Lobster Settlement and Abundance in Rhode Island: An Evaluation of Methoprene Application and Other Factors Potentially Influencing Early Survival.

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Issue Introduction-

The fishery for American lobster (*Homarus americanus*) was one of the most valuable in the state of Rhode Island. During peak years, the fishery landed 8.2 million pounds of product worth 31.6 million dollars in ex-vessel landings. The inshore lobster fishery suffered a major decline from 1999 to 2004, partly as a result of a major oil spill in Block Island Sound in 1996 that killed 9 million juvenile lobsters destined to recruit to the commercial fishery (Gibson et al. 1997, Cobb and Clancy 1998). An extensive remediation plan based on v-notching female lobster was devised to rebuild the damaged lobster population (Gibson 1998, French et al. 2003). The party responsible for the spill consented to contract commercial fishermen, to procure hard shell female lobster, and to fund a v-notch program that including an observer oversight element. The objective of the “North Cape” program was to prolong the lifespan of remaining female lobster until their lifetime egg production had equaled that of an un-impacted population. Notching tail flippers with v-shaped marks and prohibiting their taking and possession via regulation were measures designed to increase the survival rate of reproductive females. The program began in 2000, underwent significant quality control improvements in 2001, and was in full operation by 2002. The industry-supported program was very successful such that the court ordered egg production from v-notched females was reached in 2006 (Gibson and Angell 2006). The official, funded program ended in the summer of 2006 with over 1.5 million notched. Some fishermen have continued to v-notch on a voluntary basis following completion of the North Cape program.

Independent sampling by the RI Division of Fish and Wildlife (RIDFW) onboard commercial lobster vessels confirmed that the abundance of egg bearing females increased dramatically with large scale v-notching (Figure 1). A reduction in fishing mortality was documented (Gibson and Angell 2006). It is worthwhile to note that egg abundance declined in 2007 suggesting that voluntary efforts by industry have not matched the conservation benefits of the North Cape program. In addition to fishery sampling, the RIDFW also monitors the abundance of newly settled juvenile lobster in September each year. New settlers, or young of the year (YOY), to the benthic habitat originate from larvae spawned by egg-bearing females in the summer. After egg hatching, lobster larvae spend about six weeks in the water column as larvae and then settle as post larvae to the bottom to assume a two-dimensional, benthic life style. Local
settlement survey results are plotted in Figure 2. From 1990 to 2003, settlement strength fluctuated with periods of high and low abundance. Since 2004, settlement has been consistently below average despite very high egg abundance in 2005 and 2006 from v-notching. The lobster industry has noticed this and argued that the lack of improvement in settlement success was due to larval mortality from methoprene application in Rhode Island. The Rhode Island Department of Environmental Management (RIDEM) has provided methoprene to municipalities since 2000 for use in mosquito control programs designed to reduce the risk of West Nile virus to humans. Methoprene can have deleterious effects on lobster larvae, increasing mortality rates and interfering with molting at concentrations ranging from 1 to 5 ppb (Walker 2005). However, experiments by RIDEM that introduced methoprene cakes into storm drains and simulated rainfall events by flushing the drains, showed that residual methoprene in sea water samples taken near the drain out fall was at undetectable levels and unlikely to harm lobster (Butler 2005). To further examine the methoprene impact hypothesis advanced by industry, this study examined statistical relationships between lobster abundance and mortality and various factors including methoprene.

