Size-composition of Annual Landings in the White Shrimp, *Litopenaeus setiferus*, Fishery of the Northern Gulf of Mexico, 1960–2006: Its Trend and Relationships with Other Fishery-dependent Variables

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Introduction

Location and Importance of the Fishery

The white shrimp, *Litopenaeus setiferus*, fishery of the northern Gulf of Mexico is bounded by Shrimp Statistical Subareas 10–21 (Fig. 1), and encompasses inshore (estuarine) and offshore (Gulf of Mexico) territorial waters of Texas, Louisiana, Mississippi, Alabama, and northwestern Florida, and part of the adjoining U.S. Exclusive Economic Zone (EEZ). In 2006, landings from this fishery totaled 84.5 million pounds (38,300 t; "tails" only, the edible abdominal portion, with shells on), with an ex-vessel value of $185.2 million U.S. We use the term "landings" because recorded landings do not include all white shrimp caught within the boundaries of this fishery, because unknown portions of the catch are discarded or otherwise not reported (Kutkuhn, 1962; Rothschild and Brunenmeister, 1984; Neal and Maris, 1985; Poffenberger[1]).

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The Problem and Research Objectives

The historical overview of the U.S. Gulf of Mexico penaeid shrimp fishery by Condrey and Fuller (1992) showed that there was early concern about the potential for both growth overfishing and recruitment overfishing in the white shrimp fishery of the northern Gulf of Mexico. However, this concern seemed to wane with emergence of new fisheries for brown shrimp, *Farfantepenaeus aztecus*, and pink shrimp, *F. duorarum*, in the late 1940's. Thereafter, the potential for growth overfishing and its possible detrimental economical consequences appears to have been of no major concern to Federal or state shrimp management entities, and the focus of management turned to preventing recruitment overfishing.

In the context of surplus production theory, growth overfishing occurs when fishing effort is higher and sizes of individuals smaller than levels of effort and size that produce maximum sustainable yield (MSY) or maximum yield-per-recruit. Unlike recruitment overfishing, which can lead to collapse of a fishery, growth overfishing does not affect the ability of a population to replace itself (Gulland, 1974). However, increases in

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[1] Poffenberger, J. R. 1991. An overview of the data collection procedures for the shrimp fisheries in the Gulf of Mexico. Unpubl. rep. on file at the U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southeast Fish. Cent., Miami, Fla. See also Gulf Shrimp System (http://www.sefsc.noaa.gov/gssprogram.jsp).

ABSTRACT—The potential for growth overfishing in the white shrimp, Litopenaeus setiferus, *fishery of the northern Gulf of Mexico appears to have been of limited concern to Federal or state shrimp management entities, following the cataclysmic drop in white shrimp abundance in the 1940's. As expected from surplus production theory, a decrease in size of shrimp in the annual landings accompanies increasing fishing effort, and can eventually reduce the value of the landings. Growth overfishing can exacerbate such decline in value of the annual landings.*

We characterize trends in size-composition of annual landings and other annual fishery-dependent variables in this fishery to determine relationships between selected pairs of these variables and to determine whether growth overfishing occurred during 1960–2006. Signs of growth overfishing were equivocal. For example, as nominal fishing effort increased, the initially upward, decelerating trend in annual yield approached a local maximum in the 1980's. However, an accelerating upward trend in yield followed as effort continued to increase. Yield then reached its highest point in the time series in 2006, as nominal fishing effort declined due to exogenous factors outside the control of shrimp fishery managers. The quadratic relationship between annual yield and nominal fishing effort exhibited a local maximum of $5.24(10^7)$ pounds (≈ MSY) at a nominal fishing effort level of $1.38(10^5)$ days fished. However, annual yield showed a continuous increase with decrease in size of shrimp in the landings.

Annual inflation-adjusted ex-vessel value of the landings peaked in 1989, preceded by a peak in annual inflation-adjusted ex-vessel value per pound (i.e. price) in 1983. Changes in size composition of shrimp landings and their economic effects should be included among guidelines for future management of this white shrimp fishery.

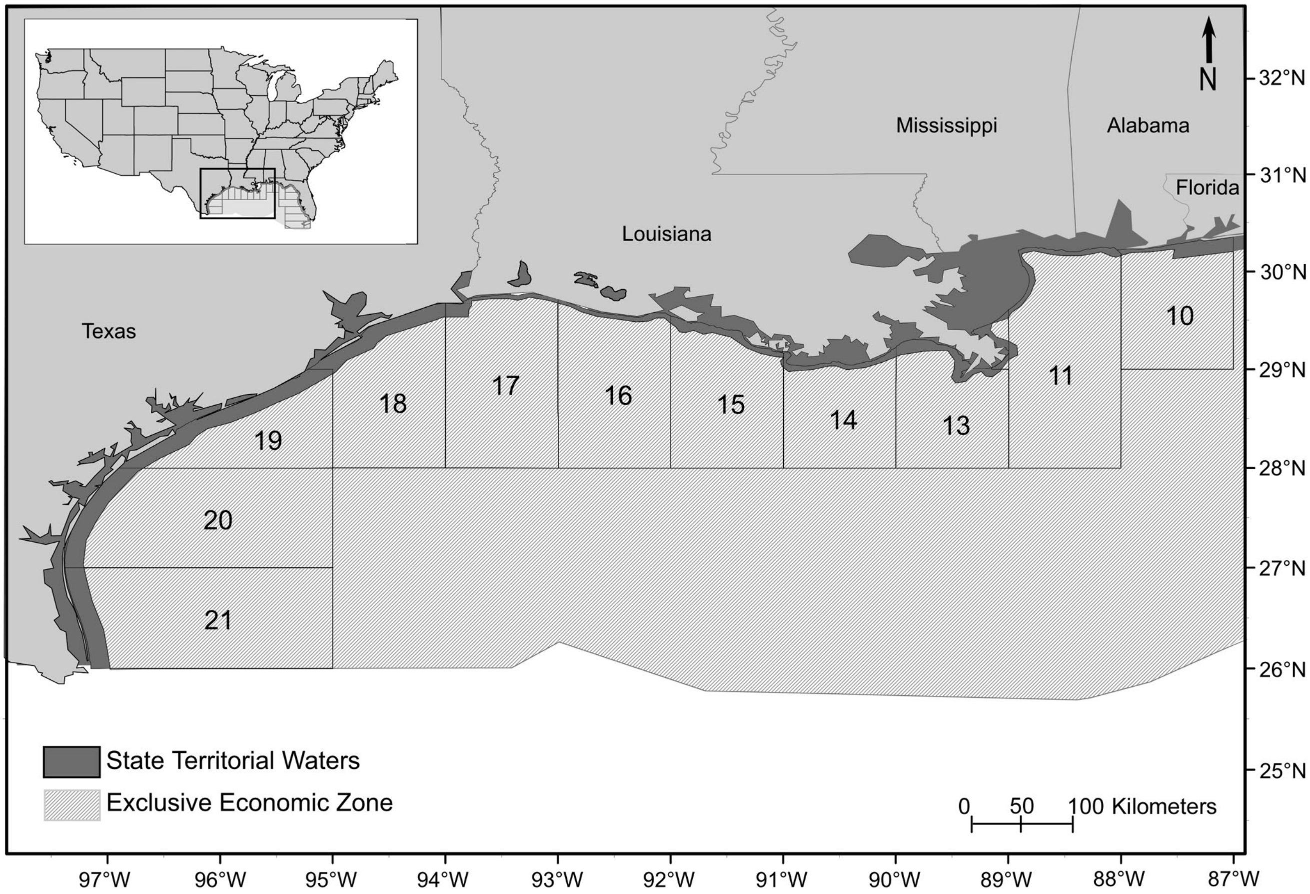

Figure 1.—The white shrimp fishery encompasses inshore (estuarine) and offshore state territorial waters and part of the adjoining Federal EEZ within shrimp statistical subareas 10–21 in the northern Gulf of Mexico. Source: NMFS Southeast Fisheries Science Center, Galveston Laboratory.

fishing effort, if large enough, can be accompanied by decreases in size of shrimp (various species) in the annual landings, which can eventually decrease the ex-vessel value (i.e. value to the fishermen or harvesting sector) of the landings (Kutkuhn, 1962; Caillouet and Patella, 1978; Caillouet et al., 1979, 1980a, 1980b, 2008; Caillouet and Koi, 1980, 1981a, 1981b, 1983; Neal and Maris, 1985; Onal et al., 1991; Condrey and Fuller, 1992; Nance et al., 1994). Growth overfishing can amplify these effects (Caillouet et al., 2008). Growth overfishing precedes recruitment overfishing, so it provides an early warning to managers to proceed with caution (Rothschild and Brunenmeister, 1984).

