coral cover, percent hard bottom, and latitude. The first four variables were measured by divers during each visit to an SSU. All habitat variables were averaged to produce PSU-level observations and were subsequently standardized by subtracting the mean and dividing by the standard deviation. Variable standardization produced scale-independent variables, which helped to facilitate convergence of the Markov chain–Monte Carlo algorithm and allowed the magnitudes of the slope coefficients to be compared directly.

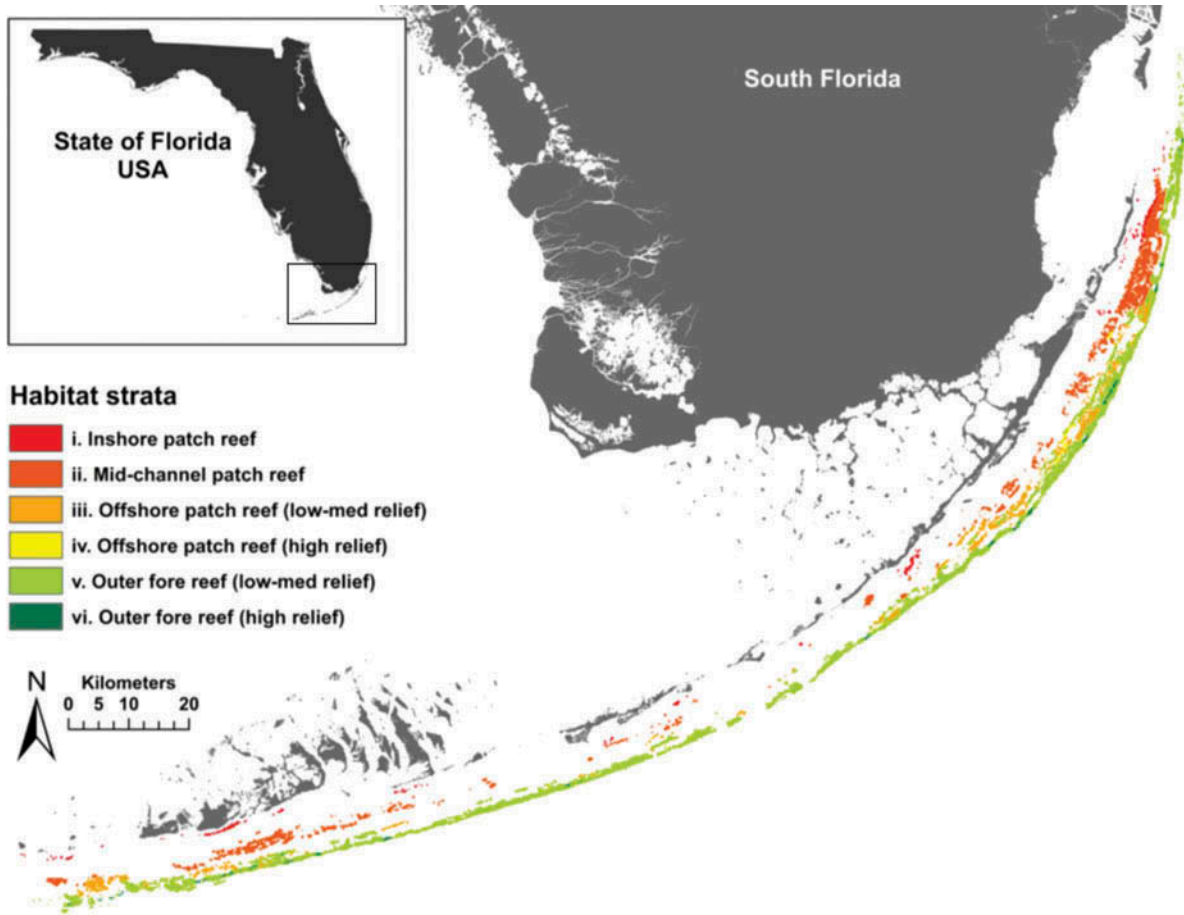


FIGURE 1. Map of the Florida Keys coral reef tract. Reef strata are described in Table 1.

TABLE 1. Physical and biological habitat characteristics of primary sampling units (PSUs) during 2003–2011. Abbreviations are as follows: *n* = the number of PSUs sampled, min = the minimum value, max = the maximum value, and avg = the mean value.

Habitat stratum type	Rugosity	<i>n</i>	Bottom depth (m)			Vertical relief (m)			% Coral cover			Latitude (decimal degrees)			% Hard bottom		
			Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
i. Inshore patch reef	Low–med	99	1.8	3.5	7.8	0.10	1.16	3.12	0	13.8	45.6	24.51	24.96	25.74	17.5	75.6	100
ii. Midchannel patch reef	Low–med	390	1.5	5.3	12.6	0.12	1.37	4.27	0	10.7	52.2	24.46	25.03	25.52	10.7	77.1	100
iii. Offshore patch reef	Low–med	228	2.1	7.0	13.5	0.10	1.08	4.00	0.2	6.2	32.2	24.44	24.91	25.55	12.5	73.2	100
iv. Offshore patch reef	High	45	2.2	6.2	12.4	0.90	2.41	3.97	2.2	9.0	26.0	25.10	25.11	25.29	35.0	79.2	98.2
v. Outer fore reef	Low–med	1,184	2.1	9.0	18.0	0.10	0.79	3.20	0	3.3	25.0	24.43	24.97	25.74	0	70.6	100
vi. Outer fore reef	High	279	2.8	6.6	17.1	0.32	2.19	4.42	0.6	5.3	36.8	24.43	24.76	25.58	23.7	74.2	100

Resource selection functions.—We evaluated logistic regression and more complex zero-inflated binomial models in our preliminary development of RSFs using occurrence data. Logistic occurrence probability was modeled using the binomial density function

$$Z_i \sim \text{binomial}(J_i, \psi_i), \quad (1)$$

where Z_i , the number of positive detections at PSU $_i$, is a function of the occurrence probability, ψ_i , and the number of SSUs visited at PSU $_i$, J_i . Hall (2000) introduced the zero-inflated binomial model for bounded count data to account for excess zeros, which was later extended to site occupancy modeling of animal distributions (MacKenzie et al. 2002; Tyre et al. 2003). Site occupancy models consist of several approaches similar to logistic regression but in which two binomial processes are jointly estimated (MacKenzie et al. 2002, 2006; Royle and Dorazio 2009):

$$Z_i \sim \begin{cases} 0, & \text{with probability } 1 - \psi_i \\ \text{binomial}(J_i, p_i) & \text{with probability } \psi_i. \end{cases} \quad (2)$$

The number of positive detections, Z_i , is a function of the probability of occurrence, ψ_i , and the conditional probability of observation, p_i , that arises from the J_i samples (visits) in the second binomial process. The probability of a zero observation at a particular PSU can be thought of as the sum two possible outcomes: (1) no individuals were present (which has the probability $1 - \psi_i$) or (2) one or more individuals were present but went unobserved (which has the probability $\psi_i[1 - p_i]^{J_i}$).

A logit-linear occurrence submodel ψ_i' was used to describe occurrence as a function of habitat variables (X_k):

$$\psi_i' = \mu + \alpha_{s[i]} + \sum_{k=1}^5 \beta_{k,s[i]} X_{ik}, \quad (3)$$

with probability of occurrence (ψ_i) written as

$$\psi_i = \exp(\psi_i') / (1 + \exp(\psi_i')). \quad (4)$$

In equation (3), the notation $s[i]$ refers to the cross-shelf reef stratum containing PSU $_i$, μ is the grand mean, and α_s refers to the categorical reef strata coefficients. Slope coefficients $\beta_{k,s}$ were modeled as random effects to enable responses to vary among reef strata:

$$\beta_{k,s[i]} = \mu_{\beta k} + \delta_{k,s[i]}, \quad (5)$$

where $\mu_{\beta k}$ is the mean slope for coefficient k and $\delta_{k,s[i]}$ are random coefficients describing stratum-level deviations with variances $\sigma_{\delta k}^2$.