Data Sources-

Lobster Settlement Survey- Dr. Richard Wahle of Bigelow Laboratory, Maine, initiated a regional lobster settlement survey in 1989. Results are reported to cooperating and interested parties in an annual report (Wahle 2008). The Rhode Island component is part of a larger New England lobster settlement survey. The goal of the survey is to estimate lobster year class strength, especially that of newly settled YOY lobsters that have arrived in near-shore coastal waters. Divers using suction devices can sample them in a standardized way from nursery habitats along the coast (Wahle 1993). A total of six (6) fixed stations are surveyed with twelve (12) randomly selected 0.5 meter$^2$ quadrats at each station for a total of 72 samples. Sample stations are sighted in rocky, near shore habitats from Sachuest Pt, Newport west to the Harbor of Refuge at Pt Judith. All lobster captured are measured for carapace length, sexed, and enumerated to generate relative densities (number per m$^2$). Lobster 13 mm or less in carapace length are considered YOY. Lobster greater than 13 mm are considered age 1 or older. YOY abundance is used in regional lobster stock assessments (ASMFC 2006) and to forecast recruitment to the fishery (Wahle et al. 2004). Trends in abundance of newly settled and juvenile lobster populations have been monitored in Rhode Island since 1990 and overall trends were discussed earlier (Figure 2).

Fishery Sea Sampling and Egg Abundance- The RIDFW commercial fishery sampling program began in November 1990, and currently consists of 2 inshore (Narragansett Bay and Rhode Island Sound) sea sampling trips per month. Industry members voluntarily take RIDFW observers on selected fishing trips. To date, RIDFW scientists have sampled more 107,000 commercial pot hauls and over 290,000 lobsters. While onboard commercial lobster vessels, staff scientists enumerate the lobster catch. They determine sex, reproductive status, carapace lengths, and v-notch presence/absence for all lobsters caught. Observations are made on the occurrence and severity of shell disease. They also record the number of traps hauled on the trip as a measure of fishing effort. A catch per
unit effort (CPUE) index of abundance for “old eggers” that is those egg bearing lobster that will hatch off eggs in the summer, was computed as the number of eggers divided by the number of traps hauled (Figure 1). These animals are in contrast to “new eggers” or those females that have just extruded eggs and will carry them until the following summer. Details of the RIDFW lobster observer program may be found in Angell and Olszewski (2006). Because this program samples catch from commercial lobster traps that contain escape vents, most of the catch is near legal or legal in size. To sample smaller lobster, RIDFW began a research trap survey using un-vented pots in 2006.

**Bottom Trawl Survey**- The RIDFW bottom trawl survey program began in 1979, with spring and fall cruises being conducted in Narragansett Bay, Rhode Island Sound and Block Island Sound. The survey is based on a random stratified sampling design with stratification by depth and area. A total of 42 tows are made during each cruise, 26 in Narragansett Bay, 6 in Rhode Island Sound, and 10 in Block Island Sound. The trawl net employs a ¼” net liner and lobster as small as 14 mm have been captured. In 1990, the trawl survey program was expanded to include monthly sampling in Narragansett Bay at a series of 12 fixed stations. The monthly component of the survey was added to provide better resolution of the seasonal occurrences of fish and invertebrates in the Bay. The RIDFW trawl survey lobster catch is highly correlated (r=0.85, P<0.01) with catch in the URIGSO survey enabling examination of lobster abundance trends over decadal time scales. Bottom trawl gear cannot be fished on rough bottom and cannot sample lobster in rocky habitat where commercial pot gear can be deployed. However, lobster size frequencies from trawl gear and the new un-vented pot gear are similar suggesting that they are sampling the same population. All lobster taken in trawl catches are sampled consistently with that described above for commercial sea sampling. As an alternative to the fishery dependent CPUE index above, an index of female spawner abundance was computed as the mean number per tow of female lobster 73 mm and larger from the summer (June-Sept) cruises of the monthly survey. The size cutoff is the 50% maturation point for female lobster in our area and is based on examination of reproductive condition of many females since sampling began. The summer time period was chosen since trawl catch rates are at their highest point of the year and ovigerous females are close to hatching off eggs. Abundance indices for several stages of lobster in Rhode Island are given in Table 1. Details of the RIDFW research trawl program can be found in Lynch (2006).