Our research objectives were to characterize trends in size-composition of annual landings and other annual fishery-dependent variables in the white shrimp fishery of the northern Gulf of Mexico during 1960–2006, to determine relationships between selected pairs of these variables, and to determine whether growth overfishing occurred. We applied the same analytical approach in this paper that we (Caillouet et al., 2008) used to detect growth overfishing in the brown shrimp fishery of Texas, Louisiana, and the adjoining EEZ.

As background, we present summaries of the white shrimp fishery, the white shrimp life cycle, and the multi-jurisdictional, compartmentalized approach that has been used to manage the fishery. White shrimp fishery-dependent data are voluminous and complex, and they have several shortcomings (Kutkuhn, 1962; Rothschild and Brunenmeister, 1984; Neal and Maris, 1985; Poffenberger[1]) that affect not only our results, but also those of all previous stock assessments based on them. We anticipated that some readers would not be familiar with these peculiarities of white shrimp landings and fishing effort data or with our analytical approach (Caillouet et al., 2008), so we have provided detailed descriptions and explanations.

Life Cycle and Population Characteristics

Kutkuhn (1962), Muncy (1984), and Neal and Maris (1985) detailed the white shrimp life cycle and population characteristics. White shrimp are short-lived, have high fecundity, have the potential to spawn more than once within a year, and produce annual crops. Females mature and spawn in the Gulf of Mexico, usually at depths of 10–15 fm, where eggs hatch and larval development occurs. White shrimp enter coastal estuaries as post larvae and grow to subadult stages before emigrating seaward. Harvest of each new annual crop begins with juveniles and subadults inshore and continues offshore through the adult life stage. A relatively small number of spawners can produce a large year-class under favorable environmental conditions. Environmentally influenced variations in year-class strength produce variations in recruitment, which in turn produce variations in annual landings. These population characteristics led to the belief that high fishing mortality could be tolerated, and in many situations recruitment overfishing was not a major concern, even when fishing pressure was high (Neal and Moris, 1985).

Management of the Fishery

White shrimp management jurisdiction[2] is shared by the Gulf of Mexico Fishery Management Council (GMFMC), Texas Parks and Wildlife Department (TPWD), Louisiana Department of Wildlife and Fisheries (LDWF), Mississippi Department of Marine Resources (MDMR), Alabama Department of Conservation and Natural Resources (ADCNR), and the Florida Fish and Wildlife Conservation Commission (FFWCC). Multi-species shrimp fishery management plans[2] (FMP) were established by the GMFMC in 1981, by TPWD in 1989, and by LDWF in 1992. MDMR, ADCNR, and FFWCC have no formal shrimp FMP's, but they have shrimping rules and regulations. All of these management plans, rules, and regulations take into account that shrimp crops vary annually. For the most part, management[2] has involved control of the size and other characteristics of shrimp fishing units and gear, setting minimum legal sizes of shrimp, and establishing temporal-spatial closures to shrimping, to allow small shrimp to grow to larger, more valuable sizes before harvest.

We offer five explanations why there apparently was no major concern on the part of Federal or state shrimp management entities about the potential for growth overfishing and its possible detrimental economical consequences, but instead the focus of management turned to preventing recruitment overfishing:

1) Emergence of new fisheries for brown shrimp and pink shrimp in the late 1940's following the cataclysmic drop in white shrimp abundance (Condrey and Fuller, 1992),
2) "Conventional wisdom" that penaeid shrimp stocks can withstand increasingly high levels of fishing effort without substantial biological or economic risk (Neal and Maris, 1985),
3) Wide variations in annual landings of penaeid shrimp resulting from environmentally influenced variations in year-class strength (Neal and Maris, 1985), which may have obscured the effects of fishing (Caillouet et al., 2008),
4) Competition between inshore and offshore components of the harvesting sector for shares of each annual crop (Caillouet et al., 2008), and
5) Compartmentalization of shrimp fisheries management jurisdiction[2] among the GMFMC, TPWD, LDWF, MDMR, ADCNR, and FFWCC (Caillouet et al., 2008).

White shrimp management has focused on preventing recruitment overfishing. The GMFMC's shrimp FMP[2] defined maximum sustainable yield (MSY) and optimum yield (OY) as "all the shrimp that can be taken during open seasons in permissible areas in a given fishing year with existing gear and technology without resulting in recruitment overfishing." The 2006 report[3] on the status of U.S. fisheries concluded that Gulf of Mexico white shrimp are not recruitment overfished. However, while Neal and Maris (1985) recognized that penaeid fisheries have generally remained productive despite intensive exploitation, they cited Neal (1975) in stating, "A possible exception to this pattern is the Louisiana population of *P. setiferus* [*L. setiferus*], for which spawning stocks have apparently been reduced sufficiently to reduce harvest over a 20-year period." Rothschild and Brunenmeister (1984) concluded "an increase in effort would be of limited economic value to the fishermen and could result in an increased risk of population collapse or in sustained reduction in the production of the population." Gracia (1996) showed that recruitment overfishing occurred in a white shrimp fishery in the southern Gulf of Mexico.

Although economic problems in U.S. shrimp fisheries of the Gulf of Mexico are not new (Kutkuhn, 1962), they have worsened in recent years[4] (Keithly and Roberts, 2000; Haby et al., 2002a; Diop et al., 2006). In 2000, TPWD[5] determined that shrimp (multiple species) stocks in Texas bays were growth overfished, and in 2001 TPWD imposed additional regulations aimed at reducing the size of the inshore fleet, reducing growth overfishing, and avoiding recruitment overfishing. However, Haby et al. (2002b) predicted that these additional regulations would have relatively minor impacts on yield and ex-vessel value across the shrimping industry in Texas.

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[2] Shrimp FMP's include 1) The Fishery Management Plan for the shrimp fishery of the Gulf of Mexico, United States Waters. Gulf Mex. Fish. Manage. Counc., Tampa, Fla., Nov. 1981 (http://www.gulfcouncil.org), 2) The Texas shrimp fishery, a report to the Governor and the 77th Legislature of Texas, Executive Summary and Appendices A–H, Sept., 2002. (http://www.tpwd.state.tx.us/publications/pwdpubs/media/pwd_rp_v3400_857.pdf), and 3) A Fisheries Management Plan for Louisiana's penaeid shrimp fishery, Louisiana Dep. Wildl. Fish., Baton Rouge, La., Dec. 1992. Mississippi, Alabama, and Florida do not have formal FMP's, but they have various shrimping rules and regulations in lieu of FMP's.

[3] NMFS Report on the status of the U.S. fisheries for 2006 (http://www.nmfs.noaa.gov/sfa/domes_fish/StatusoFisheries/2006/2006RTCFinal_Report.pdf).

[4] Report to Congress on the impacts of Hurricanes Katrina, Rita, and Wilma on Alabama, Louisiana, Florida, Mississippi, and Texas fisheries, July 2007, U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Silver Spring, Md. (http://www.nmfs.noaa.gov/msa2007/docs/HurricaneImpactsHabitat_080707_1200.pdf).

[5] Texas shrimp fishery briefing book, April 2000, Tex. Parks Wildl. Dep., Austin, Tex., 82 p.

In April 2005, the GMFMC[6,7] acknowledged that the U.S. shrimping industry in the northern Gulf of Mexico EEZ was experiencing serious economic problems, attributing them to increased fuel costs and competition from imported shrimp. A 2007 report to the U.S. Congress[4] concluded that hurricanes Katrina (August, 2005), Rita (September, 2005), and Wilma (October, 2005) accelerated the regional decline in shrimp fishery participation and production, said to have begun in 2001. This report attributed the regional decline to high fuel costs, poor market prices for domestic shrimp, fishery overcapitalization, rising insurance costs, and the erosion and conversion of waterfront property in some areas from fishing industry use to tourism-based and alternative uses.

Interestingly, although these hurricanes caused substantial damage and loss to the harvesting and processing sectors of the shrimp industry, thereby further reducing fleet size and fishing effort, they apparently had no detrimental impacts on Gulf shrimp stocks.[4] Finally, a temporary moratorium on fleet size in the EEZ, proposed in 2005 by the GMFMC[6, 7], was approved by the U.S. Secretary of Commerce in September 2006.

Materials and Methods

Using the analytical approach of Caillouet et al. (2008), we examined white shrimp fishery-dependent variables over calendar years 1960–2006 (Table 1). Although this analytical approach has evolved and improved through numerous previous papers (e.g. Caillouet and Patella, 1978; Caillouet et al., 1979, 1980a, 1980b, 2008; Caillouet and Koi, 1980, 1981a, 1981b, 1983), it still requires careful reading for a clear understanding. Because we applied the approach to 47 years of annual summaries of voluminous quantities of white shrimp landings and fishing effort data, it is statistically and analytically intensive.

Table 1.—Descriptions, symbols, and units of measure for fishery-dependent variables in the white shrimp fishery of the northern Gulf of Mexico, 1960–2006.

