Rationale and Evaluation of an Artificial Reef System Designed for Enhanced Growth and Survival of Juvenile Gag, *Mycteroperca microlepis*

Justificación y Evaluación de un Sistema de Arrecifes Artificiales Diseñados para un Mayor Crecimiento y Supervivencia de Juveniles del Mero Gag, *Mycteroperca microlepis*

Justification et Évaluation d'un Système de Récifs Artificiels conçus afin D'améliorer la Croissance et la Survie des Juvéniles de Gag, *Mycteroperca microlepis*

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ABSTRACT

The Steinhatchee Fisheries Management Area (SFMA) is a federally permitted, large-area artificial reef system in the northeastern Gulf of Mexico, designed and constructed to test a bottleneck hypothesis for juvenile gag. Gag have a spatially stage-structured life history, with juveniles (ages 1 - 4) occupying patch reefs on the shallow continental shelf. Prior experiments demonstrated density-dependent habitat selection and growth, with the tension between mortality risk and growth potential favoring available shelter as a primary element of habitat quality. The SFMA is 259 km^2 on the shallow shelf, enhanced with 500 "conservation reefs" designed and randomly distributed to improve growth rates and survivorship of juvenile gag. The SFMA is not a "no-take marine protected area". Instead, locations of small conservation reefs are not publicly known, which in combination with small reef size and wide dispersion is a passive constraint on directed fishing. The evaluation plan involves monitoring reefs offshore that bracket the region, a tagging study and comparisons of gag growth and mortality rates between the SFMA and adjacent, unenhanced shelf areas. Those parameter estimates will be inputs for spatial modeling of habitat effects on gag population dynamics.

KEY WORDS: Artificial reef, bottleneck hypothesis, spatial dynamics, habitat quality

INTRODUCTION

Strong expression of density-dependent habitat selection (DDHS) by gag (Lindberg et al. 2006) and MacCall's (1990) Basin Model for changes in stock distribution as a function of stock size, together, provide the basis for potentially accurate and sensitive measures of annual abundance through habitat-based fisheries independent monitoring. Similarly, the strong DDHS by gag favoring shelter over growth (Lindberg et al. 2006) and Werner and Gilliam's (1984) theory of ontogenetic habitat shifts (i.e., decision rule to minimize μ/g, the ratio of mortality risk to growth potential), together, suggest a demographic bottleneck during the juvenile life history stage that might be alleviated through habitat enhancement (Lindberg and Relini 2000, Lorenzen 2008, Caddy 2011). The program described here continues the development of fisheries-independent monitoring for gag and helps to evaluate the efficacy of habitat enhancement as a direct tool in gag fisheries management (Bortone 2011).

Bortone (2011, p. 311) emphasized that *"…artificial reefs play almost no role in the management of any fishery…at least through an official management agency or group with management jurisdiction over fisheries*." Nevertheless, artificial reefs remain very popular with the fishing public and contribute significantly to local economies (see Adams et al. 2011 for a synopsis). States in the southeastern United States continue to invest directly and indirectly in artificial reef programs; in Florida this is done through the Division of Marine Fisheries Management of the Florida Fish and Wildlife Conservation Commission (FWC). Thus, artificial reefs are being used informally to manage socio-economic aspects of reef fish fisheries without a direct, formal connection to the management of biological stocks. Bortone (2011) also emphasized that only certain species have the behavioral, ecological, life history and fisheries characteristics amenable to management intervention through reef development to alleviate suspected bottlenecks; he used gag as a case study to illustrate a path forward.

The potential of gag for management applications of artificial reefs was recognized a decade earlier (Lindberg and Relini 2000, pp. 221-231) and the Steinhatchee Fisheries Management Area (SFMA) was federally permitted in 2004 (USACOE permit number 200204178(IP-LCP) issued to the University of Florida, renewed in 2009).