**Auxiliary Explanatory Variables**- Several environmental and ecological variables thought to influence post-larval lobster abundance and survival were considered. Water temperature is believed to influence settlement success since larval development time is inversely related to temperature (Ennis 1995). Also, surface dwelling post-larvae are reluctant to descend through temperature gradients of 4-5 C to settle (Lawton and Lavalli 1995). Anomalous temperatures could result in prolonged larval stage duration, delayed settlement, and higher mortality. Analyses of long-term ocean temperature data in New England show a rise of about 0.04 C per year since 1970 (Nixon et al. 2004). Temperature regime shifts of this magnitude have been associated with major changes in the ecology of Rhode Island coastal waters (Oviatt 2004). Water temperature in the Rhode Island area has been routinely measured during monthly cruises of the RIDFW
and URIGSO trawl surveys. It has also been recorded at nearby Millstone Power Station (MPS) in Niantic, Connecticut. Mean annual values from RI data sets for years 1990 to 2007 were computed for this study.

Predation by benthic fishes may influence survival rates of descending post-larvae, new settlers, and juvenile lobster (Cobb et al. 1983, Hudon 1987, Wahle and Steneck 1992). Fishes such as sculpin, cunner, tautog, scup, striped bass, and black sea bass are known predators of lobster. Experimental and observational evidence indicate that lobster mortality will be higher and growth rate reduced in the presence of abundant predators (Cobb 1995). Tethering experiments indicate that predation mortality on lobster is higher in southern New England than in the Gulf of Maine (Brown 2007). Variations in predation pressure have been advanced as a possible reason for the decadal increase and recent decline of lobster stocks (ASMFC 2006, Steneck 2006). To test for an impact on settlement, an index of predator abundance was constructed from the RIDFW trawl survey database.

Lobster in the Rhode Island area have experienced an epizootic outbreak of shell disease in the past decade (Castro and Angell 2000, Dominion 2008). The proportion of animals infected increased from trace amounts in 1996 to over 30% by 2002 based on RIDFW sea sampling data. It is important to note that most of the expansion of shell disease occurred from 1996 to 1999 before any methoprene was used. Females express about double the rates of disease occurrence of males owing to their much longer intermolt period (older shells). Shell disease is the bacterial degradation of the external shell and is believed to occur when the rate of bacterial cuticle degradation exceeds the rate of internal deposition by the lobster (Tlusty et al. 2007). Severe cases can result in death or premature molting with loss of the egg clutch (RIDFW- unpublished data). The implications to reproductive success and resource sustainability are obvious. Female rates of shell disease for 1990 to 2007 from RIDFW sea sampling were summarized for this study.

Atmospheric and oceanographic conditions, particularly current pattern and wind strength, are believed to influence the distribution and transport of surface dwelling post-larvae (Fogarty 1983, Hudon 1994, Incze and Naimie 2000, Xue et al. 2006). Modeling exercises and empirical evidence support the hypothesis that inshore lobster stocks receive a subsidy of larvae produced by offshore stocks (Katz et al. 1994, Fogarty 1998, Crivello et al. 2005). Indeed, stock-recruit models for crustaceans can sometimes be improved by adding key environmental variables (Penn and Caputi 1986, Wahle 2003). The North Atlantic Oscillation (NAO) has been suggested as a mechanism influencing fishery production including lobster on broad geographic scales (Oviatt 2004, Sullivan et al. 2005, JS Cobb pers. comm.). The winter NAO index is a measure of the atmospheric pressure differential between Greenland and the Azores during December to March. Variation in the winter NAO is associated with changes in the position of the jet stream, frequency of storm events, and patterns of temperature, wind, and precipitation during the year (Hurrel 1995). As such, it may influence the transport, survival and settlement of lobster in near shore nursery areas. The winter NAO index was downloaded from the NOAA national weather service climate prediction center website (http://www.cpc.ncep.noaa.gov/).
Finally, I examined methoprene usage in Rhode Island as a variable linked with settlement success as proposed by industry. Since a time series of application amounts was not available, it was treated as an indicator or dummy variable (Box and Draper 1987). For years 1990 to 1999 the variable was assigned a value of zero while for years 2000 to 2007 it was set at 1.0, consistent with the state history of West Nile control efforts and provision of methoprene to municipalities. A summary of the auxiliary variables used is found in Table 2.

