FLORIDA SEA GRANT COLLEGE PROGRAM
R/LR-E-18

FLSGP-T-01-002 C2



# Biological and Economic Modeling and Assessment of Limited Entry Strategies in Multi-Species Fisheries in South Florida

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TP-114

Sea Grant
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This technical paper was supported by the National Sea Grant College Program of the U.S. Department of Commerce's National Oceanic and Atmospheric Administration under NOAA Grant No. NA76RG-0120. The views expressed herein do not necessarily reflect the views of the University of Florida, NOAA or any of its sub-agencies.

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Sea Grant Technical Paper Number 114
Project Number R/LR-E-18
September, 2001

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# ACKNOWLEDGMENTS

This research project was funded under Florida Sea Grant College Program Project R/LR-E-18. We thank Dr. James Cato and Dr. William Seaman for their support and assistance during project implementation. We are indebted to Drs. Robert Muller (FFWCC) and Douglas Harper (NMFS) for their assistance providing information for the analyses and valuable input on data interpretation.

The author bears sole responsibility for the contents of this report.

# EXECUTIVE SUMMARY

The commercial fishing industry of Monroe County, in southwest Florida, generates approximately 20 percent of the total Florida landings and is leader for several high-valued species such as spiny lobster, stone crabs and king mackerel. Management issues such as overfishing, overcapitalization, and significant interactions and competition for finite resources among users characterize these fisheries. A single-species open-access fisheries management approach has been the traditional way to resolve resource use issues in these congested fisheries. The finite nature of the resource base and the ever increasing demand for fish products and other competing uses of the resources make that future management efforts must account for the multi-species, multi-gear nature of these fisheries. This situation is especially critical when limited entry to these fisheries is presently being implemented and the propensity exists for effort redirection by fishery participants.

The single species management approach had unintended consequences in the case of the Florida spiny lobster trap certificate program that was set up in 1992 to control total effort through the limitation on the total number of traps allowed given that it was known that total catch could not have been impacted by the effort reductions. In this particular case, the failure to initially consider multi-species participation by commercial fishers generated cumulative impacts on several other highly managed fisheries such as the stone crab trap fishery and the king and Spanish mackerel fisheries.

Decisions by the South Atlantic and Gulf of Mexico Fishery Management Councils to establish in the near-future limited access systems for reef fish and mackerel species may have long-term consequences for the number and composition of fishers in Monroe County. This is particularly important considering that the Florida Fish & Wildlife Conservation Commission is developing a limited access system for the stone crab fishery.

The research reported here provides an assessment of the operational impacts emerging from implementation a limited access strategy in the Florida spiny lobster and the biological and economic consequences of such actions on Florida's stone crab fishery.

The Florida spiny lobster fishery is influenced by external sources of recruitment that appear to contribute to the sustainability of landings independently of the extremely high number of traps used in the fishery. One clear effect of the excess of gear observed in this fishery is on gear efficiency as indicated by the negative correlation found between the catchability coefficient and number of traps. Similarly, the stone crab fishery has greatly increased the number of traps that reached over 1.3 million in 1998, hence creating a similarly congested situation that has also lowered the trap catching efficiency in that fishery. Two production models used in this report show that trap density is instrumental in shaping production trends and the relationship between landings and effort appears to be mostly indicative of the level of utilization of the seasonal available stock biomass by the fisheries. Consequently, fishing effort regulations appear to be less biologically meaningful but significant from economic and operational points of view.

The spiny lobster trap reduction program implemented in 1992 has reduced the number of traps in the spiny lobster fishery to levels that at present correspond to those observed in a period (1978-1986) prior to the consideration of the trap limited access. This level of effort also corresponds to trap benchmarks generated by the break-even-point or open access conditions used in the bio-economic analyses. The fishing mortality rates at break-even-point trap benchmarks are similar to those obtained in stock assessments carried out by Muller et al. (2000) for the 1999/2000 fishing season. These levels of fishing mortality are biologically adequate as 40% of the spawning potential ratio is still present in the stock and the yield per recruit is not affected under the effort levels necessary to comply with the break-even-point condition. Hence, the trap reduction program may be seen as one that has improved the economic status of the fishery operations and has reduced conflicts derived from the excess of traps in the fishery. Further trap reductions to accomplish MEY will result in a less efficient biological production. This later effect may have consequences at other levels of the industry as landings at MEY may impact supply for the highly demanded spiny lobster products.

The stone crab fishery shows a stabilized level of effort at about 600,000 traps during the period 1986-1992. This level was similar to the 600,000-trap level observed in the spiny lobster fishery but during the period 1978-1986 – a trend that significantly changed after 1987 to reach close to 1 million traps in 1991. The impact of the 1992-spiny lobster trap reduction program on effort redirection to the stone crab fishery took place in a steady manner during the period 1992-1996. The combined number of spiny lobster and stone crab traps during 1986-1996 were at about 1.4 million traps a fact that supports the concept of effort migration between the two fisheries. The extraordinary increase in the number of stone crab traps during 1997 and 1998 may not be a response to the spiny lobster reduction program but a reaction to the potential limiting the access of stone crab traps.

In summary, the results from the bio-economic analyses of the spiny lobster fishery justify the reduction in the number of traps used in that fishery but the operational time gains obtained from the trap reduction program created the opportunity for fishers to participate more intensively in the already saturated stone crab fishery. Bio-economic analyses for the stone crab fishery indicate that a significant reduction in effort is required not only to improve the economic aspects of the fishing operations, but also the reduction is very much required to prevent any potential biological impact of the excessive fishing mortality that is been exerted the male stone crab stock fraction as a consequence of the spiny lobster displaced effort.

## 1. Introduction

The important commercial fishing industry of Monroe County, in southwest Florida, generates approximately 20 percent of the total Florida landings and is leader for several high-valued species (40 % of the stone crab, 90 % of the spiny lobster, 25 % of the snapper, and 40 % of the king mackerel landed in Florida). Management issues such as overfishing, excessive gear deployed (overcapitalization), and significant interactions and competition for finite resources among users characterize each of the main species. Efforts to address management issues in these congested fisheries have historically been approached on a single-species basis, with management strategies traditionally used in open-access fisheries. The finite nature of the resource base and the ever increasing demand for fish products and other competing uses of the resources make that future management efforts must account for the multi-species, multi-gear nature of these fisheries. There is an urgent need to recognize the propensity for effort redirection by fishery participants as single-species controls are implemented to regulate participation. The need to move to restricted access management measures has already been reflected in the management of the spiny lobster fishery and more recently by studies underway to restrict access to the important stone crab, mackerel and snapper fisheries. However, the inherent multi-species character of these fisheries may require a more comprehensive adoption of restricted access measures.

Limited access strategies have been adopted for fisheries management as a tool to control, and in some cases to reduce, the excess of effort and over-harvesting that are characteristic of an open-access fishery. In virtually every limited entry system, the management objective is to control the number of units of effort to limit fishing mortality compatible with levels of optimum production. Optimality, however, rarely represents a single management definition. Hence, limited entry to improve catch per unit of effort (CPUE) for a single species or to improve economic performance may be desirable goals, but also employment generation may have critically important consideration. Unfortunately, these desirable goals are many times antagonistic and a trade-off must be reached through consensus among stakeholders and policy development.

The single species approach fails to account for commercial fisher's participation in two or more fisheries that may be required to provide a desired income and return on investment in the vessel and equipment. Likewise, it does not recognize the existence of other economic opportunities to expand individual activities to other fisheries if time and capital are available. The single species management focus had unintended consequences in the case of the Florida spiny lobster trap certificate program that was set up in 1992 to control total effort through the limitation on the total number of traps allowed given that it was known that total catch could not have been impacted by the effort reductions. The management objective under the goal of the trap certificate program was to improve CPUE for spiny lobster and to reduce the confrontation among fishers and other users of the waterways (sport fishing, pleasure boating, etc.). However, the program prompted fishers to participate more intensively in other fisheries by redirecting effort to the other open access fisheries where similar gear or vessels are utilized.

In this particular case, the failure to initially consider multi-species participation by commercial fishers obscured the cumulative impacts of single-species limited access management. In areas such as Monroe County, where commercial fishers' incomes are based on a few high-valued species (e.g., spiny lobster, stone crabs, reef fish, and king mackerel), these cumulative impacts can be substantial. The need for such management tool is underscored by provisions within the already established Florida Keys National Marine Sanctuary. For example, the development of Ecological Reserves and Sanctuary Preservation Areas may displace traditional harvesting activities in the local trap fisheries, with some of this effort potentially redirected toward other species within the multi-species, multi-gear fishery in Monroe County. In summary, complex fishery production systems in southwest Florida clearly cannot be managed by simple single-species conceptual frameworks.

Decisions by the South Atlantic and Gulf of Mexico Fishery Management Councils to establish in the near-future limited access systems for reef fish and mackerel species may have long-term consequences for the number and composition of fishers in Monroe County. This is particularly important considering that the Florida Fish & Wildlife Conservation Commission is developing a limited access system for the stone crab fishery. Surprisingly, existing theoretical and empirical fishery management models do not provide a comprehensive framework to evaluate the long-term impacts of these single species management decisions on participants in a multi-species fishery. The research work reported here provides an assessment of the operational impacts emerging from implementation a limited access strategy in the Florida spiny lobster and the biological and economic consequences of such actions on Florida's stone crab fishery. For this purpose, the biological implications of limiting access in the spiny lobster fishery are jointly analyzed with the impact of the spiny lobster effort redirection to the stone crab fishery and the economic and biological implications of such effort redirection on the later fishery.

## 2. The Spiny Lobster Fishery

### 2.1. Characteristics of the Species and Fishery

Spiny lobsters, *Panulirus argus,* inhabit in shallower areas of the Continental shelf, mostly associated with coral reefs assemblages, in the Central Western Atlantic Ocean. The species occurs from Bermuda to Brazil, including the southeast coast of the United States (Florida). Within this geographical range *P. argus* supports important fisheries in the United States, Cuba, The Bahamas, Nicaragua, Honduras and Brazil. The fisheries sustained by *P. argus* are the second most economically important fisheries in the region (US$420 million dock side in 1998), surpassed only by the very large penaeid shrimp fisheries.

The Florida Fish & Wildlife Conservation Commission (FFWCC) manages the Florida spiny lobster fishery within the State territorial waters (0-9nm). Under agreement with the Gulf of Mexico and South Atlantic Fishery Management Councils, the State of Florida is also responsible for managing the spiny lobster fishery in the Fishery Conservation Zone (9-200nm). Spiny lobster fishery management regulations mostly correspond to those of the State of Florida and are contained in the laws and regulations of the State. Until recently, the most important among these regulations were those designed to protect the reproductive capabilities of the stock. These include a closed season from April to July to protect egg-bearing females during peak summer spawning months, a minimum carapace size of 76.2 mm. (3 in.) in the landings (corresponding to the size when spiny lobsters in Florida appear to reach first maturity), and no berried or egg carrying females should be landed. Another regulation declares that lobsters must be landed whole for the primary reason to secure implementation of the minimum carapace size regulation. Several other management measures that relate to spiny lobster commercial harvesting practices include the use of slat wooden traps made of degradable materials as the only gear allowed in the commercial fishery and restrictions in the use of "shorts" or juvenile lobsters as attractants. There are no catch quotas imposed upon the commercial fishery and until 1992, no fishing effort limitations were in place. The most important regulation, however, is the spiny lobster trap reduction program established in 1992 with the purpose of making the fishery more efficient. This program is in fact limiting trap access to the fishery through an elaborated trap certificate program. This management action was implemented based on the characteristic that historic spiny lobster landings in Florida show natural variability but with no trend over a very wide range of fishing effort between 250,000 and 950,000 traps. It was assumed, therefore, that a significant reduction in the number of traps would reduce unnecessary gear competition and over capitalization while at the same time significantly increasing the average landings per trap. This last condition was seen at the time of implementation as an important step to improve the economics of spiny lobster fishing operations and to reduce user's conflicts in the sea (e.g. boating activities interacting with trap buoys and lines). The trap reduction program is being implemented in a gradual way by assigning transferable trap licenses to fishers, which is equivalent to a trap limited entry program. An analysis of the initial performance of the Florida spiny lobster certificate program is found in Milon et al., (1998).

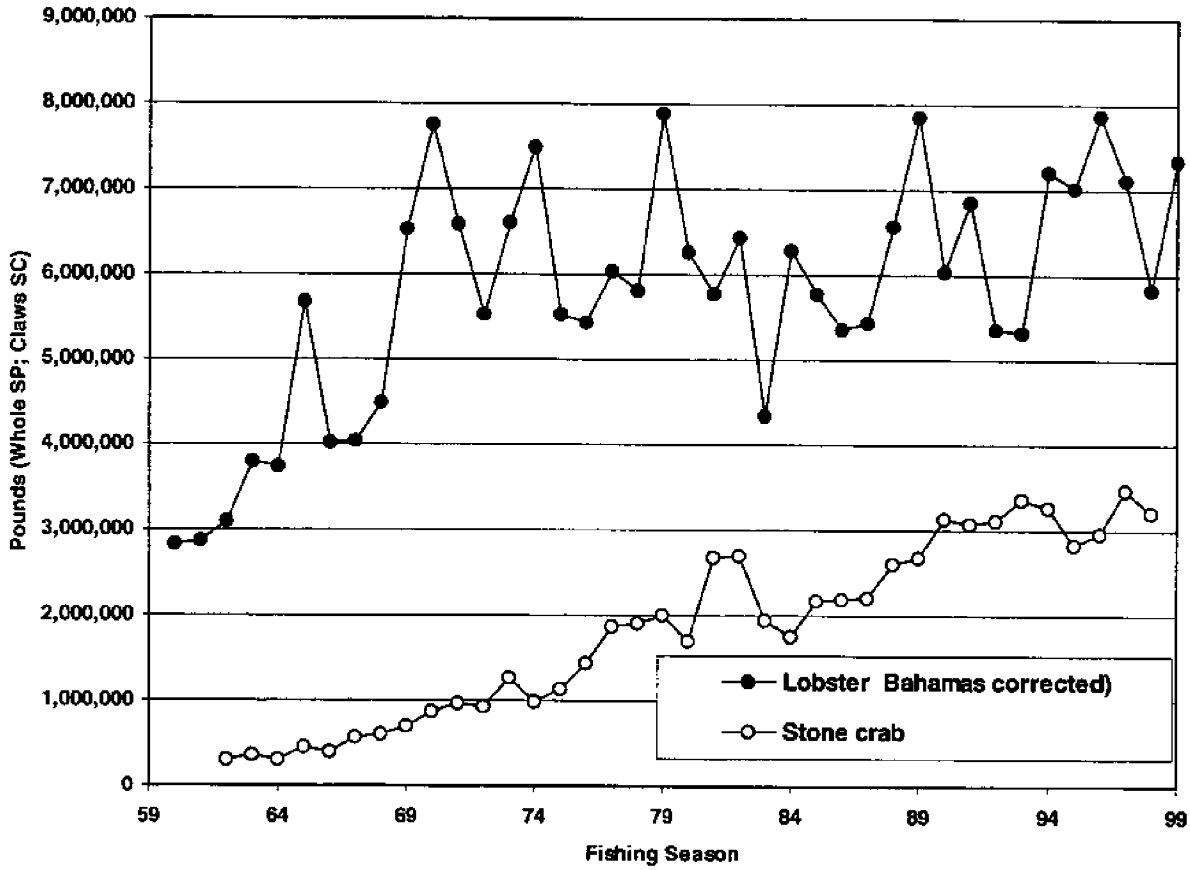
## 2.2. Historic Landings and Fishing Effort

Seasonal spiny lobster landings are available from the General Canvas Landing System of the National Marine Fisheries Service (NMFS) for the 1960-1984 fishing seasons (August to March), and from the former Florida Department of Environmental Protection (FDEP) now FFWCC's Trip Ticket data files starting in the 1985 fishing season. Landings refer to pounds of whole weight spiny lobsters that are bought directly by licensed wholesale dealers from fishers; therefore, spiny lobsters caught by recreational fishers or not sold to wholesalers are not included in the reported landings used in the analysis. Number of spiny lobsters landed in each month since 1985 are estimated from monthly landings in weight reported by FDEP and individual length and weight frequency data collected during those months by the same institution.

Fishing effort that incorporates time units is only available since the implementation of FDEP Trip Ticket data system in 1985. These data include areas fished, depths, trap soak times and number of trips voluntarily reported for a small fraction of fishers. The absence of time in effort statistics from the development years of the fishery (1960-1978) makes this data series unusable in bio-economic production modeling analysis. However, number of traps operated in the commercial fishery estimated by NMFS personnel each January based on data obtained during an annual canvas of seafood dealers is available from 1960 to 1992. Trap numbers from 1992 to date are available from the trap certificate program. In this report, number of traps are used as an approximate unit of fishing effort in lieu of total soaking time per season, which is a better unit of effort indicative of the amount of fishing mortality exerted on the stock. Soaking time estimation requires statistics on number of trips and soaking time between trips as well as number of traps and this information is not available for the entire history of the fishery.

