Incorporating Toxic Disturbance Effects into a Population Model of a Crustacean Fishery

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ABSTRACT

Population models have been used to describe and predict changes in population structures through time. In fishery applications these models (utilizing such factors as growth, recruitment, fishing mortality and natural mortality) are used to manage and regulate fishing activities. As our waters are increasingly impacted by both point and non-point source pollution theparameter of "natural mortality" must be examined in greater detail. Toxicological studies based on both commercially important species and proxy species have shown a variety of physiological effects that have not been addressed in practical applications of modeling. Stage specific mortality, altered rates of development and reduced growth have been reported. These effects were documented in a xanthid crab exposed to sub-lethal concentrations of the mosquito larvicide, methoprene, and have been incorporated into a crustacean fishery model. Impacts on survival and fecundity produce a much different picture for long term population growth that needs to be considered in the application of population models. Multi-species tropical fisheries will tend to magnify the effects demonstrated on prey species through complex tropho-dynamic linkages. Design and placement of marine protected areas or attempts to rehabilitate degraded habitats must consider the effects of xenobiotics in the aquatic habitat and provide for restrictions of terrestrial inputs as part of their overall management strategy.

KEY WORDS: Crustacea, *Eurypanopeus depressus,* fisheries, methoprene, modeling, toxicity

INTRODUCTION

A large volume of toxicity data exists that is of considerable importance and should be of considerable interest to ecologists, fishery scientists and natural resource managers. Unfortunately much of the information is in a format that is not readily accessible for those who are not practicing organic- or bio-chemists. Often only the cursory information is disseminated. As the impacts of these exogenous products continue to impact our coastal systems, it will become increasingly important for effective cross-over studies to interpret these findings with respect to anticipated population effects for a larger, more diverse audience.

The lethal and sub-lethal effects should be incorporated into population models, if the models are to accurately reflect observed effects on important fishery species, particularly those of coastal crustaceans.

Crustaceans are represented in estuaries, coastal wetlands, and seagrass areas by species of both commercial and ecological importance. Commercial shrimp and crab species comprise a majority, up to 97% by weight, of the seafood harvest in the Gulf of Mexico (Duke and Kruczynski (and sources therein), 1990; McHugh, 1977). All these harvested species are estuarine dependent, at least during a portion of their life cycles (Boesch and Turner, 1984; Weinstein, 1979).

Throughout the Caribbean, crustacea, such as the spiny lobster (*Panulirus argus)*, represent an extremely valuable portion of the fishery catch (Richards and Bohnsack, 1990). As arthropods, crustaceans are closely related both phylogenetically and physiologically to the target pests of insecticidal treatments (Williams and Duke, 1979). As species that are tied to estuarine/coastal areas, these invertebrates are exposed to point and non-point source pollutants at critical times during their development. These exposures create the potential for ecological disruptions.

Ecologically, both commercial and non-commercial crustaceans play critical roles in estuarine and other wetland ecosystems (Epifanio and Dittel, 1984; McDonald, 1977). They participate in the planktonic and detrital food webs with diverse feeding habits. Estuarine crustaceans provide the critical link between these more basic energy resources and organisms feeding at higher trophic levels (Closs and Lake, 1994; Mauchline, 1980; Welsh, 1975). Substantial reductions in their populations would adversely impact trophic couplings within the estuarine or coastal environment (Markle and Grant, 1970; Smith *et al.*, 1984).