Analytical Methods-

Broad Scale Approach- I examined the relationship between settler abundance, spawner abundance, and auxiliary variables at the fishery spatial scale using the Ricker stock-recruitment (S-R) model. S-R models are usually applied to generational data in the form of parental abundance and resulting progeny. However, their theoretical underpinnings are derivations of how mortality rates operate between successive stages of a cohort (Rothschild 1986). Although the Beverton-Holt asymptotic S-R model is arguably more appropriate for lobster (Fogarty and Idoine 1986, Caddy 1986), Ricker’s over compensatory curve has better statistical properties particularly when adding additional explanatory variables. In that case, the linearized version of the model has the form of a multiple regression equation the properties of which are better understood (Hilborn and Walters 1992). It is particularly useful in examining factors inducing non-stationarity in S-R relationships as was done by Walters et al. (1985) and Gibson and Wahle (2005). The behavior of alternative S-R curves at very high stock abundance is unimportant in this study although it may be relevant to management of restored resources. Ricker’s (1975) classic S-R curve has the form:

\[ R = \alpha S \exp(-\beta S) \]  \hspace{1cm} (1)

where:
- \( R \) = recruitment (settlers)
- \( S \) = spawning stock index
- \( \alpha \) = maximum rate of recruitment
- \( \beta \) = coefficient of compensatory mortality.

The \( \alpha \) parameter defines the slope at the origin of the curve or the maximum rate of recruitment in units of settlers per spawner. The \( \beta \) parameter defines the density dependent mortality rate per unit of spawning stock. The curve rises from the origin to a maximum recruitment at a spawning stock level equal to \( 1/\beta \). From the maximum, the curve declines monotonically with further increase in spawning stock. A regression solution to the Ricker curve given a set of data can be found using the linearized version that assumes lognormal errors:

\[ \ln(R/S) = \ln(\alpha) - \beta S + \epsilon \]  \hspace{1cm} (2).

The transformation in eq.2 reveals the classical mortality rate derivation of the Ricker model. Overall mortality rate from spawned eggs to recruitment is composed of a density
independent factor and a factor dependent on initial cohort abundance. When factors other than spawner abundance are thought to influence mortality, they can be included in the model as auxiliary variables:

\[ \ln(R/S) = \ln(\alpha) - \beta S - \gamma C + \varepsilon \]  

where: 
- \( \gamma \) = coefficient of mortality due to auxiliary factor
- \( \varepsilon \) = lognormal error term.

In this study, settler abundance was considered the measure of recruitment (R). Two proxies for spawner abundance (S), fishery egger CPUE and trawl CPUE of reproductive size females were considered. The five auxiliary variables noted above were tested for significance in term C of eq.3. In total, 12 regression models were fit, two with spawner indices alone and five auxiliary variables tested with each of the 2-spawner abundance indices. Regressions were computed in EXCEL. Model output and residual diagnostics were reviewed. Regression F–statistics and Akakie’s information criterion (AIC) were computed and used to select the best fitting model.

**Fine Scale Approach** - The above approach, utilizing fishery and research survey data, examines lobster population dynamics on a broad spatial scale, corresponding to what is known as the Rhode Island “inshore area”. This includes Rhode Island state waters and federal waters of RI Sound out to Cox’s Ledge, officially statistical reporting area 539. Given the relatively small amounts of methoprene used in storm drains, the enormous marine dilution factors, and the short half life of the chemical, it might be expected that any adverse impacts would occur on a relatively small scale, that is very close to the points of application. To more closely look for methoprene impacts to lobster, I focused on the Black Point area of Narragansett. Methoprene usage by the town has been relatively high in the 204 catchment basins of the Eastwood Look and Scarborough Hills neighborhoods (A. Gettman- pers. comm.). RIDFW maintains lobster settlement and bottom trawl sampling stations just offshore of Black Point. To test for an impact to YOY, I split the Black Point settlement survey data into 2 time series, 1990-1999 (no methoprene) and 2000-2007 (methoprene used). Mean YOY abundance by time period was tested for significant difference using a two-sample t-test assuming equal variances. The same test was also applied to age 1+ lobster abundance data from the same survey. A final t-test was applied to catches of lobster in the RIDFW bottom trawl stations off Black Point with the same year blocks. Significant differences were assessed at the standard P=0.05 level. Use of the t-test on time series data assumes that the observations within each time block are independent, have constant mean and variance and are not serially correlated. Ignoring the latter when present can bias the estimation of variance in t-tests. The data series in question however are too short for use of formal time series methods. Serial correlation was assumed to be zero based on data plots at lag 1.

