

MARINE CONSERVATION

SCIENCE, POLICY, AND MANAGEMENT

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We theoretically assessed the effectiveness of the existing reserve at ECLSP and single nominal reserves at each of the other three sites by estimating the degree to which larvae produced at a reserve were redistributed as recruits among all the sites. We did not address the relative merit of a single reserve and several small reserves, but instead emphasized the importance of spatial position upon reserve success. Enhancement of recruitment was deemed optimal when all four sites (i.e., the metapopulation) received recruits from the single functional or nominal reserve. Each nominal reserve was of a sufficient size (approximately 15% of coastal reefs) to meet the threshold requirement for enhancement of recruitment.

Using a circulation model, we theoretically assessed the effectiveness of the ECLSP reserve and nominal reserves at each of the exploited sites in enhancing metapopulation recruitment by estimating the degree to which larvae produced at a particular site were transported and redistributed to all the sites (Fig. B8.1.1b). Enhancement of recruitment was deemed optimal when all four sites (i.e., the metapopulation) received recruits from a particular site. Larvae discharged from ECLSP and EI recruited throughout Exuma Sound, with EI having the most equitable distribution of larvae. Larvae released from LSI and CI only recruited to CI and LSI due to selective hydrodynamic transport by gyres, which prevented larvae produced in southern Exuma Sound from reaching northern sites. Hence, a reserve at EI would be most suitable for enhancing metapopulation recruitment. A reserve at ECLSP functioned less effectively in enhancing metapopulation recruitment, though significantly more so than reserves at CI and LSI.

In assessing criteria useful in reserve designation for metapopulation enhancement, the use of information on habitat quality or adult density for the Caribbean spiny lobster in Exuma Sound was no more of a guarantee for success than if one were to determine the reserve site simply by chance. The only strategy that increased the likelihood of selecting an effective marine reserve for augmenting metapopulation recruitment was that which incorporated transport processes, resulting in the selection of either EI or ECLSP. Hence, the designation of a reserve location for exploited marine species requires careful attention to data on metapopulation dynamics and recruitment processes, when the opportunity to use such information presents itself.

Sources: Bohnsack (1994); Botsford *et al.* (2001); Crowder *et al.* (2000); Hanski (1998); Lipcius *et al.* (2001); Lipcius *et al.* (1997); Roberts (1997); Roberts and Polunin (1993); Stockhausen *et al.* (2000); Stockhausen and Lipcius (2001)

Box 8.2 Patterns of reef-fish larval dispersal in Exuma Sound, Bahamas

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Most coral-reef fishes, like most marine animals, have a two-phase life cycle in which relatively sedentary adults in local populations release their gametes into the water column, where their developing larvae then disperse at sea before settling as new recruits to either nursery or adult habitats. Thus, offspring may settle at or near the same reef where they were spawned (self-recruitment) or disperse various distances to other local populations (connectivity). Documenting patterns of self-recruitment and connectivity is essential for understanding population dynamics, and consequently, for both managing and conserving marine populations effectively.

Determining geographic patterns of larval dispersal—where a fish was spawned and where it settled—is challenging due to the minuscule sizes of larvae and the vast areas of ocean through which they may travel. Directly determining patterns of larval dispersal involves the unequivocal identification of the birth and settlement locations of individual fish. Direct tagging of larval fish involves labeling the otoliths (ear stones) of developing embryos with radioisotopes before larval dispersal. Newly recruited juveniles can then be examined for distinctive traces of these chemical tags. Unfortunately, this method can be both expensive and logistically difficult.

One alternative means of directly documenting larval dispersal is genetic parentage analysis. Parentage analysis is a practical approach provided that the parent and offspring have not moved substantial distances before being sampled, as is true for most reef fishes. Furthermore, parentage analysis directly distinguishes among individuals such that numerous fish from many populations can be matched with their parents. Importantly, genetic sampling does not require a fish to be killed; a properly preserved fin clip is all that is needed.

In 2004 and 2005, we sampled 751 adult and recently settled bicolor damselfish (*Stegastes partitus*) from 11 reefs located around the perimeter of Exuma Sound, Bahamas (Fig. B8.2.1). Bicolors are abundant planktivores widely distributed throughout the Bahamas and Caribbean. After settlement to reef habitat, they rarely move more than a few meters. Males guard demersal eggs, which after hatching are planktonic for approximately 28 days. The Exuma

(Continued)

