Multispecies Survey Design for Assessing Reef-Fish Stocks, Spatially-Explicit Management Performance, and Ecosystem Condition

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INTRODUCTION

The southern Florida coral reef ecosystem supports lucrative fishing and tourism economies. Management concerns over the productivity of reef-fish stocks include non-sustainable rates of exploitation for target species, the impacts of fishing on ecosystem trophic structure and food-web dynamics, and non-fishing human threats from habitat and water quality alterations. This ecosystem-oriented perspective has given rise to the use of new management tools including no-take marine reserves (NTMRs) that have the dual purpose of controlling exploitation as well as conserving biodiversity in the face of environmental variability. In contrast to fishery-dependent data sources, fishery-independent surveys are well-suited to addressing some of the principal information needs for ecosystem-based management.

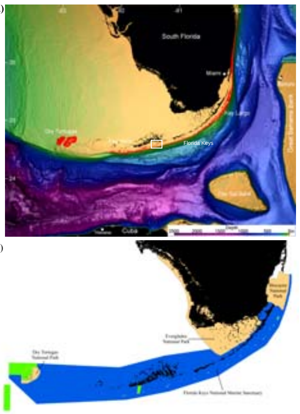

Figure 1. South Florida reef fish visual survey domain. **(A)** Seafloor topography (see color scale for depths) of the coral reef ecosystem and the Straits of Florida with mapped coral reefs (red); land is black; the rectangle denotes area of detail shown in Fig. 3A. **(B)** Managed area boundaries for the Florida Keys National Marine Sanctuary (blue), Biscayne, Everglades and Dry Tortugas National Parks (tan), and no-take marine reserves (green).

This poster presents the design and implementation of a fishery-independent, non-destructive, diver visual survey of size-structured population abundance of exploited and non-target reef fish species in the Florida coral reef ecosystem. The survey was tailored to provide data to: (1) support multispecies stock assessments; (2) evaluate the effectiveness of NTMRs and other spatially-explicit management issues; and, (3) estimate metrics of ecosystem condition of the reef fish community.

METHODS

Visual sampling was conducted along the Florida coral reef tract that extends about 400 km southwest from Miami to the Dry Tortugas (**Fig. 1**). The domain was subdivided into two regions, the Florida Keys (Miami to Key West; **Table 1A**) and the Dry Tortugas (**Table 1B**). Abundance and size data for reef-fishes were collected by highly trained and experienced SCUBA divers using a standard, *in situ*, nondestructive monitoring method (**Fig. 2A**; Brandt et al. 2009). A two-stage stratified random sampling design was employed (Cochran 1977). The primary sample unit (PSU) was defined as a 200 x 200 m map grid cell and the second-stage unit (SSU) was defined as a 15 m diameter visual plot (**Fig. 2B**).

Table 1. Habitat stratum (h) characteristics, numbers of primary sample units (N_h), and respective areas (A_h, km^2) for management zones in the (A) Florida Keys and (B) Dry Tortugas sampling domains.

(A) Florida Keys

		Management Zones			
		Open		Protected	
Habitat Class	Rugosity	N_h	A_h	N_h	A_h
Inshore patch reefs	Low-Medium	169	6.76	32	1.28
Mid-channel patch reefs	Low-Medium	3483	139.32	56	2.24
Offshore patch reefs	Low-Medium	1099	43.96	78	3.12
	High	68	2.72	19	0.76
Fore reef shallow <6 m	High	102	4.08	156	6.24
	Low	1374	54.96	113	4.52
Fore reef mid 6-18 m	Low	5489	219.56	355	14.2
Fore reef deep 18-33 m	Low	1376	55.04	--	--
TOTAL		**13,160**	**526.4**	**809**	**32.36**

(B) Dry Tortugas

		Management Zones			
		Open		Protected	
Habitat Class	Rugosity	N_h	A_h	N_h	A_h
Contiguous reef	Low	2465	98.60	2447	97.88
	Medium	189	7.56	22	0.88
	High	54	2.16	349	13.96
Patch reefs	Low	532	21.28	458	18.32
	Medium	525	21.00	633	25.32
	High	7	0.28	64	3.56
Spur-groove reef	Low	273	10.92	10	0.4
	High	96	3.84	23	0.92
TOTAL		**1,318**	**52.72**	**4,006**	**160.24**

The design performance measure used to evaluate survey precision was the coefficient of variation (CV) of mean density, which is the standard error expressed as a proportion of the mean. Performance with respect to survey costs was evaluated in terms of relative sample sizes.