**Results**
Fishable and recruit lobster abundance in Narragansett Bay and Rhode Island coastal waters increased from 1979 to 1997 and supported a major commercial fishery through 2000 (Figures 3 and 4). The population and fishery collapsed to low levels by 2002-2004. This decline was preceded at the appropriate demographic interval by the collapse of the YOY index in 1995 and 1996 (Figure 2). Low abundance of these cohorts is confirmed one year later by the trawl data for the smallest size class regularly captured (Figure 5). The failure of the 1995 and 1996 cohorts to settle was a watershed event for the local population and fishery that depends almost entirely on new recruits, that is animals that have just molted to the 86 mm legal size (ASMFC 2006). An oil spill in January of 1996 inflicted a major mortality event on the already weak 1995 and older juvenile cohorts. Over 9 million lobster with a modal length of 26 mm were killed. These circumstances were unrelated to methoprene usage but together blew a huge hole in the demographics of the juvenile population that eventually made its way into the adult, fishable stock.

Survivors were further compromised by shell disease. This epizootic is unlikely related to methoprene since the outbreak and expansion occurred in RI and eastern CT before methoprene usage began in 2000 (Figure 6). The recent trawl data indicate that the lobster population has increased somewhat through 2007 probably due to the 1997 and 1999 cohorts of YOY and reduced fishing mortality on females (Gibson and Angell 2006). The recovery may not be sustained because of weak cohorts in 2000 and 2002 and cessation of v-notching.

Results of fitting the suite of Ricker S-R models were informative and are summarized in Table 3. Models using the summer trawl index of spawners were generally superior to those using egger CPUE from commercial fishery monitoring (model 1 vs. 7). This is not surprising since the ability to fit S-R models reliably depends in part on the range in variation of spawner abundance (Hilborn and Walters 1992). Fishery egger CPUE only ranges 3-fold and displays hyperstability in comparison to research trawl abundance (10-fold variation). It is not known why commercial catch rates vary less than the research trawl but the ability of industry to mitigate low abundance by modification of fishing practices and trap saturation at high abundance is suspected. The addition of auxiliary variables improved S-R model performance especially the NAO index (models 3 and 9). Shell disease, water temperature and predator abundance did not make significant contributions so models containing them were not considered further. Methoprene, when paired with egger CPUE, was not significant (p=0.085) and model 2 was clearly inferior to egger CPUE with the NAO index (model 3) in terms of the F-statistic and AIC. Further, when paired with the trawl index of spawners (model 8), the methoprene parameter was still not significant (p=0.103). The best fitting model was for the trawl index of spawners paired with the NAO index (model 9). It explained 77% of the variation in settlement and it was the only model in which all three parameters were judged significant at P<0.05. This model had the 2nd highest F-ratio and the lowest AIC. It was the only model in which estimation of both the α and β parameters of the Ricker model was improved by an auxiliary variable. Model 9 predicted settler abundance well and tracked the observed data (Figure 7). These results strongly suggest that settler abundance in RI has not been impacted by methoprene use but rather that settler abundance is a function of local egg abundance and oceanographic conditions that deliver
larvae from more distant locations. Compensatory mortality at higher egg abundance is also indicated.