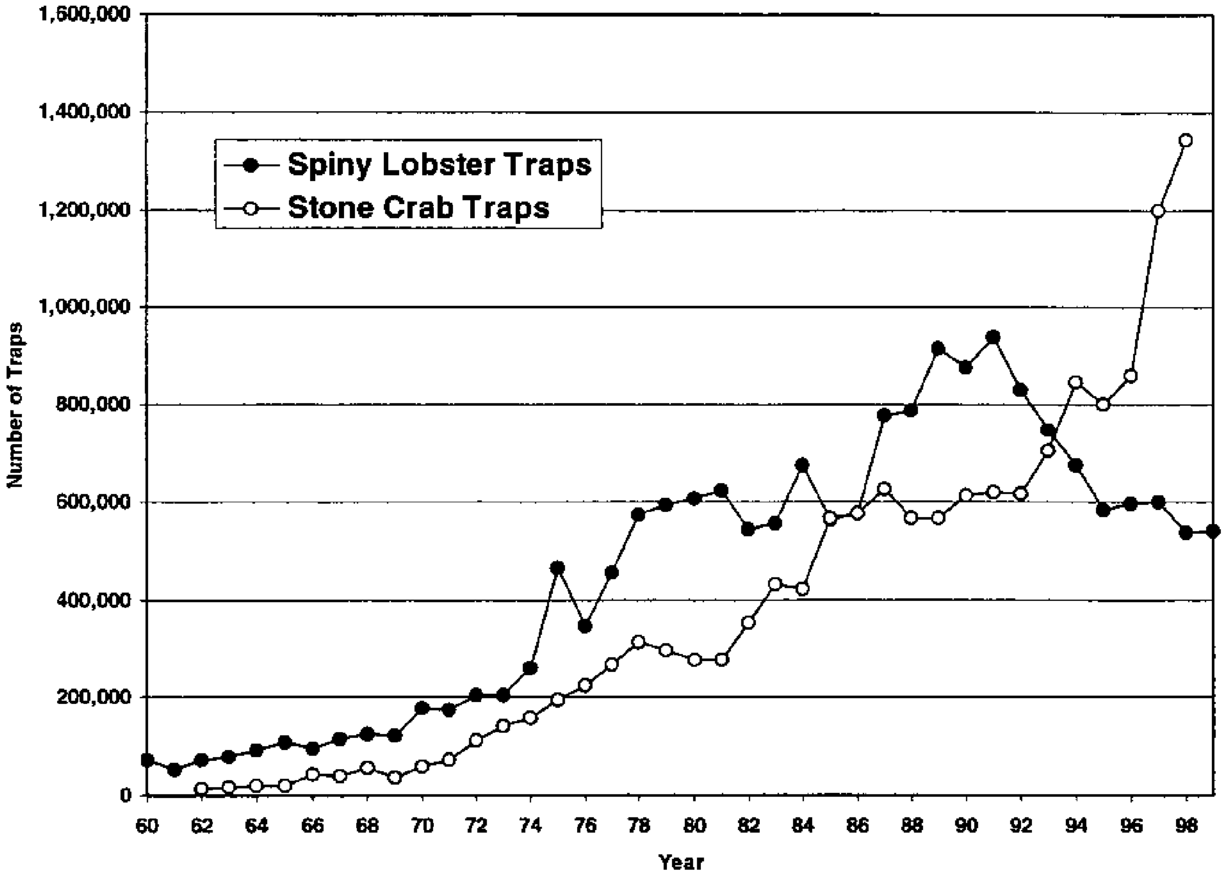
The Florida spiny lobster fishery developed slowly between the 1920's and the 1950's as a consequence of poorly developed marketing systems, to the extent that supply of spiny lobsters exceeded demand up to the 1960's. Total landings in Florida reached an equivalent of 2.8 million lb. of whole weight in 1960, and peaked for the first time at 7.7 million pounds in 1970 (Fig. 1).

Figure 1. Landings Spiny Lobster and Stone Crab




A conspicuous characteristic of the fishery is that during the period 1969-1999 landings varied significantly but with no significant trend (Fig. 1). Fishing effort, measured in number of traps operated during the August to April fishing season increased steadily from 74,000 traps in the 1960-1961 season to about 260 thousand traps in 1974 (Fig. 2). A significant increase in traps operated in the fishery is observed between 1975 and 1978. This increase was due to incorporation of fishing effort displaced from US fishing operations in the Bahamas fishery in 1975 when the Bahamas Government closed their grounds to international fleets. Then, during the 1978-1986 fishing seasons, the number of traps were maintained at an average of about 600,000. However, in 1987 speculations about the potential implementation of a trap regulation to the fishery resulted in a significant increase in the number of traps operated in the fishery in the following seasons (1987-1991). During this later process the fishery reached a maximum of 949,000 traps in the 1991-1992 fishing season (Fig. 2). With the implementation of the trap reduction program in 1992, the number of traps used in the fishery was gradually reduced to about 583 thousand in 1995. Several arguments regarding lower abundance and the need of further testing of the trap reduction program maintained the number of traps at or slightly below

Figure 2. Spiny Lobster and Stone Crab Traps




600,000 traps until the 1999-2000 fishing season. This level represents roughly the number of traps that were operated in the fishery during the 1978-1986 period.

2.3. Spiny lobster production model

2.3.1. Population structure, units of stock, and production model design

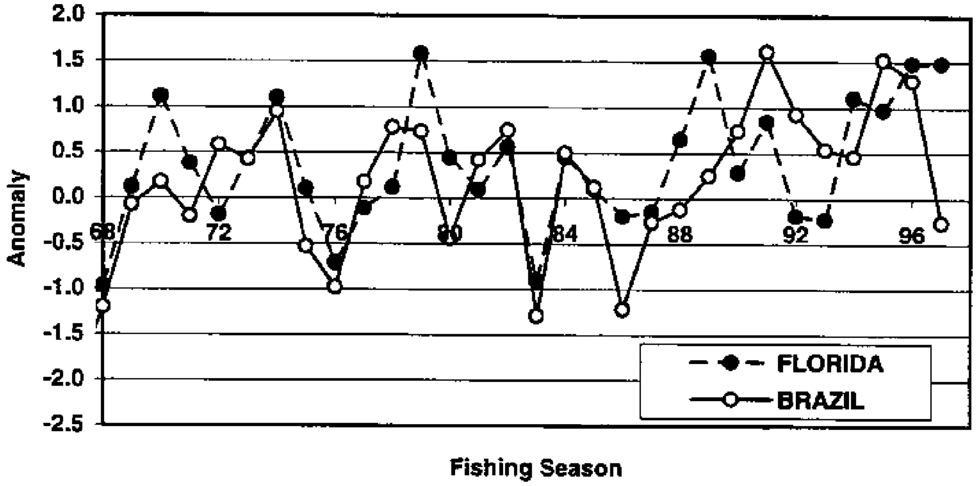
A significant requirement for any production model is that it must contain a population production function that reflects the response of the population growth to the mortality process. This characteristic of the models represents a major impediment in the case of the Florida spiny lobster fishery due to the general concept that units of stock are difficult to define for the species. The reason for this difficulty is based on the fact that *P. argus* larvae may remain in the water column for six to ten months and up to a year (Lewis, 1951; Lyons, 1980) before settling in a suitable juvenile habitat. This peculiar larval dynamics when coupled to strong ocean currents dominating the general environment where these larvae are found throughout the Caribbean Sea make plausible that spiny lobster larval resources from far upstream may colonize regions far downstream -- thus the Pan-Caribbean theory of Caribbean spiny lobster populations. Under these circumstances, any management action in one country's fishery may have consequences on other regional fisheries and application of production models to undefined units of stock may prove to be erroneous regarding the fishery management benchmarks that they generate.

Several earlier studies suggest the likelihood that spiny lobster stocks may originate from a single gene pool in the Caribbean Sea (Menzies and Kerrigan, 1980; Lyons, 1981). Caribbean-wide genetic studies based on mitochondrial DNA performed during the 1990's provide more conclusive evidences that sustain the Pan-Caribbean origin of spiny lobster. In effect, results from those studies show a consistent lack of major geographical differentiation in adults of *P. argus* (Silberman et al., 1994.a) and a lack of seasonal variation in genetics of pueruli arriving in the Florida Keys (Silberman et al., 1994.b). Lack of significant differences in the genetic structures among the adult spiny lobster population analyzed is an indication of high levels of mixing, while the lack of seasonal variation at the larval stages in a downstream area (e.g., Florida) is an indication of the constancy of the mixing. Furthermore, Sarver et al., (1998) suggests that the Brazilian *P. argus* might by a sub-species (defined by the authors as *Panulirus argus westonii*) while Sarver et al., (2000) found occasional intrusions of Brazilian *P. argus* in Florida in the genetic material analyzed for the spiny lobster population of Florida. These latter findings on genetic mixing are indicative of the extraordinary distances that these larvae may travel before settling, hence supporting the old argument that extreme long distance colonization is possible in this species.

If in fact spiny lobster larvae are capable of remaining in the pelagic environment for extended periods of time until they find suitable substrate for settling, then spiny lobster larvae spawned up-stream in the Caribbean region are likely to reach the coasts of North America through the Yucatan Passage, the Loop Current of the Gulf of Mexico and/or the Gulf Stream along the Florida Keys. Seasonal gyres on the Pourtales Shelf off the Florida Keys may be important for spiny lobster larval advection from the Gulf Stream into the Lower Florida Keys (Yeung and McGowan, 1991). On the other hand, Powers and Bannerot (1984) report that at high levels of exploitation, observed fluctuations in landings in the Florida spiny lobster fishery corresponded to fluctuations in recruitment because landings consist primarily of new recruits. Similarly, Muller et al., (2000) show that a large fraction of the spiny lobster catch in the Florida fishery is comprised of animals of age 2 years that form the recruits entering the fishery. Similar to the Florida case, exploitation in the Brazil spiny lobster fisheries (the farthermost upstream fishery) is very high and fluctuations in the landings from that fishery may equally represent recruitment variability (Ehrhardt, 2000).

Anomalies (observation minus mean divided standard deviation) of landings for the 1968-1997 period were calculated in this study to express possible abundance trends in Florida and Brazil. The results are shown in figure 3 where it is observed that the overall production pattern between these two far separated regions have extraordinary similitude. From these results one can conclude that during the period 1968-1997 a significantly common annual trend in relative abundance characterized the two regional fisheries with only few significant region-specific deviations. These trends can be explained either if spiny lobster larvae in Brazil and Florida underwent recruitment processes with similar inter-annual relative spawning potential, larval retention rates, and mortality and growth rates, or if in effect the contribution of larvae from the upstream sources is sufficiently large as to mimic a generalized regional recruitment variability that is observed in the downstream fisheries. Since oceanographic regimes influencing each of the two

**Figure 3. Anomalies of Florida and Brazil Spiny Lobster Production**



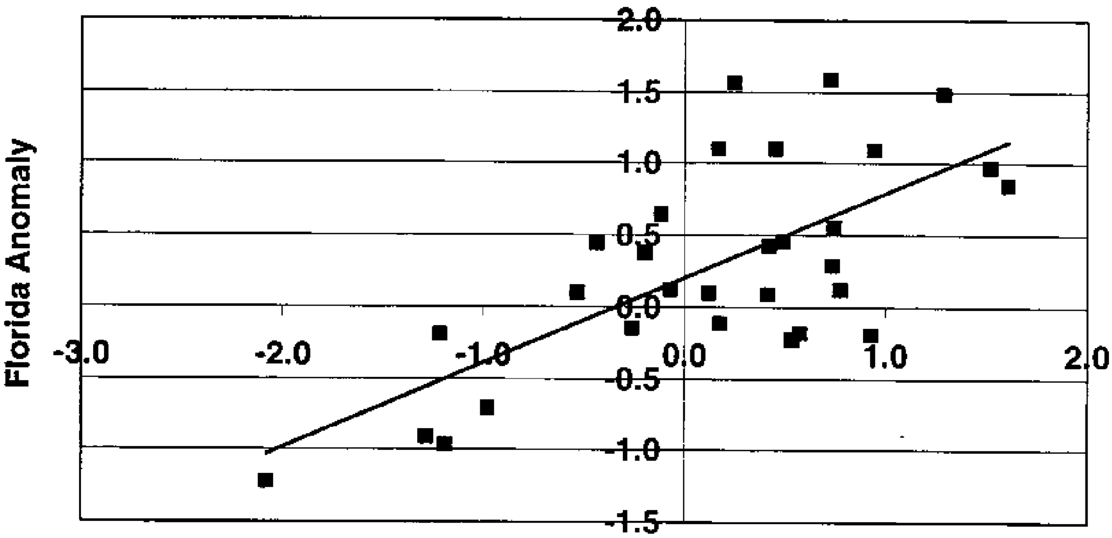

areas (Brazil and Florida) are very different, it cannot be easily explained that these different, and supposedly separate, populations could be able to generate strikingly similar patterns in stock production over a two decade time span. It is plausible, therefore, that the observed patterns in abundance anomalies among the two regions are the result of high levels of regional larval mixing – a fact that is coincident with results of the genetic studies on *P. argus*. Under these considerations, deviations of anomaly trends in some years might be the result of significant local events affecting local larval recruitment.

The previous arguments are important in terms of the decision to use standard production models that take into consideration population regeneration characteristics of the stock. In effect, a fraction of the total landing anomalies in Florida is explained by the behavior of the anomalies in Brazil (Fig. 4). This finding may represent further evidence that spiny lobster resources in Florida are significantly dependent of the extraterritorial spiny lobster populations. Similar trends to those explained above were found by Ehrhardt (1994, 2000) between spiny lobster production in Central America and Brazil, and Central America and Florida. These analyses support, therefore, the assumption that spiny lobster landings in Florida do not entirely correspond to local population regeneration processes and as such the fishery is making use of the biomass that may grow from a conglomerate of recruits having different regional sources.

2.3.2. Spiny lobster production modeling approach

Two considerations were adopted to develop the basic production modeling approach for the Florida spiny lobster fishery: 1) a large significance of the Pan-Cañbbean population generation function on total landings, and 2) a significant effect of trap density on catchability

**Figure 4. Florida and Brazil Production Anomalies**




(defined as the fraction of the stock caught per trap during a given fishing season) of spiny lobsters. The later assumption is a common effect in trap (passive gear type) fisheries due to the interaction among traps when retaining individuals at higher levels of fishing intensity, or effort density (number of traps per unit of area). The later assumption needs to be demonstrated by comparing seasonal behavior of the catchability coefficient on levels of fishing effort (number of traps).

The seasonal catchability coefficient, q, required in the catchability-effort analysis was estimated from a modified seasonal DeLury-type depletion model (Chien and Condrey, 1985) applied to monthly catch-per-unit-effort (CPUE) and cumulative monthly catch using Braaten's (1969) correction. The model assumes that once spiny lobsters recruit to the fishery, a closed adult population is created and it is available to the seasonal fishery, and that constant fishing effort occurs during the fishing season. The first assumption is affected in part by the varying seasonal spiny lobster recruitment trends historically observed in the CPUE during the period November-December, however, CPUE trends in the time period before those two months do not include significant changes in the seasonal CPUE depletion trends. The second assumption of constant seasonal effort may be realistic in the spiny lobster fishery in Florida because the number of traps used per season is fixed at the start of the season and traps fish continuously throughout any given season with catch retrieved from traps during each fishing trip. A significant number of traps are retrieved from the fishery at later dates during the second half of the fishing season but those time periods will not used in the fitting of the seasonal depletion models.

According to Chien and Condrey (1985), q is estimated from a regression of catch in numbers per unit effort (CPUE) on corrected cumulative catch in numbers (K) over a number of time periods to yield a slope estimate Q. That is

$$CPUE_t = qN_0 - \left(\frac{1}{\bar{f}}\right)\left(1 - e^{-(q\bar{f}+M)}\right) K_t \qquad (1)$$

where K according with Braaten's (1969) catch correction is defined as

$$K_t = \sum_{t=1}^{n-1} C_t + \frac{C_n}{2}$$

where $C_t$ is the catch in numbers in month t of a given season i, and n is the last month of the series of seasonal CPUE used in the regression. Thus the slope of the line in equation 1 is expressed by

$$Q = \left(\frac{1}{\bar{f}}\right)\left(1 - e^{-(q\bar{f}+M)}\right)$$

The catchability quotient is then estimated as

$$q = \left(-\frac{1}{\bar{f}}\right)\left[Ln(1 - Q * \bar{f}) + M\right]$$

where f = average number of traps operated per month during the regression range, and
M = monthly natural mortality rate.

Examination of seasonal q-estimates suggested a relationship between q and values of fishing effort of the form:

$$q_f = q_0 \times e^{-b \times f_i} \qquad (2)$$

where b = trap density efficiency parameter,
$f_i$ = fishing effort in number of traps in season i,
$q_0$ = catchability coefficient when fishing effort is zero (no trap interaction).

Differing from the traditional constant catchability assumption adopted in production models for yield and effort assessments (Schaefer 1957; Fox 1970, Prager 1994, etc.), the production modeling approach adopted for the Florida spiny lobster fishery considers the incorporation of trap density effects on yield. Trap density is incorporated in the production models through the catchability-effort model expressed by equation 2. This model hypothesizes that at higher trap densities (expressed by the number of traps used in the fishery) the catchability coefficient (q) will be lower than at lower effort levels as a consequence of interactions among passive gear units (traps) competing for a fixed seasonal level of local resource availability. In this manner, the production model under the two fundamental assumptions of restricted population regeneration capability and effort-controlled catchability becomes a biomass utilization model. That is, the amount of catch landed is a direct function of the average biomass that is available to the gear during the fishing season and the amount caught will tend towards an asymptotic maximum that can be identified with the average maximum catchable spiny lobster population abundance. Furthermore, the maximum landings will be independent of fishing effort (number of traps) over a wide range of fishing effort as a consequence of the much lower catchability of the traps as their density increases and due to the plausible Pan-Caribbean recruitment factor on Florida lobster production.

The above arguments suggest that the biomass utilization model for spiny lobster in Florida should be of the form

$$Y = Y_{max} - Y_{max} \times e^{-r \times f} \qquad (3)$$

where the parameter $Y_{max}$ is the asymptotic catch attainable at a very high level of fishing effort (f). Yield is estimated in the model as the difference between the asymptotic yield minus the potential yield that survives fishing effort ($Y_{max}\, e^{(-r\, f)}$). The parameter r is a shape parameter that describes the rate at which the yield curve approaches the asymptotic $Y_{max}$ as fishing effort increases and impacts catchability. Thus, the parameter r reflects the dynamic effect of trap densities on yield and a constant natural mortality rate that occurs during the season. This model has the unique connotation that catch is a function of an average available catchable biomass that depends on the levels of regional and local recruitment and the carrying capacity of the local habitat. This may be a desirable feature in the Florida spiny lobster fishery since a large fraction of the annual recruitment may be from sources away from local parent stock. Parameters in the above model were estimated by standard least-squares non-linear regression techniques.