RESULTS

Stratification & Allocation.- Reef habitat features (e.g., rugosity, depth) were used to partition the 885 km2 sampling domain into sub-areas or strata of low to high variance of fish density (**Fig. 3**; **Table 1**). Spatial management zones were incorporated as a second stratification variable (**Fig. 1B**). Sampling effort was spatially allocated according to both stratum size and stratum variance of fish density.

Design Performance.- Sampling efficiency of the stratified random design was improved over time via an iterative learning process by which past survey data were used to refine the stratification and allocation schemes of future surveys. This is illustrated for black grouper in **Fig. 4** during the period 1980-2008.

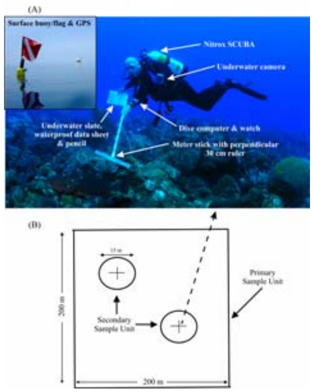

Figure 2. Visual survey methods: (A) scientific diver inside 15 m diameter cylinder measuring a red grouper (*Epinephelus morio*) with the aid of a 30 cm ruler on a meter stick (photo: J. Luo); (B) spatial layout of primary and second-stage sample units.

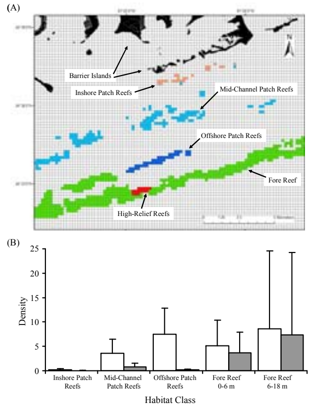

Figure 3. (A) Detail of Florida Keys sampling grid (rectangle in Fig. 1A) showing reef habitat classes; squares are primary sample units (200 x 200 m). (B) Mean density and associated standard deviation by cross-shelf habitat class for yellowtail snapper juveniles (open bars) and adults (shaded bars) from the 1997 survey.

Population & Community Metrics.- Survey performance for the period 1999-2008 is compared for 49 species of the broader reef-fish community in **Table 2**. This comparison includes all reef species with an average frequency of occurrence per SSU above 10% over the ten-year period in both the Florida Keys and Dry Tortugas regions. For 13 exploited species, the 10-year average CV of mean density ranged from 10 to 35% in the Florida Keys and from 7 to 50% in the Dry Tortugas. Average CVs were less than 20% for 9 of 13 species in the Florida Keys and 7 of 13 species in the Dry Tortugas. Although the sampling design was tailored for exploited species, the surveys of 1999-2008 also performed well for 36 principal non-target species.

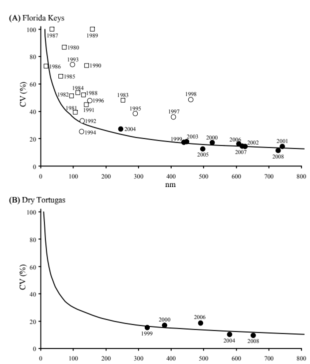

Figure 4. Coefficient of variation of black grouper mean density (all life stages) dependent upon survey sample size (*nm*) for 1980-2008 in the (A) Florida Keys and (B) Dry Tortugas. Open squares denote 1980-1991 surveys with limited geographical and habitat coverage; open circles denote 1992-1998 surveys with complete coverage of the domain prior to implementation of the formal stratified random sampling design; and, solid black circles denote 1999-2008 surveys post-implementation of the formal design. Solid lines are the predicted CVs at given sample sizes presuming optimal sample allocation.