In partnership with the FWC Artificial Reef Program, the University of Florida developed the SFMA (Figure 1) to test a bottleneck hypothesis for gag based on prior experiments (Lindberg et al. 2006), and, if confirmed, to demonstrate how large-scale, designed reef systems might function as fisheries management tools. Almost 259 km^2 of seafloor in the NE Gulf of Mexico are now enhanced with 500 small, widely scattered conservation reefs; 452 built in mid-June 2011 and 48 built in July 2012, which gives a distinct time-zero (T_0) for an ecosystem manipulation of this scale. To judge gag output from the SFMA, a line of 40 standardized "evaluation" reefs were built in September 2005, bracketing the Big Bend of Florida

(Figure 1A) specifically for fisheries-independent monitoring of the output from this major region of shallow-shelf habitat adjacent to extensive young-of-the-year nursery grounds. These evaluation reefs were sampled annually since 2006 by two prior projects, covering the period prior to construction of the SFMA conservation reefs. The research described here will:

i) Continue the fishery-independent sampling into the "post-treatment" period,
ii) Estimate demographic parameters needed to evaluate the efficacy of conservation reefs as management tools, and
iii) Generate habitat-related vital rates for spatially explicit modeling of gag population dynamics.

CONCEPTUAL FRAMEWORK AND PROGRAMMATIC CONTEXT

The scientific rationale for this program is applying established fisheries ecology concepts, processes and theories (i.e., intrinsic habitat quality, density-dependent habitat selection, essential fish habitat, ideal-free distribution, Basin-Model; see below) to the very practical problems of indexing stock abundance and evaluating the utility of artificial reefs as fisheries management tools. As explained below, we can do this because of what is already understood scientifically about the habitat-related behavior, growth performance and fishing effects for juvenile gag on the shallow continental shelf (e.g. Larson 2005, Lindberg et al. 2006, Biesinger 2011). Furthermore, we extended our