Many of the commercially important crustaceans have been difficult to maintain in the laboratory for extensive evaluations of toxic responses so alternate species have been used as proxies to represent the Crustacea in toxicological screenings. This paper reports on the effects of the pesticide methoprene on *Eurypanopeus depressus* (Smith), a xanthid mud crab likely to undergo incidental exposure in an estuarine setting during surface water run-off or pesticide spraying events. Laboratory exposure parameters were chosen to mimic natural exposure conditions and bracket chemical concentrations recommended for field application. Ontogenetic variations in physiological and biochemical responses were documented throughout the larval development. The impacts of the pesticide on individual organisms has been extrapolated to some likely consequences at higher levels of organization. To relate the effects to fishery or ecological science, this paper compares the sub-lethal responses of *E. depressus* to other published studies documenting toxic effects to commercially and ecologically important species. It, further, suggests ecological effects that are likely to show up in fisheries as direct toxic effects and through disruption of trophic dynamics. These effects are significant enough that they should be considered when placing marine protected areas or setting goals for habitat restoration in impacted coastal zones.

METHODS AND MATERIALS

Primary study

Eurypanopeus depressus (Smith) is one of the more numerous xanthid crabs found as juveniles in estuarine plankton (Walton and Williams, 1971) and as adults inhabiting oyster reefs (McDermott, 1060; McDonald, 1977). As a full time resident of estuaries, it is subject to coastal pollutants throughout its entire life cycle. To obtain larva with known backgrounds of chemical exposures, a breeding stock was maintained in a flow-through sea water system in the Environmental Research Laboratory (U.S. Environmental Protection Agency's Sabine Island facility) in Gulf Breeze, Florida. Randomly selected *E. depressus* larvae were exposed to the single isomer (S)-methoprene (isopropyl [2E, 4E, 7S]-methoxy-3, 7, 11-trimethyl-2, 4-dodecadienoate), in a dynamic, flow-through system in nominal concentrations of 64, 32, 16, 8, 4, and 2 µg/l and compared against control (0 µg/l) exposures. Methoprene, a highly specific pesticide, is an analogue of a naturally occurring juvenile hormone. It is classed as an insect growth regulator. Complete details of the pesticide exposures were reported by Hill (1995).

Stage-specific survival and intermolt duration were monitored for each of the four zoeal stages (Z^{I} - Z^{IV}) through the metamorphosis of the megalopae (Meg) to the postlarval first crab (C-1) stage. Subsamples of each stage and all surviving crabs were weighed and dried to determine ash weights and elemental compositions of carbon, hydrogen, and nitrogen (CHN). CHN analyses were performed on a Perkin Elmer PE 2400 CHN Elemental Analyzer. Using published conversion factors/equations, the elemental contents were converted to "equivalent contents" as carbohydrates, proteins, lipids and energy (joules) (Donnelly *et al.*, 1993; Salonen *et al.*, 1976). These comparisons provided <indications of bioenergetic alterations attributable to the exposures to the juvenile hormone analog.

Results were analyzed with the Statistical Analysis System (SAS Institute, Inc., 1989) on the VAX 4000-500 using the General Linear Models procedure. Analysis of variance (ANOVA) was used to test for significant differences at α = 0.05. Duncan's multiple-range test was used to test for significant differences between treatment means. Dunnett's test was used to compare dose-response values against control treatments (Zar, 1984).

Comparative species examinations

The current literature identifies a variety of toxicity studies that have examined both commercially important species and those that are either ecologically important or proxy species. Test procedures and results that compared toxic responses between a commercially important species and the more commonly used test animals were evaluated to investigate the validity of using the primary test results, above, to infer general population responses.

Model investigation.

A review of the more common population or fishery models investigated the use of natural mortality as a model variable or parameter. Population growth models frequently use mortality as their primary indicator of future population directions. More complex models, such as virtual population analysis, use either "assumed constant" or size-specific mortality values and often gloss over the importance of natural mortality since it is difficult to verify. The confounding effects of lethal and sub-lethal responses can be well illustrated using an exponential decay model, so it is presented here to demonstrate model effects.