Variable	Symbol	Units of measure
Calendar year	T	1960, 1961, … , 2006
Annual index of cumulative percentage of pounds landed by count category	b	
Annual index of cumulative percentage of nominal ex-vessel value of landings by count category	d	
Difference between annual indices b and d	D	b–d
Annual yield	W	pounds, heads-off
Annual nominal fishing effort	E	24-hour days fished
Annual average yield per unit effort	$WPUE$	pounds, heads-off
Annual inflation-adjusted ex-vessel[1] value of landings	V	$\$US_{2006}$, heads-off
Average average inflation-adjusted ex-vessel value per pound	VPP	$\$US_{2006}$, heads-off
Coded calendar year	T_{Coded}	T – mean T, where mean $T = 1983$
Coded annual index of cumulative percentage of pounds landed by count category	b_{Coded}	b – mean b, where mean $b = -0.0246$
Coded annual index of cumulative percentage of nominal ex-vessel value of landings by count category	E_{Coded}	E – mean E, where mean $E = 99{,}716$ days fished

[1]The value to the fishermen or harvesting sector of the fishery.

Our approach involved a search for best-fitting polynomial regressions representing trends in annual fishery-dependent variables (Table 1) and relationships between selected pairs of these variables. When significant trends or relationships were detected, we examined them for linearity and curvilinearity. When significant curvilinearity occurred, we examined the curve for local maxima and local minima.

White shrimp fishery landings and fishing effort, by shrimping trip, are archived by the NMFS Southeast Fisheries Science Center's Galveston Laboratory (see Kutkuhn, 1962; Poffenberger[1]). For each calendar year T, summaries of these data over all trips within the fishery produced the fishery-dependent variables (Table 1) we examined. Such summaries aggregated and integrated all within-year temporal-spatial effects of shrimp gender, recruitment, mortality, and growth, as well as fishing effort, gear selectivity, effects of discarding, etc. on the landings and fishing effort data.

Annual Index *b* of Size Composition of Landings

Most of the archived landings of white shrimp have been graded into marketing categories referred to as count categories, which (statistically) are count class intervals or bins (Kutkuhn, 1962; Poffenberger[1]). In this paper, white shrimp count is the number of shrimp tails per pound. Count categories have been determined mostly by factors influencing the marketing of shrimp of various sizes rather than by their potential use in shrimp stock assessments. We emphasize that white shrimp landings apportioned among count categories are not weight-frequency distributions of shrimp tails in the landings. However, count-graded landings obviously reflect weight-frequency distributions of white shrimp tails. We emphasize that the annual summaries of count-graded landings aggregated and integrated all within-year temporal-spatial effects of shrimp gender, recruitment, mortality, and growth, as well as fishing effort, gear selectivity, effects of discarding, etc. that affected white shrimp landings by count category.

In the absence of a statistically sufficient time series of annual weight-frequency distributions of white shrimp tails in the landings, we used an annual index (b), described by Caillouet et al. (2008), to examine changes in size composition of white shrimp annual landings. Use of index b reduces voluminous annual landings by count category into a single, simple, statistical surrogate for annual size composition of white shrimp landings, based on summaries of count-graded landings.

The eight standard count categories used in this study were: <15, 15–20,

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[6]Final draft amendment number 13 to the Fishery Management Plan for the shrimp fishery of the Gulf of Mexico, U.S. waters with environmental assessment regulatory impact review, and Regulatory Flexibility Act analysis. April 2005. Gulf Mex. Fish. Manage. Counc., Tampa, Fla., and Natl. Mar. Fish. Serv., Southeast Reg. Off., St. Petersburg, Fla.

[7]Minutes of the Gulf of Mexico Fishery Management Council 200th Meeting, Palace Hotel, Biloxi, Miss., May 11–12, 2005. Gulf Mex. Fish. Manage. Counc., Tampa, Fla.

21–25, 26–30, 31–40, 41–50, 51–67, and >67 count. The archived landings data include two additional non-numerical categories, “pieces” (broken tails) and “unknown” (landings recorded without count class intervals). For each year, we assumed that the actual shrimp size composition of annual pounds in the “pieces” and “unknown” categories was the same, proportionately, as that of count-graded pounds apportioned among the eight standard categories. We could not test this assumption, but annual count-graded poundage constituted 97.9–100.0% of the annual yield (*W*) over the time series. We considered such large samples to be representative of the size composition of *W*, which is the annual sum of count-graded landings and landings of “pieces” and “unknown” categories.

For each year, we cumulated the count-apportioned annual pounds landed, using as count class markers the lower limits, C_i, of the count categories. To cumulate the count-apportioned pounds over small to large shrimp, we began the cumulation with the category of highest count shrimp (i.e. >67 count, representing the smallest shrimp) and continued through the category of lowest count (i.e. <15 count, representing the largest shrimp). We then converted the annual cumulative pounds of count-graded landings to percentages of pounds landed, P'_i, to relate it to C_i (Fig. 2A is an example, for the year 2006). Note that P'_i decreases in stair-step fashion, from its maximum of 100% toward its minimum, as C_i increases (Fig. 2A). The exponential model (Caillouet et al., 2008) underlying estimation of *b* is

$$P'_i = ae^{bC_i} \qquad (1)$$

where b is the annual index,
P'_i is the annual cumulative percentage of pounds landed within the standard count category with i^{th} lower limit,
C_i is the i^{th} lower limit (15, 21, 26, 31, 41, 51, and 68) of seven (i = 1, 2, … 7) of the eight standard count categories, respectively,
a is an empirical constant, and
e is the natural logarithm base.

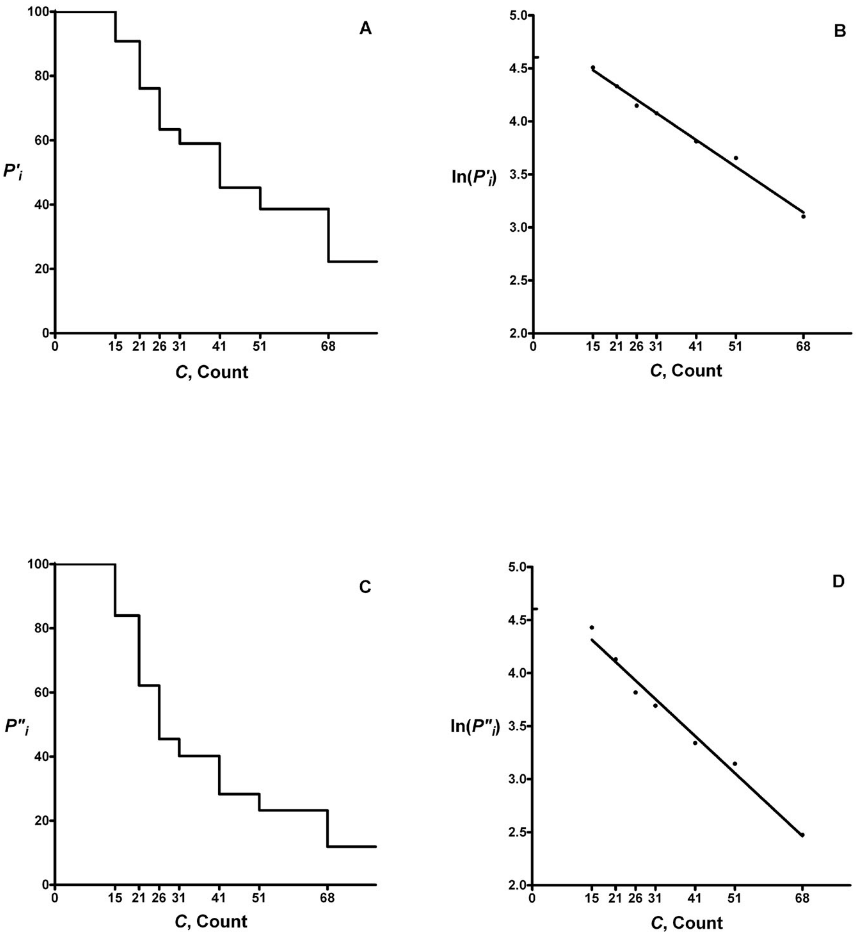

Figure 2.—Year 2006 example relationships between P'_i and C_i, ln(P'_i) and C_i, P''_i and C_i, and ln(P''_i) and C_i, in the white shrimp fishery of the northern Gulf of Mexico (see Eq. (2) and (4), Tables 2 and 3). Values for C_i are depicted by tick marks on the abscissa scale for count, *C*.