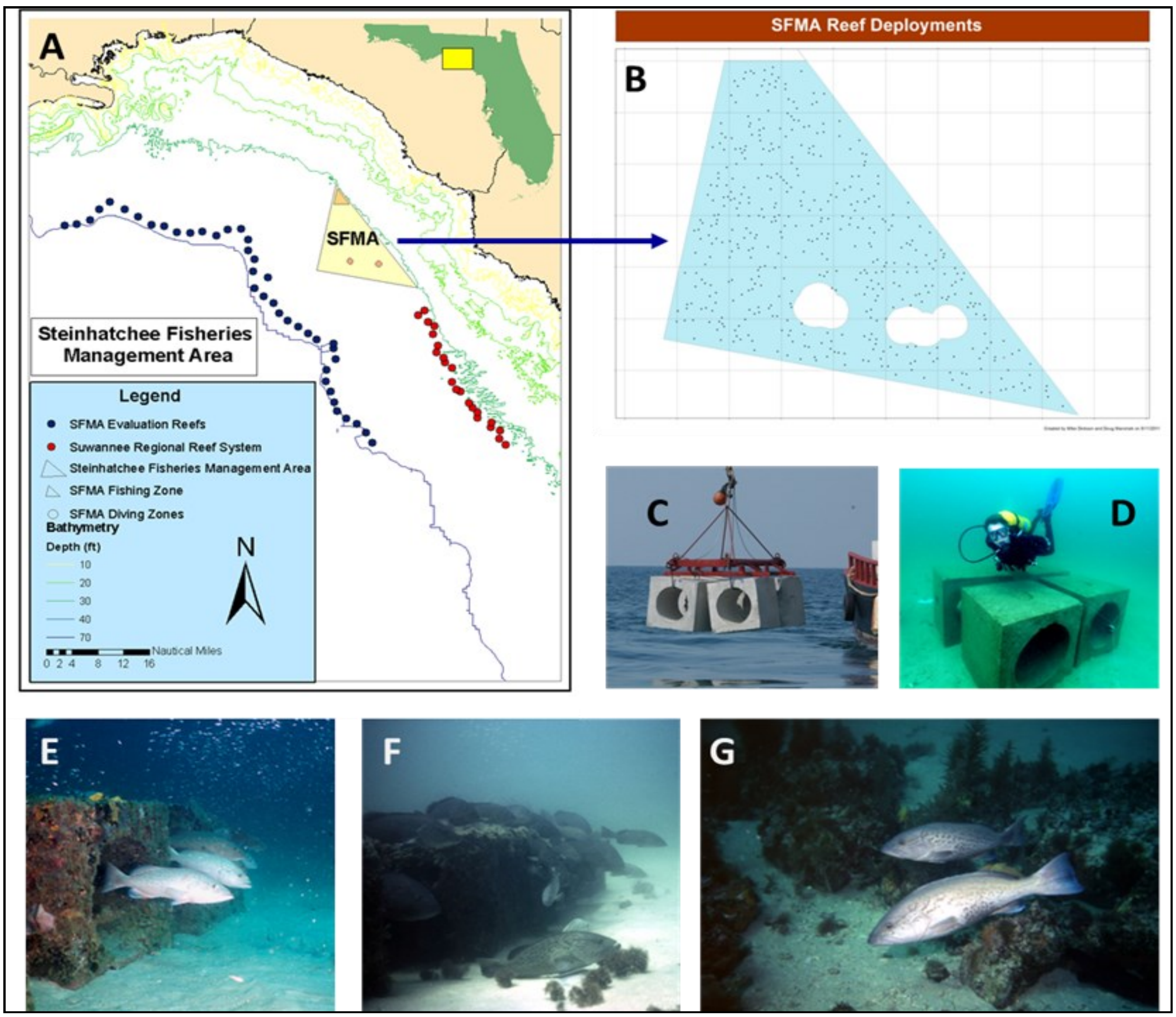

Figure 1. Reef systems in the NE Gulf of Mexico that are sampling sites and habitat manipulations for this program: (A) Location map showing the Suwannee Regional Reef System (SRRS, red dots), the Steinhatchee Fisheries Management Area (SFMA, yellow triangle), and the SFMA evaluation reefs (blue dots); (B) Chart showing randomly selected locations of 500 conservation reefs deployed in the SFMA (black dots, white areas are excluded zones); (C & D) photos of one conservation reef being deployed and on the seafloor in 2011; (E & F) gag on SRRS patch reefs of relatively lower and higher habitat quality, 4-cube vs. 16-cube, respectively; (G) gag on natural hard-bottom habitat of intermediate habitat quality in the NE Gulf.

research into the geological foundations of grouper habitat in the northeastern Gulf of Mexico and the landscape characteristics of gag EFH across the shallow shelf (Lindberg et al. 2011, Lindberg and Switzer 2012). This was necessary to partition the effects of spatial habitat variation when indexing annual abundances of gag and assessing gag output from the SFMA.

Habitat Quality, Habitat Selection and Fish Distribution Models

It is intuitively obvious that habitat is important to fishes and fisheries, and that quality of habitat matters. It's less obvious what exactly constitutes habitat quality and how best to account for it in fisheries management. This is especially true for fishes like gag that occupy patchy natural hard-bottom, rock outcrops and ledges across a broad continental shelf. High quality grouper habitat could be defined by where fishers get their best catches. However, that may or may not identify the habitat characteristics and locations that actually contribute the most to sustain a broader fish population, particularly when fisheries are fully exploited and fishermen direct their efforts among habitat patches to maintain their catch (Walters and Martell 2004, Lindberg et al. 2008). Habitat suitability indices based on fish density estimates can be confounded by predation and fishing mortality. And many involved with benthic habitat classification and mapping efforts now define habitat quality in terms of biodiversity and environmental degradation (see Diaz et al. 2004). For our purposes, we use habitat quality simply to refer to the intrinsic characteristics of habitat patches that are preferred by fishes and affect their growth, survival and/or reproduction (*sensu* Fretwell 1972, MacCall 1990, Kramer 1997). As will be explained below, our past experiments and gag habitat sampling enable us to identify relative habitat quality based on the physical, structural complexity of the seafloor, and to manipulate habitat quality for scientific and management objectives, as done by the SFMA conservation reefs.