The above model was used to assess trap utilization benchmarks (benchmarks are defined as levels of fishing effort generating desired levels of optimum exploitation) and then use these benchmarks to assess the status of exploitation of the spiny lobster stock in Florida. The benchmarks are all making reference to the rate of change of yield regarding a unit of change in fishing effort. Hence, the fundamental expression to develop the benchmarks is the first derivative of yield (Y) with respect to effort (f) in equation 3, which is given as

$$\frac{dY}{df} = r \times Y_{max} \times e^{-r \times f} \qquad (4)$$

The three case scenarios to evaluate trap benchmarks with the biomass utilization model are: Maximum Sustainable Yield, the Open-Access-Equilibrium or Break-Even Point, and the Maximum Economic Yield. These benchmark points for trap numbers are given below.

CASE I. Maximum Sustainable Yield.

In this case to maximize yield the first derivative of yield with respect to effort (Equation 4) is set to zero (dY/df=0). This condition can only be reached when $f = \infty$ because at that fishing effort level the negative exponential term in equation 4 becomes 0 and the derivative is also 0. Thus, the model does not have a maximum within reasonable fishing effort boundaries. An arbitrary solution to this problem might be to adopt an arbitrary fishing effort level, which may corresponds to, say, 95% of $Y_{max}$ or use a point on the slope of the production curve that may have interest to the management of the species.

CASE II. Open-Access-Equilibrium or Break-Even Point.

In this case scenario total revenues from fishing (TR) is equal to total production cost (TC). When TR=TC the fleet component of the fishery system does not generate revenues. With the biomass utilization model in equation 3 we have that

$$TR = V \times Y = V \times (Y_{max} - Y_{max \times} e^{-r \times f}) \qquad (5)$$

where V = unit value of the catch and

$$TC = C \times f \qquad (6)$$

where C = total annual cost per unit of fishing effort (f).

The equation to estimate the number of traps to achieve the break-even point is therefore

$$\frac{f}{(1 - e^{-r \times f})} = \frac{V \times Y_{max}}{C}$$

This equality does not provide an explicit solution for f, hence, an iterative solution has to be applied. The GOAL SEEK function in EXCEL TOOLS can be easily used to search for f-values given the other parameters in the indeterminate equation.

CASE III. Maximize Economic Yield

In this scenario we need to set marginal revenues equal to marginal costs. That is,

$$\frac{dTR}{df} = \frac{dTC}{df}$$

or according to equations 5 and 6 this is

$$V \times r \times Y_{max} \times e^{-r \times f} = C$$

This equality has an explicit solution for f as

$$f = -\left(\frac{1}{r}\right)\ln\left(\frac{D}{C \times r \times Y_{max}}\right)$$

An important assumption in the above benchmark modeling is the fact that total cost (TC) in equation 6 is directly proportional to the total number of traps deployed in the fishery. In reality, total cost in the spiny lobster fishery of Florida may be a monotonically increasing non-linear function of the total number of traps. For example, as trap density increases the fraction of buoys (traps) lost per year may increase as a function of trap density. This is due to the expected higher rate of encounter of boats and vessels with buoy lines, which are entangled in propellers and shafts and the lines are usually cut. Hence, at higher trap densities (higher rates of propeller entanglements) the number of traps to be replaced is higher which is an element of cost dynamically changing with trap density. Also, at higher trap densities, fishers tend to move traps more often to avoid fishing in already depleted areas with the consequent loss of time, fuel, labor, vessel wear out, etc. These conditions are not considered in the analyses presented in this study.

## 3. The Stone Crab Fishery

### 3. 1. Characteristics of the Species and Fishery

Stone crabs, *Menippe mercenaria,* inhabit bays, estuaries (Manning, 1961), and to depths of 54 m offshore (Bullis and Thompson, 1965). The species occurs along the southeast coast of the United States from North Carolina to Florida, and through the Gulf of Mexico (Williams, 1965) into the Caribbean Sea (Karendeyva and Silva, 1973). Within this geographical range *M. mercenaria* supports important fisheries in the U.S., the Bahamas, and Cuba.

Stone crabs are noted for possessing two powerful and disproportionately large claws which constitute approximately one-half of the body weight in adult individuals (Sullivan, 1979). This characteristic makes stone crabs a valuable resource mainly for their claws. The U.S. stone crab fishery is a trap fishery directed to the exploitation of claws only, and it is largely restricted to areas off the west coast of Florida where stock densities are believed to be the greatest due to more favorable habitats (Bert et al., 1978).

Stone crabs are jointly managed by the State of Florida within state territorial waters (0-9 nm) and by the Gulf of Mexico Fishery Management Council in the Fishery Conservation Zone (9-200 nm). Management regulations for the greater part correspond to those of the State of Florida and are contained in the laws and regulations of the State, and in a Fishery Management Plan (FMP) developed by the Gulf of Mexico Fishery Management Council (GMFMC) which was implemented in 1979. A Draft of Amendment 7 to the FMP is presently under preparation (GMFMC, October 2000) to include better effort limitation strategies in the management of the fishery.

Regulations include a closed season established from May 16 to October 14 to protect egg-bearing females during peak summer spawning months, and a minimum claw size (propodus length) of 70 mm (2.75 in.) established mostly because of marketing convenience. Another regulation declares that claws are the only legally harvestable portions and that declawed crab bodies must be returned to the water. The primary reason for this measure is that stone crabs like other brachiurans, possess the ability to regenerate appendages after losing them. It is thought, therefore, that those crabs surviving fishing operations may contribute to future catches after regenerating new claws.

Survival of declawed stone crabs and regeneration of claws have been demonstrated by Savage and Sullivan (1978), Davis et al., (1979) and Sullivan (1979). According to these authors, adult stone crabs are able to regenerate approximately 70% of the original claw size in the first molt and reach 100% of that size in the subsequent molt. Various survival rates due to declawing have been estimated form 0 to 10% in tagging experiments with declawed crabs (Ehrhardt et al., 1990), from 53 to 78% during declawing experiments carried in the laboratory (Davis et al. 1979), and from 25 to 97% in the commercial fishery (Bert et al., 1978). Savage et al., (1975) estimates the number of regenerated claws landed at 9.95% of the total landings based on an examination of the stridulatory patterns in the claws which are altered during regeneration. Ehrhardt and Restrepo (1989) developed a mathematical algorithm to estimate yield per recruit that takes into consideration claw regeneration characteristics of stone crabs and demonstrated the potential of "re-using" the resource.

Several other measures related to harvesting practices have also been promulgated and implemented to enhance crab survival during the time between capture and declawing. There are no limitation in the number of traps that can be used in the fishery or catch quotas imposed upon the fishery, however, a moratorium to stabilize participation in the fishery is in place while Florida develops forms of effort limitation in the stone crab fishery.

Assessment of the status of exploitation of the stone crab stocks has been cumbersome due to the lack of adequate techniques for stone crab population assessments when only appendages are landed (Ehrhardt and Restrepo, 1989; Muller and Bert, 1997). In this report a production model incorporating trap density effects on claw landings is used to estimate trap benchmarks that can be used to further investigate the impacts of trap numbers on the general biology of the species.

## 3.2. Analysis of Historic Landings and Fishing Effort

Stone crab claw landing statistics were obtained from the general Canvas Landing System of the National Marine Fisheries Service for the period October 1962 to September 1985 and from the Florida Department of Natural Resources (FDNR) Trip Ticket data files for the period October 1985 to date. In general, landings refer to pounds of stone crab claws that are bought directly by licensed wholesale dealers from fishermen; similar to spiny lobster statistics, stone crabs caught by recreational fishermen or not sold to wholesalers are not included in the reported landings.

Fishing effort has not been defined for the stone crab fishery; however, number of traps operated in the commercial fishery are estimated by NMFS personnel each January based on data obtained during an annual canvas of seafood dealers (Sutherland 1988). Since the implementation of FDNR Trip Ticket data in 1985 areas fished, depths, and trap soak times are voluntarily reported for a small fraction of fishermen. Total number of traps are also reported through the Saltwater Permit License (SPL), however the number supplied in those statistics grossly overstate the number of traps used in the fishery (D.

Harper, NOAA, NMFS, Miami Laboratory, Personal Communication). In recent years (1997 and 1998) surveys were carried out to assess the trap participation in this fishery and that database was available through the National Marine Fisheries Service (D. Harper, NOAA, NMFS, Miami Laboratory, Personal Communication).

The Florida stone crab fishery developed slowly as a consequence of poorly developed marketing systems, and supply of stone crabs exceeded demand up to 1962. Landings in South Florida reached an equivalent of 4,680 lb. of claws in 1895 and 22,000 lb. in 1919 (Schroeder, 1924). Landings from the Gulf of Mexico were under 50,000 lb. claws per year until the 1950's but these increased significantly from 250,000 lb. in 1962 to more than 500,000 lb. in 1968 (Fig. 1). This expanding trend continued through the 1982-1983 fishing season when landings reached over 2.7 million pounds. Then landings declined significantly to 1.85 million lb. and to 1.75 million lb. in the 1983-1984 and 1984-1985 fishing seasons, respectively. From the 1985 through the 1990 fishing seasons, landings show a steady increase that reached 3.1 million pounds of claws in 1990. During the period 1990-1999, landings appear to have reached an asymptote at about 3 million lb. with inter-annual variation but with no definite trend (Fig. 1).

Fishing effort, measured in number of traps operated during the 7-month fishing season (October 15 - May 15), increased from 74,600 traps in the 1962-1963 season to 113,300 traps in 1971-1972 and 567,000 traps during the 1985-1986 fishing season (Fig. 2). From 1986 through 1992 the number of traps operated in the stone crab fishery were rather stable at a level between 560 and 623 thousand traps during a time span when landings were steadily increasing (Fig. 1). Following the introduction of the trap reduction program in the spiny lobster fishery in 1992, traps in the stone crab fishery have doubled from 613,000 in the 1992 season to over 1.3 million in the 1998 fishing season. Landings during this later period have ranged from 2.8 million lb. to 3.5 million lb. with no trend.

### 3.3. Stone crab production model

Differing from traditional production models for yield and effort assessment (Schaefer 1957; Fox 1970), the production modeling approach adopted in this study considers the incorporation of trap density effects on yield while keeping the population generation function inherent to production models intact. Trap density is incorporated in the production model through a catchability model under the hypothesis that at higher trap densities (expressed by the number of traps used in the fishery) the catchability coefficient (q) will be lower as a consequence of interactions among passive gear units competing for a fixed level of local resource availability.

The stone crab production model is expressed as a Schaefer production model that takes into consideration the trap density effect on catchability (equation 2). This consideration is important as the traditional equilibrium surplus production models as well as dynamic production models assume that the catchability coefficient is constant through time and with regard to fishing effort levels. Essentially the catch-effort modeling process used in this study is as follows: fishing effort is standardized from nominal units by means of a relative trap efficiency factor estimated from a seasonal catchability-effort model. Then, the catch-effort parabolic model of Scheafer (1957) is fitted to the catch and standardized (catchability corrected) effort. The estimated parameters are then used in a nominal effort production model.

The most likely general pattern of change in catchability q with fishing effort was obtained by estimating approximate seasonal q-values following the modified De Lury model (Chien and Condrey, 1985) explained in Section 2.3.2 and by plotting the estimated values on effort. The seasonal instantaneous fishing mortality rate, $F_i$, was expressed as usual as the product of the catchability coefficient and effective fishing effort ($f^*$) as

$$F_{i,f} = q_f \times f_i^*$$

In the analysis, fishing effort and trap density are considered synonymous since under the assumption that for a given state of fishery development, the spatial distribution of the fishery corresponds to full utilization of the resource available in that area. This assumption leads to another assumption, which expresses that there is no time-lag effect in gear saturation as the fishery historically expanded to new grounds.

A relative stone crab trap efficiency factor (RTEF) was developed as the ratio of $q_f$ to $q_0$, where $q_0$ is the base catchability when there is no trap effect affecting this parameter and $q_t$ is given by equation 2. Therefore,

$$RTEF_{i,f} = \frac{q_f}{q_0} = e^{-b \times f_i} \qquad (7)$$

This RTEF was used to standardize nominal seasonal fishing effort, $f_i$, measured in number of traps. Hence, effective seasonal standardized fishing effort units, $f^*$, were expressed as

$$f_i^* = f_i \times e^{-b \times f_i}$$

The effective seasonal standardized fishing effort in number of traps and seasonal landings in claw weight were used to fit a parabolic equilibrium surplus production model (Schaefer, 1957). This model is of the form

$$Y_i = A \times f_i^* - B \times f_i^{*2} \qquad (8)$$

where $Y_i$ = equilibrium yield in season i, and A and B are parameters.

Given that trap benchmarks need to reflect the economics (costs and revenues) of the fishery on a-per-nominal fishing effort units. Hence, once the parameters A and B in the effective fishing effort yield model given by equation 8 are estimated, the nominal fishing effort yield model is simply transformed back from the previous model as

$$Y_i = A \times f_i \times e^{-b \times f_i} - B \times f_i^2 \times e^{-2 \times b \times f_i} \qquad (9)$$

In the last model b is the exponent in equation 2 and f is the nominal fishing effort measured in number of traps operated in each season.

Similar to the cases involving spiny lobster benchmarks, it is again necessary to estimate the derivative of yield with respect to effort but now using equation 9. The first derivative is given as

$$\frac{dY}{df} = (1 - b \times f)(e^{-b \times f}[A - 2B \times f \times e^{-b \times f}]) \qquad (10)$$

The three cases to evaluate stone crab trap benchmarks are those used in the case of the spiny lobster fishery:

Case I. Maximum Sustainable Yield.

This condition is met when the first derivative of yield with respect to effort given in equation 10 is set to zero and solved for f. Under this condition an indeterminate effort equation is obtained of the form

$$f \times e^{-b \times f} = \frac{A}{2B}$$

Because the equality above does not provide an explicit solution for f, then the f-benchmark is estimated through an iterative algorithm using the GOAL SEEK function in EXCEL TOOLS.

CASE II. Open-Access-Equilibrium or Break-Even Point.

In this scenario total revenues (TR) equal total costs (TC). These two quantities are defined as

$$TR = V \times Y = V \times (A \times f \times e^{-b \times f} - B \times f^2 \times e^{-2b \times f}) \qquad (11)$$

and

$$TC = C \times f \qquad (12)$$

In this particular case V is a variable representing unit value of the landings while C is a variable representing total cost per unit of effort.

Thus, by equating TR=TC we obtain an equality such as

$$\frac{V \times (A \times e^{-b \times f} - B \times f \times e^{-2b \times f})}{C} = 0$$

The above equality cannot be solved explicitly for f, therefore an iterative solution similar to Case I above is required.

CASE III. Maximize Economic Yield

In this scenario annual profits are maximized by equating marginal revenues to marginal costs and then solving for f. Marginal revenue is defined as the first derivative of TR with respect to f and marginal cost as the first derivative of TC with respect to f. That is,

$$\frac{dTR}{df} = \frac{dTC}{df}$$

Each derivative considering equations 11 and 12 is

$$\frac{dTR}{df} = V \times (1 - b \times f)(e^{-bxf})(A - 2B \times f \times e^{-bxf})$$

and

$$\frac{dTC}{df} = C$$

Therefore the equation to be solved for f is given as

$$(1 - b \times f)(e^{-bxf})(A - 2B \times f \times e^{-bxf}) = \frac{C}{V}$$

There is no explicit solution for f, which then needs to be estimated through iterative procedures as indicated in Case I.

4. Economic Parameters to Define Trap Benchmarks

The solutions for several of the trap benchmarks outlined by the different models explained above require information on the average unit price paid for product landed (V) and the cost per trap operated in the fisheries. Under Florida Sea Grant Project R/LR-E-16 granted to J.W. Milon (UF) and N.M. Ehrhardt (UM) and reported in Milon et al., (1999), a survey was conducted in the Fall and Summer of 1997 to collect a stratified sample representing approximately 9% (or 55 fishers) of all owners with at least 100 spiny lobster certificates during the 1995-1996 fishing season. The information collected included the general characteristics of the fishers and their historical involvement in the multi-species fisheries in Monroe County, Florida. Specific data for cost analysis consisted of total spiny lobster and stone crab landings during the 1996 fishing season, the number of spiny lobster and stone crab traps operated in that season by each interviewed fisher as well as the variable and fixed costs associated with their participation in the two fisheries. Among the variable cost information there were fuel and oil, bait, ice, food and supplies, other costs, vessel repairs, trap and net repairs, information on crew size per fishery, fishing trip characteristics, and lobster trap certificate lease. The fixed cost data consisted of vessel value and life of the vessel with which to estimate vessel depreciation, annual dockage cost, trap costs and usable life with which to estimate trap depreciation, and interest payments. The average unit price paid to fishers for products landed during the 1996 fishing season was $3.79 per pound of lobster and $6.60 per pound of stone crab claws (Milon et al., 1999).

Cost analysis carried out in this study takes into consideration that fixed costs related to vessel depreciation and dockage should be proportionally distributed between stone crab and spiny lobster fishing operations as 77% of the spiny lobster fishers reported stone crab landings in the 1996 survey reported by Milon et al., (1999). This assumption may not be entirely correct as the 1996 survey showed that additionally, 35% of spiny lobster fishers also reported king mackerel landings, and 17% reported snappers and grouper landings (Milon et al., 1999 Table 4-1). However, due to the extended seasonality of the spiny lobster and stone crab fisheries relative to the other finfish fisheries, the assumption may still be statistically robust.