While our primary interest was in occupancy probabilities, we also wanted to explore how the observation process p ,

expressed as a function of the habitat variables, could affect model fit. Thus, p was expressed as a logit-linear observation submodel of PSU-level habitat variables:

$$p_i' = v + \sum_{k=1}^3 \omega_k X_{ik}, \quad (6)$$

with the mean intercept v expressed as a probability (p_i):

$$p_i = \exp(p_i') / (1 + \exp(p_i')). \quad (7)$$

The coefficients ω_k corresponded to maximum vertical relief, depth, and coral cover.

The Bayesian approach was used to fit logistic regression and site occupancy models in OpenBUGS (Lunn et al. 2009; Kéry and Schaub 2012). In RSF development, some model variants were considered that were not well supported by the data and were excluded from our final model formulations. These models included ones with quadratic terms (X_k^2) to screen for curvilinear responses to habitat variables and a categorical year coefficient to account for interannual variation in occurrence probability. For the logistic regression and site occupancy model formulations, a Gibbs sampler-based variable selection technique was used to identify and select habitat variables with the highest posterior probabilities (Kuo and Mallick 1998; Congdon 2003; Ntzoufras 2009). To implement this Bayesian variable selection technique, the logit-linear responses were modified such that coefficients were multiplied by a binary indicator parameter. When the indicator parameters took on a value of 1, their associated coefficients were included in the model; when they took on a value of 0, however, the associated coefficients were excluded. The indicator parameters had Bernoulli priors with probabilities of 0.5 to give each variable an equal prior probability of inclusion. Posterior means of binary indicators determined the inclusion probabilities of their associated parameters, with those having probabilities >0.50 being retained in each RSF (Ntzoufras 2009).

Logit-scale intercept and categorical reef stratum coefficients were assigned diffuse normal priors with means zero and variances 2.7 (Lunn et al. 2012). Mean slope coefficients were assigned diffuse normal priors, and among-strata slope variances, $\sigma_{\delta_j}^2$, were assigned priors of $\sqrt{\sigma_{\delta_j}^2} \sim \text{uniform}(0, 5)$. We also conducted a sensitivity analysis for the choice of priors for the logit-scale parameters using a diffuse t -distribution (Dorazio et al. 2011). After we discarded an initial 150,000 iterations, the Markov chain–Monte Carlo algorithm converged (based on Geweke and Gelman–Rubin criteria) for all models (Geweke 1992; Congdon 2003; Gelman et al. 2004). Approximation of the posterior distribution was obtained from a subsequent 150,000 samples from two parallel chains. Model adequacy was assessed by calculating squared Pearson residuals to

compare the lack of model fit to the data against the lack of fit that would be expected from replicated data sets produced using the model's assumptions and estimated parameters (Brooks et al. 2000; Gelman and Hill 2007; Kéry 2010). The Bayesian P -value was calculated as the proportion of times that the replicated residuals were greater than the observed residuals, with values near 0.5 indicating a good fit (Gelman et al. 2004; Ntzoufras 2009).

RESULTS

Coral Reef Surveys

Diver samples at PSUs varied between 213 and 457 during 2003–2011. The PSUs sampled were located between latitudes 24.431°N and 25.749°N, which corresponds approximately to the coral reef habitats occurring between Key West and Miami, Florida (Table 1). Across all PSUs, bottom depths ranged between 1.5 and 18.0 m and maximum vertical relief ranged between 0.10 and 4.42 m. The prevalence of hard-bottom habitats varied from 0% to 100%, but the percentage of coral cover never exceeded 52.2%. There was some evidence of correlation between the standardized variables used in the site occupancy models (Pearson's $|r| < 0.38$ [all pairwise comparisons]). Average abundance at the scale of the SSU ranged between 0.0 and 8.0 individuals per sample for Black Grouper and between 0.0 and 2.5 individuals per sample for Red Grouper. Thus, there was relatively little information loss concerning habitat use patterns in recoding relative abundance as binary observations.

Red Grouper Resource Selection Functions

For Red Grouper occurrence, the logistic regression formulation (equation 1) had a poor fit to the data (Bayesian P -value of 0.99) and thus was considered to have low support as a plausible descriptor (Figure 2). The site occupancy formulation (equation 2) fit appreciably better, with a Bayesian P -value of 0.61. In each model formulation, inclusion probabilities supported reef stratum-level intercepts, which are interpreted as conditional categorical responses (α_i ; Table 2). We calculated odds ratios for the intercept coefficients using reef stratum i (low–medium relief inshore patch reefs) as a reference category (Figure 3). Odds ratios greater than 1 indicated better odds of Red Grouper occurrence relative to the reference category, and odds ratios less than 1 indicated worse odds of occurrence. While the stratum-level intercepts were mostly nonsignificant, with the exception of high-rugosity offshore fore reefs (habitat stratum vi), a cross-shelf decline in occurrence odds from inshore to offshore was evident (Figure 3).

Posterior inclusion probabilities also supported a negative occupancy relationship with maximum vertical relief in both the simple logistic and site occupancy model formulations (Table 2). Both formulations suggested negative relationships with vertical relief, but the site occupancy formulation supported vertical relief-induced heterogeneity in observation