RESULTS AND DISCUSSION

Toxicity studies

Various measurements have been used to assess the impact of pesticides on target and non-target species, as reviewed by Giesy and Graney (1989). Effects can range from gross effects on the individual or the population to more subtle impacts at the cellular-biochemical level (Capuzzo *et al.* 1988). Acute toxicity tests have been used to investigate total mortality rates and lethal dosage levels (Christiansen *et al.*, 1978, Tyler-Schroeder, 1979; Wilson and Costlow, 1987), and continue to provide guidelines for maximum concentrations of various toxicants allowed into the environment (Capuzzo *et al.*, 1988). Targeting of particularly sensitive stages such as crustacean larval stages, in either acute or chronic tests, helps to reveal minimum chemical concentrations that might impact an organism or population (Giesy and Graney, 1989).

These primary test results were derived from chronic exposure tests that examined the effects of sub-lethal concentrations of the juvenile hormone mimic (S)-methoprene on the non-target estuarine species, *Eurypanopeus depressus*. Larval development was monitored from egg hatching through metamorphosis to first-crab (C-1) at concentrations of 0, 2, 4, 8, 16, 32, and 64 µg/l. Mortality occurred most frequently during ecdysis. Exposure to 32 and 64 µg/l greatly increased mean larval mortality (from hatch to C-1), 63% ($p = 0.06$, n.s.) and

75% ($p < 0.0187$), respectively. Stage-specific mortality, resulting from exposures to 32 and 64 µg/l methoprene, showed greatest impacts in the early zoeal stages, Z^{I} to Z^{III}. At 64 µg/l, an secondary drop in survival rates, during the metamorphic molt from Meg to C-1, reflected increased sensitivity to higher levels of methoprene during metamorphosis (Hill, 1995). Similar results in natural estuarine population would result in altered abundances of all zoeal stages, megalopae and crabs.

Toxic effects on growth rates and growth efficiencies have routinely been quantified by recording changes in body weights, respiration rates and ammonia excretion rates (Capuzzo and Lancaster, 1982; Laughlin and Neff, 1981; McKenney, 1985; McKenney and Celestial, 1993). *E. depressus* larvae exposed to methoprene demonstrated dose-dependent effects that were measured as changes in mean dry weight. The effects were most evident in the Meg.

Exposure to 2 µg/l caused a reduction in mean dry weight of 28.3%; the greatest decrease was after exposure to 64 µg/l which showed a 35.2% mean reduction in dry weights ($p < 0.002$) compared to the control. In the post-metamorphic first crabs 64 µg/l again produced the most significant reductions in mean growth (31.5%; $p < 0.008$). Smaller sized individuals are typically subject to increased mortality due to predation and display decreased reproductive potentials, e.g., spawning frequency, fecundity, hatching success, and F_1 generation mating (Tyler-Schroeder, 1979).

These variations in growth and scope for growth can be traced to biochemical and cellular abnormalities in metabolic demands and energetic utilizations (Amsler and George, 1984b). The analysis of elemental (CHN) composition can be used to construct energy budgets (Mootz and Epifanio, 1974; Levine and Sulkin, 1979). Mathematical conversion of the elemental contents to energy, protein, carbohydrates and proteins (Donnelly *et al.*, 1993; Salonen *et al.*, 1974) provided indications of bioenergetic alterations attributable to the exposures to the juvenile hormone analog.

This study showed altered patterns of carbohydrate, lipid and protein utilization and storage (Hill, 1995). As a result of those biochemical alterations and the reductions in growth, energy content (joules/individual) of all larval stages was reduced. Megalopa showed significant reductions in energy contentresulting from all methoprene concentrations. The most severe reduction in mean energy content, to 71% of the control animals, resulted from the 32 µg/l exposure. The effect persisted into the juvenile crab stage with energy reduced from 54 - 74% (Hill, 1995). For the population this can mean reduced fecundity and hatching success, due to depleted energy reserves; and, ecologically this translates into less energy transfer per feeding foray for predators of these species.