Mean abundance of YOY at the Black Point station is plotted in Figure 8. Mean density of YOY from 1990 to 1999 was 0.58 with a standard error of 0.34. From 2000 to 2007, mean YOY density was 0.73 (SE=0.50). There was no significant difference in the YOY means (t=0.67, P=0.26). Mean density of age 1+ lobster from 1990 to 1999 was 0.86 with a standard error of 0.54. From 2000 to 2007, mean 1+ density was 0.88 (SE=0.43. There was no significant difference in the 1+ means (t=0.10, P=0.46). Trawl abundance of lobster near Black Point is plotted in Figure 9. As with the settlement survey data, there is no clear pattern before and after onset of methoprene usage in 2000. Mean lobster abundance from 1990 to 1999 was 6.22 per tow with a standard error of 4.76. From 2000 to 2007, mean abundance was 6.86 per tow (SE=5.53). There was no significant difference in the means (t=0.26, P=0.40). These results strongly indicate that there has been no reduction in lobster abundance near a known site of methoprene use since 2000 when applications began.

Discussion-

Detailed analysis of abundance and mortality rate for several life stages of lobster in the Rhode Island area failed to reveal any evidence that the methoprene used in mosquito control programs has had any impact on the local lobster population. Methoprene is a growth disruptor for invertebrates that grow through molting and metamorphosis. It has the potential to kill and alter molting of larval lobster and may interfere with chitin deposition in shells of juveniles and adults (Walker 2005). The capable concentrations however are far above that likely to occur near the outfall of treated storm drains (Butler 2005). Moreover, the relatively short half-life of methoprene in water (Schaefer and Dupras 1973) and the enormous dilution factors operating on spatial scales of the fishery make it extremely unlikely that adverse impacts have occurred. Methoprene did not consistently improve the fit of S-R models applied to lobster settlement and spawner abundance data indicating that there was no incremental effect on larval mortality associated with the pesticide use on a broad fishery scale. At a finer spatial scale, Black Point Narragansett, there was no evidence that abundance of settler, juvenile, or adult lobster was lower during years of methoprene usage (2000-2007) than years prior to usage (1990-1999).

Lobster in southern New England have experienced an epizootic outbreak of bacterial shell disease. It is likely that mortality rate in lobster has been increased by the disease (Gibson and Wahle 2005, Dominion 2008, ASMFC 2006). The outbreak however began in 1996, accelerated in 1997, and was well underway by 1999, before any methoprene treatments began. It is unlikely that methoprene had anything to do with a disease that still affects over 20% of the animals in the area. That is not to say that shell disease has not impacted the lobster population. It has likely killed some animals outright, induced abortive molts in some egg bearing females, and reduced growth rate in other animals. Still, with tens of thousands of animals examined the number dying remains relatively low at about 3% (Dominion 2008) and abortive molts are very rare and show no pattern.
with regard to methoprene usage (Figure 10). Continued study of the disease is warranted but it does not appear that methoprene is a strong candidate for new research. Altogether, the results do not support a methoprene impact hypothesis. Methoprene was similarly indicted in Long Island Sound as cause for a lobster die off but ultimately no evidence was found and increasing water temperatures were deemed more likely responsible (Dove et al. 2005).

The S-R modeling exercise did indicate that the abundance of new settlers in our area is a function of both local egg abundance and environmental factors operating on large spatial scales. The NAO index greatly improved the fit of the S-R models whereas methoprene, temperature, predators and disease status did not. The final, best model had local egg abundance as a compensatory mortality factor with NAO as a modulating density independent factor. Good lobster settlement occurs when local egg abundance is adequate and when the NAO is strongly positive. Conversely, poor settlement can occur even with good egg abundance if the index is strongly negative. It is believed that the NAO index represents a suite of key oceanographic and climatic factors that are important to larval delivery and survival. This belief is consistent with the view of Stenseth and Mysterud (2005) that the population dynamics of a number of animal taxa are more correlated with broad, integrative indices than local factors with arguably more mechanistic operation. Additional evidence of the large spatial scale of operation can be found in the fact that larval lobster abundance at MPS in Niantic CT is also positively correlated with the same NAO index studied here (r=0.41, P=0.04, df=22). MPS is about 40km away from Pt. Judith and lobster larvae have been sampled at the plant in the condenser cooling water since 1984 (Dominion 2008). Further, the long-term URIGSO trawl survey catch of lobster in Narragansett Bay is positively correlated with the NAO at lag seven years (r=0.49, P<0.001, df=46). Other lags from 0 to 10 had lower correlations. Seven years is approximately the generational lag from larval to adult lobster. The S-R modeling results from above, the noted regional NAO correlations, lobster tagging results at MPS (Dominion 2006), and the microsatellite analysis of larvae at MPS by Crivello et al. (2005) strongly support the interconnectiveness hypothesis of Fogarty (1998) for inshore and offshore lobster populations. Migration of adults from inshore to offshore waters and advection of larvae from offshore spawners to inshore nursery areas likely provides for a stabilizing system for heavily exploited inshore populations.