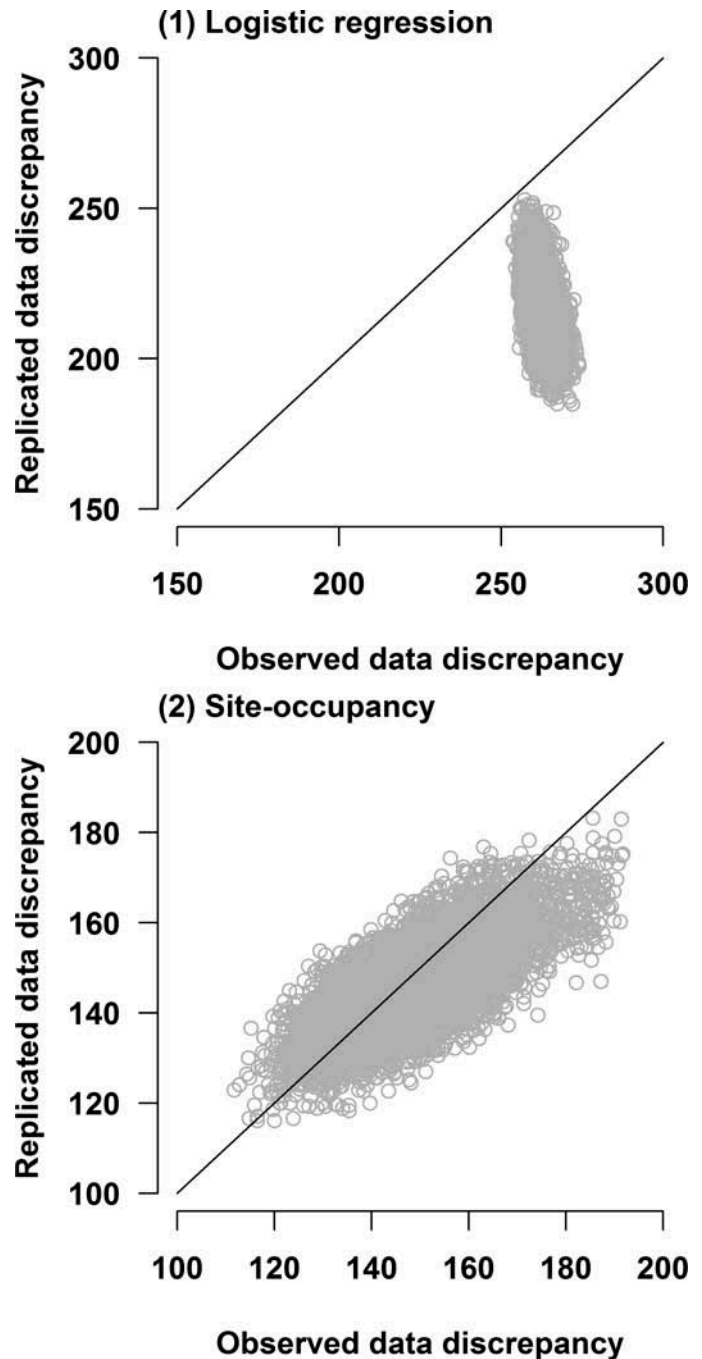


FIGURE 2. Goodness-of-fit plots for Red Grouper resource selection functions. Shown are the observed and replicated discrepancy measures calculated from the squared Pearson residuals for each binomial model formulation.

probability rather than in occupancy probability. The predicted responses from zero-inflated submodel components p and ψ were plotted against maximum vertical relief (Figure 4). The trends illustrate how the predicted source (p or ψ) of a negative response to vertical relief changed based on whether heterogeneity in the observation process

TABLE 2. Variable inclusion probabilities and coefficient means for Red Grouper statistical models. Asterisks indicate variables included in resource selection functions; values in parentheses are standard errors; na = not applicable.

Parameter	Variable inclusion probability		Site occupancy coefficient means	
	Logistic regression	Site occupancy	Base diffuse priors	<i>t</i> -distribution diffuse priors
Occurrence submodel				
Mean slope (μ_j)				
Depth	0.02	0.13	na	na
Vertical relief	0.91*	0.27	na	na
% Coral cover	0.01	0.03	na	na
Latitude	0.01	0.03	na	na
% Hard bottom	0.00	0.02		
Random slopes (δ_j)				
Depth	0.14	0.16	na	na
Vertical relief	0.16	0.27	na	na
% Coral cover	0.11	0.44	na	na
Latitude	0.61	0.57	na	na
% Hard bottom	0.02	0.07	na	na
Reef stratum (α_s)	1.00*	1.00*	0.71 (0.75)	0.66 (0.75)
Strata i to vi			0.92 (0.68)	0.80 (0.69)
			0.86 (0.70)	0.75 (0.69)
			0.35 (1.05)	0.41 (1.05)
			-0.49 (0.65)	-0.58 (0.65)
			-2.31 (0.72)	-2.44 (0.75)
Grand mean (μ)	na	na	-0.06 (0.65)	0.04 (0.66)
Conditional submodel				
Mean slope (ω_j)				
Depth	na	0.13	na	
Vertical relief	na	0.78*	-0.52 (0.08)	-0.53 (0.07)
% Coral cover	na	0.01	na	
Grand mean (ν)	na	na	-0.88 (0.11)	-0.89 (0.11)

was included in model structure. In addition, there was weak support in the inclusion probabilities for differences in occurrence responses to latitude among habitat strata, but the latitude slope coefficients were nonsignificant and no systematic trends were apparent. We examined whether these results (and those for Black Grouper below) were sensitive to the form of the diffuse logit-scale priors used in the analysis.

Using an alternative *t*-distribution prior, we found posterior distributions of model parameters to be quite similar between priors (Tables 2, 3).

Black Grouper Resource Selection Functions

The fit of the logistic regression model to the data was poor, with a Bayesian *P*-value of 1.0. The site occupancy

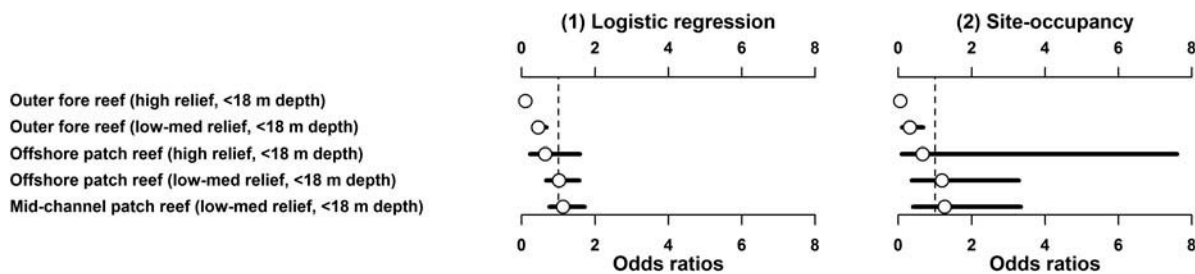


FIGURE 3. Intercept odds ratios of Red Grouper occurrence in each reef stratum. Odds ratios were calculated relative to reference stratum i, defined as low-medium relief inshore patch reefs. The circles denote means, and the lines are centered 95% confidence intervals.

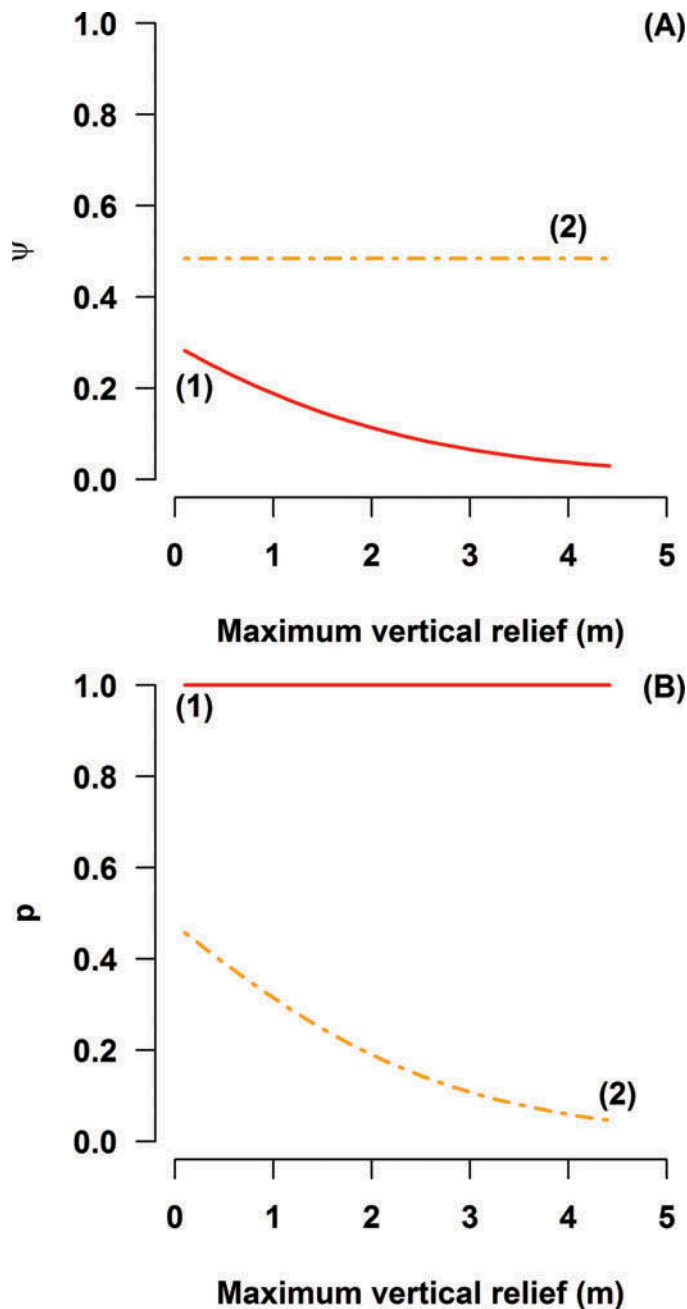


FIGURE 4. (A) Red Grouper responses to maximum vertical relief from the occurrence submodel (ψ) and (B) the observation submodel (p). The solid (1) and dashed (2) lines correspond to the logistic regression and site occupancy formulations, respectively.

model fit appreciably better, with a Bayesian P -value of 0.67. Posterior inclusion of maximum vertical relief and latitude were supported by logistic regression (Table 3). As with Red Grouper, when the observation process (p) was allowed to vary in relation to habitat variables, the inclusion probabilities supported vertical relief-induced heterogeneity in p and vertical relief no longer corresponded to occurrence probability

(A) (Table 3). However, unlike in the case of Red Grouper, p varied positively with maximum vertical relief. The inclusion probabilities did not support reef stratum intercepts, but there was support for reef stratum-level differences in the response of occurrence probability to depth (Table 3).