A natural logarithmic transformation of Eq. (1) linearized it to

$$\ln(P'_i) = \ln(a) + bC_i \qquad (2)$$

Slope *b* of Eq. (2) was estimated by linear regression. Note that data for the <15 count category were excluded from the estimation of *b*; i.e. a data point for ln(P'_0) was not included in the linear regression (Eq. (2)), to be consistent with (Caillouet et al., 2008), and because the percentage of pounds in the <15 count category was disproportionately low (0.2–9.2%) over all years. Therefore, when P'_0 = 100 is plotted in ln-transformed scale, ln(100), it does not follow the linear regression (Eq. (2)) based on the other seven count categories (Fig. 2B). For the year 2006 (which had the highest *W*), examples of P'_i and the linear regression (Eq. (2)) are shown in Fig. 2A and 2B, respectively. A right-facing tick mark on the ordinate of Fig. 2B marks the data point for ln(P'_0), which we included in the graph only for visual comparison with data points of the other seven ln(P'_i).

Annual index *b* has only negative values (Eq. (2), Table 2, Fig. 2B). An increase in *b* indicates a decrease in size of shrimp in the landings, and a decrease in *b* indicates an increase in size of shrimp in the landings. This peculiarity of *b* can be confusing, but it becomes understandable when one considers that count is the reciprocal of pounds per shrimp tail. For purposes of our analyses, we believe that *b* substantially represents the annual distribution of weight of all landings among the count categories, because it is based on 90.8–99.8% of *W* over all years. Although these percentages exclude landings in the <15 count, "pieces," and "unknown" categories, they still represent very large samples. Index *b* is useful for examining trends in size composition of white shrimp landings, as well as relationships between *b* and other fishery-dependent variables. It is noteworthy, though not essential to our paper, that the empirical constant, ln(a), also estimated in fitting Eq. (2), was very closely correlated with *b*; adjusted $r^2 = 0.865$ for the regression, $\ln(a) = 4.471 - 20.13b$, based on the 47-year series.

Annual Index *d* of Nominal Ex-vessel Value Composition of Landings

We calculated annual index *d* (Table 3) of the cumulative percentage of nominal ex-vessel value of landings by count category in a manner similar to that used to calculate annual index *b*. In comparing *d* to *b*, it is important to recognize and understand that both *b* and *d* are based on the annual distribution of pounds landed among count categories. However, *d* differs from *b* in that it also incorporates differences in nominal ex-vessel value per pound (i.e. price) among the count categories. We did not adjust nominal ex-vessel value among count categories for inflation, assuming that within-year inflation was negligible as compared to year-to-year inflation. Within-year inflation effects were aggregated and integrated by annual summations of nominal ex-vessel value by count category over all trips within a year. In addition, these summations also aggregated and integrated all within-year temporal-spatial effects of shrimp gender, recruitment, mortality, and growth, as well as fishing effort, gear selectivity, effects of discarding, etc. that affected white shrimp landings and their shrimp size composition, as well as nominal ex-vessel value per pound. The data point for the <15 count category was excluded from the estimation of *d* for the same reasons it was excluded from the estimation of *b*.

Table 2.—Annual index, *b*, of cumulative percentage of pounds landed by count category, in the white shrimp fishery of the northern Gulf of Mexico, 1960–2006.[1]

Year, *T*	*b*	ln(*a*)	r^2	*F*
1960	–0.0520	5.586	0.970	197.52
1961	–0.0381	5.241	0.993	829.56
1962	–0.0270	5.095	0.980	289.92
1963	–0.0351	5.281	0.971	201.59
1964	–0.0372	5.191	0.998	3,109.37
1965	–0.0264	4.959	0.999	6,026.31
1966	–0.0278	5.036	0.974	224.45
1967	–0.0326	5.004	0.992	739.09
1968	–0.0285	5.037	0.995	1,151.23
1969	–0.0282	5.038	0.996	1,373.97
1970	–0.0292	4.988	0.986	419.00
1971	–0.0271	4.990	0.996	1,659.31
1972	–0.0241	4.912	0.990	603.79
1973	–0.0222	4.961	0.997	878.34
1974	–0.0216	4.829	0.977	261.30
1975	–0.0197	4.830	0.976	249.35
1976	–0.0246	4.929	0.985	387.84
1977	–0.0223	4.934	0.990	605.22
1978	–0.0239	4.934	0.985	405.23
1979	–0.0264	4.967	0.989	562.72
1980	–0.0186	4.875	0.993	878.61
1981	–0.0240	4.934	0.982	336.66
1982	–0.0187	4.884	0.995	1,206.45
1983	–0.0234	4.982	0.995	1,327.60
1984	–0.0284	5.084	0.992	756.33
1985	–0.0238	4.985	0.989	527.75
1986	–0.0228	4.968	0.993	801.31
1987	–0.0233	4.987	0.992	725.95
1988	–0.0222	5.019	0.965	166.86
1989	–0.0177	4.851	0.994	939.87
1990	–0.0232	4.949	0.990	589.24
1991	–0.0195	4.834	0.993	795.58
1992	–0.0189	4.902	0.982	333.60
1993	–0.0202	4.899	0.989	520.73
1994	–0.0163	4.848	0.976	248.64
1995	–0.0233	4.937	0.995	1,127.82
1996	–0.0249	4.988	0.994	957.10
1997	–0.0188	4.888	0.977	252.57
1998	–0.0233	4.930	0.998	2,719.78
1999	–0.0173	4.809	0.989	551.74
2000	–0.0195	4.886	0.990	612.47
2001	–0.0190	4.843	0.992	770.10
2002	–0.0222	4.862	0.986	434.15
2003	–0.0203	4.865	0.991	682.91
2004	–0.0218	4.896	0.990	618.78
2005	–0.0257	4.901	0.990	578.37
2006	–0.0253	4.864	0.989	542.14

[1] The intercept ln(*a*), adjusted coefficient of determination r^2, and ANOVA *F* are also shown for each linear regression (see Eq. (2)). All regressions were significant at $p < 0.001$.

Table 3.—Annual index, *d*, of cumulative percentage of nominal ex-vessel value of landings by count category, in the white shrimp fishery of the northern Gulf of Mexico, 1960–2006.[1]

Year, *T*	*b*	ln(*a*)	r^2	*F*
1960	–0.0637	5.742	0.986	419.62
1961	–0.0473	5.369	0.997	1,773.09
1962	–0.0377	5.251	0.993	817.04
1963	–0.0520	5.545	0.988	481.82
1964	–0.0494	5.332	0.997	2,126.04
1965	–0.0376	5.061	0.996	1,694.68
1966	–0.0378	5.144	0.988	498.30
1967	–0.0473	5.134	0.984	373.16
1968	–0.0431	5.197	0.992	765.36
1969	–0.0439	5.253	0.992	762.11
1970	–0.0473	5.199	0.979	279.32
1971	–0.0480	5.259	0.995	1,318.78
1972	–0.0399	5.080	0.982	337.08
1973	–0.0340	5.136	0.993	830.85
1974	–0.0370	4.904	0.980	122.73
1975	–0.0377	5.041	0.967	179.28
1976	–0.0440	5.156	0.976	243.58
1977	–0.0383	5.120	0.980	289.77
1978	–0.0422	5.176	0.980	291.02
1979	–0.0446	5.208	0.984	379.06
1980	–0.0300	5.017	0.988	511.46
1981	–0.0394	5.092	0.970	194.13
1982	–0.0313	5.050	0.990	613.98
1983	–0.0378	5.186	0.997	1,765.12
1984	–0.0446	5.280	0.995	1,129.22
1985	–0.0380	5.142	0.997	1,857.93
1986	–0.0405	5.215	0.997	1,775.80
1987	–0.0342	5.073	0.994	988.13
1988	–0.0329	5.111	0.994	1,074.74
1989	–0.0296	4.920	0.993	905.10
1990	–0.0344	5.043	0.992	744.47
1991	–0.0303	4.878	0.983	342.22
1992	–0.0274	4.950	0.995	1,241.45
1993	–0.0336	5.010	0.995	1,296.70
1994	–0.0262	4.949	0.984	361.46
1995	–0.0349	4.995	0.994	932.20
1996	–0.0381	5.090	0.997	1,999.49
1997	–0.0317	5.018	0.990	586.76
1998	–0.0379	5.017	0.990	589.72
1999	–0.0284	4.828	0.988	514.08
2000	–0.0302	4.959	0.995	1,120.85
2001	–0.0302	4.870	0.982	327.28
2002	–0.0332	4.870	0.979	287.51
2003	–0.0347	4.947	0.981	314.14
2004	–0.0348	4.944	0.986	424.35
2005	–0.0346	4.889	0.989	528.38
2006	–0.0349	4.838	0.980	294.72

[1] The intercept ln(*c*), adjusted coefficient of determination r^2, and ANOVA *F* are also shown for each linear regression (see Eq. (4)). All regressions were significant at $p < 0.001$.

The exponential model underlying estimation of *d* is

$$P''_i = ce^{dC_i} \tag{3}$$

where d is the annual index,
P''_i is the annual cumulative percentage of nominal ex-vessel value of landings within the count category with i^{th} lower limit,
C_i is the i^{th} lower limit (15, 21, 26, 31, 41, 51, and 68) of seven ($i = 1, 2, \ldots 7$) of the eight standard count categories, respectively,
c is an empirical constant, and
e is the natural logarithm base.