Table 2. Annual average percent occurrence P per SSU (177 m2), average density D per SSU, and survey precision (CV of D, percent) for the ten year period 1999-2008 for target (exploited) and non-target species in the Florida Keys (10 annual surveys) and Dry Tortugas (5 annual surveys). Species analyzed had average percent occurrence greater than 10% in both regions (49 total species).

	FLORIDA KEYS			DRY TORTUGAS		
Taxa	P	D	CV(D)	P	D	CV(D)
EXPLOITED						
Jacks (Carangidae)						
Bar jack (*Caranx ruber*)	35.5	2.97	24.2	23.4	3.63	26.8
Grunts (Haemulidae)						
Porkfish (*Anisotremus virginicus*)	41.9	1.23	18.3	17.8	0.55	34.0
Tomtate (*Haemulon aurolineatum*)	18.5	13.66	34.9	31.9	25.96	22.5
French grunt (*H. flavolineatum*)	38.0	3.63	19.7	14.9	0.82	30.7
White grunt (*H. plumierii*)	73.5	8.96	14.1	79.6	6.58	17.2
Wrasses (Labridae)						
Hogfish (*Lachnolaimus maximus*)	62.5	1.15	10.1	48.1	0.55	10.7
Snappers (Lutjanidae)						
Mutton snapper (*Lutjanus analis*)	17.8	0.18	17.5	22.8	0.19	14.8
Gray snapper (*L. griseus*)	27.5	2.27	22.9	15.2	2.73	49.7
Yellowtail snapper (*Ocyurus chrysurus*)	58.5	4.12	12.3	75.7	7.56	15.1
Groupers (Serranidae)						
Graysby (*Cephalopholis cruentata*)	32.1	0.30	10.6	31.6	0.27	10.7
Red grouper (*Epinephelus morio*)	20.4	0.16	14.2	62.2	0.62	6.7
Black grouper (*Mycteroperca bonaci*)	16.2	0.14	16.2	22.2	0.22	14.1
Barracudas (Sphyraenidae)						
Great barracuda (*Sphyraena barracuda*)	10.7	0.11	23.3	17.1	0.21	30.1
NON-TARGET & AQUARIUM						
Surgeonfishes (Acanthuridae)						
Ocean surgeon (*Acanthurus bahianus*)	79.7	3.53	7.3	60.5	1.21	10.5
Doctorfish (A. *chirurgus*)	56.2	2.18	12.0	30.0	0.50	16.8
Blue tang (*A. coeruleus*)	77.5	2.92	9.7	77.7	2.25	8.1
Butterflyfishes (Chaetodontidae)						
Foureye butterflyfish (*Chaetodon capistratus*)	41.5	0.60	10.5	39.8	0.59	9.1
Spotfin butterflyfish (*C. ocellatus*)	42.8	0.53	8.5	53.7	0.69	6.9
Reef butterflyfish (*C. sedentarius*)	32.5	0.45	10.4	27.0	0.29	13.3
Squirrelfishes (Holocentridae)						
Squirrelfish (*Holocentrus adscensionis*)	10.2	0.14	24.6	13.4	0.17	26.7
Wrasses (Labridae)						
Spanish hogfish (*Bodianus rufus*)	23.8	0.25	13.7	21.5	0.19	14.6