For the logistic regression and site occupancy models for Black Grouper, predicted occurrence probability was plotted against latitude with maximum vertical relief fixed at its observed mean, and vice versa (Figure 5A, B). In each formulation, a negative occurrence probability response to latitudinal change was predicted. The analysis also revealed support for cross-shelf differences in the response of occurrence probability to depth (Table 3; Figure 6). The slope coefficients for depth in the occurrence submodel varied among reef strata and were consistently negative for the strata nearest to shore and positive for the outer-shelf fore reef strata (Figure 6).

DISCUSSION

The fishery-independent diver visual survey (Smith et al. 2011a) was designed from principles of probability-based statistical sampling, thus providing a sound foundation for occurrence modeling (Cochran 1977; Hayek and Buzas 1996; MacKenzie et al. 2006). The large spatial extent of the Florida Keys sampling domain and the innovations in survey stratification in relation to relevant habitat and environmental features enabled investigation at appropriate ecological scales (Wiens 1989; Ault et al. 2005b, 2013; Johnson et al. 2013). This survey has been tailored to the objectives of multispecies stock assessment, evaluation of the effectiveness of no-take marine reserves, and measurement of ecosystem and reef fish community condition (Smith et al. 2011a; Ault et al. 2014). Its design reflects a trade-off in sampling effort allocation between repeating site visits (to improve understanding of observation processes) and visiting many unique sites (to improve occurrence and abundance estimation) (Smith et al. 2011a). This trade-off can be complicated (for more on survey design for occupancy and detection estimation, see Field et al. 2005; MacKenzie and Royle 2005; Guillera-Arroita et al. 2010; Wintle et al. 2012; Monk 2014). In our analysis, simple logistic regression produced poor fits to the data because the number of zeroes in the data set exceeded the binomial expectation. The site occupancy models produced improved fits, so we expected that this formulation would be more reliable in evaluating trends in the probability of occupancy.

Applying the site occupancy model to the survey data did, however, introduce additional complexity in interpreting the results of the observation submodel. It may seem intuitive to interpret the observation submodel as providing detection probabilities (as is commonly done in site occupancy modeling), but the particular characteristics of grouper ecology and the fishery-independent survey make this conclusion

TABLE 3. Variable inclusion probabilities and coefficient means for Black Grouper statistical models. Asterisks indicate variables included in resource selection functions; values in parentheses are standard errors; na = not applicable.

Parameter	Variable inclusion probability		Site occupancy coefficient means	
	Logistic regression	Site occupancy	Base diffuse priors	<i>t</i> -distribution diffuse priors
Occurrence submodel				
Mean slope (μ_j)				
Depth	0.02	0.09	na	na
Vertical relief	0.90*	0.04	na	na
% Coral cover	0.29	0.04	na	na
Latitude	0.98*	0.80*	-1.10 (0.15)	-1.09 (0.15)
% Hard bottom	0.01	0.10	na	na
Random slopes (δ_j)				
Depth	0.99*	1.00*	-1.02 (0.66)	-0.99 (0.63)
Strata i to vi			-1.21 (0.32)	-1.20 (0.32)
			0.07 (0.41)	0.06 (0.41)
			-1.14 (0.70)	-1.12 (0.68)
			0.20 (0.14)	0.20 (0.14)
			2.19 (0.49)	2.15 (0.49)
Vertical relief	0.36	0.11	na	na
% Coral cover	0.05	0.05	na	na
Latitude	0.05	0.39	na	na
% Hard bottom	0.03	0.18	na	na
Reef stratum (α_s)	0.31	0.05	na	na
Grand mean (μ)	na	na	0.17 (0.19)	0.15 (0.19)
Observation submodel				
Mean slope (ω_j)				
Depth	na	0.06	na	na
Vertical relief	na	1.00*	0.61 (0.06)	0.61 (0.06)
% Coral cover	na	0.04	na	na
Grand mean (ν)	na	na	-1.23 (0.09)	-1.22 (0.09)

problematical for several reasons. Excess zeroes could have occurred if individual fish inhabiting a PSU moved into or out of the SSU, lowering the probability of their being observed by a diver. While many reef-associated fishes tend to exhibit low mobility, larger grouper species maintain home ranges considerably larger than the 200-m \times 200-m PSU (Chapman and Kramer 2000; Farmer and Ault 2011). The areal extent of an SSU in relation to that of a PSU also suggests that fine-scale spatial environmental heterogeneity could influence the propensity for not being observed by divers. A separate (but not mutually exclusive) possibility is that individual fish that are present within an SSU when it is observed by a diver are not actually detected. Thus, it is possible that in the observation submodel p is a confounding of the probability of movement into/out of an SSU, fine-scale differences in fish distribution between SSUs, and detection probability given presence in the SSU.

Accounting for observational processes in marine ecosystems remains a challenging issue in occupancy and

abundance estimation. Although the surveys that we analyzed did entail repeated visits to PSUs, the observation plots themselves were not repeatedly visited and covered only small portions of the much larger PSUs. Designs that achieve replication by conducting surveys in different observation plots within a larger sampling unit have been used for occupancy modeling (MacKenzie and Royle 2005; MacKenzie et al. 2006), but these designs may exaggerate abundance-induced heterogeneity in the observation process (Figures 4, 5). Abundance-induced observation heterogeneity arises in many sampling situations, as higher local (site) abundance is expected to yield more net detections (Royle and Dorazio 2009). With respect to detection probability, several previous studies indicate that it can vary with body size, schooling behavior, cryptic nature, distance from divers, and survey method (Byerly and Bechtol 2005; MacNeil et al. 2008a, 2008b; Bozec et al. 2011; Dickens et al. 2011). Clearly, accounting for observation processes, including detection probability, is an