Comparative species studies

Previous investigations have addressed the effects of hormonal pollutants on a variety of small crustacean species (crabs, shrimp, zooplankton, and lobsters) that are ecologically important in estuaries: *Rhithropanopeus harrisii* (Celestial and McKenney, 1994; Christiansen *et al.*, 1977a; 1977b; Forward and Costlow, 1978), *Palaemonetes pugio* (McKenney and Celestial, 1993; McKenney and Matthews, 1990b; Touart, 1989; Wilson and Costlow, 1986), *Mysidopsis bahia* (McKenney and Matthews, 1990a; Nimmo *et al.*, 1980), and copepods (Bircher and Ruber, 1988). Unfortunately, other than *Homarus americanus* larvae (Hertz and Chang, 1986), little has been reported for commercial species that can be used to directly compare the results of the primary study.

In earlier test with other types of pesticides there have been some comparative studies that can be used to compare interspecific effects. In acute studies with Mirex, Bookhout *et al.* (1972) reported comparable effects for the xanthid crabs, *Rhithropanopeus harissi*, and *Menippe mercenaria* and the portunid crab, *Callinectes sapidus*. Concentrations of 0.01 and 0.1 µg/l were sub-lethal but caused delays in development either by extending intermolt duration or by producing extra zoeal stages. Concentration of 1.0 and 10.0 µg/l proved lethal to all three species with greatest sensitivity found in the earlier zoeal stages, and in the megalopae. Both *M. mercenaria* and *C. sapidus* support sizable fisheries.

The organophosphate, Malathion, has shown variable results in acute studies comparing *R. harrisii* with *C. sapidus*. *C. sapidus* was 3 - 4 times more tolerant of Malathion than *R. harrisii* before lethal effects were observed. Sub-lethal effects however, were similar between the two species (Bookhout and Monroe, 1977). Similarities of responses support the hypothesis that trends can be deduced from comparative studies although the exact magnitudes of effect may vary. The reported effects on impacted populations may logically lead to ecological comparisons.

Ecological concerns.

Many of the effects that have been demonstrated on crustaceans from both lethal and sub-lethal pesticide exposures result in net reduction of the population size and/or fitness and can be assumed to produce alterations in relative abundances within the community. Reduced abundances of these crustacean species may be assumed to produce three rather obvious ecological consequences:

i) reduced interspecific competition resulting in altered species diversities;
ii) reduced nutrient cycling (the shredding and processing) of detrital nutrients and,
iii) reduced availability as a prey item requiring changes in feeding behaviors or reducing feeding efficiencies in the predators that feed on these crustaceans.

According to the studies referenced above, these effects would be manifest in all exposed populations of crustaceans, including crabs, lobsters, zooplankton, and shrimp. Trophic effects have been documented in laboratory studies using contaminated food items that multiply effects through bioaccumulation as they are passed up the food chain (Bookout and Costlow, 1970)

Crustacea are a major direct source of food for many of the important commercial species of the Gulf and Caribbean region. Many of these species (e.g., snappers and grunts) that prey on crustaceans have been in steady decline over the last decade or so (Appeldoorn and Meyers, 1993). Dennis (1992) analyzed the diet of several haemulid species from Puerto Rico (Figure 1). The species of greatest commercial interest, *Haemulon plumieri* (size range: 82 - 282 mm TL), utilizes crustacean species as 14% of their diet; at smaller sizes the bulk of their diet consists of zooplankton (personal observation). Small *Lutjanus apodus* (70mm FL) use crustaceans for 89% of their diet; this percentage drops to 38% for fish larger than 70 mm FL (Figure 1) (Rooker, 1991). Significant reductions in these prey populations or shifts in abundances could be contributing to the decline of these reef associated species, as well as other guilds of benthic feeders or zooplanktivores.

Modeling effects.

Fisheries models can include those as simple as Growth Models, such as von Bertalanfy and Gompertz (Sparre *et al.* 1989). The obvious effects on growth as a result of toxicosis will have serious effects, altering rates of growth (K) and asymptotic length (L_∞). Increases in rates of predation and reductions in fecundity as a result of smaller size at age are well known for crustaceans and fish.