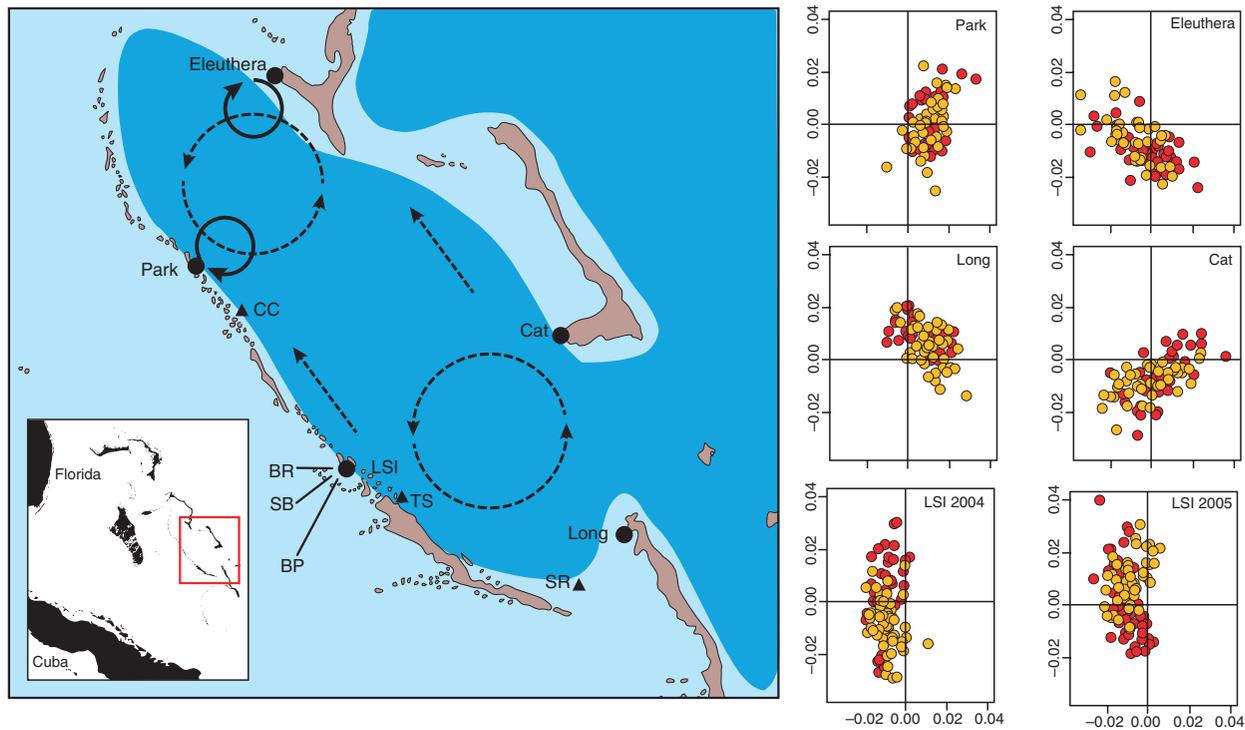


Fig. B8.2.1 Patterns of larval dispersal of bicolor damselfish in Exuma Sound, Bahamas. Parentage analysis identified two parent-offspring pairs (solid arrows), which directly documented self-recruitment at the two northern-most sites. Light sea floor indicates the shallow Great Bahama Bank, whereas dark sea floor indicates the Exuma Sound and nearby open Atlantic Ocean. Dashed arrows, including seasonal gyres, indicate prevailing surface currents. Triangles and straight arrows indicate 2004 sample sites, and filled circles indicate 2005 sample sites: Park = Exuma Cays Land and Sea Park, CC = Compass Cay, BR = Bock Rock, SB = String Bean Cay, BP = Barb's Point, LSI = Lee Stocking Island, TS = Three Sisters, SR = South Reef. The plots on the right represent principal coordinate analysis on all pair-wise relatedness values of sampled bicolor damselfish at five sites, with results separated by sampling location for clarity. Adults are represented by red circles and recruits are represented by yellow circles. Both axes combined explain 42% of the total variation.

Sound is a semi-enclosed basin with an average depth of 1500m. To the west lies the Great Bahama Bank, a wide but shallow (<3m deep) carbonate bank that has little suitable coral-reef habitat. To the east lies the open Atlantic Ocean. Within the Exuma Sound, seasonal mesoscale gyres could couple eastern and western reefs via larval dispersal. Furthermore, a general northwesterly flow derived from the Antilles Current could serve to transport larvae from southern to northern reefs.

All fish were genotyped at seven microsatellite loci, which are repeating, non-coding regions of nuclear DNA. These genetic markers are especially useful for parentage analysis because they are highly variable, which means that there are many different versions (alleles) of each microsatellite at each location (locus) on a chromosome. Pair-wise measures of genetic differentiation between sample sites (e.g., F_{ST}) were not significantly greater than zero, suggesting high levels of gene flow over evolutionary time periods.

In order to determine ecologically relevant patterns of larval dispersal, we applied novel Bayesian parentage analyses. These methods fully account for the hundreds of thousands of pair-wise comparisons that could result in pairs of fish sharing alleles by chance. Applying these methods, we identified two parent-offspring pairs at the two northern-most sampling locations: Exuma Cays Land and Sea Park (Park) and Eleuthera (Fig. B8.2.1). In both cases, the parent and offspring were sampled at the same site, indicating that self-recruitment occurred at both locations. Demographic estimates of adult population sizes at these sites were very large (>100,000 fish). These estimates, coupled with our relatively small sample sizes (Land and Sea Park: adults = 44, recruits = 45; Eleuthera: adults = 49, recruits = 37), suggest that self-recruitment must have occurred at high rates. The Exuma Cays Land and Sea Park is a long-established and effective marine reserve, and these parentage results indicate that larvae spawned within their borders may replenish marine reserves.