Although this study failed to implicate methoprene as a factor in poor settlement and low lobster abundance, valuable understandings were achieved. It should be clear that egg abundance and programs such as v-notching to increase population fecundity are valuable albeit on larger scales than currently practiced. Good lobster settlement is unlikely to occur when egg production is very low even if environmental factors are accommodating. Egg reservoirs in both the inshore and offshore areas are essential to long-term stock stability. On the other hand, high egg abundance does not guarantee good settlement. These conclusions are not surprising in view of the meta-analytic work of Meyers and Barrowman (1996) who showed that S-R relationships are the rule rather than the exception and Wahle (2003) who concluded that crustacean S-R relationships are frequently obscured by environmental factors. Still, high egg production is a safer recruitment bet for exploited fish stocks. It is clear that the collapse of the Rhode Island
inshore lobster stock and fishery in 2002-2004 and continued low abundance is not due to methoprene application. It occurred as a result of a “perfect storm” of failed settlement by the 1995-1996 cohorts, an acute mortality event (1996 oil spill) that winnowed extant juvenile populations, chronic shell disease, and overfishing (truncated age structure). The first factor was unavoidable, fishery managers can not control long-term forcing by climatic events. The second event while technically avoidable, was a result of human error that happens from time to time. The magnitude of shell disease as a mortality agent has yet to be fully understood but is believed low. Overfishing in the lobster fishery is given short shrift among all the factors that can be blamed. Despite the warnings of three peer reviewed stock assessments (ASMFC 1996, 2002, 2006) it is still not appreciated how vulnerable a recruitment based fishery is. The truncation of the inshore lobster size composition by fishing is well known such that mean catch weights today are about one quarter of what they were 140 years ago (ASMFC 2006). The vulnerability of truncated populations and the fisheries that depend on them is also established (Anderson et al. 2006, Fogarty and Gendron 2004, Hseih et al. 2008). Had overfishing not been the rule for decades, the inshore population would likely have been able to buffer some of the cohort failures and anthropogenic insults encountered. Annual fishery yields are a mortality-growth convolution of several past cohorts. Under low fishing mortality (F), yield is spread across many cohorts, in effect a moving average of high order. When F is high, yield is derived from a narrow moving average of cohorts. High F insures that cohort failures, occurring for whatever reason, will seriously harm the fishery. Fishery managers should reduce F on over exploited lobster populations so as to make them less vulnerable to factors outside of managerial control. Direct output type controls may become increasingly necessary if industry does not commit to voluntary v notching on a large scale. Measures to increase egg production such as v notching need to be considered on broader spatial scales than currently practiced given the interconnectedness of the populations.

Acknowledgments

This study would not have been possible without the considerable efforts of several Fish and Wildlife staff members. Tim Lynch has faithfully sampled lobster in the Division bottom trawl survey for 30 years. An understanding of local population dynamics would be absent without his dedication. Tom Angell has sampled lobster on board commercial fishing vessels for 20 years. His meticulous observations underpin much of what we know about molting, reproduction, and shell disease in inshore lobster. Dr. Stan Cobb of the University of Rhode Island has spent a career studying lobster and provided valuable discussions on larval lobster dynamics. Dr. Jeremy Collie of the University of Rhode Island Graduate School of Oceanography provided corroborating lobster abundance data from the schools trawl survey.