Models of mortality for highly fecund fast growing species, such as shrimp, have frequently been characterized using exponential decay curves where population size is dependent on the interaction between $N_{(t)}$, population at a previous time and the instantaneous mortality rates (Ricker 1975). Z, the total mortality rate is composed of F, the instantaneous mortality rate due to fishing efforts, and M, the instantaneous rate of mortality due to all other causes (predation, disease, emigration, parasitism, etc.) An increase of annual mortality rate of 58% as seen in *E. depressus* (Hill, 1995) is equivalent to a drop in Z of 0.55. Using the equation $N_t = N_0 e^{-Zt}$, this amounts to a reduction of 40% in the expected population after only one (1) time interval. After three (3) time intervals this difference has been magnified to a 78% decrease in the population (Figure 2). To further examine the consequences on fishery production, the historical catch data from the Cuban shrimp fishery are plotted in Figure 3 (Baisre, 1993). Cuban coastal waters are subject to run-off and riverine inputs,

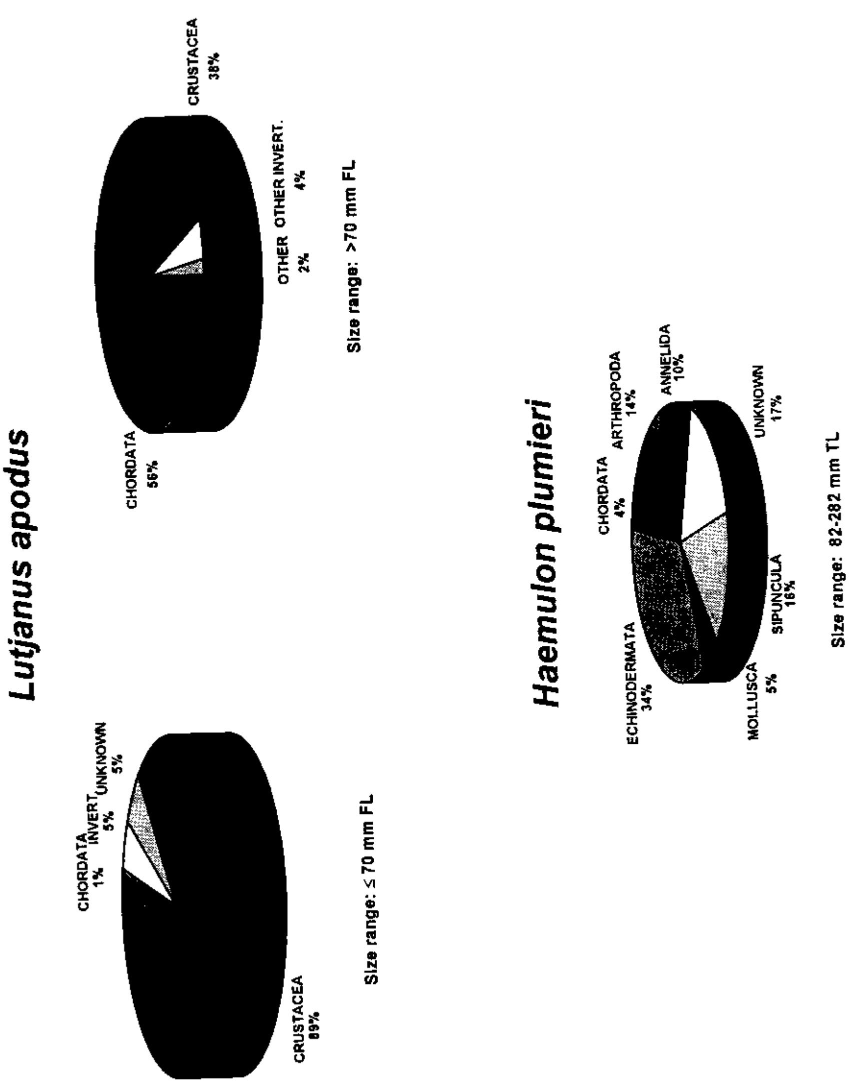

Figure 1. Dietary compositions for *L. apodus* (Rooker, 1991) and *H. plumieri* (Dennis, 1992).