In order to distribute the fixed costs among stone crab and spiny lobster operations, the total number of fishing days (the product of number of seasonal fishing trips by the length in days of the trips reported in the 1996 sample survey) carried out by each fisher in the sample for each fishery were used to calculated the fraction of time allocated to stone crab and spiny lobster, respectively. The annual vessel depreciation was then estimated as the vessel value divided by useful life of the vessel (estimated at 18 years) and distributed according to the fraction of annual time that the vessel participated in each of the two fisheries under analysis. A similar procedure was applied to dockage when this item was associated to a given vessel.

Trap depreciation was estimated according to the useful life of a spiny lobster trap reported in the survey (3.86 years). This value was also applied to the stone crab traps for similitude.

Similar to Milon et al., (1999), labor cost was estimated under two scenarios: minimum wage in 1996 and a share of total revenues. For estimating the minimum wage cost component, the number of crew reported by each fisher sampled as participants in the stone crab or spiny lobster fishery was multiplied by the number of effective days that they participated in each of the two fisheries independently. This product was then multiplied by the reported number of hours worked per day in the spiny lobster fishery (the average number of hours per day in the reported spiny lobster survey was 10.3). In the case of the stone crab fishery a 10-hour working day was assigned as a realistic number by extension from the spiny lobster trap operations. The average minimum wage for 1996 was that reported by Milon et al., (1999) ($5.15/hour). The share of total revenues from landings was estimated as

$$\text{Share} = \left[\frac{\text{Total Revenue}}{(\text{Crew} + \text{Vessel})}\right] \bullet (\text{Crew} - 1)$$

Long-run and short-run marginal cost functions were estimated following similar arguments as in Milon et al., (1999). These estimates were obtained separately for each of the labor cost components. The resulting total cost data (fixed plus variable costs) are plotted on number of traps reported in the samples in figures 5 and 6 for spiny lobster and figures 7 and 8 for stone crab, respectively. The observed cost trends are well defined in the data presented in the above figures where about 62% to 73% of the overall variability in total cost is explained by the number of traps operated. These percentages represent a remarkably high degree of association among the two variables given the general lack of homogeneity in the characteristics of the vessels reported in the samples (Fig. 9), and the lack of a strong correlation between the number of traps and the size of the vessels (Fig.

10). However, there is a strong degree of non-linear association between the number of vessels and the number of traps historically operated in both fisheries (Figs. 11 and 12), which may be indicative that costs are more associated to a per-trip condition than technological characteristics of the fleets.

**Figure 5. Spiny Lobster Total Cost per Trap: Equal Share**

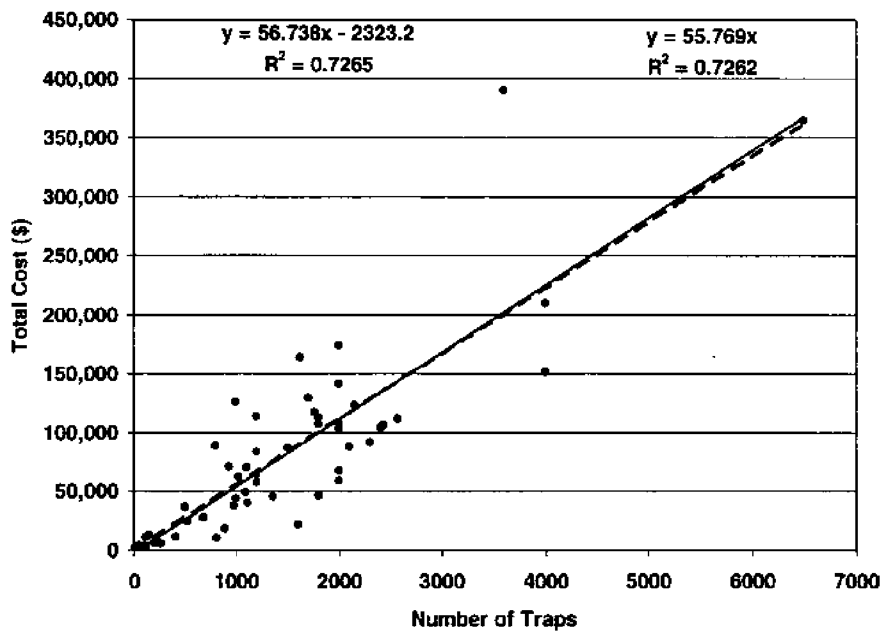



**Figure 6. Spiny Lobster Total Cost per Trap: Minimum Wage**

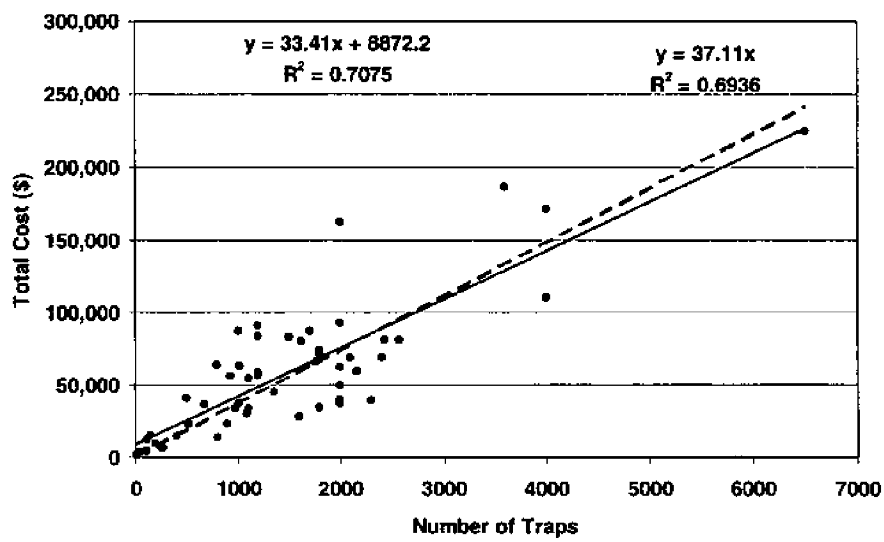


Figure 7. Stone Crab Total Cost per Trap: Equal Share

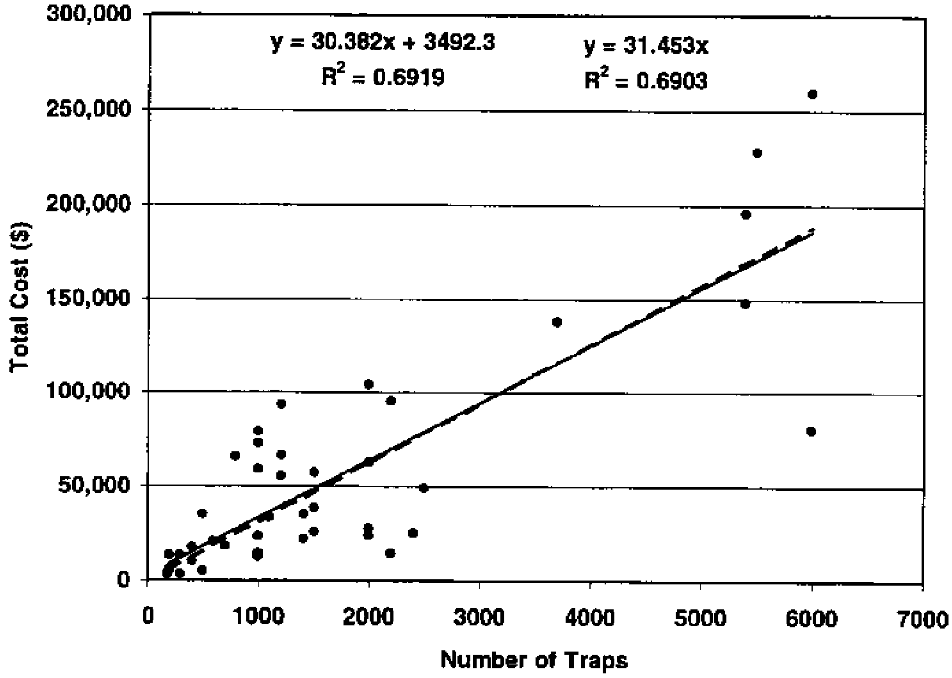



Figure 8. Stone Crab Total Cost per Trap: Minimum Wage

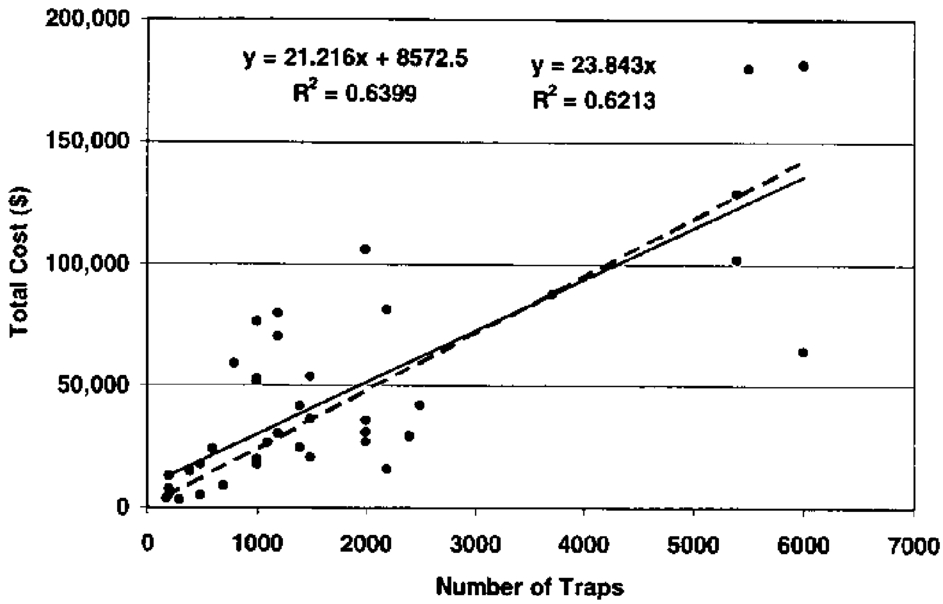


Figure 9. Vessel Characteristics

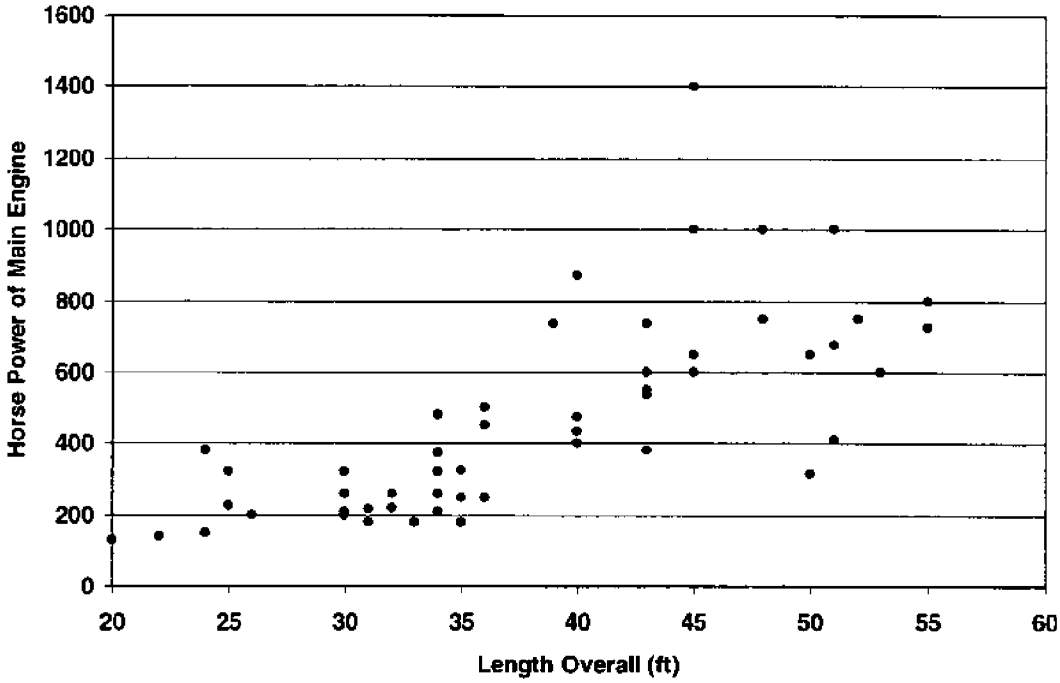



Figure 10. Spiny Lobster (SL) and Stone Crab (SC) Traps per Vessel According to Size.

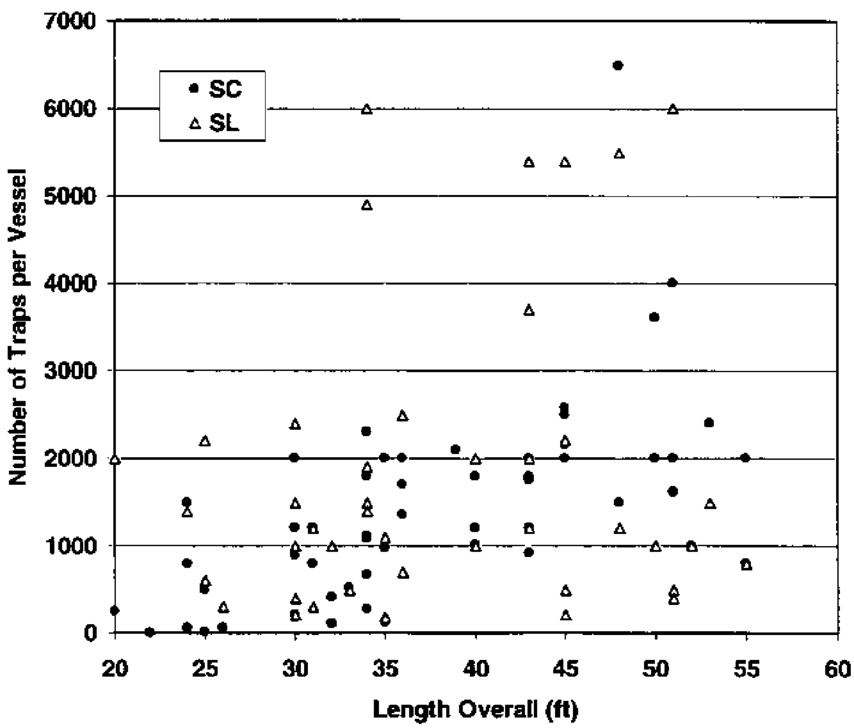


Figure 11. Number of Spiny Lobster Traps per Vessel

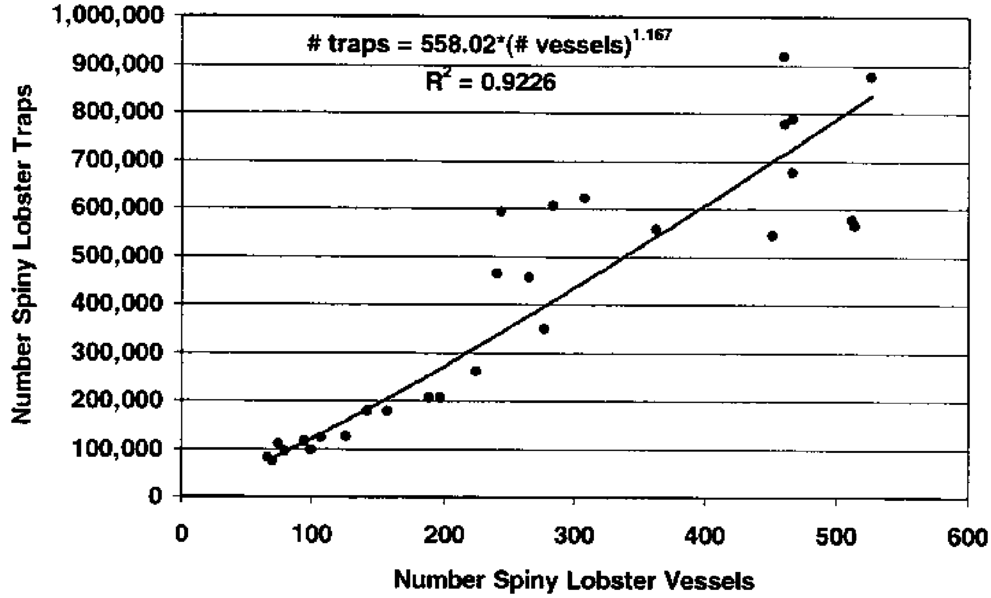
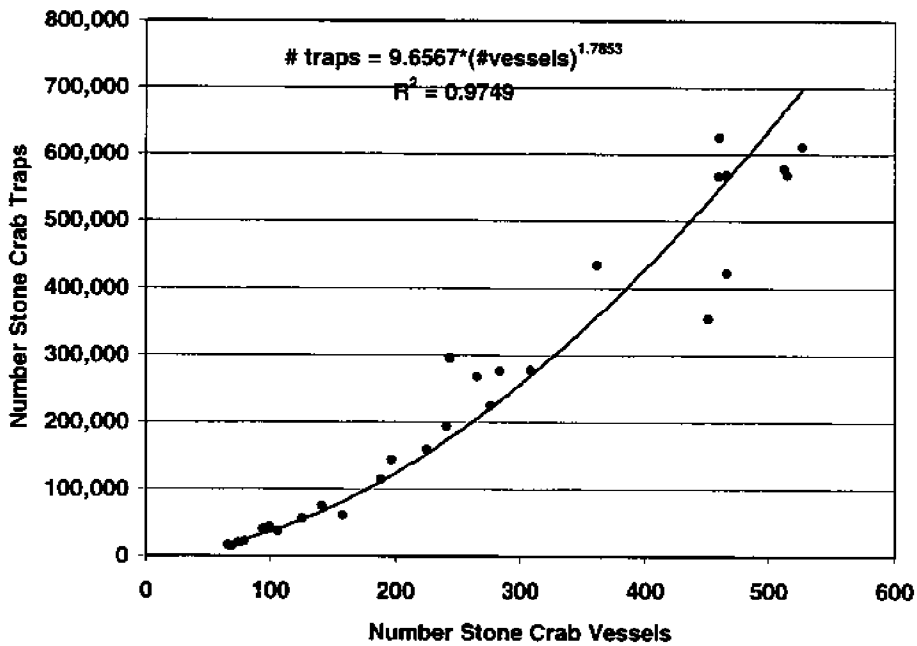



Figure 12. Number of Stone Crab Traps per Vessel




The marginal costs expressed as the simple slopes of the lines in figures 5 to 8 are presented in the following table:

| | Spiny Lobster | | Stone Crab | |
|---|---|---|---|---|
| Labor Type | Long-Run | Short-Run | Long-Run | Short-Run |
| Minimum Wage | $37.11 | $33.41 | $23.84 | $21.22 |
| | (0.69) | (0.71) | (0.62) | (0.64) |
| Share of TR | $55.77 | $55.74 | $31.45 | $30.38 |
| | (0.73) | (0.73) | (0.69) | (0.69) |

These marginal increments correspond, therefore, to the values of the parameter C in the equations to estimate trap benchmarks in sections 2.3.2 and 3.3, above.