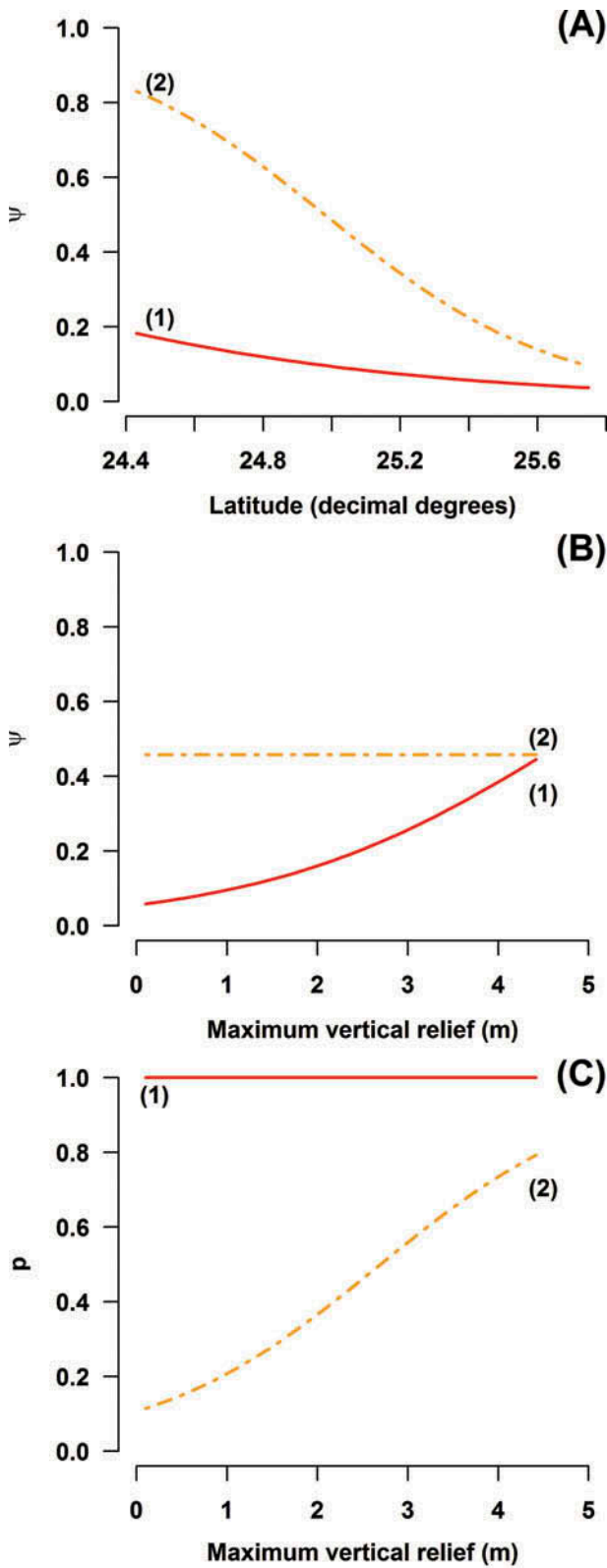


FIGURE 5. Black Grouper responses to (A) latitude and (B) maximum vertical relief from the occurrence submodel (ψ) and (C) vertical relief from observation submodel (p). The solid (1) and dashed (2) lines correspond to the logistic regression and site occupancy formulations, respectively.

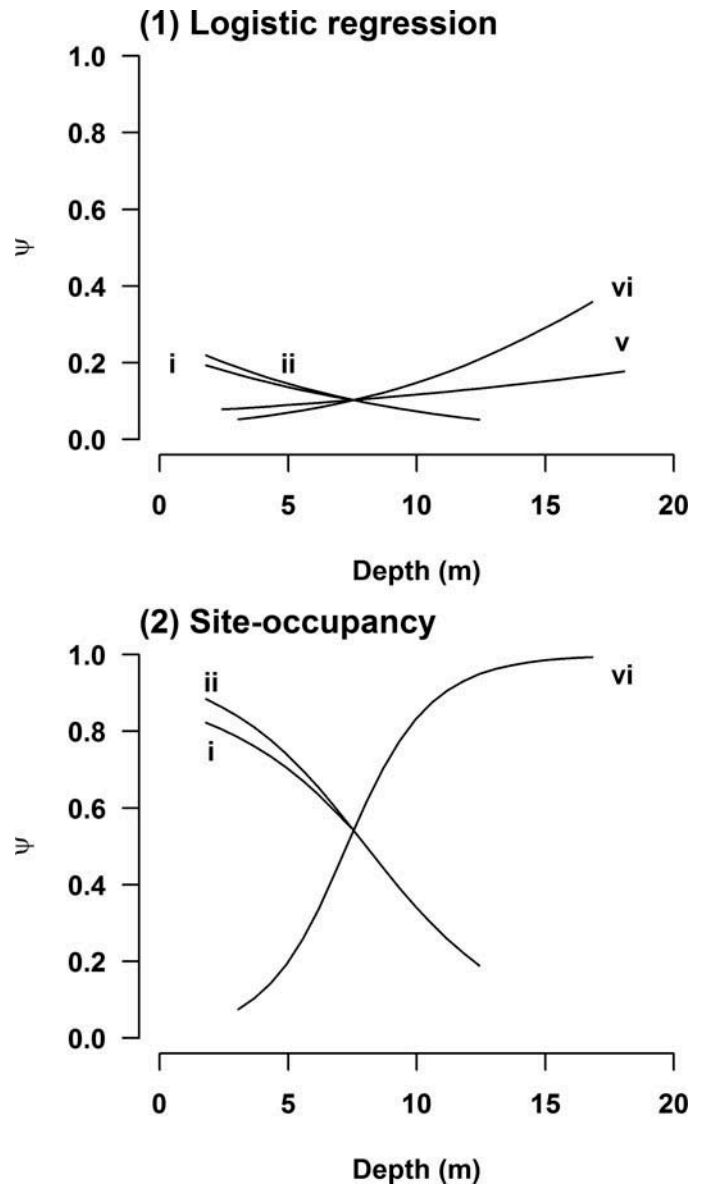


FIGURE 6. Conditional responses in Black Grouper occurrence probability (ψ) to depth within each reef stratum for the logistic regression and site occupancy model formulations. Reef strata (i–vi) are described in Table 1. Only reef strata with statistically significant slope coefficients are shown.

important step in statistical occupancy and abundance estimation, but one that is currently not receiving sufficient attention in the analysis of marine ecosystems (Monk 2014).

Both Red and Black grouper demonstrated occurrence responses that varied with regional topographic features of the Florida Keys reef tract. The occurrence of preexploitation-size Red Grouper appears to vary systematically with the proximity of reef habitat to the coastline. Occurrence probability was predicted to be higher in

nearshore patch reef habitats than in offshore fore reef habitats. The strength of this pattern was somewhat inconsistent, but inshore-to-offshore occurrence patterns were observed in all model formulations. Positive occurrence nearer to shore confirms previous observations that preexploitation-stage Red Grouper inhabit inshore waters of the Florida Keys (Moe 1969; Sluka et al. 1994). The probability of occurrence of preexploitation-phase Black Grouper tended to decrease from Key West (24.60°N) to Key Largo (25.07°N) and toward Miami. This southwest-to-northeast decline is intriguing in the context of the related distribution of Black Grouper spawning abundance. Although latitude (a north–south gradient) was used in our analysis, spawning abundance is highly correlated with longitude (Pearson's $\rho = 0.93$) given the geographic orientation of the Florida Keys reef tract (Figure 1). Using the same intensive diver surveys analyzed in this study, Ault et al. (2013) reported on the recovery of exploited reef fishes in marine reserves of the Dry Tortugas. While the Dry Tortugas region contains about 22% of the broader Florida Keys–Dry Tortugas coral reef habitat, it accounts for over 50% of Black Grouper spawning abundance (Ault et al. 2013). Ault et al. (2013) raise the question whether the Dry Tortugas region functions as an important recruitment source. This possibility is also supported by the directionality of the regional currents that may transport larval fish across the Florida Keys (Lee et al. 1994; Domeier 2004).