Slippery dick (*Halichoeres bivittatus*)	70.0	4.85	8.8	77.2	7.18	7.8
Yellowhead wrasse (*H. garnoti*)	67.7	3.30	8.3	81.6	3.95	7.4
Clown wrasse (*H. maculipinna*)	56.4	2.31	8.7	42.6	0.89	13.0
Puddingwife (*H. radiatus*)	27.2	0.25	12.1	11.9	0.09	21.3
Bluehead (*Thalassoma bifasciatum*)	92.1	17.69	6.6	94.8	15.58	8.1
Goatfishes (Mullidae)						
Spotted goatfish (*Pseudupeneus maculatus*)	35.9	0.67	19.1	62.0	1.10	9.7
Jawfishes (Opistognathidae)						
Yellowhead jawfish (*Opistognathus aurifrons*)	10.7	0.25	26.7	49.8	2.59	14.2
Angelfishes (Pomacanthidae)						
Blue angelfish (*Holacanthus bermudensis*)	16.6	0.14	16.5	57.1	0.83	7.2
Queen angelfish (*H. ciliaris*)	27.2	0.23	12.7	23.4	0.20	12.9
Gray angelfish (*Pomacanthus arcuatus*)	58.1	0.82	10.1	46.0	0.58	12.7
French angelfish (*P. paru*)	21.1	0.19	14.8	14.3	0.12	17.3
Damselfishes (Pomacentridae)						
Blue chromis (*Chromis cyanea*)	21.9	1.37	17.2	23.3	0.95	24.7
Beaugregory (*Stegastes leucostictus*)	24.2	0.27	14.8	34.6	0.58	12.0
Bicolor damselfish (*S. partitus*)	81.0	19.55	8.4	73.9	7.71	8.6
Threespot damselfish (*S. planifrons*)	28.6	0.61	14.5	36.0	1.08	12.1
Cocoa damselfish (*S. variabilis*)	55.1	0.89	9.5	91.8	5.07	5.2
Parrotfishes (Scaridae)						
Striped parrotfish (*Scarus iseri*)	80.2	7.55	7.1	91.6	11.22	13.4
Princess parrotfish (*S. taeniopterus*)	16.7	0.34	21.5	12.0	0.28	21.7
Greenblotch parrotfish (*Sparisoma atomarium*)	40.9	1.01	12.3	49.7	1.10	12.9
Redband parrotfish (*S. aurofrenatum*)	88.5	3.97	6.0	83.9	2.94	13.0
Redtail parrotfish (*S. chrysopterum*)	27.3	0.57	18.4	14.5	0.18	25.7
Yellowtail parrotfish (*S. rubripinne*)	19.7	0.34	20.9	11.0	0.13	23.0
Stoplight parrotfish (*S. viride*)	64.2	1.41	8.7	60.5	1.20	9.9
Basslets (Serranidae)						
Butter hamlet (*Hypoplectrus unicolor*)	32.9	0.33	11.1	48.4	0.62	9.4
Tobaccofish (*Serranus tabacarius*)	9.9	0.12	23.6	14.6	0.18	23.7
Harlequin bass (*S. tigrinus*)	35.4	0.35	9.6	34.0	0.34	12.2
Porgies (Sparidae)						
Saucereye porgy (*Calamus calamus*)	35.3	0.45	13.1	75.5	1.43	8.8
Puffers (Tetraodontidae)						
Sharpnose puffer (*Canthigaster rostrata*)	44.4	0.48	8.7	30.9	0.28	13.3