5. Yield-per-Recruit Analysis of Trap Benchmarks

Once trap-benchmarks are established from production modeling analysis, the corresponding levels of fishing mortality rates that they generate are estimated as the product of the catchability coefficient at the trap-benchmark (estimated by equation 2) times the trap-benchmark. Determination of the impact of alternative fishing mortality rates on yield and other biological characteristics for the spiny lobster and stone crab fisheries under a given minimum size already imposed on the fisheries are obtained through yield-per-recruit and spawning-per-recruit theory and analyses.

One of the most significant aspects of the yield per recruit theory is that it integrates the growth and natural mortality processes and generates yield responses to different levels of exploitation for given selectivity patterns. In the case of the spiny lobster and stone crab, the segmented growth character of the two species complicates the integration of the biological and fishery processes. Therefore, a new model was developed in this study to portray the segmented growth character of these two crustaceans. Also, an extensive review of the literature was carried out to obtain and integrate the pertinent population dynamics parameters to form the fundamental database with which to assess the impact of trap controls (benchmarks) on the status of exploitation of the two jointly exploited stocks. A brief account of each component in the yield-per-recruit analysis is as follows:

5.1. Growth.

5.1.1. Spiny Lobster

A wide variety of methods and data sources have been used in attempts to elucidate growth curves that would best describe the nature of growth of *P. argus* in the Western Central Atlantic Ocean. Despite these efforts, accurate descriptions of spiny lobster growth are surprisingly rare, most likely as a consequence of problems that arise from applying standard fishery statistical procedures and classical fishery growth functions to crustacean growth (McCaughran and Powell, 1977; Mauchline, 1977). In effect, most of the methods used to study *P. argus* growth consist in variations of modal progression techniques to obtain size-at-age and fits of the standard von Bertalanffy growth equation (Beverton and Holt, 1957) to the resulting average size-at-age data. This has resulted in a disparity of growth parameter estimates, which can not be easily compared and adopted in stock assessment work.

A pre-requisite to study crustacean growth is to understand the frequency of molting and the magnitude of the growth increment at each molting. These are commonly estimated by examining the relationship between premolt and postmolt sizes (Hiatt, 1948) and the relationship between intermolt period and premolt size (Caddy, 1987). The information required for this purpose is fundamentally derived from tagging programs. In spite of the numerous tagging studies with *P. argus* done regionally and in Florida these data are seldom applicable to study growth. There are two fundamental circumstances to this problem: 1) Fishing intensity is usually very high. Thus, tagging studies usually provide data with extremely short time-at-large, and therefore, growth is almost nil between tag release and recapture, and intermolt periods are very seldom estimable under this condition, and 2) A very low rate of tags returned from a highly valuable resource profusely exploited over their entire habitat do not permit accumulation of data to express appropriate regression ranges. In this work, premolt-postmolt relationships and intermolt-premolt functions necessary to construct segmented growth curves for spiny lobsters derived from two major tagging studies performed in the Florida fishery during 1977 to 1981 and 1983 to 1985 (Mr. John Hunt, Florida Fish & Wildlife Conservation Commission, Marine Research Institute, Marathon, Florida) and reported in Ehrhardt and Pike (In Preparation) were available. The database consisted of 7,343 multi tag-recaptures of *P. argus* obtained in the middle and lower Florida Keys. Spiny lobster tagged in these programs ranged in size from 32 to 122-mm. carapace length.

In Ehrhardt and Pike (In Preparation) premolt-postmolt carapace length (CL) data were handled separately for males and females to account for the sexual dimorphism observed in the species. The apparently linear relationships that may change upon attainment of maturity (Kurata, 1962; Caddy, 1987) were fitted according to the segmented regression model proposed by Somerton (1980):

$$L_t \ \begin{cases} a + bL_0 & L_0 \le L_m \\ (a + bL_m) + b'(L_0 - L_m) & L_0 \ge L_m \end{cases}$$

where $L_t$ and $L_0$ are the postmolt and premolt carapace lengths, respectively, and a, b, b', and $L_m$ are parameters. The estimation procedure consisted of fitting two straight lines constrained to meet at a point where the premolt size takes the value of $L_m$. Thus, $L_m$ is the size at which the slope of the regression switches from b to b'. Therefore, the corresponding equations are:

Males

$$L_t \ \begin{cases} -0.064 + 1.116L_0 + \varepsilon_1 & L_0 \le 65 \text{ mm CL} \\ 72.476 + 0.953(L_0 - 65) + \varepsilon_2 & L_0 \ge 65 \text{ mm CL} \end{cases}$$

Females

$$L_t \ \begin{cases} 7.492 + 0.981L_0 + \varepsilon_1 & L_0 \le 65 \text{ mm CL} \\ 71.192 + 0.921(L_0 - 65) + \varepsilon_2 & L_0 \ge 65 \text{ mm CL} \end{cases}$$

The fit to the data indicated a strong linear correlation for males ($r^2$ =0.922) and females ($r^2$ = 0.924). The above relationships have normally distributed error terms $\varepsilon_1 \sim N(0, 1.752)$ and $\varepsilon_2 \sim N(0, 2.168)$ for males, and $\varepsilon_1 \sim N(0, 1.782)$ and $\varepsilon_2 \sim N(0, 1.915)$ for females (Ehrhardt and Pike, In Preparation).

The estimates of the slopes for each sex indicate that spiny lobsters less than 65 mm CL tend to grow slightly more per molt, relative to the premolt carapace length, than those larger than 65 mm CL. The estimate of $L_m$ = 65 mm for both males and females may be interpreted as an approximate estimate at which spiny lobster commence reaching the size of first maturity.

The relationship between intermolt period and premolt carapace size is usually expressed as an exponential function (Mauchline, 1977) such as

$$IP = a \exp^{bL_0}$$

where IP is the intermolt period, $L_0$ is the premolt carapace length and a and b are parameters. Data on intermolt periods and premolt carapace length for Caribbean spiny lobster is reported by Sweat (1968). This author reared 17 lobsters from puerulus stage (6 mm CL) to 49 mm CL for periods up to 600 days. These data are very restricted in sample size and size range, and for this reason intermolt periods were estimated following the maximum likelihood approach of Hoenig and Restrepo (1989) applied to the Florida tagging database.

Parameters of the intermolt period-premolt size relationship from Ehrhardt and Pike (in Preparation) resulted in the following:

| | |
|---|---|
| Males | $IP = 1.188\, e^{(0.0356\, L_0)}\, \varepsilon$ |
| Females | $IP = 1.126\, e^{(0.0404\, L_0)}\, \varepsilon$ |

where $\varepsilon$ is a lognormal error equal to 0.0902 estimated from the data of Sweat (1968).

5.1.2. Stone Crab

Similar to the spiny lobster segmented growth models, Ehrhardt and Restrepo (1989) provide hyperbolic relationships relating post-molt (PO) to pre-molt (PR) carapace width (CW) in males and females stone crab. The hyperbolic functions were found significant at carapace widths greater than 40 mm. but not significant below that size. This sexual dimorphic characteristic of stone crab growth was associated by the above authors to the fact that stone crab matures at an approximate size of 40 mm. carapace width. The resulting equations that will be used in the analysis in this study are:
Mature Males

$$PO = \frac{PR}{0.0015\, PR + 0.7234}$$

Mature Females

$$PO = \frac{PR}{0.0019 PR + 0.7463}$$

Immature Males and Females

$$PO = \frac{PR}{.0005PR + 0.7904}$$

Similar relationships were found by Ehrhardt and Restrepo (1989) for pre-molt carapace width (PR) and inter-molt period (IP) and given as follows:

Males

$$PR = \frac{IP}{0.0062IP + 0.2551} - 47.0047$$

Females

$$PR = \frac{IP}{0.0065IP + 0.4546} - 28.7529$$

Construction of claw-size-at-age equations from the above relationships require a functional relationship between carapace width and claw size. For this purpose the relationship given by Savage and Sullivan (1978) was used by Ehrhardt and Restrepo (1989). A claw length-weight relationship developed by the last authors was also used in the yield per recruit computations.

5.2. Natural mortality estimates.

5.2.1. Spiny Lobster

There are no quantitative evidences of the different sources generating natural mortality in *P. argus*. However, mortality due to predation must account for a significant fraction of the natural mortality rate in spiny lobster, and most likely with a greater incidence among juvenile stages. Published natural mortality estimates are mostly derived from analytical formulations that use growth parameters and average size in length frequency samples. Therefore, the estimates are subjected to the inherent uncertainty in von Bertalanffy growth parameter estimations as well as in the assumptions of the models relative to the average length in the catch. Based on tagging studies Waugh (1981) estimated natural mortality fractions for unexploited juvenile (<50 mm CL) female and male spiny lobsters in areas around Grand Bahama Island, Bahamas. These annual estimates were 18% (M=0.20) and 23.3% (M=0.27) for females and males, respectively. The same author provided natural mortality fractions of 18.5% (M=0.21) and 43.5% (M=0.57) for female and male spiny lobsters in the same unexploited stock but for the 50 - 70 mm. carapace length size range. Since emigration from the inshore grounds is known to occur in individuals within the later size range, Waugh (1981) considered that the last estimates are slightly overestimated. Munro (1974) estimated annual instantaneous natural mortality rates between 0.14 and 0.52 for spiny lobsters inhabiting three localities in Jamaica. Olsen et al., (1971) reported estimates of natural mortality of 0.48 for 60 - 77-mm. CL males in offshore areas of Puerto Rico, and 0.43 for smaller males (36.5 - 59 mm CL) inshore. The same authors reported a rate of 0.52 calculated for females (98 - 132 mm CL) in offshore areas. From all these estimates, an average instantaneous natural mortality rate of 0.37 is calculated. Ehrhardt (1996) developed a natural mortality rate based on estimates of the seasonal instantaneous total mortality rate (Z) estimated from length converted catch curves and landings for the spiny lobster fishery in the Bahamas using data for the period 1989-1994. The models expressing a possible relationship between Z-values and landings are as follows:

Linear $\quad Z = 0.352 + 5.4852E\text{-}08 \text{ LANDINGS}$

Exponential $\quad Z = 0.382\, e^{9.8666E\text{-}08 \text{ LANDINGS}}$

These models provide an estimate of the natural mortality rate when the variable LANDINGS equals zero. Thus, for the linear model, M = 0.352, and for the exponential model, M = 0.382. These M-estimates are in close agreement with the average instantaneous natural mortality rate obtained above from all published natural mortality estimates. Muller et al. (2000) used a natural mortality rate of 0.35 in their Florida spiny lobster stock assessment work. Therefore, in the analysis that follows a round up natural mortality rate of 0.35 will be adopted for each of the sexes.

### 5.2.2 Stone Crab

Natural mortality information for stone crab is available in the literature mostly in the form of qualitative sources of mortality (mostly due to predation). Ehrhardt (1990) generated the first quantitative estimates of the natural mortality rate of stone crabs in Florida based on tagging experiments. The estimates are presented by age groups as follows:

| | |
|---|---|
| For ages 1.5 to 3.5 | M = 0.78/year |
| For ages 2.5 to terminal age | M = 1.903/year |
| For ages 3.5 to terminal age | M = 6.867/year |

In the analysis included in this study the natural mortality estimate of 0.78 has been adopted as it represents an age range that is representative in the landings.

## 5..3. Reproductive parameters

### 5.3.1. Spiny Lobster

Fecundity estimates in numbers of eggs-at-size are scarce for most *P. argus* stocks in the Central Western Atlantic. Crawford and DeSmith (1922) observed that a

87.5 mm CL Female spiny lobster carried 500,000 eggs, while a 100 mm CL female carried 700,000 eggs. Dawson (1949) and Smith (1948) noted in separate studies that a 76.2 mm CL female can lay 500,000 eggs. Gregory et al. (1982) reported that a 67.5 mm CL female produces 143,167 eggs and a 107.5 mm CL female produces 690,000 eggs. Lyons et al. (1981) provides a larger fecundity data-set that could be used for fitting a functional regression. However, the best information on *P. argus* fecunfity is available from Cruz and de León (1991) for the spiny lobster stocks in Cuba. The combined data for the spiny lobster in the Southeastern Shelf and the Gulf of Batabano was used by these authors to fit a power function between fecundity and carapace length which is given as

$$FEC = 0.5911\ CL^{2.9666}$$

This relationship will be used in the analysis presented in this study.

Maturity-carapace length data for spiny lobster has been variously reported in the scientific literature. However, Cruz and de León (1991) question the validity of most of the reported size at first maturity under arguments that gear selectivity and differential catchabilities of gravid female spiny lobsters prevented determination of the true maturity-at-size distributions. In this section a comparison of the maturity data collected in the Bahamas by Kanciruk and Herrnkind (1976) and in Cuba by Cruz and de León (1991) is made. For this purpose a common sigmoid function was fitted to all data sets. This sexual maturity function can be expressed as

$$MAT = \frac{1}{1 + EXP(D * (CL - L50)}$$

where MAT is the fraction mature at size, D is a constant, and L50 is the length at 50% maturity.

Data from Kanciruk and Herrnkind (1976) correspond to females partially maturing at an autumnal secondary spawning season (September-November). Therefore, the fraction of mature females in the samples is much lower relative to what it should be expected during the main spawning season in the Bahamas (February-May). For this reason, only females carrying eggs were considered in the analysis. The results are shown in the following table where the number of mature females was estimated from the percentage of egg bearing females in total sample size from Table 4 of Kanciruk and Herrnkind (1976):

| CL | Median CL | Number Mature | % Cumulative Frequency |
|---|---|---|---|
| ≤70 | 65 | 0 | 0 |
| 71-80 | 75 | 21.88 | 0.205 |
| 81-90 | 85 | 55.86 | 0.729 |
| 91-100 | 95 | 24.80 | 0.963 |
| ≥100 | 105 | 3.99 | 1.000 |

Similar data reported by Cruz and de León (1991) for two localities in Cuba (Gulf of Batabano and Southeastern Shelf) were pooled and used in the comparative analysis.

Fitting of the model to the above data resulted in the following parameter estimates:

| | Bahamas data | Cuba data |
|---|---|---|
| D | 0.239 | 0.188 |
| L50 | 80.824 | 79.946 |

From the L50-parameter estimates it may be concluded that size-at-first maturity of spiny lobsters in the Bahamas and Cuba are remarkably close (80.8 cm. and 79.9-cm., respectively). These values compare very approximately with 79 mm CL reported for *P. argus* in Brazil (Soares and Cavalcante, 1984), and the size of first maturity of 81-82 mm CL reported by Evans (1990) for Bermuda – the two most extreme spiny lobster populations in the Central Western Atlantic. Data on spiny lobster maturity found in Lyons et al. (1981) contains mature females as small as 67 mm CL. A maturity-carapace function fitted to these data generated D = 0.421 and L50 = 90.3 m CL. These parameters differ significantly from those presented above, therefore, the average of the parameters for functions in the Bahamas and Cuba will be used in the present analysis.

### 5.3.2. Stone Crab

Noe (1967) studied the fecundity of five stone crabs in Biscayne Bay and demonstrated that fecundity increased monotonically from 160,000 to 350,000 eggs in females ranging in size between 72 and 95 mm. CW. This author did not develop a functional relationship for fecundity at size. However, Ros et al., (1981) provide a functional fecundity size relationship for female stone crab which is given as

$$F(x10^3) = -431.083 + 872CW$$

Maturity at size was reviewed from the literature by Restrepo (1989) and concluded that stone crabs appear to be 0% mature at about 40 mm. CW and approach 100% maturity at about 85 mm. CW. Using these maturity range, Restrepo (1989) estimated that the parameters D and L50 for the sigmoid maturity-size function (similar to the one developed for the spiny lobster in section 5.3.1) were 0.409 and 62.5, respectively. These parameters will be used in the analysis in this report.

## 5.4. Yield-Per-Recruit Model for Crustacean Segmented Growth Characteristics

Determination of the impact of fishing under different benchmark scenarios on a cohort is based on two fundamental considerations: 1) maximization of yield from a cohort (yield-per-recruit), and 2) controlling an adequate amount of spawning products to keep a viable stock (spawning potential ratio). Therefore, two models based on Thompson and Bell (1934) yield-per-recruit theory are necessary to calculate these impacts.

The rationale followed by the two models is that minimum size is referenced to legal size categories given in carapace length and claw size for spiny lobsters and stone crabs, respectively. Therefore, the age-of-first-capture necessary to estimate abundance has to be numerically defined for each legal minimum size from the segmented growth curves. Once an age of first capture is defined, a cohort is numerically constructed with ages older by one-year intervals starting from the minimum age making use of the segmented growth equations constructed for each of the species. The process starts with a giving minimum size and through numerical computations that take uncertainty of the relationships into consideration, a value of $t_c$ (age corresponding to a minimum size) is found in the segmented growth curve. Then the cohort is formed by yearly multiples of $t_c$ using the same segmented growth equations. Once the age-size compositions of each cohort are defined for each of the minimum size of each species, the yield per recruit (YPR) and egg per recruit (EPR) estimations are accomplished following the Thompson-Bell procedure.