Red and Black grouper also exhibited occurrence responses that varied with the local habitat characteristics of the PSUs. Both species responded to vertical relief, but in opposite ways (Figures 4, 5). We note that the final site occupancy model formulations included vertical relief in the observation submodel rather than the occupancy submodel. However, the directionality of occurrence in relation to vertical relief is more consistent with abundance-induced observation heterogeneity (occurrence patterns) than with observation complexities (detection heterogeneity). For instance, the declining detection of Red Grouper with increasing vertical relief could reflect the difficulty of detecting cryptic fishes in highly rugose habitats, but this is inconsistent with the gregarious and possibly territorial responses of Red Grouper reported by approaching divers. Instead, the declining occupancy response with respect to vertical relief probably reflects the species' use of benthic substrates for foraging and shelter. Like other members of the genus *Epinephelus*, Red Grouper probably utilize crevices in hard substrates for shelter and for ambushing benthic prey (Smith 1961; Cailliet et al. 1986; Parrish 1987; Brulé and Rodríguez Canché 1993; López-Rocha and Arreguín-Sánchez 2008; Coleman et al. 2010). Conversely, Black Grouper tend to forage above the bottom, are slender and have a tapering body form, and appear to be more agile swimmers (Parrish 1987). Like other

mycteroperoid groupers, they maintain a fish-dominated diet that includes fast-swimming and pelagic prey species (Randall 1967; Parrish 1987; Brulé et al. 2005). The positive association between Black Grouper and vertical relief could be indicative of the diversity of this species' forage base and the larger habitat volume created for forage fish by vertical structures. In support of this possibility, observational studies of the Florida Keys reef tract report the occurrence of Black Grouper near a diversity of reef formation types (Sullivan and Sluka 1996).

Our analysis of multilevel slope coefficients suggests that the occurrence response of Black Grouper to depth differed among reef strata. Within inshore and midchannel patch reefs, Black Grouper occurred with higher probability in the shallowest of available depths, while occurrence at outer fore reefs was highest in the deepest of available habitats (Figure 6). This result could mean that Black Grouper are not cueing on depth at all but that the variation in occurrence associated with depth reflects the influence of more ecologically meaningful variables. For instance, the occurrence of Black Grouper may reflect their forage base, which could be correlated with depth in some of the reef strata. Black Grouper have a diverse forage base, including pelagic and demersal species (e.g., Pomacentridae, Carangidae, Scaridae, and Labridae) that occur in both nearshore habitats and deeper-water fore reef habitats (Williams 1991; Overholtzer and Motta 1999; Brulé et al. 2005; Aguilar-Perera and Appeldoorn 2008; Collins and McBride 2011). This highlights a potentially unexplored aspect of Black Grouper ecology and the usefulness of multilevel models for identifying unforeseen variance structure in fish distribution patterns. More broadly, the occurrence patterns of both species suggest foraging characteristics that reflect a rather incomplete aspect of our analysis. Given our interest in improving survey design, it seems prudent that subsequent analyses move beyond simply linking fish distributions to abiotic surrogates of the underlying processes that result in occupancy. Rather, examining the spatial variance structures of predatory species (groupers) should move toward analysis of forage base habitat use and subsequently link forage base distributions to predator distributions. Such an approach could be influential in improving the precision of surveys that are essential for resource management (Smith et al. 2011a; Xu et al. 2015).

ACKNOWLEDGMENTS

We thank two anonymous reviewers for comments that led to the improvement of this manuscript. Financial support for this research was provided by the Cooperative Institute for Marine and Atmospheric Studies of the University of Miami (NOAA cooperative agreement NA10OAR4320143), the NOAA Coral

Reef Conservation Program grant NA17RJ1226, NOAA MARFIN Grant NA11NMF4330129, and a Natural Sciences and Engineering Research Council of Canada postgraduate scholarship to W.J.H.