MacCall's (1990) Basin Model describes the geographic expansion and contraction of pelagic fisheries stocks as a function of stock size. This was an extension of Fretwell's (1972) Ideal Free Distribution (IFD) theory to fisheries populations, and both models were predicated on the ecological process of density-dependent habitat selection (DDHS). Strong DDHS was confirmed experimentally for pre-reproductive gag on the shallow continental shelf exhibit (Lindberg et al. 2006). As such, we expect that gag distributions among habitat patches of known and contrasting qualities will vary as a function of regional population abundance, consistent with the Basin Model applied to reef habitat quality (rather than geographic range). While marginal habitat should be occupied only at high population abundance, and highly preferred habitat should be readily occupied at all but the lowest population levels, the numbers of gag occupying habitat patches of intermediate quality should be particularly sensitive to changes in regional population abundance. That basic logic was confirmed by analyses in Lindberg et al. (2013).

Building on Past and Current Research

In 1991-1993 we built the Suwannee Regional Reef System (SRRS) (Figure 1; see Lindberg et al. 2006 for details) as an unprecedented experiment to test hypotheses critical to understanding how characteristics of reef habitat affect habitat preferences, trophic coupling, and the bioenergetic performance of mobile reef fishes like gag (i.e., criteria for judging habitat quality). Although the management issue initially justifying the SRRS was the Attraction-Production Question for artificial reefs (see Lindberg 1997), the research since 1996 directly addressed Essential Fish Habitat (EFH) research needs.

Some major results from the first decade of SRRS research were synthesized in Lindberg et al. (2006). In summary, gag demonstrated density-dependent habitat selection, preferring shelter and larger patch reefs even at the expense of growth – which was enhanced on the smaller, less preferred experimental patch reefs. This trade-off between mortality risk and growth was consistent with Werner and Gilliam's (1984) μ/g and Foraging Arena Theory (Walters and Juanes 1993, Walters and Korman 1999). Available shelter limited gag density, which in turn regulated their growth and condition (i.e., weight adjusted for length), and the surrounding habitat context altered experimental reef treatment effects. Pre-reproductive females resided on reefs for an overall average of 9.8 months, but the duration greatly depended on patch reef size and spacing (i.e. the habitat patchiness of the landscape). After they emigrated, 28% of the sonically tagged gag were caught by fishers, mostly west-northwest of the SRRS, with 12.5% of the returns coming surprisingly from the western Gulf of Mexico. SRRS gag also demonstrated home ranges averaging about 350 m in diameter and an ability to home from 2 - 3 km away (Kiel 2004). More recent studies in the SFMA, using advanced acoustic telemetry, found gag foraging arenas around standardized reefs to be 7.5-times larger in fragmented hard-bottom landscapes than in sand-bottom landscapes (Biesinger 2011), consistent with predictions from theory (Biesinger et al. 2011). Previously we found that prey consumption by gag was density-dependent (D. Murie et al. unpublished data), and it appears that activity levels are, too (M. Butler et al. unpublished data). The bulk of gag prey came from off-reef. Habitat structure, spatial layout and behavior affected the growth performance of juvenile gag, and this apparently involved a trade-off with their risk of natural mortality. However, it's still an open question as to how much regulation of the gag population actually occurs at this intermediate life history stage.

In a very practical experiment the exact locations for some SRRS sites were released to the fishing public in November 1996. By the next summer virtually all legal-sized gag were gone from the published reef sites, with little change at the unpublished sites. Six to eight years later the unpublished sites, and *especially* those with the largest and most concentrated patch reefs, showed reduced numbers of legal-sized gag, and on some reef types even reduced numbers of sub-legal gag (Larsen 2005). We concluded that:

i) Fishing effort is directed mostly to reef configurations that are easiest to find and easiest to fish,
ii) Detailed geographic information about fisheries habitat can substantially increase fishing mortality, and
iii) Small, widely scattered patch reefs could enhance fish growth, as noted above, while passively controlling fishing pressure.