A natural logarithmic transformation of Eq. (3) linearized it to

$$\ln(P''_i) = \ln(c) + dC_i \tag{4}$$

Examples of cumulative percentages P''_i and the linear regression (Eq. (4))

in 2006 are shown in Fig. 2C and 2D, respectively. A right facing tick mark on the ordinate of Fig. 2D marks the data point for $\ln(P''_0)$, which was included in the graph only for visual comparison with data points of the other seven $\ln(P''_i)$.

Like index *b*, slope *d* has only negative values (Table 3). An increase in *d* indicates a shift in the distribution of nominal ex-vessel of landings among count categories toward smaller shrimp, and a decrease in *d* indicates a shift toward larger shrimp. As with ln(*a*) vs. *b*, the empirical constant ln(*c*), estimated in fitting Eq. 4, was closely correlated with *d*. Adjusted $r^2 = 0.766$ for the regression, $\ln(c) = 4.277 - 21.53d$, for the 47-year series.

Additional fishery-dependent variables

We calculated the difference, *D*, between each year's pair of annual indices *b* (Table 2) and *d* (Table 3), as $D = b - d$, so that *D* had only positive values. *D* is an annual index of differences in nominal ex-vessel value per pound among the seven count categories used in estimating *b* and *d*. An increase in *D* indicates a widening of differences in nominal ex-vessel value per pound among count categories, and a decrease in *D* indicates a narrowing.

The concepts surrounding development and use of indices *b*, *d*, and *D* are not new. What is new, beginning with Caillouet et al. (2008), is the application of index *b* in attempts to detect growth overfishing in shrimp fisheries, and the application of indices *d* and *D* in assessing some of the economic implications of decreases in size of shrimp caused by increasing fishing effort. Also new is our examination of a longer time series of white shrimp landings and fishing effort data than ever before examined in the state and Federal waters of the northern Gulf of Mexico. Indices similar to *b* and *d* were developed and used over 3 decades to examine trends in U.S. shrimp fisheries in the Gulf of Mexico and along the U.S. southeastern coast (see papers by Caillouet and others in the Literature Cited).

Annual yield (*W*) was obtained by summing pounds landed from all trips in each year, including count-graded pounds and pounds in the "pieces" and "unknown" categories. Annual nominal ex-vessel value of landings was obtained by summing the nominal ex-vessel value of landings from all trips in each year, including count-graded, "pieces," and "unknown" categories. These annual totals for nominal ex-vessel value were then converted to annual, inflation-adjusted ex-vessel value (*V*) in $\$US_{2006}$, using the annual producer price index (PPI_T).[8] To make this conversion, we divided each year's annual nominal ex-vessel value by the fraction PPI_T/PPI_{2006}. Annual average inflation-adjusted ex-vessel value per pound of landings (*VPP*) was calculated as $VPP = V/W$.

The estimation of nominal fishing effort (*E*) included only the shrimping effort determined to have targeted white shrimp, since other shrimp species can be caught along with white shrimp. We used the method described by Nance (1992) to select effort targeting white shrimp from the available trip effort data. Kutkuhn (1962) and Gallaway et al. (2003) described the standard method used historically by NMFS to estimate *E* based upon trips within temporal-spatial cells, as well as statistical problems associated with this method. This standard method involves dividing total landings in a temporal-spatial cell (obtained through censuses of onshore shrimp dealerships where fishermen offload their landings) by estimated landings per unit effort (obtained from interviews of fishermen from a sample of trips) from the same temporal-spatial cell. The improved estimation procedure using electronic logbook data (Gallaway et al., 2003) was not used in sample projections in this paper.

Nominal fishing effort (*E*) was calculated as the annual sum of all the individual effort estimates for white shrimp-targeted trips, over all temporal-spatial cells, and represented the best available effort data for the 1960–2006 time series (since the electronic logbook method was not applicable to all years in this entire time series). However, Kutkuhn (1962) stated, "high correspondence between curves of effort and yield generally reflects the techniques used to estimate the former from the latter," which suggests that estimates of *E* may not be completely independent (statistically) of *W*. Kutkuhn (1962) remarked further that "Effort data … [are] biased to varying degree in direction and magnitude because of suspect sample projection techniques." Gallaway et al. (2003) developed a new electronic logbook method for estimating shrimp fishing effort that may solve this problem for the future. We derived annual average pounds of white shrimp landed per unit effort (*WPUE*) as $WPUE = W/E$.

It is noteworthy that variables *b*, *d*, *D*, *W*, *V*, and *VPP* are not affected by the historically standard method used by NMFS to estimate *E*. However, variables *E* and *WPUE*, as well as their trends and relationship with other fishery-dependent variables, are affected by this method of estimating *E*.

Examination of Fishery-dependent Variables

Statistical applications including Excel[9] (Microsoft Corp.), Analyse-it (Analyse-it Software Ltd.), SAS/STAT (SAS Institute Inc.), and Prism 5 (GraphPad Software) were used to fit polynomial regressions (first through sixth order) to each data pair (Table 4). Sokal and Rohlf (2000) suggested coding independent variables in polynomial regressions to reduce potential correlations between their odd and even powers to zero. We coded our independent (abscissa) variables (Table 1) by subtracting the arithmetic mean of each independent variable from its annual values, as recommended by Sokal and Rohlf (2000).

We examined ANOVA results for each regression, and plots of variances of residuals (deviations from regression) vs. the highest polynomial order of each regression. For each set of

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[8] U.S. Department of Labor, Bureau of Labor Statistics (http://data.bls.gov/cgi-bin/surveymost). These annual PPI data were originally expressed in $\$US_{1982}$, but we converted them to $\$US_{2006}$.

[9] Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Table 4.—Best-fitting polynomial regressions for trends (over calendar years, *T*) in fishery-dependent variables (see Table 1), and for relationships between selected pairs of fishery-dependent variables, in the white shrimp fishery of the northern Gulf of Mexico, 1960–2006.[1]

Regression	Polynomial term	Coefficient	r^2	F	p
b on T_{Coded}	intercept	$-2.1159878(10^{-2})$	0.634	40.87	<0.0001
	linear	$2.9780296(10^{-4})$			
	quadratic	$-1.8719440(10^{-5})$			
d on T_{Coded}	intercept	$-3.5882545(10^{-2})$	0.532	27.17	<0.0001
	linear	$3.7149630(10^{-4})$			
	quadratic	$-1.1577290(10^{-5})$			
D on T_{Coded}	intercept	$1.4714445(10^{-2})$	0.373	10.13	<0.0001
	linear	$-2.7541076(10^{-4})$			
	quadratic	$-7.0974690(10^{-6})$			
	cubic	$6.0844002(10^{-7})$			
W on T_{Coded}	intercept	$4.2671053(10^{7})$	0.567	21.12	<0.0001
	linear	$1.7344303(10^{5})$			
	quadratic	$8.1771116(10^{3})$			
	cubic	$1.7194573(10^{3})$			
E on T_{Coded}	intercept	$1.1577685(10^{5})$	0.606	36.41	<0.0001
	linear	$1.4244971(10^{3})$			
	quadratic	$-8.7286204(10^{1})$			
$WPUE$ on T_{Coded}	intercept	$3.6939310(10^{2})$	0.399	11.16	<0.0001
	linear	-5.9687001			
	quadratic	$4.9460871(10^{-1})$			
	cubic	$2.0917540(10^{-2})$			
V on T_{Coded}	intercept	$2.2289398(10^{8})$	0.581	32.84	<0.0001
	linear	$2.6369369(10^{6})$			
	quadratic	$-2.1009322(10^{5})$			
VPP on T_{Coded}	intercept	5.1752209	0.627	39.66	<0.0001
	linear	$4.0419750(10^{-3})$			
	quadratic	$-5.2122318(10^{-3})$			
d on b_{Coded}	intercept	$-3.8008315(10^{-2})$	0.823	214.35	<0.0001
	linear	1.0458616			
W on b_{Coded}	intercept	$4.4178846(10^{7})$	0.097	5.96	0.0186
	linear	$7.5318754(10^{8})$			
V on b_{Coded}	intercept	$1.8426049(10^{8})$	0.281	19.02	<0.0001
	linear	$5.5601369(10^{9})$			
b on E_{Coded}	intercept	$-2.2994975(10^{-2})$	0.559	30.16	<0.0001
	linear	$1.5534596(10^{-7})$			
	quadratic	$-1.7312336(10^{-12})$			
W on E_{Coded}	intercept	$4.7348641(10^{7})$	0.333	12.49	<0.0001
	linear	$2.6275191(10^{2})$			
	quadratic	$-3.4134535(10^{-3})$			
V on E_{Coded}	intercept	$2.0110527(10^{8})$	0.563	30.62	<0.0001
	linear	$1.5823372(10^{3})$			
	quadratic	$-1.8146748(10^{-2})$			

[1] The adjusted coefficient of determination r^2, ANOVA F, and probability p are also shown for each regression. The independent variable in each regression was coded by subtracting its arithmetic mean from each of its values; mean T = 1983, mean $b = -0.0246$, and mean E = 99,716 days fished. However, trends and relationships in Fig. 3–6 are plotted in the original scale of each independent variable.

paired data, we accepted as best fitting the lowest order polynomial regression that minimized the variance of residuals (deviations from regression), as judged from plots of ANOVA mean squares of residuals vs. order of polynomial, and from paired comparisons (using Prism 5) between sequential polynomial regressions at $p \leq 0.01$.