The basic form of the Thompson-Bell yield-per-recruit (YPR) model is given as

$$YPR = F[\frac{1 - e^{-(F+M)}}{F+M}] \sum_{t=t_c}^{t_{max}} (N_t e^{-(F+M)(t-t_c)}) W_t$$

where F and M are the fishing and natural mortality rates, $t_c$ is the age of first capture that is defined by the minimum size, $t_{max}$ is the maximum observable age in a cohort, $N_t$ is cohort abundance and is equal to $\exp(-M^*(t_c-t_r))$ when $t=t_c$ and $t_r$ is age of recruitment set to 0.5 years, and $W_t$ is the average weight at age t estimated numerically from the segmented growth equation and a length-weight relationship for the species.

Spawning potential ratio (SPR) is the fraction of egg-per-recruit (EPR) in an exploited phase ($t_c$, F ) to the egg-per-recruit when the stock is in the virgin state (F=0). Thus

$$SPR = \frac{EPR_{\overline{t_c,F}}}{EPR_{\overline{F=0}}}$$

When $t_r<t_c<t_m$ , where $t_r$ is the age of first recruitment and $t_m$ is the age of first maturity, then

$$EPR \Big|_{t_c,F} = \sum_{t=t_c}^{t_{max}} (N_t \cdot e^{-(F+M)}). FEC_t \cdot MAT_t$$

where

$$N_t = e^{-M(t_c - t_r)}$$

When $t_r < t_m < t_c$

$$EPR_{\overline{t_c,F}} = \sum_{t=t_r}^{t_c-1} N_t^{l} e^{-M} \cdot FEC_t \cdot MAT_t + \sum_{t=t_c}^{t_{max}} N_t^{ll} e^{-(F+M)} \cdot FEC_t \cdot MAT_t$$

where $N_t^{1}$ is 1 when $t=t_r$ , and when $t=t_c$ , then

$$N_t^{ll} = e^{-M(t_c - t_r)}$$

Egg-per-recruit in stocks in virgin state we have that

$$EPR_{\overline{F=0}} = \sum_{t=t_r}^{t_{max}} N_t^{l} e^{-M} \cdot FEC_t \cdot MAT_t$$

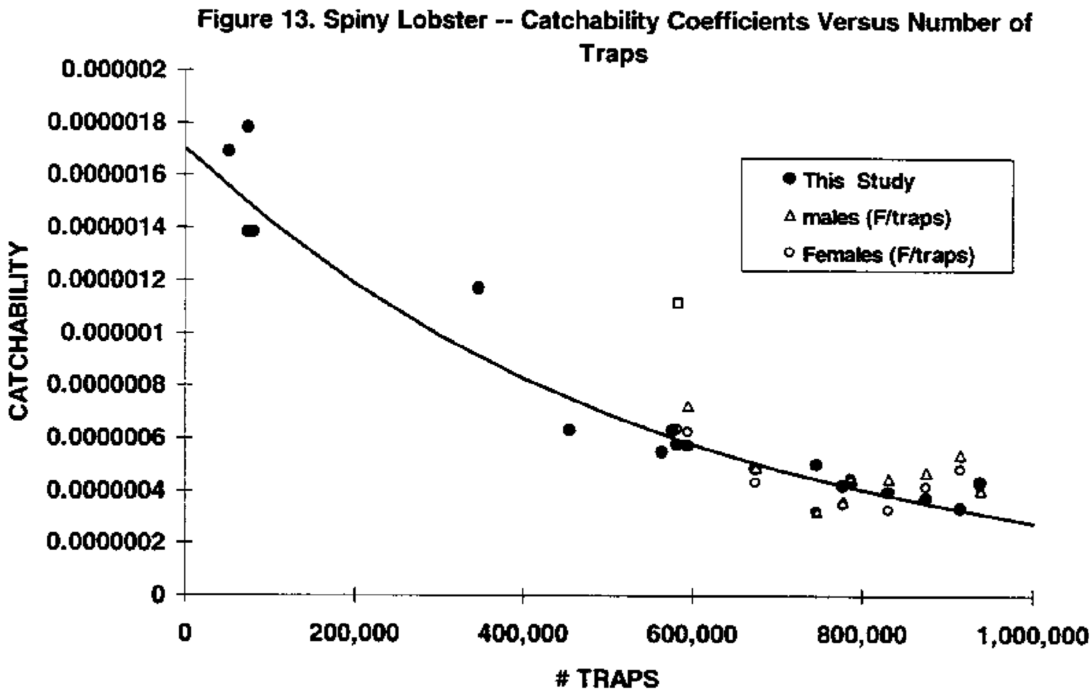
where $N_t^{1} = 1$ when $t=t_r$ .

In all analyses with the segmented growth curves it was assumed that age of first recruitment ($t_r$) was 0.5 or 6 months.

A computer program denominated CRUSTYPR written in Microsoft FORTRAN was developed to perform all the above computations.

6. Results and Discussion
6.1. Production Modeling
6.1.1. Spiny Lobster

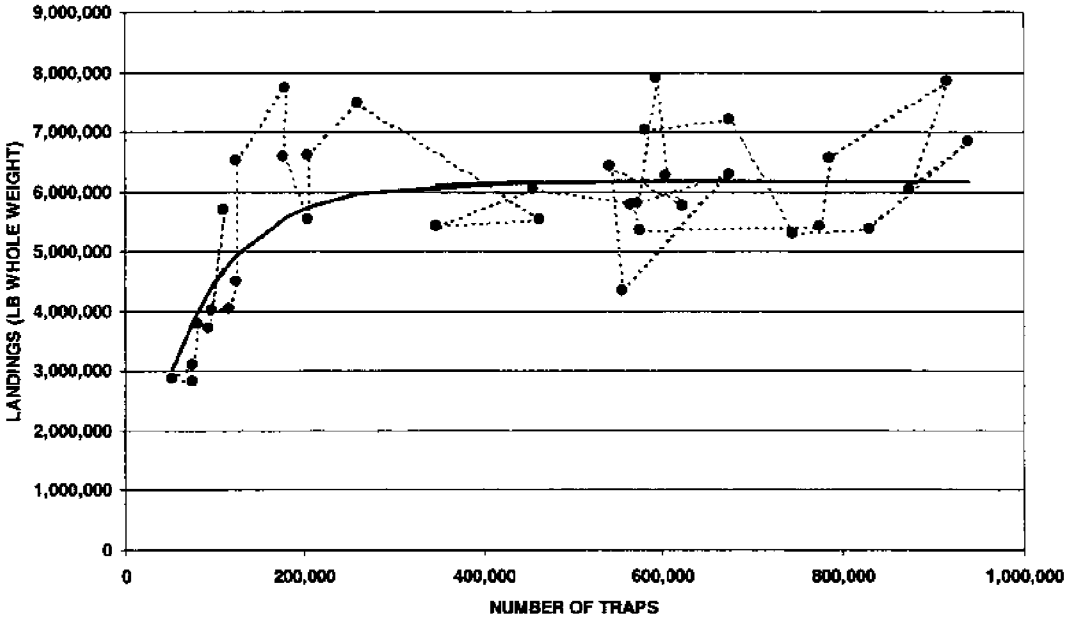
Figure 13 shows the estimates of seasonal catchability coefficients, q, obtained with the seasonal depletion model (equation 1) plotted on the number of spiny lobster traps fished per season. Catchability coefficients were not estimated for seasons corresponding to the period when Florida landings included catch realized in the




Bahamas fishery (1964-1976) because landings and effort for those years can only be corrected annually but not monthly as required by the seasonal depletion model. The values of q estimated above were obtained with a constant natural mortality rate M of 0.029 per month or M = 0.35 per year (Ehrhardt 1996; Muller et al. 2000). Included in figure 13 are seasonal values of catchability coefficients for males and females spiny lobsters estimated as the ratio of the average weighted annual fishing mortality rate, F, estimated from sequential population analysis by Muller et al. (2000) and the corresponding number of traps fished per season. In general there is a good correspondence between the sets of catchability estimates in spite of the large difference in methods and data used in the calculations. Only one point in Muller's et al. (2000) data deviates significantly from the generally decreasing trend of catchability on effort in figure 13. The significance of the relationship found between catchability and fishing effort justifies the use of the biomass utilization model concept in spiny lobster analysis.

The spiny lobster biomass utilization model (equation 5) was fitted by non-linear least-squares procedures to the catch and nominal effort data shown in figures 1 and 2. The parameter estimates for the model resulted in Ymax = 6,191,372 and r = -0.0000122688. The fit was significant ($F_{1,34}$=71.09; P<<<0.0000) with a corrected correlation coefficient of 0.584. The estimated parameters were used to calculate seasonal expected catch at effort. Observed and expected catch trends are plotted in figure 14. The model fits the data well as it portrays the flat top characteristic of the Florida spiny lobster catch over a wide range of effort. The fitted model will be used in trap benchmark estimations.

Figure 14.Spiny Lobster Production Function




The total number of traps that optimizes each of the three benchmark scenarios (maximum sustainable yield, break-even-point and maximum economic yield) is given in Table 1. A wide range in trap numbers is observed in Table 1 as a result of the significantly different conditions associated with each of the scenarios. Under Case I, traps at maximum sustainable yield (Ymax) in the biomass utilization model are not applicable since Ymax is reached at an infinite number of traps. However, arbitrary decisions could be made relative to this benchmark. For example, the number of traps catching an arbitrarily selected 95% of Ymax may be obtained by factoring out f in equation 8 where Y can be made equal to 0.95*Ymax. Using this assumption, the resulting number of traps is 236,103 that will catch an average of 5,881,803 pounds whole weight spiny lobsters (Table 1) that could generate about 24.9 lb. per trap per season. This catch rate is about 1.8 times greater than the catch rate observed in the fishery in the 1999 fishing season and 2.3 times greater than the catch rate observed in the 1998 fishing season. Another possibility is to develop a concept similar to that of the $F_{0.1}$ adopted in yield per recruit analyses (Gulland and Boerema, 1973). In this case a fishing effort level could be defined at a point on the production curve where the slope is 10% of the slope at the origin of the curve. That is, estimate the number of traps at a point on the production curve where the slope equals $0.1{*}(dY/df)_{@orig}$. In this particular case the slope at the origin is 74.6298, therefore, factoring out f from the first derivative of the biomass utilization model that has been set to dY/df=7.46298 gives a total of 185,516 traps that will catch an average of 5,603,191 pounds of whole weight spiny lobsters (Table 1). At this benchmark the fishery on average will generate about 30.2 lb. per trap per season. This catch rate is about 2.2 times greater than the catch rate observed in the fishery in the 1999 fishing season and 2.8 times greater than the catch rate observed in the 1998 fishing season. Clearly, while the asymptotic catch (Ymax) estimated by the model is approximately 6.2 million pounds, and obtainable with an extremely large number of traps, the two adopted MSY conditions can catch only slightly less than Ymax

Table 1. Number of traps required to accomplish each case scenario in the spiny lobster fishery using the biomass utilization model.

**Case I.** Number of traps at maximum sustainable yield

| Condition | Number of Traps | Expected Landings (lb) |
|---|---|---|
| 95% of Ymax | 263,103 | 5,881,803 |
| 10% Slope dY/df | 185,516 | 5,603,191 |

**Case II.** Number of traps at Break-Even-Point

| Condition | # Traps Long-Run | Expected Landings (lb) | # Traps Short-Run | Expected Landings (lb) |
|---|---|---|---|---|
| Minimum Wage | 632,524 | 6,184,348 | 702,438 | 6,190,538 |
| Share Total Revenue | 422,731 | 6,162,457 | 422,953 | 6,162,457 |

**Case III.** Number of traps at Maximum Economic Yield

| Condition | # Traps Long-Run | Expected Landings (lb) | # Traps Short-Run | Expected Landings (lb) |
|---|---|---|---|---|
| Minimum Wage | 164,113 | 5,419,669 | 172,391 | 5,496,611 |
| Share Total Revenue | 132,009 | 5,031,635 | 132,051 | 5,032,259 |

(5% and 8%, respectively) with a number of traps similar to levels observed in the fishery during the period 1970-1974 (Fig. 2). The trap levels under the arbitrary conditions adopted in the MSY scenario are containing the lower boundary initially defined in the trap reduction program but still well below the average number of traps operated in the fishery in the last 5 fishing seasons (1995-2000).

The break-even-point scenario provides a wide range in total number of traps (between 422,731 to 702,438 traps) depending if minimum wages or share of the total revenues are considered and if short-run or long-run marginal cost conditions are adopted. It is noted in the results presented in Table 1 that in spite of the large differences in trap numbers according to conditions adopted in the analysis, the expected landings vary little between 6.16 and 6.19 million pounds when the asymptotic landing is approximately 6.2 million pounds. These results are due to the obvious flat character of the production function within the range of traps defined by the conditions under which the open access or break-even-point was estimated. By far the greatest differences in the number of traps are a consequence of the labor cost conditions. In this regard the minimum wage condition should be used as an opportunity cost threshold to participate in the spiny lobster fishery and the share of the total revenue condition as the average condition to participate in the fishery. It is important to note that the number of traps operated in the spiny lobster fishery during the period 1995-2000 averaged about 600,000. This number falls in the upper number of traps range in the break-even-point scenario but slightly bellow the conditions expressed by the minimum wage. For this reason the catch rates for the 422,731 to 702,438 trap benchmark range (14.6 lb. per trap per season to 8.8 lb. per trap per season, respectively) contains the catch rates observed in the 1998 (10.9 lb. per trap) and 1999 (13.9 lb. per trap) fishing seasons. This finding may be indicative that the spiny lobster fishery managed under the trap reduction program is presently operating at conditions that are equivalent to those found in the break-even-point analysis. Moreover, the economic outcome of the present conditions in the fishery are more identified with a labor cost structure that approximate the minimum wage condition than the share of total revenue condition. It is also important to note that the spiny lobster fishery operated slightly below 600,000 traps during the period 1978-1986 (Fig. 2) when landings varied about an average of 6 million pounds. This then may be an indication that the trap reduction program as so far reduced the number of traps to the historic levels immediately before the conspicuous increase in traps in seasons prior to the adoption of the limited entry system in the spiny lobster fishery.

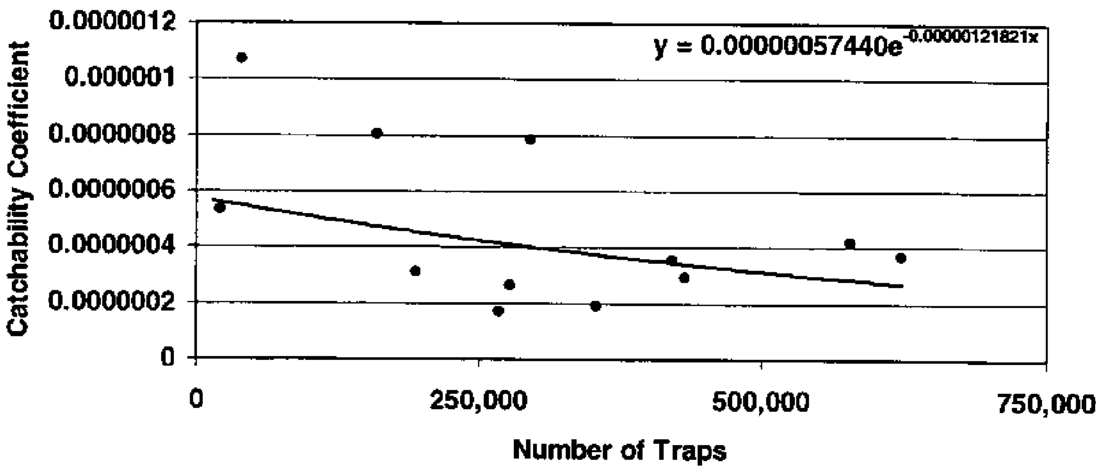
Under the MEY scenario the number of traps required to optimize economic yield is much lower and it varies much less than in the break-even-point scenario. This range is between 132,009 and 172,391 traps depending on the cost conditions used for estimating MEY (Table 1). It is noted in Table 1 that the differences in landing estimates are between 5.0 and 5.5 million pounds or 19% and 11% below the asymptotic yield, respectively. The conditions under the MEY scenario point to a much lower number of traps than the average number of traps operated in the fishery during 1995-2000 and also below the lower boundary initially defined in the trap reduction program. The catch rates generated by the above trap range are 38.1 and 31.9 lb. per trap per season, respectively. These rates are 3.5 and 2.9 times greater than the observed 1998 catch rates and 2.3 and 2.8 times greater than the 1999 observed rates, respectively.

The trap benchmarks estimated under the three scenarios presented above do not consider of course any social implications of using fewer traps in the fishery. The results, however, clearly indicate that regulations of optimum trap participation are more economically than biologically driven. Therefore, under a labor efficient production system one would expect the spiny lobster fishery to be operating at trap levels that should be closer to the MEY or at the very least below the open-access trap threshold defined by the share of the total revenue labor cost condition. These circumstances provide an obvious opportunity for the spiny lobster fishers to expand their fishing activities to other technologically compatible resources and fisheries.

### 6.1.2. Stone Crab

Estimates of seasonal catchability q and number of traps fished per season are shown in Figure 15. Catchability coefficients could not be estimated for all fishing seasons due to conspicuously increasing trends in catch per trap observed earlier in the season in some years. Apparently, the observed trends in catch per trap may have resulted as a consequence of significant recruitment occurring during those seasons and as such invalidating the use of the DeLury-type seasonal depletion model. The values of q estimated with the depletion model (equation 1) were obtained with a constant natural mortality rate M of 0.065 per month or M = 0.78 per year (Ehrhardt, 1990). Because of the recruitment influence on the seasonal stone crab CPUE trends, the variability in the estimates are larger than those observed in the lobster fishery. Unfortunately, and as a consequence of the October 15 start of the fishing season, the recruitment effect cannot be avoided by moving the regression range to earlier months when recruitment is less conspicuous as in the case of the spiny lobster fishery.