Lindberg et al. (2006) hypothesized that juvenile gag can experience a growth-focused demographic bottleneck in their transition from inshore nursery grounds to the offshore spawning stock, since natural habitat that favors both growth and survival is apparently sparse on the shallow inner shelf. The incremental growth of gag on smaller patch reefs was 15% greater than on larger patch reefs or from the local commercial fishery (Lindberg et al. 2006). The SFMA conservation reefs are the same design as those smaller patch reefs and are expected to alleviate density-dependent (DD) growth. Given the overfished status of the GOM gag stock, our bottleneck hypothesis would apply primarily when strong year classes transit the shelf and as the stock rebuilds (Lorenzen and Enberg 2002, Lorenzen 2008), with late-stage juvenile growth being critical (Hazlerigg et al. 2012). Bortone (2011) outlined a logic model using gag as an example of how artificial reefs might be applied judiciously in fisheries management, and Caddy (2011) examined how artificial reefs could reduce the impacts of mortality-focused reef fish bottlenecks. Lindberg and Relini (2000) reported the rationale and initial evaluation plans, emphasizing DD growth, for the Steinhatchee Fisheries Management Area (SFMA). This program is now undertaking the quantitative evaluation for the years 2 - 4 (T_{2-4}) immediately following the SFMA conservation reef manipulation.

Importance of the Geologic Landscape Context

The research to date, and common sense, argues strongly that the geology of the shallow continental shelf literally determines the spatial distribution of gag essential fish habitat (EFH). However, the pertinent geology has been rather poorly known for the northeastern Gulf of Mexico. The study area has unique geological features that, heretofore, have not been understood with respect to:

i) Sea-level fluctuations,
ii) Drowned reefs,
iii) Coastal sedimentary development/preservation,
iv) Paleo-fluvial drainage, and
v) Submarine spring and sinkhole activity.

In general, the broad west Florida shelf has a very low gradient (1:5000 in places) and is underlain by limestone making it a classic carbonate ramp. As such, many past shorelines have tracked across it in response to multiple sea -level fluctuations. The modern seafloor is a product of those numerous rises and falls, which shaped the topography and probably left a patchwork of past coastal features. Unfortunately, to date these features are barely mapped at spatial scales pertinent to gag habitat selection and movement on the shelf.

As summarized above, we know that habitat characteristics at the scale of gag home ranges can greatly affect gag densities on features like our standardized reefs. We also have evidence that spatial characteristics of gag EFH on broader scales (i.e. the landscape of the shelf) can affect gag movements in ways that are expected to add spatial variation to otherwise standardized gag counts and gag emigration rates.

Practicality and Potential of the Research

The SRRS reefs at 13 m depth and the 40 SFMA evaluation reefs along the 20 m depth contour (Figure 1A) provide a unique opportunity to develop indices of abundance for a critical life history stage of gag in the northeastern Gulf of Mexico. Refined fisheries independent indices are warranted by stock assessment needs and the results to date (Lindberg et al. 2013).

Those results demonstrate the effect of and sensitivity to habitat quality when indexing gag abundance. The higher quality standardized reefs had a lagged dip in gag abundance after an episodic mortality event that was included in the gag update assessment model, and then gag abundance rebounded. By contrast, the reefs of lower, intermediate habitat quality showed a significant decline in gag abundance. The significant interaction of reef type and year (Lindberg et al. 2013) confirmed our predictions from theory (i.e. MacCall 1990) and could lead to improved precision by comparing trends from habitats of different qualities.

On a broader scale, the SFMA evaluation reefs (Figure 1) are the same design as the SRRS reefs that captured the declining trend in Lindberg et al. (2013). As such, the SFMA reefs should also yield an index of abundance particularly sensitive to declining trends in the gag stock. Gag colonization to equilibrium takes 3 - 4 years for this reef design (Lindberg et al. 2006, 2011). We are now 7 years into the monitoring plan so future trends should reflect stock trends rather than initial colonization. However, geographic differences in gag colonization along the line of 40 SFMA reefs (Lindberg 2011), and prior tag returns (Lindberg et al. 2006), suggest differences in cross-shelf connectivity, likely due to natural habitat distributions. This inference of habitat corridors can be tested and the effect partitioned statistically.