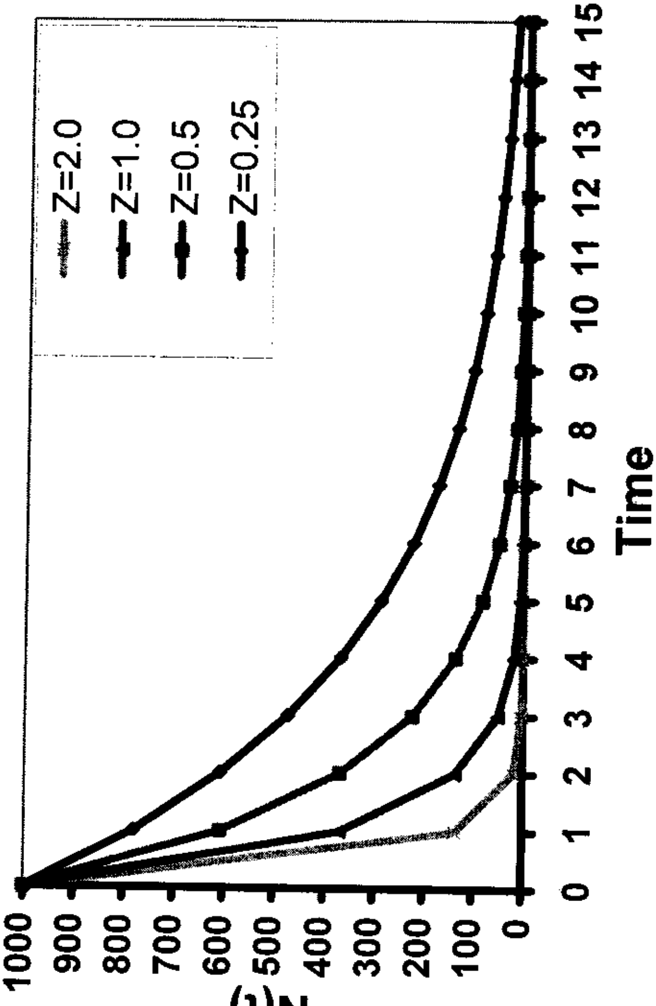

Figure 2. Exponential population decline for various values of Z, total mortality.