Literature Cited


Gibson, M.R. 1998. Potential egg production from lobsters killed in the North Cape oil spill and replacement estimates using recycled commercial catch. Rhode Island Division of Fish and Wildlife, Wickford RI.


Table 1- Abundance Indices Used in the Ricker Models
Relating Settlement Strength to Measures of Spawner Abundance.

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<th>Year</th>
<th>Settlers</th>
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<th>Trawl CPL</th>
<th>BP YOY</th>
<th>BP Trawl</th>
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<td>0.55</td>
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<td>1.50</td>
<td>4.83</td>
</tr>
<tr>
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<td>0.56</td>
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</tr>
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<td>0.63</td>
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<td>0.00</td>
<td>3.86</td>
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</table>

/1 Mean density of YOY lobster (No. per m²) in the RIDFW settlement survey
/2 Mean number per trap haul of egg bearing lobster in RIDFW sea sample survey
/3 Mean number per tow of 73+ mm female lobster in RIDFW summer trawl survey
/4 Mean density of YOY lobster (No. per m²) at the Black Point
/5 Mean number per tow of all lobster in RIDFW trawl survey near Black Point
Table 2- Auxiliary Explanatory Variables Used in the Ricker Models Relating Settlement Strength to Measures of Spawner Abundance.

<table>
<thead>
<tr>
<th>Year</th>
<th>/1</th>
<th>/2</th>
<th>/3</th>
<th>/4</th>
<th>/5</th>
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<td>1990</td>
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<td>0.00</td>
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<td>0.54</td>
</tr>
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<tr>
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<td>0.71</td>
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<td>1.00</td>
<td>0.32</td>
<td>11.84</td>
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</tr>
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<td>1.00</td>
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<td>1.00</td>
<td>0.38</td>
<td>13.43</td>
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</tbody>
</table>

/1  Proportion of females infected from RIDFW commercial pot sampling
/2  Indicator variable, 0=no use, 1=use
/3  North Atlantic oscillation index, mean of Dec-March values
/4  Mean water temperature in RIDFW trawl surveys
/5  Mean catch per tow of lobster predators in RIDFW trawl surveys
Table 3- Summary of Ricker Type S-R Models Fit to Lobster Settlement Data and Several Estimators of Spawner Abundance and Auxiliary Variables

<table>
<thead>
<tr>
<th>Model No</th>
<th>SSB Estimator</th>
<th>Auxiliary Variable</th>
<th>R2</th>
<th>SE Reg.</th>
<th>F Ratio</th>
<th>F Prob</th>
<th>No.Parms</th>
<th>No. Sig.</th>
<th>Aux Prob</th>
<th>AIC</th>
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</thead>
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<tr>
<td>1</td>
<td>Egger CPUE</td>
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<td>Methoprene</td>
<td>None</td>
<td>0.281</td>
<td>0.592</td>
<td>2.927</td>
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<tr>
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<td>NAO Index</td>
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<td>0.549</td>
<td>4.614</td>
<td>0.027</td>
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<tr>
<td>4</td>
<td>Predators</td>
<td>None</td>
<td>0.160</td>
<td>0.639</td>
<td>1.433</td>
<td>0.269</td>
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<tr>
<td>5</td>
<td>Temperature</td>
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<td>0.174</td>
<td>0.634</td>
<td>1.577</td>
<td>0.239</td>
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Fig.1- Lobster Egg Abundance in Area 2 Based on RIDFW Sea Sampling Data
Fig. 6 - Incidence of Shell Disease in Rhode Island Inshore Lobster and at Millstone Power Station, Niantic CT

Figure 7 - Observed and Model Predicted Lobster Settlement Density in RI Waters
Figure 8- Abundance of YOY Lobster at the Black Point Dive Station Before and After Methoprene

Figure 9- Lobster Abundance in the RIDFW Seasonal Trawl Survey in the Vincinity of Black Point, Narragansett
Figure 10- Proportion of Female Egg Bearing Lobster Undergoing Molting by Year Observed in RIDFW Inshore Sampling