In some borderline cases, we chose as best fitting the lowest order model that came close to meeting the $p \leq 0.01$ criterion; i.e. when p only slightly exceeded 0.01. An adjusted r^2, overall ANOVA F, and p were reported for each best fitting regression model. When a curve gave the best fit to a trend or relationship, we determined its first derivative to detect local maxima and local minima, if any, using a program written in MathCad 13 (Parametric Technology Corp.). Local maxima, local minima, and the levels of the independent variable at which they occurred were also estimated using this program (Table 5).

Results

All estimates of b and d differed significantly from zero at $p < 0.001$, and the linear regressions from which they were derived had high ANOVA F and adjusted r^2, indicating very close fits of Eq. (2) and Eq. (4), respectively (Tables 2 and 3, Fig. 2B and 2D). In other words, the linear models from which b and d were estimated were very close fitting. We recognize that the P'_i are serially correlated, and so are the P''_i, in their respective estimations of b and d. However, we liken our statistical treatment of $\ln(P'_i)$ vs. C_i in Eq. (2), and $\ln(P''_i)$ vs. C_i in Eq. (4), to graphical methods used to examine transformed cumulative frequency distributions (ogives), to determine whether their parent distributions are normal (see Sokal and Rohlf, 2000).

In other words, we have used our linear models, Eq. (2) and Eq. (4), only to describe the percentage cumulative distributions of pounds landed by count category and nominal ex-vessel value of landings by count category, respectively, in a manner not unlike that using transformed ogives to test for normality of frequency distributions. Our approach reduced voluminous data into two simple, single statistics (b and d, respectively) used to examine changes in pounds landed by count category (i.e. size composition) and nominal ex-vessel value (i.e. value composition) of landings by count category.

In Table 4, best fitting trends and relationships are shown with independent variables coded (i.e. T_{Coded}, b_{Coded}, and E_{Coded}). Equations in Table 4 can be used to generate the fitted straight lines and curves shown in Fig. 3–6. Figures 3–6 show T, b, and E in their original (noncoded) scales, for simplicity and clarity. Detransformation of T_{Coded}, b_{Coded}, and E_{Coded} was necessary. This detransformation involved adding mean T = 1983, mean $b = -0.0246$, and mean E = 99,716 days fished, to all levels of T_{Coded}, b_{Coded}, and E_{Coded}, respectively. Shapes of the curves in Fig. 3–6 do not change with coding vs. not coding. Only the scale of the independent variables in these figures changes with coding vs. none.

Best fitting polynomial regressions fell into three groups with regard to goodness of fit, as indicated by adjusted r^2 (Table 4). The closest-fitting (adjusted $r^2 > 0.8$) was d on b_{Coded}, as expected since they share the same component; i.e. pounds landed by count category (d differs from b in that it contains an added component; i.e. nominal ex-vessel value per pound by count category). Intermediate in goodness of fit ($0.5 <$ adjusted $r^2 \leq 0.8$) were b on T_{Coded}, d on T_{Coded}, W

on T_{Coded}, E on T_{Coded}, V on T_{Coded}, VPP on T_{Coded}, b on E_{Coded}, and V on E_{Coded}. Poorest-fitting (adjusted $r^2 \leq 0.5$) were D on T_{Coded}, $WPUE$ on T_{Coded}, W on b_{Coded}, V on b_{Coded}, and W on E_{Coded}. All but one of the 14 polynomial regressions were significant at $p < 0.0001$ (Table 4). The exception was the borderline linear regression of W on b_{Coded}, which was significant at $p = 0.0186$ (Table 4); i.e. it was close to acceptable at the 99% confidence level.

Local maxima and local minima within the data range for the curved trends and relationships are shown in Table 5. Among the curved trends and relationships, only the sigmoid (cubic) trend in W (Table 4, Fig. 3D) had neither a local maximum nor a local minimum within the data range. The lowest point on this fitted curve (Fig. 3D) was in 1960, and the highest was in 2006; i.e. at both ends of the curve.

Discussion

Polynomial regressions are empirical fits to data, and their polynomial terms have no structural meaning (Sokal and Rohlf, 2000). Therefore, caution should be exercised in interpreting our results. The best fitting trends and relationships reflected concomitant variation between pairs of variables, but did not necessarily represent cause and effect. Nevertheless, it is likely that causes and effects within this white shrimp fishery influenced the scatter of data points and the fitted regressions. We emphasize that significant trends and relationships were detected despite sometimes wide variability (deviations from regression), probably caused for the most part by environmentally influenced fluctuations in annual recruitment. Other factors also could have contributed to the observed variability.

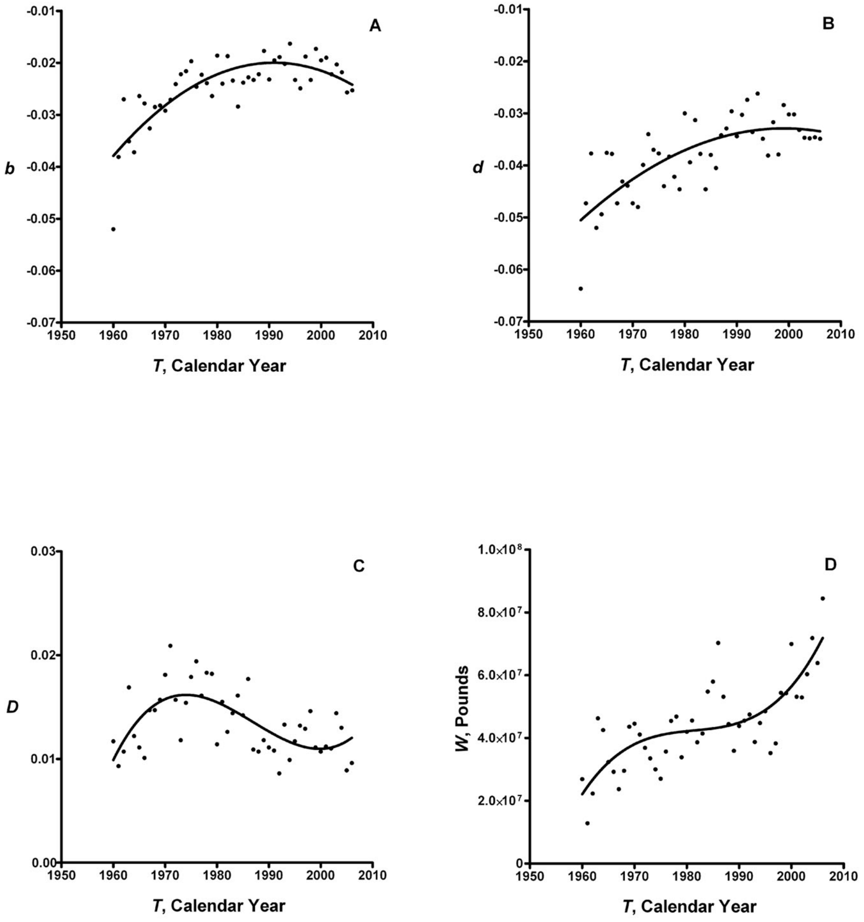

Figure 3.—Trends in b, d, D ($= b - d$), and W in the white shrimp fishery of the northern Gulf of Mexico during 1960–2006 (see Tables 1–5).

Table 5.—Trends and relationships that had estimable local maxima, local minima, or both, and the estimated level of the independent variable at which each occurred, in the white shrimp fishery of the northern Gulf of Mexico, 1960–2006 (see Tables 1 and 4).