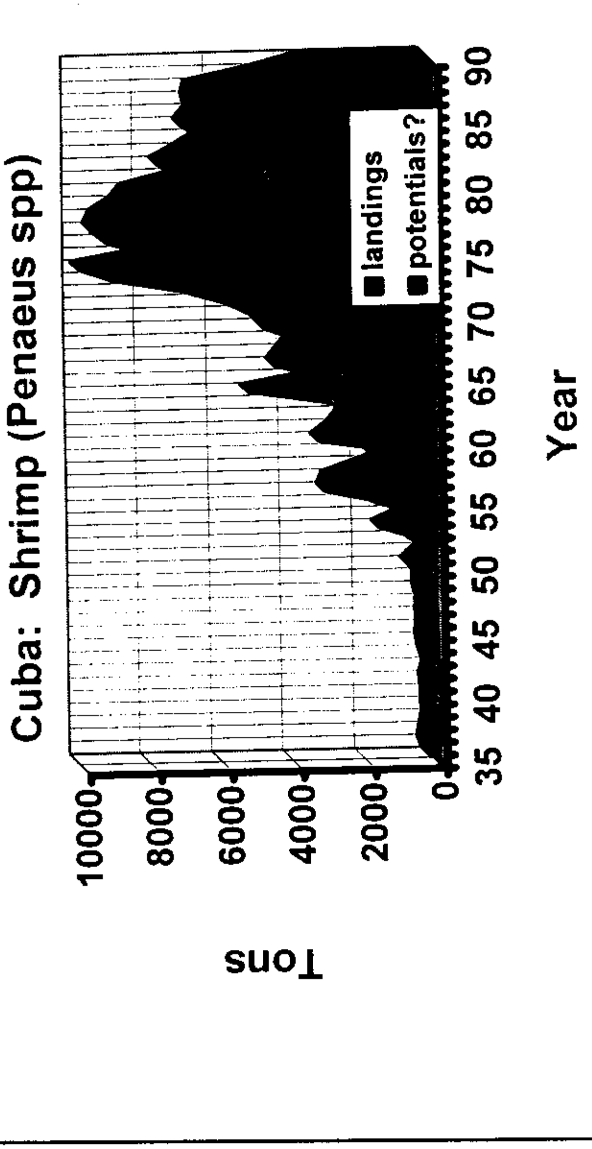

Figure 3. Speculation of the potential yields from the Cuban shrimp fishery, under the assumption that populations are currently depressed because of the influence of pesticide exposure. (Baisre 1993.)

likely to contain pesticide residues from agricultural practices. These exogenous inputs are likely to affect wetland species such as the penaeid shrimp. The secondary curve in Figure 3 assumes that impacts were similar to those reported above and speculatively predicts the potential yields that may have been available if the stocks were not impacted. Stocks that were not depressed through toxicosis would also be expected to be more resilient to fishing pressure.

CONCLUSIONS

Numerous studies have shown lethal and sub-lethal concentrations of xenobiotics to affect a wide variety of organismic responses, beyond those cited here. Particularly important is alteration of an organism's physiological ability to osmoregulate or to manage environmental stresses such as the cycling of temperature and/or salinity (Christiansen *et al.*, 1977a; 1977b; Laughlin and Neff, 1981; McKenney and Hamaker, 1984; Shirley and McKenney, 1987; Voyer and Modica, 1990). The ability to tolerate regular changes of temperature and salinity is an essential aspect of an estuarine animal's life (McKenney, 1986).

Chemically induced alterations in behaviors, such as phototaxic response (Wilson et al., 1985) and swimming speed (Forward and Costlow, 1976; 1978), have been documented, suggesting increased rates of predation and/or the loss of animals from suitable habitats by countering the naturally-selected mechanisms for predator avoidance and for estuarine retention. As with direct reduction in population survival, growth and fitness, these induced behavioral changes can be assumed to reduce recruitment and therefore abundances of local populations (Farr, 1977; Sulkin, 1984). These "unnatural" sources of mortality can considerably affect population dynamics that should be addressed in models of populations or fisheries.

Vetter (1988) reviewed the techniques for assigning M for various populations: (1) assume that M is relative to some population (life history) parameter K, L_∞, or r (Gunderson, 1980); (2) analyze catch data; (3) estimate deaths from predation. From just this preliminary analysis of some of the toxic responses that can be impacting important crustacean fishery species, it is likely that our estimates of M are lacking in their consideration of exogenous inputs into our coastal systems. These concerns must be addressed in fishery management, whether it is in stock assessments or design of marine protected areas (MPA). Stock characteristics from one geographical region may not be reflective of life history traits in another if one of the stocks is impacted from pesticide run-off or over-spray. Similarly an MPA placed in an estuary or marine catchment basin that is subject to agricultural run-off is not likely to produce the same results as one located in a more isolated habitat. Capuzzo and Leavitt (1988) have demonstrated that energy resources, in a crab and a shellfish, marine catchment basin that is subject to agricultural run-off is not likely to produce the same results as one located in a more isolated habitat. Capuzzo and Leavitt (1988) have demonstrated that energy resources, in a crab and a shellfish, will vary as a direct result of pollutant gradients. Attention to coastal details and maintenance or restoration of coastal wetlands will provide natural barriers and enhance conditions for protection of coastal fishery resources.

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