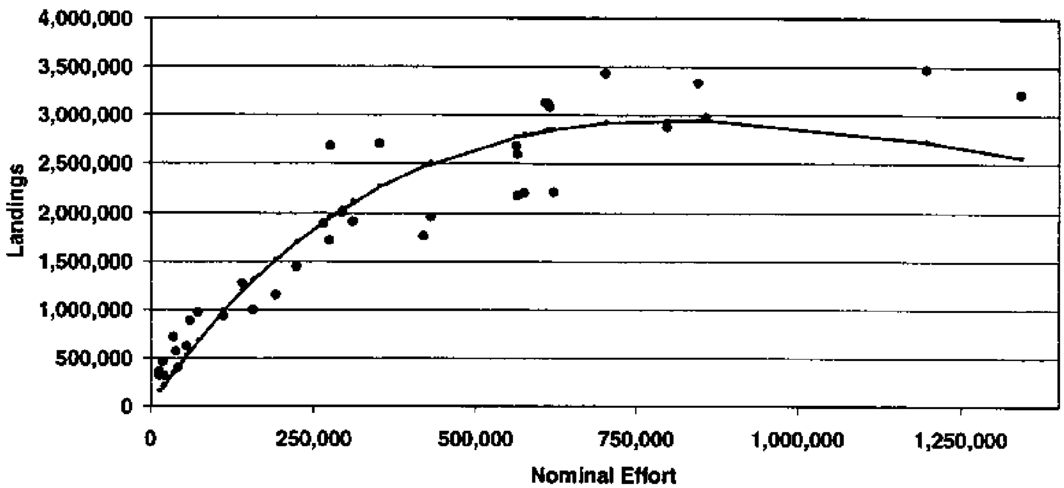
**Figure 15. Stone Crab -- Catchability Coefficients Versus Number of Traps**




A least-squares regression of the trap corrected production model (equation 8) was used to fit the model to the seasonal landings and standardized effort data. The parameter estimates resulted in A = 10.02124 and B = -0.0000087132. The regression was highly significant ($F_{1,37}$=113.34; P<<<0.0000) with a coefficient of determination of 0.83. The estimated parameters were used in the nominal effort version of the model (equation 9). The observed and expected catch and nominal effort are presented in figure 16. It appears from this figure that the expected values generated by the effort-corrected Schaefer-type production model captures the yield path when q varies dynamically with effort levels.

The total number of traps that optimizes each of the three trap benchmark scenarios (maximum sustainable yield, break-even-point and maximum economic yield) is given in Table 2. Similar to the cases of the spiny lobster fishery, a wide range in trap numbers is observed in Table 2 as a result of the significantly different conditions associated with each of the scenarios. In Case I, the number of traps at maximum sustainable yield (MSY) in the effort-corrected production model is 891,000 generating about 3 million pounds of claws (Table 2). The catch rate corresponding to the MSY level is approximately 3.4 lb. claws per trap per season. This rate is 1.42 as large as the 1998 observed catch rate of 2.39 lb. of claws per trap per season. However, because of the flat character of the production curve at the MSY effort level, landings at 5% below

Figure 16. Stone crab -- Production Function




or above the MSY create a trap range of over 200,000 traps around the effort at MSY (Fig. 16). Hence, the trap number at MSY is highly sensitive to small changes in expected catch about the MSY. In spite of this condition, the number of traps operated in the stone crab fishery in the 1998 fishing season (last season for which reliable fishing effort statistics were available for this study) was over 1.3 million or about 400,000 traps above the estimated number of traps generating MSY.

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Table 2. Number of traps required to accomplish each case scenario in the stone crab fishery using the trap corrected production model.

Case I. Number of traps at maximum sustainable yield

| Number of Traps | Expected Landings (lb) |
|---|---|
| 891,000 | 3,015,818 |

Case II. Number of traps at Break-Even-Point

| Condition | # Traps Long-Run | Expected Landings (lb) | # Traps Short-Run | Expected Landings (lb) |
|---|---|---|---|---|
| Minimum Wage | 815,792 | 3,026,192 | 911,483 | 3,009,118 |
| Share Total Revenue | 589,449 | 2,880,797 | 617,604 | 2,916,627 |

Case III. Number of traps at Maximum Economic Yield

| Condition | # Traps Long-Run | Expected Landings (lb) | # Traps Short-Run | Expected Landings (lb) |
|---|---|---|---|---|
| Minimum Wage | 349,365 | 2,287,520 | 382,753 | 2,406,245 |
| Share Total Revenue | 263,966 | 1,917,852 | 275,063 | 1,971,645 |

The break-even-point scenario provides a wide range in total number of traps (between 589,449 to 911,483 traps) depending if minimum wages or share of the total revenues are considered and if short-run or long-run marginal cost conditions are adopted. It is noted in Table 2 that in spite of the large differences in trap numbers according to conditions adopted in the analysis, the expected landings vary only between 2.9 and 3.0 million pounds when the MSY is approximately 3 million pounds. These results are due to the flat character of the stone crab production function within the range of traps defined by the conditions under which the open access or break-even-point was estimated. The greatest difference in the number of traps is due to labor cost conditions, and similar to the spiny lobster analyses, the minimum wage condition should be used as the opportunity cost threshold to participate in the stone crab fishery while the share of the total revenue condition is used as the average condition to participate in the fishery.

The number of traps operated in the stone crab fishery increased from 567,100 traps in the 1985-fishing season to 860,262 traps in the 1996-fishing season. This trap range coincides very closely with the range of traps in the break-even-point scenario provided by the conditions expressed by the minimum wage and share of the total revenues. Catch rates for the range of trap benchmarks in the break-even-point vary between 4.9 lb. claws per trap per season to 3.3 lb. claws per trap per season, respectively, when the catch rates were 2.4 and 2.9 lb. of claws per trap in the 1997 and 1998 fishing seasons, respectively. This finding may be indicative that starting in the 1997 fishing season the stone crab fishery is operating under conditions of significant over-capitalization that are beyond those of the break-even-point conditions.

Under the MEY scenario the number of traps are significantly lower and it varies less than in the break-even-point scenario. This range is between 263,966 and 382,753 traps depending on the conditions used for estimating MEY (Table 2). Differences in landings shown in Table 2 are between 1.9 and 2.4 million pounds of claws or 36% and 20% below the MSY, respectively. The conditions under the MEY scenario point to an optimum number of traps that is much lower than the 1.3 million traps operated in the fishery during the 1998 fishing season. The catch rates generated by the above range are 7.3 and 6.3 lb. of claws per trap per season, respectively. These rates are 2.5 and 2.2 times greater than the observed 1997 catch rates and 3.0 and 2.6 times greater than the 1998 observed rates, respectively.

Under any of the three scenarios expressed above, the benchmarks are well below the number of traps deployed in the stone crab fishery in the 1998-fishing season. This is then a clear indication of gear overcapitalization in this fishery when higher catch rates can be obtained at much lower levels of traps used in the fishery without compromising the landings from the resource.

### 6.1.3. Combined trap assessment

Results in the previous sections are indicative of a spiny lobster fishery that is operating at levels of effort that are identified with those that may just generate a break-even condition in the fishery while the stone crab fishery has increased the number of traps far beyond the levels that are economically reasonable for the exploitation of the resource. In both fisheries, however, there are no definite signs of biological overexploitation as expressed by landings at maximum but variable levels with no clear decreasing trends.

The historic trends in number of traps in both fisheries as depicted in Figure 2 show that spiny lobster traps were maintained at about 600,000 traps during the period 1978-1986 while stone crab traps were maintained at a similar level but during the period 1985-1992. Speculations about a limited entry or control on the number of traps in the spiny lobster fishery increased considerably the number of traps utilized in that fishery during the period 1987-1991. After the implementation of the spiny lobster trap certificate program in 1992, the number of traps in the stone crab fishery began increasing steadily between 1993 and 1996 and experiencing a steep increase in 1997 and 1998 (Fig. 2). The increase in the number of traps incorporated to the stone crab fishery after 1992 appears negatively correlated to the decrease in traps under the spiny lobster trap reduction program (Fig. 2). The interactive nature of the spiny lobster trap reduction program on the open access condition in the stone crab fishery is further depicted in figure 17. In the figure one can appreciate that during the period 1990-1996 there was a significant linear relationship between the number of traps in the spiny lobster fishery and the stone crab fishery with a negative slope of 0.78 and a coefficient of determination of 0.87. That is, for every trap retrieved in the spiny lobster fishery, it appears that 0.78 traps were added to the stone crab fishery. In 1997 and 1998, however, increments in the number of traps in the stone crab fishery departed significantly from the previous trend (Fig. 17) indicating the possible speculative nature of the entry into the stone crab fishery in those years due to the eventual implementation of a stone crab limited entry system. On the other hand, the combined number of traps used in both fisheries (Fig. 18) was kept at a surprisingly similar level between 1.4 and 1.5 million traps during the period 1987-1996 with a significant increase in the combined number of traps during 1997 and 1998 due to the already mentioned extraordinary increase in the number of traps deployed in the stone crab fishery during those two years.

**Figure 17. 1989-1998 Spiny Lobster to Stone Crab Trap Correlation**

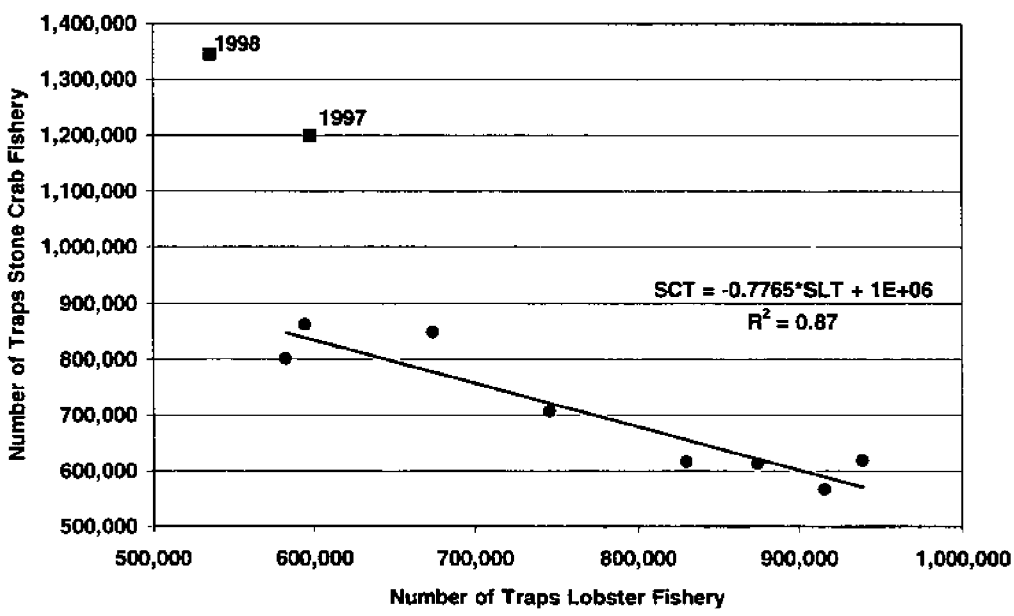
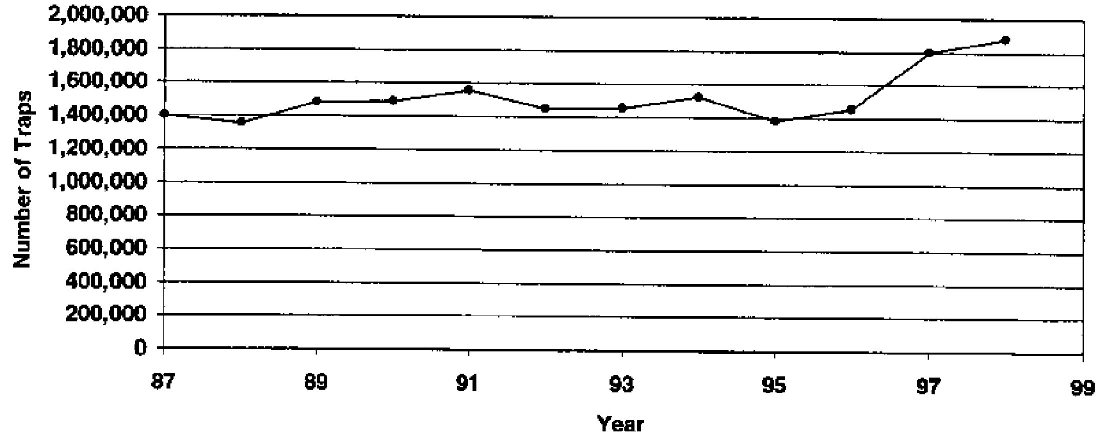


Figure 18. Total Spiny Lobster and Stone CrabTtraps



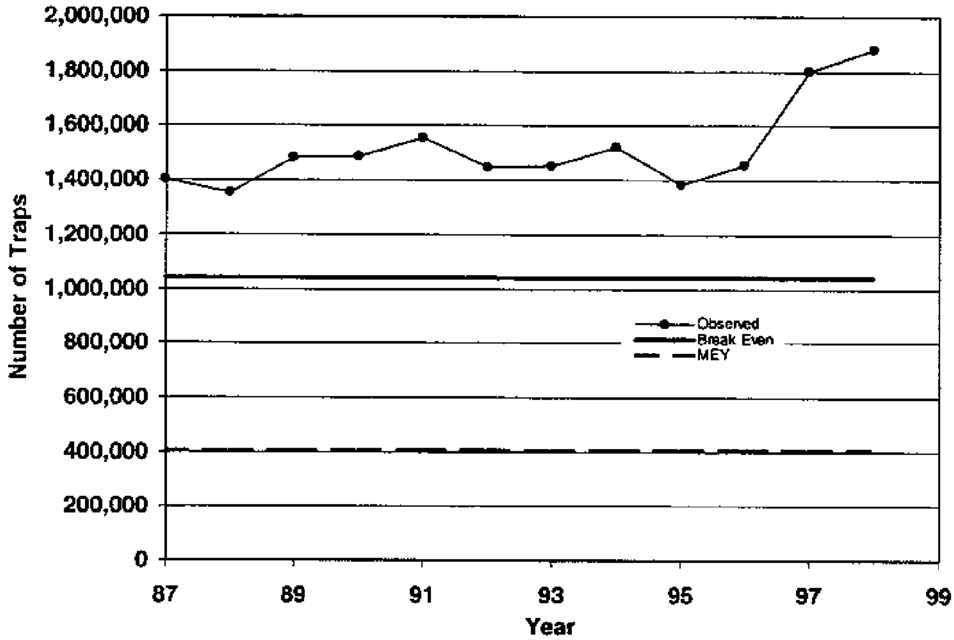

These results are all indicative of the multi-species nature of the fishing operations practiced by trap fleets in south Florida where limiting effort in one resource created a re-distribution of the effort into other available resources to the fleets.

Under the assumption that the most desirable labor cost to these fisheries is the one expressed by the share of the total revenues and that long-run marginal costs are applicable to the trap management framework, then the trap benchmarks for each fishery and for the total of both fisheries will be:

| | NUMBER OF TRAPS UNDER DIFFERENT BENCHMARKS | | |
|---|---|---|---|
| Condition | Spiny Lobster | Stone Crab | Total |
| MSY | 185,516-263,103 | 891,000 | 1,076,516-1,154,103 |
| OAE | 422,953 | 617,604 | 1,040,557 |
| MEY | 132,051 | 275,063 | 407,114 |
| Current (1998) | 535,492 | 1,343,676 | 1,879,168 |

The information in the above table indicates that if management desires to control entry into these fisheries by adopting the break-even or open access equilibrium condition (OAE) it needs to reduce the spiny lobster traps by about 113 thousand from the current conditions and to reduce the number of traps in the stone crab fishery by about 726 thousand. If economic optimization of fishing operations is the desirable framework for these fisheries, then the spiny lobster fishery requires a reduction of about 403 thousand traps from the current (1998) conditions while the stone crab fishery will be confronted with the retrieval of about 1.1 million traps. When the combined amount of traps that can be used under the different trap benchmarks are compared to the 1998 conditions (Fig. 19), it is apparent that the multi-species fisheries needs to retrieve either 836,611 or 1,472,054 traps if the OAE or the MEY is preferred.

Figure 19. Total Spiny Lobster and Stone Crab Traps




6.2. Yield-per-Recruit

6.2.1. Spiny Lobster

Figure 20 shows yield-per-recruit curves for females and males spiny lobsters under the minimum legal size in the fishery. The Y/R is given in grams of tails yielded per each individual recruiting to the fishery. The curves show two distinct characteristics: 1) females generate slightly lower yields than males because of differences in growth at age, and 2) maximum yield-per-recruit is generally flat at higher levels of fishing mortality given the size of first capture. In the figure, it is observed that a plateau of maximum levels of yield-per-recruit is attainable at values of fishing mortality rate starting at 0.4 for females and 0.8 for males. The spawning potential ratio (SPR) for females given the minimum size adopted in the fishery and for several values of fishing mortality are given in figure 21. In the figure is evident that 40% SPR (a reasonable and conservative level for SPR) is attained at values of fishing mortality rate that are slightly below 0.4.

The above figures were used to measure the biological impact of fishing mortality levels generated by the trap benchmarks. These fishing mortality levels are presented in Table 3. The open access or break-even-point condition (adopting the long-run cost function) generates the highest fishing mortality rates irrespective of the labor cost. These values are 0.34 for the two labor conditions and they are similar to the current (1999/2000) average male-female fishing mortality rate estimated by Muller et al. (2000). These values have no biological impacts on the resources given that in figures 20 and 21 yield per recruit is not compromised and the spawning potential ratio is about 40%. Hence, economic gains by reducing the number of traps under any of the conditions of the analysis will reduce fishing mortality and will not biologically impact the resource. However, fishing mortality rates obtained at trap benchmarks generated at the maximum economic yield appear to be biologically well below the asymptotic maximum yield per recruit that could be generated by the species, hence they appear biologically less efficient.