Dependent variable	Local maxima	Independent variable	Local minima	Independent variable
b	–0.0200	$T = 1991$		
d	–0.0329	$T = 1999$		
D	0.0162	$T = 1974$	0.0110	$T = 2000$
E	$1.22(10^5)$ days fished	$T = 1991$		
$WPUE$	$5.19(10^2)$ pounds	$T = 1963$	$3.54(10^2)$ pounds	$T = 1988$
V	$\$2.31(10^8)_{2006}$	$T = 1989$		
VPP	$\$5.18_{2006}$	$T = 1983$		
b	– 0.0195	$E = 1.45(10^5)$ days fished		
W	$5.24(10^7)$ pounds ≈ MSY	$E = 1.38(10^5)$ days fished		
V	$\$2.36(10^8)_{2006}$	$E = 1.43(10^5)$ days fished		

Trends in indices b and d (Fig. 3A and 3B, respectively), the trend in D (Fig. 3C), and the relationship between d on b_{Coded} (Fig. 5A), provided useful information not usually available in shrimp fishery assessments (Tables 4, 5). The trend in b (Fig. 3A) reached its local maximum (–0.0200) in 1991 (Table 5), indicating decreasing size of shrimp before 1991 and increasing size of shrimp thereafter. The trend in d (Fig. 3B) reached its local maximum (–0.0329) in 1999, indicating that the distribution of nominal ex-vessel value of landings among count categories shifted toward smaller shrimp until 1999, then toward larger shrimp thereafter. It is important to emphasize that the trend in b reached its local maximum 8 years before the trend in d reached its local maximum.

Because nominal ex-vessel value per pound characteristically increases with size of shrimp (Kutkuhn, 1962; Caillouet et al., 2008), b exceeded d in all years (Tables 2 and 3, Fig. 3A–C and 5A). In other words, slope d (Eq. (4), Table 3) was steeper than slope b (Eq. (2), Table 2) in all years, showing that proportionately more of the nominal ex-vessel value of landings was concentrated in count categories containing larger shrimp than was the weight of landings (see examples, Fig. 3A–D). However, D was not constant over the years. The trend in D was sigmoid, initially rising in the early years, reflecting a widening of the difference between b and d, until D reached its local maximum (0.0162) in 1974 (Tables 4 and 5, Fig. 3C). D then declined to its local minimum (0.0110) in 2000, and increased again but only slightly.

Theoretically, if D were to reach zero, the fitted straight lines (Eq. (2) and (4), respectively) from which b and d are derived would be identical (i.e. superimposed). This could occur only if proportionate distributions of pounds and nominal ex-vessel value of landings among count categories were identical; i.e. if there were no differences in nominal ex-vessel value per pound among the count categories. Therefore, the trend in D reflected a trend in the price spread among the count categories. At $D = 0$, nominal ex-vessel value per pound would no longer differ among the count categories.

The trend in D is consistent with findings of Diop et al. (2006), who showed a continuing decline in inflation-adjusted ex-vessel (dockside) value per kilogram in southeast U.S. shrimp, 1980–2001. While the size of white shrimp in the landings was increasing after 1991, price spread (as indexed by D) among the count categories was declining toward its local minimum in 2000 (Tables 4 and 5, Fig. 3C). The trend in D, and the relationship between d and b, would be well worth monitoring in the future.

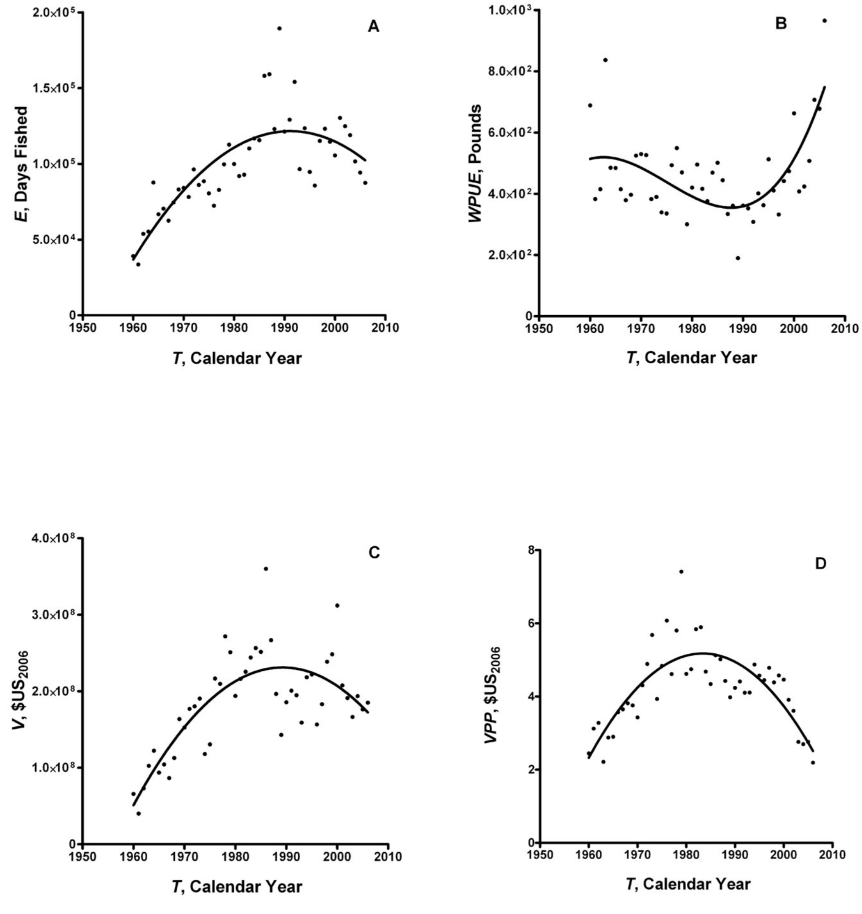

Figure 4.—Trends in E, *WPUE*, V, and *VPP* in the white shrimp fishery of the northern Gulf of Mexico during 1960–2006 (see Tables 1, 4, and 5).

The sigmoid trend in W showed an undulating but continuous increase, with no local maxima or local minima during 1960–2006 (Tables 4 and 5, Fig. 3D). However, W initially increased at a decelerating rate as E increased, suggesting that W might have reached a local maximum had E continued to increase, but instead E went into decline after 1991 (Fig. 4A) due to exogenous factors.[3–7] W began to increase at an accelerating rate later in the time series, consistent with this decline in E (Fig. 4 A), after E reached its local maximum in 1991. The maximum W, $8.45(10^7)$ pounds, occurred in 2006. The trend in E had a local maximum of $1.22(10^5)$ days fished in 1991, declining thereafter (Fig. 4A). The trend in *WPUE* (Fig. 4B) had a local maximum of 519 pounds in 1963, and a local minimum of 354 pounds in 1988, then showed an accelerating increase thereafter.

The accelerating rise in *WPUE* after 1988 indicated that catch rates improved remarkably with the decline in E. Year 2006 had the highest *WPUE*, 966 pounds per day fished, in the time series. This trend in *WPUE* is consistent with the concave upward trend in white shrimp biomass (with a minimum around the late 1980's) measured by a Fall Resource Assessment Survey[4] conducted by NMFS in the northern Gulf of Mexico during years 1972–2006. It is also consistent with an apparently concave upward trend in log-transformed white shrimp catch rates (expressed both in numbers and weight of shrimp caught) in Louisiana during 1970–1997 (Diop et al., 2007).

The trend in V reached its local maximum, \$$2.31(10^8)$, in 1989 (Fig. 4C, Table 5), 6 years after the local maximum in *VPP*, \$5.18, occurred (Fig. 4D, Table 5). Both of these local maxima preceded local maxima for trends in b (in 1991), d (in 1999), and E (in 1991), as well as the highest W, which occurred in 2006. The local maxima for trends in b, d, and E occurred after the local minimum for the trend in $WPUE$, which occurred in 1988 (Table 5). However, they lagged well behind the local maximum for the trend in D, which occurred in 1974 (Table 5). This suggests that increased fishing effort, and the reduction in size of shrimp in the landings that accompanied it, affected V and VPP as well as W. However, W and $WPUE$ accelerated their rates of increase as E declined, while V and VPP did not show similar recoveries.

The linear relationship (of borderline significance) between W and b (Tables 4 and 5, Fig. 5B) was not consistent with concepts of surplus production. It suggested that W continued to increase with decrease in size of shrimp in the landings. Such a relationship provided no evidence of growth overfishing. Were it not for exogenous factors[3–7], which led to the decline in E after 1991, indications of growth overfishing might not have been equivocal. The relationship between V and b (Tables 4 and 5, Fig. 5C) was also linear, showing that V continued to increase as shrimp size decreased. However, of all the best fitting polynomial regressions examined, those for W on b_{Coded} and V on b_{Coded} were the poorest fitting.

The relationship between b and E (Tables 4 and 5, Fig. 6A) suggests that size of shrimp in the landings decreased as nominal fishing effort increased to a point, but b showed an unexpected decline (i.e. an increase in size of shrimp) at levels of E higher than $1.45(10^5)$ days fished at which b had a local maximum (-0.0195). Perhaps an asymptotic regression would better describe this relationship, but we did not attempt to fit one to the data for consistency with our use of polynomial regression (Caillouet et al., 2008), and because there was an obvious downturn in b as levels of E continued to increase. Partial statistical dependence between E and W (Kutkuhn, 1962) may be a reason for this downturn in b with increase in E. However, the trends in b and E (Tables 4 and 5, Fig. 3A and 4A, respectively) were both quadratic, concave downward, and had local maxima in the same year (1991), suggesting that size of shrimp decreased as E increased, and size of shrimp increased as fishing effort declined.