Strata-weighted estimates of mean richness per PSU, a community measure of biodiversity were relatively precise for a variety of taxa groupings. For the 2008 Dry Tortugas survey, mean richness of parrotfishes (14 total species), a principal herbivore family, was 5.0 ± 0.1 (SE) species, and mean richness of groupers (17 total species), a principal carnivore family, was 2.3 ± 0.1 species. PSU observations of richness were associated with reef habitat features for these two families: parrotfish richness was higher in shallower depths and habitats with low rugosity (**Fig. 5A**), and grouper richness was higher in high rugosity habitats (**Fig. 5B**).

Size-Structured Abundance.- The survey time-series of abundance-at-length estimates for black grouper are shown in **Fig. 6** for the two survey regions. Estimates of average length of the exploited life stage, a population sustainability metric (Ault et al. 2005), were comparable between our fishery-independent survey and fishery-dependent catch-sampling in the southern Florida region (**Fig. 7**), suggesting that our visual survey is sampling the same reef-fish stocks as the commercial and recreational fisheries.

No-Take Marine Reserves.- As illustrated for black grouper, the spatial framework of the survey design enabled evaluation of NTMRs with respect to local, inside-outside effects (**Fig. 8A**) as well as population-wide effects (**Fig. 8B**). Differences in mean density between the protected and open zones were able to be statistically detected by the 2000 survey, three years after NTMR implementation. By 2002-2004, about 40% of the exploited black grouper population inhabited the NTMRs (6% of the domain area).

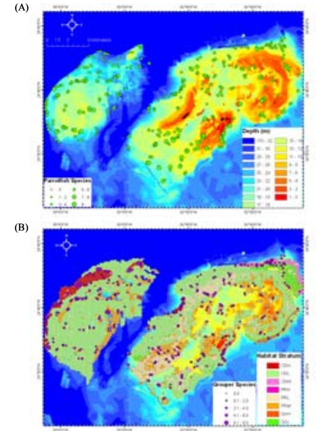

Figure 5. Spatial distribution of species richness per PSU from the 2008 Dry Tortugas survey for (A) parrotfishes (14 total species) in relation to bathymetry and (B) groupers (17 total species) in relation to reef habitat classes.

DISCUSSION

Our results demonstrate the feasibility of conducting relatively precise and cost-effective fishery-independent monitoring that can support stock assessments and spatially explicit evaluations of habitats and management zone effectiveness for single species, as well as assessments of exploited and non-exploited species at community and ecosystem scales in coral reef environments. Our findings suggested that a better understanding of fish-habitat relationships may improve the performance of future surveys via more effective stratification schemes.

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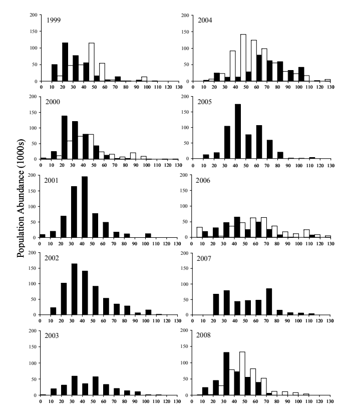

Figure 6. Black grouper abundance-at-length for the 1999-2008 surveys in the Florida Keys (dark bars) and Dry Tortugas (open bars).

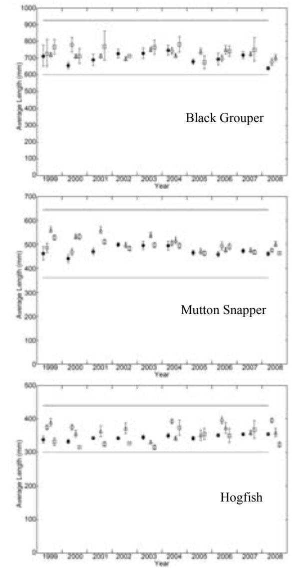

Figure 7. Visual survey estimates of average length (±SE) of exploited phase fishes during 1999-2008 in the Florida Keys (solid circles) and Dry Tortugas (open circles) for black grouper, mutton snapper, and hogfish. Also shown are average length estimates from fishery-dependent surveys of the recreational fleet (open triangles, MRFSS; open squares, Headboats) in south Florida. The lower dashed lines are the respective minimum legal lengths of capture, and the upper solid lines are the respective average lengths at maximum sustainable yield.

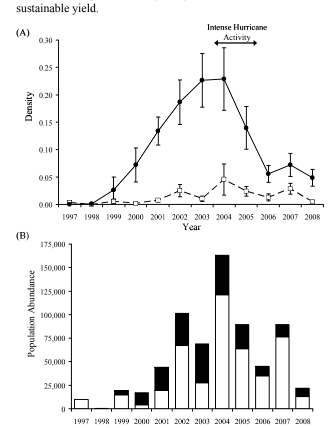

Figure 8. Survey estimates for evaluating performance of NTMRs in the Florida Keys. (A) Habitat-stratified mean densities per SSU (± SE) for exploited phase black grouper (TL ≥ 600 mm) in the open access (open squares) and protected (solid circles) management zones. (B) Population abundance for exploited phase black grouper, denoting the proportions inhabiting protected (dark bars) and open access (open bars) management zones.

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