The processes affecting growth and mortality are intimately related (e.g. μ/g, Werner and Gilliam 1984;

foraging arena theory, Walters and Juanes 1993, Walters and Korman 1999; habitat-related bottlenecks, Caddy 2007) and density dependence in both vital rates is consequential to population regulation (e.g., Lorenzen 2008, Hazlerigg et al. 2012), mediated by behavior, habitat configuration and scale (Lindberg et al. 2006, White et al. 2010). Indeed, John Caddy (FAO, retired) suggested that population dynamics could be modeled by using density-dependent (DD) growth in lieu of DD mortality (*personal communication*). For large, mobile reef fish like gag, growth rates and total mortality rates can be empirically estimated by established methods and compared for habitat-mediated differences. The size-frequency and size-at-age distributions of gag on our reef systems are conducive to mark-recapture and catch-curve analyses for habitat effects on gag ages 1 - 4. We previously reported habitat-mediated DD growth for gag (Lindberg et al. 2006) and have collaborators who are expert in fish age and growth.

However, estimating natural mortality empirically for the desired comparisons of SFMA versus non-SFMA gag is not easily done, given the open system and several necessary assumptions. Therefore, growth differences will be our primary *test* of the bottleneck hypothesis. Simultaneously, we will approach mortality estimates as an intense, large-scale pilot project *toward* a more definitive test of our prediction that natural mortality (M) is improved by the SFMA. At the very least, we can estimate and compare total mortality (Z) and begin to validate some assumptions to derive natural mortality (M).

Some of the assumptions necessary to estimate M in this context will be of contemporary interest, in their own right. Obviously, assumptions about tag retention, handling stress, tag-induced mortality, etc. are not problematic because SFMA and non-SFMA gag will be treated identically. Similarly, if we were comparing just a few small, isolated and unpublished artificial reefs to natural habitat we might assume that emigration, fishing effort and predator visitations were similar among the compared sites, because of similar scales of the reef treatments and our observations, i.e. the habitat patch scale. However, the SFMA is a landscape-scale manipulation comprised of a large number of discrete habitat patches. Residency times of gag on individual SFMA reefs are expected to be about 160 days, given the patch size and spacing (Lindberg et al. 2006), but gag are likely to be retained within the SFMA for an extended period compared to adjacent non-enhanced landscapes. Thus, the assumption of equal emigration must be examined for M to be estimated. Coordinates of the SFMA conservation reefs are not publicly known and small, widely spaced patch reefs are not as readily discovered by fishers (Larson 2005), but public awareness of the SFMA might induce more fishing effort. Thus, the assumption of comparable fishing effort inside and outside the SFMA (i.e. equal F) also needs to be examined. Just as importantly, our prediction that M is reduced for SFMA gag assumes that natural predator behavior (e.g. sharks and dolphins) and density-dependent M is not substantially altered by the reef treatment. This assumption might be valid at the habitat patch scale yet invalid at the spatial scale of the SFMA and temporal scale of juvenile gag transiting the shallow shelf (see White et al. 2010, Hunsicker et al. 2011). Direct examination of the predator-prey assumption, with gag as the prey, is well beyond the scope of our proposed MARFIN effort. However, the proposed comparison of Z, with examination of the other assumptions and the habitat manipulation of the SFMA, will provide valuable data toward future research on reef fish predator-prey dynamics.

Colleagues in quantitative fisheries science at the University of Florida, and elsewhere, have strong interests in stock assessment modeling, spatially explicit population dynamics modeling and ecosystem modeling. These colleagues, associated with the NMFS Recruitment, Training and Research (RTR) Program at UF, collaborated to recruit a doctoral student interested in spatially explicit modeling of gag population dynamics, specifically to evaluate the stock-level consequences of spatial management practices such as the SFMA. Parameter estimates from our mark-recapture and catch-curve studies will be inputs to that modeling effort.

For artificial reef program management, the critical question to be answered is: Given observable (or assumed), habitat-related differences in density-dependent growth and mortality, how much enhancement of juvenile gag habitat would be necessary to see a detectable response at the fishery stock level?

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