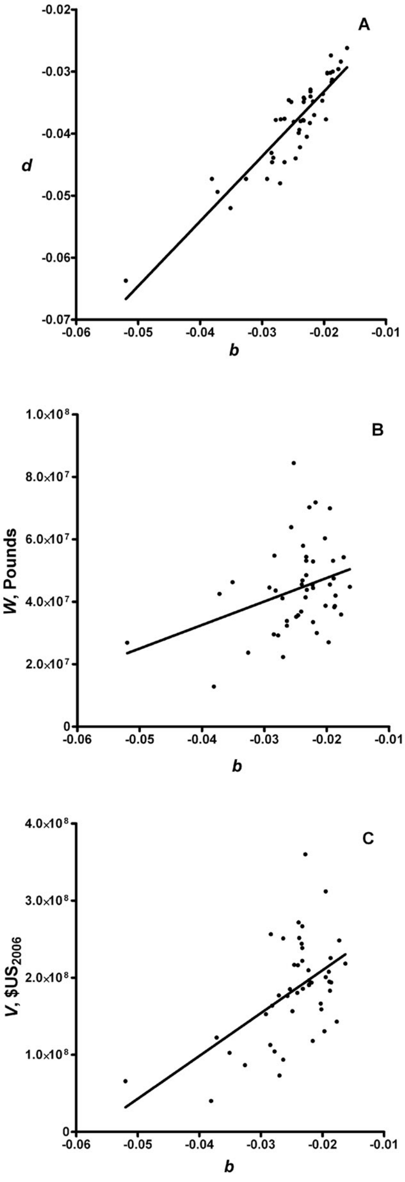

Figure 5.—Relationships between d and b, W and b, and V and b in the white shrimp fishery of the northern Gulf of Mexico during 1960–2006 (see Tables 1–5).

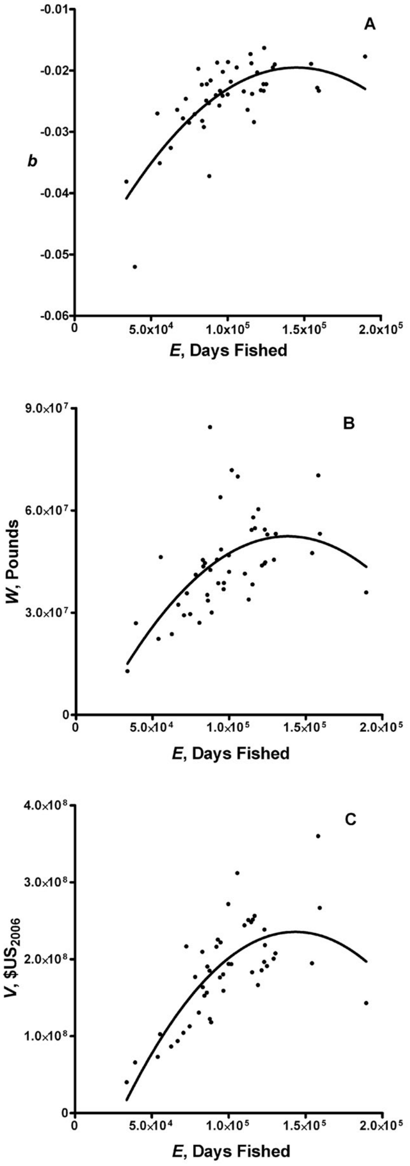

Figure 6.—Relationships between b and E, W and E, and V and E in the white shrimp fishery of the northern Gulf of Mexico during 1960–2006 (see Tables 1, 2, 4, and 5).

The relationship between W on E had a local maximum of $5.24(10^7)$ pounds at an E of $1.38(10^5)$ days fished (Tables 4 and 5, Fig. 6B). This local maximum in W approximates MSY. This relationship was not forced through the origin ($W = 0$, $E = 0$), as it is in the Graham-Schaefer surplus production model which assumes the origin, and therefore it fits the data better. The relationship between W and E, with its local maximum (≈ MSY), suggests that growth overfishing occurred, given the caveats concerning the method used to estimate E, the linear relationship between W and b, and the quadratic, concave downward relationship between b and E. Interestingly, the local maximum V of \$2.36(10^8) occurred at an E level of 1.43(10^5) days fished (Tables 4 and 5, Fig. 6C), which was higher than the level of 1.38(10^5) days fished at which W was maximized (≈ MSY) in relation to E. If growth overfishing did occur, it was short-lived.

Unevaluated influences

Commercial shrimpers' long-standing practice of discarding small shrimp to increase ex-vessel value of their landings (Kutkuhn, 1962; Rothschild and Brunenmeister, 1984; Neal and Maris, 1985) affects the results of all northern Gulf of Mexico shrimp stock assessments based on the archived landings data. However, discarding would be a problem for our analyses only if a significant trend of change in discarding rate occurred over the time series. Rothschild and Brunenmeister (1984) mentioned seasonal changes in discarding rates, which peaked early in the shrimping season. They wrote that discarding rates were high at times, and variable among years, but they did not mention whether there was a significant trend in discarding rate over years. Available data on discarding were intermittent and too variable to determine their potential effects on the annual distribution of size of shrimp in the landings over our time series. We assumed the effects of discarding on our results were negligible.

Significant trends of change in areas fished, traveling distance to and from fishing areas, duration of fishing trips, market demand for shrimp of various sizes, operating costs, characteristics of shrimp fishing units and gear, and other factors could also have influenced our results. Also, compensatory effects of trends in shrimp fishing effort on species other than shrimp in the Gulf of Mexico ecosystem (Walters et al., 2008) could have influenced our results. Evaluating these possible influences was not within the scope of our paper.

Warnings by Rothschild and Brunenmeister (1984) apparently went unheeded, and detrimental socio-economic consequences of further increases in fishing effort occurred before rising fuel costs, competition from imported shrimp, damage and losses from hurricanes, and other exogenous factors caused fishing effort and fleet size to decline.[4, 6, 7] Even though the white shrimp stock appears to be recovering rapidly (i.e. W and $WPUE$ are increasing at accelerating rates), and white shrimp in the landings are getting larger, the beneficial effects of these improvements seem counteracted by declining VPP.

The fleet size moratorium should limit future expansion of the fleet that fishes the EEZ. The new shrimping regulations implemented by the TPWD in 2001 should limit expansion of the fleet that fishes Texas' waters, and the temporary moratorium[6, 7] on fleet size, implemented in 2006, should limit expansion of the fleet that fishes in the EEZ.

In our opinion, these management actions were in the right direction. While they may limit future expansion of fishing effort, they cannot remedy economic problems associated with decline in price spread among count categories and the overall decline in VPP, despite the recent increase of size of shrimp in the landings. Nevertheless, the effect of fishing effort on size of shrimp in the landings, and the effect of size composition on ex-vessel value of the landings, should be included among guidelines for future management of this fishery by Federal and State agencies.

Conclusions

If growth overfishing of white shrimp did occur, it was short-lived and quickly abated with the decline in E, and both W and $WPUE$ showed accelerating recoveries in response. However, V and VPP continued their decline, despite the decline in E. Fleet size also declined[6], and was further reduced by catastrophic impacts of hurricanes[4] in the northern Gulf in 2005. The white shrimp stock appears to be recovering[4] rapidly in terms of $WPUE$ and W, but VPP and V continued to decline. We conclude from these trends that exogenous factors[3–7] are dominating the white shrimp fishery, and keeping V and VPP low, while allowing the white shrimp stock to recover.

Our investigation suggests that the management strategies of the past, which encouraged harvest of all the shrimp possible from each annual crop (with relatively few constraints), might have led to growth overfishing in this white shrimp fishery had it not been for the decline in E resulting from factors outside the control of shrimp fishery managers. Larger shrimp generally have higher ex-vessel value per pound than do smaller shrimp, but the differences in ex-vessel value per pound among count categories have narrowed due to exogenous factors beyond the control of shrimp fishery managers. It is clear that sizes of shrimp landed, yields of shrimp, and inflation-adjusted ex-vessel value of these yields are inextricably intertwined (Nance et al., 1994). Unlike the case with the brown shrimp fishery (Caillouet et al., 2008), evidence of growth overfishing of white shrimp was equivocal. Our paper was not intended as an economic assessment of this white shrimp fishery, but it provides information of possible importance and use to future economic assessments. It remains to be determined whether the observed declines in fishing effort and fleet size will increase profitability in this white shrimp fishery, or in the domestic shrimp fishery of the Gulf of Mexico as a whole.

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