These estimates of self-recruitment were further bolstered by pair-wise relatedness analyses, which measure the number of shared alleles between all pairs of individuals. We used principal coordinates analyses to examine the relatedness values, an ordination procedure where individuals that share identical alleles would lie directly on top of one another, whereas genetically dissimilar individuals would be far apart in multivariate space. These analyses

showed that recruits from all sampled sites shared more alleles with adults sampled from the same sites, which is further indicative of self-recruitment (Fig. B8.2.1).

These methods revealed that, for the years we sampled, self-recruitment is the relevant ecological pattern of larval dispersal of bicolor damselfish within Exuma Sound. We also detected patterns of sweepstakes reproduction, whereby only a small proportion of the total number of adults successfully contributed to the next generation. Indications of sweepstakes reproduction included greater levels of relatedness within recruit samples than within adult samples, greater genetic differentiation among recruit samples than among adult samples, and lower levels of genetic diversity within recruit samples than within adult samples. Further evidence of sweepstakes events included significant differences in allele frequencies between samples of recruits collected at Lee Stocking Island over the two years we sampled. These observations suggest that temporal variation may play a substantial role in shaping the genetic structure of populations of bicolor damselfish in the Exuma Sound.

Future work should focus in improving the resolution and ease of methods for detecting ecologically relevant patterns of larval dispersal. Future genetics methods will likely utilize thousands of markers that will undoubtedly help to elucidate subtle population structure. The combination of rapid methodological and theoretical advances will soon allow for near real-time estimates of population connectivity and self-recruitment. The challenge thereafter will be for scientists, policymakers, and other stakeholders to use such new information to design Marine Protected Areas and other spatially explicit management measures to sustain fisheries and conserve marine biodiversity more effectively than ever before.

Sources: Christie (2010); Christie *et al.* (2010); Hedgecock *et al.* (2007); Jones *et al.* (1991)

conclusion is that current parks are vulnerable to changes of their surroundings, and that the scale of management is considerably larger than protected areas themselves.

A related, important issue is the Department of Marine Resources' recent establishment of four marine reserves (Fig. 8.1), with the future intent of a network of marine reserves, i.e., "no-take" fishery areas that would also include conservation of biodiversity and essential habitats. Marine reserves differ substantially from parks, which emphasize biodiversity protection and education. Conversely, marine reserves are intended mainly for long-term preservation of essential habitats (reefs, seagrasses, mangroves, and creek nursery areas), enhancement of non-intrusive human activities, enhanced support for fisheries production, and scientific research. The complimentary purposes of parks and reserves were recognized in 1986 when the Exuma Cays Land and Sea Park was declared a fisheries "no-take" area in 1986, the first of its kind in the Caribbean.

8.4.2 Government policy

One of the most significant initiatives for environmental conservation in The Bahamas has been the establishment of the Ministry of the Environment in 2004, with a vision for future environmental and economic sustainability, accompanied by responsibilities for environmental policy, climate change, biodiversity, and coastal development (Box 8.3). One of the Ministry's most important accomplishments was passage by The Bahamas' Parliament in July 2010 of the *Planning and Subdivision Act: an Act to Combine, Consolidate and Revise the Law Relating to Town Planning and the Law Relating to the Development of Subdivisions and to Provide for Matters Connected Thereto*. Its purposes are to:

- (a) provide for a land use planning based development control system led by policy, land use designations, and zoning;
- (b) prevent indiscriminate division and development of land;

- (c) ensure the efficient and orderly provision of infrastructure and services to the built environment;
- (d) promote sustainable development in a healthy natural environment;
- (e) maintain and improve the quality of the physical and natural environment;
- (f) protect and conserve the natural and cultural heritage of The Bahamas;
- (g) provide for planning processes that are fair by making them open, accessible, timely and efficient;
- (h) recognize the decision making authority and accountability of the Government in land use planning; and
- (i) plan for the development and maintenance of safe and viable communities, within the policies, and by the means, provided under this Act.

This Act thus seeks to address the root of the issues described above; that is, to promote sustainable development, to preserve and restore resources, and to avoid the rampant and unsustainable past development practices that have despoiled significant segments of The Bahamas' environment. In particular, it applies to the most valuable coastal strip for which comprehensive planning and zoning is fundamental—the coastal area where coral reefs, mangroves, seagrasses, beaches, and attractive seascapes predominate. The Act does not refer specifically to park or protected-area planning, or to fisheries, biodiversity, or other conservation priorities. Rather, it seeks to place development under a broad, consistent, fair, and depoliticized framework that has potential to control harmful effects on resources and to promote sustainability while maintaining and improving citizens' well-being. The Act also includes, for the first time in The Bahamas, formal environmental impact assessment (EIA) and statement (EIS) processes, intended to: (i) determine potential impacts, and the degree of such impacts of a proposed undertaking on the environment; and (ii) identify the measures to be established to mitigate against any potential adverse impacts that might occur as a result of the proposed undertaking. Should this groundbreaking Act be