REFERENCES

- Aguilar-Perera, A., and R. S. Appeldoorn. 2008. Spatial distribution of marine fishes along a cross-shelf gradient containing a continuum of mangrove-seagrass-coral reefs off southwestern Puerto Rico. *Estuarine, Coastal, and Shelf Science* 76:378–394.
- Alevizon, W., R. Richardson, P. Pitts, and G. Serviss. 1985. Coral zonation and patterns of community structure in Bahamian reef fishes. *Bulletin of Marine Science* 36:304–317.
- Ault, J. S., J. A. Bohnsack, and G. A. Meester. 1998. A retrospective (1979–1996) multispecies assessment of coral reef fish stocks in the Florida Keys. U.S. National Marine Fisheries Service Fishery Bulletin 96:395–414.
- Ault, J. S., J. A. Bohnsack, S. G. Smith, and J. Luo. 2005a. Towards sustainable multispecies fisheries in the Florida, USA, coral reef ecosystem. *Bulletin of Marine Science* 76:595–622.
- Ault, J. S., G. A. Diaz, S. G. Smith, J. Luo, and J. E. Serafy. 1999. An efficient sampling survey design to estimate pink shrimp population abundance in Biscayne Bay, Florida. *North American Journal of Fisheries Management* 19:696–712.
- Ault, J. S., S. G. Smith, and J. A. Bohnsack. 2005b. Evaluation of average length as an estimator of exploitation status for the Florida coral reef fish community. *ICES Journal of Marine Science* 62:417–423.
- Ault, J. S., S. G. Smith, J. A. Bohnsack, J. Luo, N. Zurcher, D. B. McClellan, T. A. Ziegler, D. E. Hallac, M. Patterson, M. W. Feeley, B. I. Ruttenberg, J. Hunt, D. Kimball, and B. Causey. 2013. Assessing coral reef fish population and community changes in response to marine reserves in the Dry Tortugas, Florida, USA. *Fisheries Research* 144:28–37.
- Ault, J. S., S. G. Smith, J. A. Browder, W. Nuttle, E. C. Franklin, J. Luo, G. T. DiNardo, and J. A. Bohnsack. 2014. Indicators for assessing the ecological and sustainability dynamics of southern Florida's coral reef and coastal fisheries. *Ecological Indicators* 44:164–172.
- Ault, J. S., S. G. Smith, and J. T. Tilmant. 2009. Are the coral reef finfish fisheries of South Florida sustainable? Pages 989–993 in B. Riegl and R. E. Dodge, editors. 11th International coral reef symposium proceedings. International Society for Reef Studies.
- Boyce, M. S., P. R. Vernier, S. E. Nielsen, and F. K. A. Schmiegelow. 2002. Evaluating resource selection functions. *Ecological Modelling* 157:281–300.
- Bozec, Y.-M., M. Kulbicki, F. Laloë, G. Mou-Tham, and D. Gascuel. 2011. Factors affecting the detection distances of reef fish: implications for visual counts. *Marine Biology* 158:969–981.
- Brooks, S. P., E. A. Catchpole, and B. J. T. Morgan. 2000. Bayesian animal survival estimation. *Statistical Science* 15:357–376.
- Brulé, T., E. Puerto-Novelo, E. Pérez-Díaz, and X. Renán-Galindo. 2005. Diet composition of juvenile Black Grouper (*Mycteroperca bonaci*) from coastal nursery areas of the Yucatan Peninsula, Mexico. *Bulletin of Marine Science* 77:441–452.
- Brulé, T., and L. G. Rodriguez Canché. 1993. Food habits of juvenile Red Groupers, *Epinephelus morio* (Valenciennes, 1828) from Campeche Bank, Yucatan, Mexico. *Bulletin of Marine Science* 52:772–779.
- Byerly, M. M., and W. R. Bechtol. 2005. Evaluation of scuba assessment methods for shallow-water, nearshore Black Rockfish (*Sebastes melanops*). Pages 831–850 in G. H. Kruse, V. F. Gallucci, D. E. Hay, R. I. Perry, R. M. Peterman, T. C. Shirley, P. D. Spencer, B. Wilson, and D. Woodby, editors. Fisheries assessment and management in data-limited situations. University of Alaska, Alaska Sea Grant College Program, Fairbanks.
- Cailliet, G. M., M. Love, and A. Edeling. 1986. Fishes: a field and laboratory manual on their structure, identification, and natural history. Wadsworth Publishing, Belmont, California.
- Chapman, M. R., and D. L. Kramer. 2000. Movements of fishes within and among fringing coral reefs in Barbados. *Environmental Biology of Fishes* 57:11–24.
- Cochran, W. G. 1977. Sampling techniques, 3rd edition. Wiley, New York.
- Coleman, F. C., C. C. Koenig, K. M. Scanlon, S. Heppell, S. Heppell, and M. W. Miller. 2010. Benthic habitat modification through excavation by Red Grouper *Epinephelus morio*, in the northeastern Gulf of Mexico. *Open Fish Science Journal* [online serial] 3:1–15.
- Collins, A. B., and R. S. McBride. 2011. Demographics by depth: spatially explicit life history dynamics of a protogynous reef fish. U.S. National Marine Fisheries Service Fishery Bulletin 109:232–242.
- Congdon, P. P. 2003. Applied Bayesian modeling. Wiley, Hoboken, New Jersey.
- Connell, S. D., and M. J. Kingsford. 1998. Spatial, temporal, and habitat-related variation in the abundance of large predatory fish at One Tree Reef, Australia. *Coral Reefs* 17:49–57.
- Dickens, L. C., C. H. R. Goatley, J. K. Tanner, and D. R. Bellwood. 2011. Quantifying relative diver effects in underwater visual censuses. *PLoS (Public Library of Science) ONE* [online serial] 6(4):e18965.
- Domeier, M. L. 2004. A potential larval recruitment pathway originating from a Florida marine protected area. *Fisheries Oceanography* 13:287–294.
- Done, T. J. 1983. Coral zonation: its nature and significance. Pages 107–147 in D. J. Barnes, editor. Perspectives on coral reefs. Australian Institute of Marine Science, Townsville.
- Dorazio, R. M., N. J. Gotelli, and A. M. Ellison. 2011. Modern methods of estimating biodiversity from presence-absence surveys. Pages 278–302 in O. Grillo, editor. Biodiversity loss in a changing planet. InTech, Rijeka, Croatia.
- Farmer, N., and J. Ault. 2011. Grouper and snapper movements and habitat use in Dry Tortugas, Florida. *Marine Ecology Progress Series* 433:169–184.
- Field, S. A., A. J. Tyre, and H. P. Possingham. 2005. Optimizing allocation of monitoring effort under economic and observational constraints. *Journal of Wildlife Management* 69:473–482.
- Geister, J. 1977. The influence of wave exposure on the ecological zonation of Caribbean coral reefs. Pages 23–29 in D. L. Taylor, editor. Proceedings of the Third International Coral Reef Symposium, volume 2: geology. Rosenstiel School of Marine and Atmospheric Science, Miami.
- Gelman, A., J. B. Carlin, H. S. Stern, and D. B. Rubin. 2004. Bayesian data analysis, 2nd edition. Chapman and Hall/CRC, London.
- Gelman, A., and J. Hill. 2007. Data analysis using regression and multilevel/hierarchical models. Cambridge University Press, New York.
- Geweke, J. 1992. Evaluating the accuracy of sampling-based approaches to calculating posterior moments. Pages 169–194 in J. Bernardo, J. Berger, A. Dawid, and A. Smith, editors. Bayesian statistics, volume 4. Oxford University Press, Oxford, UK.
- Gillies, C. S., M. Hebblewhite, S. E. Nielsen, M. A. Krawchuk, C. L. Aldridge, J. L. Frair, D. J. Saher, C. E. Stevens, and C. L. Jerde. 2006. Application of random effects to the study of resource selection by animals. *Journal of Animal Ecology* 75:887–898.
- Grober-Dunsmore, R., T. K. Frazer, J. P. Beets, W. J. Lindberg, P. Zwick, and N. A. Funicelli. 2008. Influence of landscape structure on reef fish assemblages. *Landscape Ecology* 23(Supplement 1):37–53.
- Grober-Dunsmore, R., T. K. Frazer, W. J. Lindberg, and J. Beets. 2006. Reef fish and habitat relationships in a Caribbean seascape: the importance of reef context. *Coral Reefs* 26:201–216.
- Guillera-Arroita, G., M. S. Ridout, and B. J. T. Morgan. 2010. Design of occupancy studies with imperfect detection. *Methods in Ecology and Evolution* 1:131–139.
- Hall, D. B. 2000. Zero-inflated Poisson and binomial regression with random effects: a case study. *Biometrics* 56:1030–1039.