**Figure 20. Spiny Lobster Yield-per-Recruit**

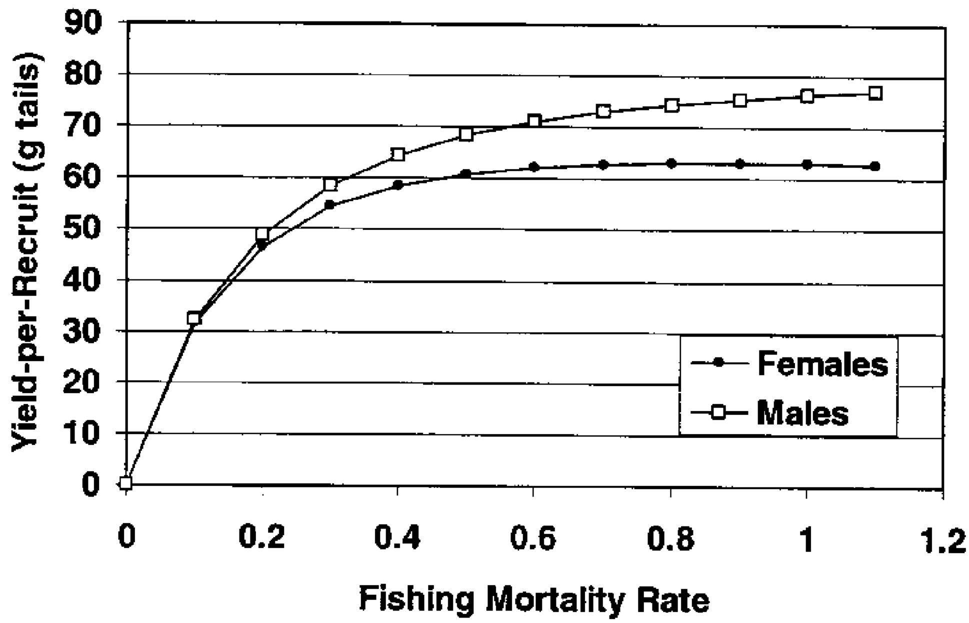



**Figure 21. Female Spiny Lobster Spawning Potential Ratio (SPR)**

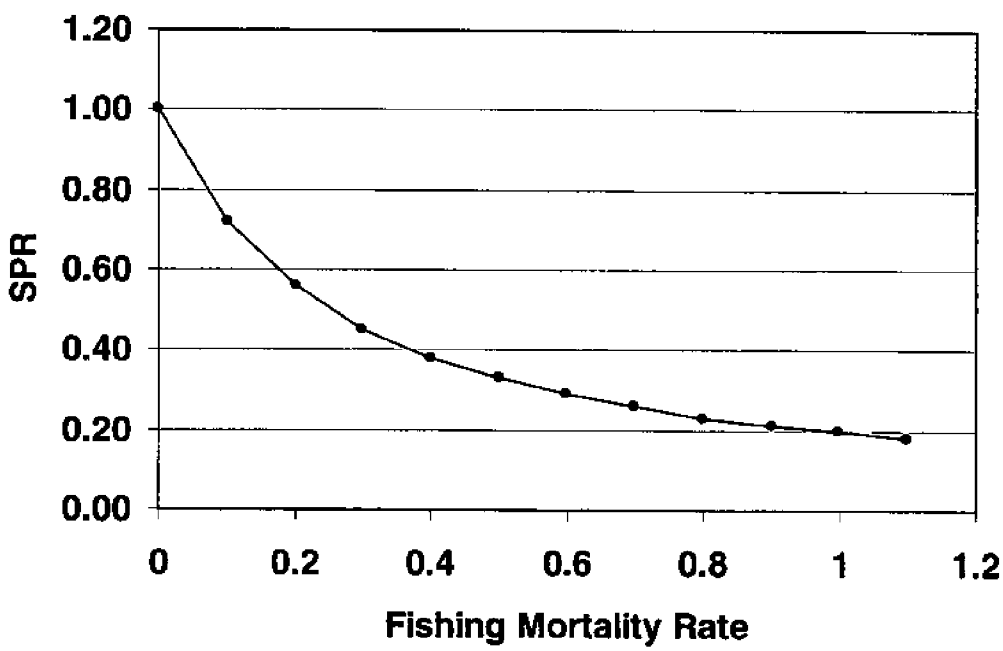


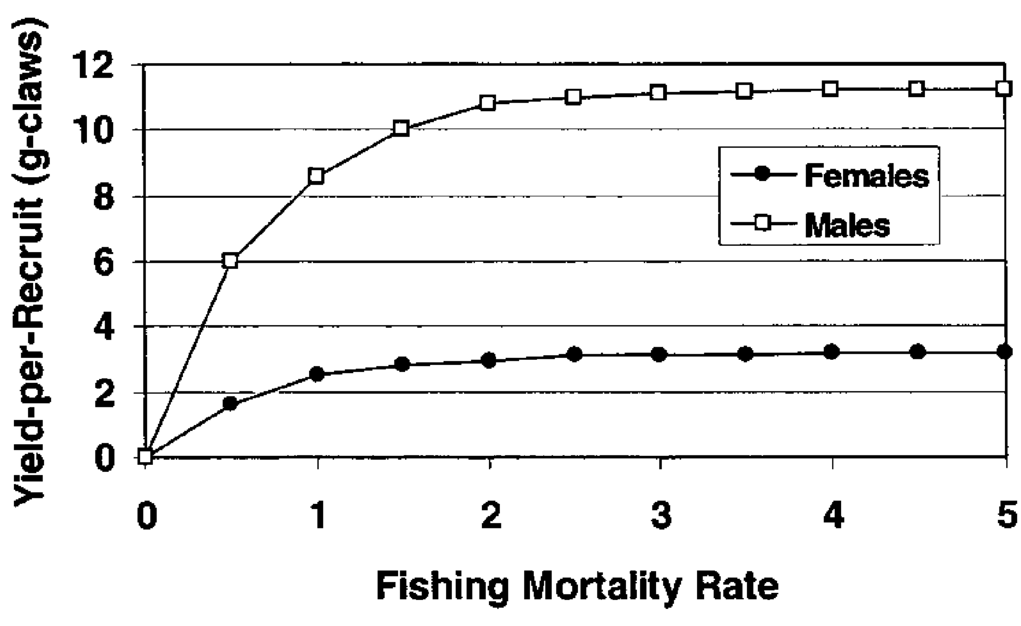
Table 3. Spiny lobster fishing mortality rates generated at different benchmarks, and considering long-run cost functions and two types of labor costs.

| Condition | Number of Traps @ Benchmark | Fishing Mortality Rate @ Benchmark |
|---|---|---|
| MSY 95% Ymax | 263,524 | 0.28 |
| MSY 10% Slope | 185,516 | 0.23 |
| Open Access, Min. Wage | 633,524 | 0.34 |
| Open Access, Share | 422,731 | 0.34 |
| MEY, Min. Wage | 164,113 | 0.21 |
| MEY, Share | 132,009 | 0.18 |
| Current (1999/2000) fishing mortality rate (Muller et al. 2000) | | 0.37 |

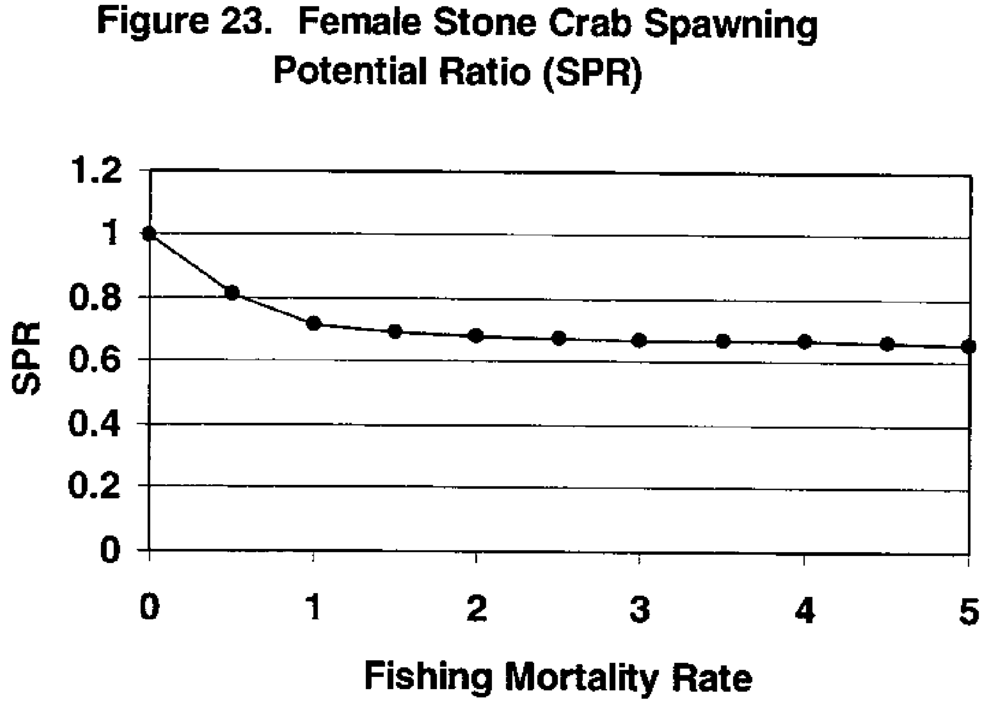
6.2.2. Stone Crab

Yield per recruit and spawning stock per recruit obtained for stone crab assuming no claw regeneration are presented in figures 22 and 23, respectively. The yield per recruit of females is much lower than those observed for males as the growth of female claws is largely bellow the minimum size imposed on the fishery, hence, recruitment to the fishery is very late in the life span of the female stone crab. The level of fishing mortality generating yield per recruit slightly below maximum levels is about 1.5 in females and 2.0 in males. The female spawning potential ratio becomes clearly asymptotic (Fig. 23) starting at a fishing mortality rate of 1.5. Therefore, the sexual dimorphism observed between the growth of males and females and the legal minimum claw size adopted in the fishery shield females from high levels of exploitation

**Figure 22. Stone Crab Yield-per-Recruit**



but makes the male stock fully vulnerable and the one actually sustaining the landings.




The fishing mortality rates at different stone crab trap benchmarks are given in Table 4. It can be observed that under the current condition (1998) of the fishery the fishing mortality rate is about 3.97, which represents a high level of fishing mortality given the natural mortality rate of the species (0.78). Because of the male-female differences in growth relative to the minimum legal size, this mortality rate fundamentally should impact the biological status of the male stock as it reduces its abundance to levels that may impact the reproductive dynamics of the species as a whole. It is also apparent from figure 22 that only a slightly lower yield per recruit may be obtained for males by reducing the fishing mortality rate to about 2.0, or a 98.5% reduction in fishing mortality rate. Similar conditions may be obtained in the female fraction of the stock. Regarding the impact of trap benchmark fishing mortality on the spawning potential ratio, we observe in Figure 23 that SPR is not significantly affected at fishing mortality levels above 1.0 as females are less affected by exploitation due to their smaller size relative to the legal size. Because of the later condition, the SPR is never reduced to levels below 60% of the pristine spawning abundance, therefore, exploitation does not appear to affect the reproductive potential of female stone crab stock.

Given the economic conditions of the fishery, the number of traps that generates MSY is higher than those that are necessary to break even in the open access condition. The fishing mortality corresponding to the trap benchmark at MSY appear to be biologically acceptable as yield per recruit is between 2.6 and 2.9 claw grams per recruit among females and 10.0 to 10.8 grams of claws per recruit among males. At this level of fishing mortality the SPR is reduced to about 68%. The fishing mortality rates generated by the break even condition under the two labor costs appears to be slightly less efficient from a biological stand point as yield per recruit between fishing mortality rates of 0.69 and 1.27 are about 7.3 and 9.5 grams of claws per recruit among males and 1.8 to 2.4 grams of claws per recruit among females (Fig. 22). The fishing mortality rates generated with trap benchmarks at the maximum economic yield appear to be biologically inefficient given that yield per recruit is low both in males and females at those fishing mortality levels and that SPR is over 80%, hence, securing a large spawning stock.

Table 4. Stone crab fishing mortality rates generated at different benchmarks, and considering long-run cost functions and two types of labor costs.

| Condition | Number of Traps @ Benchmark | Fishing Mortality Rate @ Benchmark |
|---|---|---|
| MSY | 891,000 | 1.52 |
| Open Access, Min. Wage | 815,792 | 1.27 |
| Open Access, Share | 589,449 | 0.69 |
| MEY, Min. Wage | 349,365 | 0.31 |
| MEY, Share | 263,966 | 0.21 |
| Current (1998) | 1,343,676 | 3.97 |

## 7. Conclusions

The Florida spiny lobster fishery is influenced by external sources of recruitment that appear to contribute to the sustainability of landings independently of the extremely high number of traps that were historically used to catch the species. The large number of traps used in the fishery occurs over a fairly restricted spatial distribution creating gear competition that impact gear efficiency as indicated by the historically very low catch per trap in spite of the no-trend in landings. Similarly, the stone crab fishery has greatly increased the number of traps to reach over 1.3 million in the last season for which data were available (1998) for the analyses, hence creating a similarly congested situation that has also lowered the trap catching efficiency in that fishery. The production models used in this report show that trap density is instrumental in shaping production trends and the relationship between landings and effort appears to be mostly indicative of the level of utilization of the seasonal available stock biomass by the fisheries. Consequently, fishing effort regulations appear to be less biologically meaningful but significant from economic and operational points of view. This is a result of improved catch rates at lower trap densities and the reduction of conflicts that may emerge when gear-congested fisheries are not regulated.

The spiny lobster trap reduction program implemented in 1992 has reduced the number of traps in the spiny lobster fishery to levels that correspond to those observed during a long period (1978-1986) prior to the consideration of the trap limited access. This number of traps also corresponds to the trap benchmarks of the break-even-point or open access conditions used in the bio-economic analyses. The fishing mortality rates generated by the break-even-point trap benchmarks are similar to those obtained in stock assessments carried out by Muller et al. (2000) for the 1999/2000 fishing season. These fishing mortality levels were found biologically adequate because about 40% of the spawning potential ratio is still present at those levels of mortality and the yield per recruit is not affected significantly by the reduction in effort to comply with the break-even-point condition. Hence, the trap reduction program may be seen as one that has improved the economic status of the fishery operations and has reduced conflicts derived from the excess of traps in the fishery. The spiny lobster bio-economic analyses show that further trap reductions will result in better economic conditions of the fishing operations but the analyses also suggest that a less efficient biological production will be observed in the fishery as a result. This later effect may have consequences at other levels of the industry as landings at MEY may impact supply for the highly demanded spiny lobster products.

The stone crab fishery shows a plateau in the level of effort at about 600,000 traps during the period 1986-1992. This level was similar to the 600,000-trap level observed in the spiny lobster fishery but during the period 1978-1986 – a trend that significantly changed after 1987 to reach close to 1 million traps in 1991. The impact of the 1992-spiny lobster trap reduction program on the stone crab fishery took place in a steady manner during the period following the 1992 stone crab fishing season. In effect, the combined number of spiny lobster and stone crab traps were at a strikingly similar level of about 1.4 million traps during the period 1987-1996 indicating effort migration between the two fisheries. On the other hand, the extraordinary increase in the number of traps used in the stone crab fishery during the last two years for which data were available to this study (1997 and 1998) may not be a response to the spiny lobster reduction program but rather due to a reaction to the potential condition of limiting the access of stone crab traps. Therefore, consequences of the great increase in traps in the stone crab fishery during the period 1993-1997 is seen as displaced effort from the lobster fishery that created an economic impact on the stone crab fishing operations while the 1997-1998 increase in effort may be identified with a speculative process very much similar to that observed in the 1987-1991 period in the spiny lobster fishery.

The results from the bio-economic analyses performed on the spiny lobster fishery justify the reduction in the number of traps used in that fishery. The operational time gains under the trap reduction in the spiny lobster fishery have created the opportunity for fishers to participate more intensively in the already saturated stone crab fishery. Hence, the trap reduction program has accommodated a better arrangement for the spiny lobster fishery but created the opportunity to use the displaced effort in other fisheries, more conspicuously in the stone crab fishery. Bio-economic analyses for the stone crab fishery indicate that a significant reduction in effort is required not only to improve the economic aspects of the fishing operations but more significantly, the reduction is very much required to stop any potential biological impact that such displacement of effort may be creating to the male stone crab stock fraction.

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*For Florida's 15.5 million residents and about 50 million annual visitors, the coast and its resources are a major attraction and an important part of their environment. Nowhere else in the United States are so many people so close to such an extensive and economically valuable coastline.*

*Working together, all Floridians must find a socially acceptable way to satisfy the demand for these resources while protecting their ecological integrities. Florida Sea Grant has a vital role to fill in this complex endeavor. Florida Sea Grant's mission is to enhance the practical use and conservation of coastal and marine resources to create a sustainable economy and environment. Now in its 30th year, Florida Sea Grant is the only statewide university-based coastal research, education, extension/outreach and communications program in Florida. One of 30 Sea Grant programs nationally, it is a partnership program among the National Oceanic and Atmospheric Administration, Florida's universities and Florida's citizens, businesses and governments.*

*Florida Sea Grant has a demonstrated record of success. Its program of research, education and extension earned a rating of "Excellent" from a federally mandated review by the National Sea Grant College Program in 2000. We invite you to read the 2002-2005 Florida Sea Grant College Program Strategic Plan and learn more about Sea Grant's contributions and its leadership role in helping Floridians to rationally manage continued growth in the coastal zone. The Strategic Plan is on the Florida Sea Grant web site at:*

*http://www.flseagrant.org.*

Sea Grant
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Science Serving Florida's Coast

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