- Harford, W. J., and R. L. McLaughlin. 2007. Understanding uncertainty in the effect of low-head dams on fishes of Great Lakes tributaries. *Ecological Applications* 17:1783–1796.
- Harig, A. L., and K. D. Fausch. 2002. Minimum habitat requirements for establishing translocated Cutthroat Trout populations. *Ecological Applications* 12:535–551.
- Hayek, L.-A. C., and M. A. Buzas. 1996. Surveying natural populations. Columbia University Press, New York.
- Hoffmeister, J. E. 1974. Land from the sea: the geologic story of South Florida. University of Miami Press, Coral Gables, Florida.
- Johnson, A. F., S. R. Jenkins, J. G. Hiddink, and H. Hinz. 2013. Linking temperate demersal fish species to habitat: scales, patterns, and future directions. *Fish and Fisheries* 14:256–280.
- Kendall, M. S., T. J. Miller, and S. J. Pittman. 2011. Patterns of scale dependency and the influence of map resolution on the seascape ecology of reef fish. *Marine Ecology Progress Series* 427:259–274.
- Kéry, M. 2010. Introduction to WinBUGS for ecologists: a Bayesian approach to regression, ANOVA, mixed models, and related analyses. Elsevier, Boston.
- Kéry, M., and M. Schaub. 2012. Bayesian population analysis using WinBUGS: a hierarchical perspective. Academic Press, New York.
- Kuo, L., and B. Mallick. 1998. Variable selection for regression models. *Sankhyā* 60:65–81.
- Kutner, M. H., C. J. Nachtsheim, J. Neter, and W. Li. 2005. Applied linear statistical models, 5th edition. McGraw-Hill/Irwin, New York.
- Lee, T. N., M. E. Clarke, E. Williams, A. F. Szmant, and T. Berger. 1994. Evolution of the Tortugas Gyre and its influence on recruitment in the Florida Keys. *Bulletin of Marine Science* 54:621–646.
- Lidz, B. H., C. D. Reich, R. L. Peterson, and E. A. Shinn. 2006. New maps, new information: coral reefs of the Florida Keys. *Journal of Coastal Research* 22:260–282.
- Lindeman, K. C., R. Pugliese, G. T. Waugh, and J. S. Ault. 2000. Developmental patterns within a multispecies reef fishery: management applications for essential fish habitats and protected areas. *Bulletin of Marine Science* 66:929–956.
- Lopez-Rivera, M. D. M., and A. M. Sabat. 2009. Effects of a marine fishery reserve and habitat characteristics in the abundance and demography of the Red Hind Grouper, *Epinephelus guttatus*. *Caribbean Journal of Science* 45:348–362.
- López-Rocha, J. A., and F. Arreguín-Sánchez. 2008. Spatial distribution of Red Grouper *Epinephelus morio* (Serranidae) catchability on the Campeche Bank of Mexico. *Journal of Applied Ichthyology* 24:282–289.
- Lunn, D., C. Jackson, N. Best, A. Thomas, and D. Spiegelhalter. 2012. The BUGS book: a practical introduction to Bayesian analysis. Chapman and Hall/CRC Press, Boca Raton, Florida.
- Lunn, D., D. Spiegelhalter, A. Thomas, and N. Best. 2009. The BUGS project: evolution, critique, and future directions (with discussion). *Statistics in Medicine* 28:3049–3082.
- MacKenzie, D. I., J. D. Nichols, G. B. Lachman, S. Droege, J. Andrew Royle, and C. A. Langtimm. 2002. Estimating site occupancy rates when detection probabilities are less than one. *Ecology* 83:2248–2255.
- MacKenzie, D. I., J. D. Nichols, J. A. Royle, K. H. Pollock, L. L. Bailey, and J. E. Hines. 2006. Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence. Academic Press, New York.
- MacKenzie, D. I., and J. A. Royle. 2005. Designing occupancy studies: general advice and allocating survey effort. *Journal of Applied Ecology* 42:1105–1114.
- MacNeil, M. A., N. A. J. Graham, M. J. Conroy, C. J. Fonnesebeck, N. V. C. Polunin, S. P. Rushton, P. Chabanet, and T. R. McClanahan. 2008a. Detection heterogeneity in underwater visual-census data. *Journal of Fish Biology* 73:1748–1763.
- MacNeil, M. A., E. H. M. Tyler, C. J. Fonnesebeck, S. P. Rushton, N. V. C. Polunin, and M. J. Conroy. 2008b. Accounting for detectability in reef fish biodiversity estimates. *Marine Ecology Progress Series* 367:249–260.
- Manly, B. F., L. McDonald, D. L. Thomas, T. L. McDonald, and W. P. Erickson. 2002. Resource selection by animals: statistical design and analysis for field studies, 2nd edition. Springer, New York.
- McLoughlin, P. D., D. W. Morris, D. Fortin, E. Vander Wal, and A. L. Contasti. 2010. Considering ecological dynamics in resource selection functions. *Journal of Animal Ecology* 79:4–12.
- Meester, G. A., A. Mehrotra, J. S. Ault, and E. K. Baker. 2004. Designing marine reserves for fishery management. *Management Science* 50(8):1031–1043.
- Moe, M. A. J. 1969. Biology of the Red Grouper *Epinephelus morio* (Valenciennes) from the eastern Gulf of Mexico. Florida Department of Natural Resources Marine Research Laboratory Professional Paper Series 10.
- Monk, J. 2014. How long should we ignore imperfect detection of species in the marine environment when modelling their distribution? *Fish and Fisheries* 15:352–358.
- Newman, S. J., D. M. Williams, and G. R. Russ. 1997. Patterns of zonation of assemblages of the Lutjanidae, Lethrinidae, and Serranidae (Epinephelinae) within and among midshelf and outer-shelf reefs in the central Great Barrier Reef. *Marine and Freshwater Research* 48:119–128.
- Ntzoufras, I. 2009. Bayesian modeling using WinBUGS. Wiley, Hoboken, New Jersey.
- Overholtzer, K. L., and P. J. Motta. 1999. Comparative resource use by juvenile parrotfishes in the Florida Keys. *Marine Ecology Progress Series* 177:177–187.
- Parrish, J. D. 1987. The trophic biology of snappers and groupers. Pages 405–464 in J. J. Polovina and S. Ralston, editors. Tropical snappers and groupers: biology and fisheries management. Westview Press, Boulder, Colorado.
- Pittman, S. J., and K. A. Brown. 2011. Multi-scale approach for predicting fish species distributions across coral reef seascapes. *PLoS (Public Library of Science) ONE [online serial]* 6(5):e20583.
- Randall, J. E. 1967. Food habits of reef fishes of the West Indies. *Studies in Tropical Oceanography* 5:665–847.
- Robinson, L. M., J. Elith, A. J. Hobday, R. G. Pearson, B. E. Kendall, H. P. Possingham, and A. J. Richardson. 2011. Pushing the limits in marine species distribution modelling: lessons from the land present challenges and opportunities. *Global Ecology and Biogeography* 20:789–802.
- Royle, J. A., and R. M. Dorazio. 2009. Hierarchical modeling and inference in ecology. Elsevier, Boston.
- Shinn, E. A., J. H. Hudson, R. B. Halley, and B. Lidz. 1977. Topographic control and accumulation rate of some Holocene coral reefs: South Florida and Dry Tortugas. Pages 1–8 in Proceedings of the Third International Coral Reef Symposium, volume 2. Rosentiel School of Marine and Atmospheric Science, Miami.
- Sluka, R., M. Chiappone, and K. M. S. Sealey. 2001. Influence of habitat on grouper abundance in the Florida Keys, U.S.A. *Journal of Fish Biology* 58:682–700.
- Sluka, R., M. Chiappone, and K. M. Sullivan. 1994. Comparison of juvenile grouper populations in southern Florida and the central Bahamas. *Bulletin of Marine Science* 54:871–880.
- Sluka, R., M. Chiappone, and K. M. Sullivan. 1996. Habitat preferences of groupers in the Exuma Cays. *Bahamas Journal of Science* 4:8–14.
- Sluka, R., and K. M. Sullivan. 1996. The influence of habitat on the size distribution of groupers in the upper Florida Keys. *Environmental Biology of Fishes* 47:177–189.
- Smith, C. L. 1961. Synopsis of biological data on groupers (*Epinephelus* and allied genera) of the western North Atlantic. FAO (Food and Agriculture Organization of the United Nations) Fisheries Biology Synopsis 23.
- Smith, S. G., J. S. Ault, J. A. Bohnsack, D. E. Harper, J. Luo, and D. B. McClellan. 2011a. Multispecies survey design for assessing reef fish stocks, spatially explicit management performance, and ecosystem condition. *Fisheries Research* 109:25–41.

- Smith, S. G., D. W. Swanson, M. Chiappone, S. L. Miller, and J. S. Ault. 2011b. Probability sampling of stony coral populations in the Florida Keys. *Environmental Monitoring and Assessment* 183:121–138.
- Sullivan, K. M., and R. Sluka. 1996. The ecology of shallow-water groupers (Pisces: Serranidae) in the upper Florida Keys, USA. Pages 74–84 in F. Arreguín-Sánchez, J. L. Munro, M. Balgos, and D. Pauly, editors. *Proceedings of an EPOMEX/ICLARM International Workshop on Tropical Snappers and Groupers*. International Center for Living Aquatic Resources Management, Manila.
- Tisseuil, C., J.-F. Cornu, O. Beauchard, S. Brosse, W. Darwall, R. Holland, B. Hugueny, P. A. Tedesco, and T. Oberdorff. 2013. Global diversity patterns and cross-taxa convergence in freshwater systems. *Journal of Animal Ecology* 82:365–376.
- Tyre, A. J., B. Tenhumberg, S. A. Field, D. Niejalke, K. Parris, and H. P. Possingham. 2003. Improving precision and reducing bias in biological surveys: estimating false-negative error rates. *Ecological Applications* 13:1790–1801.
- Wiens, J. A. 1989. Spatial scaling in ecology. *Functional Ecology* 3:385–397.
- Williams, D. M. 1991. Patterns and processes in the distribution of coral reef fishes. Pages 437–474 in P. F. Sale, editor. *The ecology of fishes on coral reefs*. Academic Press, New York.
- Wintle, B. A., T. V. Walshe, K. M. Parris, and M. A. McCarthy. 2012. Designing occupancy surveys and interpreting nondetection when observations are imperfect. *Diversity and Distributions* 18:417–424.
- Xu, B., C. Zhang, Y. Xue, Y. Ren, and Y. Chen. 2015. Optimization of sampling effort for a fishery-independent survey with multiple goals. *Environmental Monitoring and Assessment* 187:252.
- Yeager, L. A., C. A. Layman, and J. E. Allgeier. 2011. Effects of habitat heterogeneity at multiple spatial scales on fish community assembly. *Oecologia* 167:157–168.