FINAL REPORT

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Investigators: Kevin Stokesbury, Principle Investigator
School for Marine Science and Technology (SMAST),
University of Massachusetts Dartmouth,
706 S. Rodney French Blvd., New Bedford, MA, 02744
(508) 910-8193 Fax: (508) 999-8197
kstokesbury@umassd.edu

Talia Bigelow, Research Assistant
School for Marine Science and Technology (SMAST),
University of Massachusetts Dartmouth,
200 Mill Road, Fairhaven MA, 02719

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SUMMARY

In 1996, an oil spill off the Rhode Island coast killed an estimated nine million lobsters. Protection of female lobsters through a V-notch program was chosen as a restoration tool, aimed at increasing local egg production and recruitment. This report includes a review of restoration program documentation and implementation, database analysis, and indirect evaluation of population effects. Although some design features of the restoration program were violated (e.g., delayed implementation, uneven V-notching among years), our audit of the monitoring data indicates that the target number of females was surpassed, and the expected egg production was achieved. Mark-recapture models were used to evaluate changes in population abundance during the restoration effort. V-notching does not provide a discrete mark, so batch-tagging models (Schnabel, Schumacher and Eschmeyer, and Overton) were applied to the V-notch data. These methods were modified to account for mortality and mark-loss, thereby relaxing conventional model assumptions. Results from analysis of V-Notch mark and recapture data suggest a significant increase in the population during the restoration effort. However, statistical diagnostics indicate that model assumptions were violated and V-notch results have substantial uncertainties. Analysis of a smaller sample of banded lobsters using the Jolly-Seber family of models was more reliable and also indicates a significant population increase (approximately 6% per month) for the duration of the banding study. Therefore, these analyses indicate that the restoration effort met its V-notching goals, and there was a significant increase in the population during the program.

INTRODUCTION

Background

<u>The North Cape Oil Spill</u>

Off the south shore of Rhode Island the barge *North Cape* ran aground during a winter storm on January 19th, 1996. Approximately 828,000 gallons (20,000 barrels) of type 2 home heating fuel spilled into the ocean. The winter storm and physical ocean processes caused extensive mixing of the oil. Low temperature and high turnover inhibited evaporation and lateral diffusion. A second winter storm five days later brought the oil, which had been dissipating, back into the sensitive intertidal zone, resulting in substantial mortality of marine organisms (Gibson *et al.,* 1997). A model of the oil's fate demonstrated that less than 15% of the oil was on the surface and the majority of oil was in the water column, creating a significant pelagic and benthic impact (French McCay, 2003).

As a result of the spill, a large number of moribund and deceased animals washed ashore, including birds, clams, crabs, sea stars, finfish, other benthic microfauna, and the American Lobster, *Homarus americanus.* Quantitative or qualitative samples of most impacted species were difficult to obtain because they were too quickly consumed or washed away. However, extensive effort was put into sampling the lobster population. Invertebrate losses appeared to be greater than that for finfish, because they were locally more abundant and susceptible to the oil. Further modeling of all mortality showed that while the highest mortalities were centered around the spill site, most sites were not continually exposed because of tidal cycles (French McCay, 2003). A map of the effected area can be seen in Figure 1. While the effect of the oil spill was extensive, this report is focused on the American lobster (*Homarus americanus*) mortalities and the subsequent restoration of the population.

<u>Impact Assessment</u>

A size-based model by Gibson *et al.* (1997), which utilized estimates of moribund lobsters from beach transects, was performed to assess the extent of mortality. Seven beaches exhibiting the highest mortality rates were selected for this study. Lobsters as small as 9mm in carapace length were observed washed up, which was expected because smaller lobsters are known to be more susceptible to oil contamination. In the study, lobsters were sampled and later removed from transects, during which sex, length and reproductive stage were recorded. Sampling was conducted once a day at low tide for a period of 13 days. Transects located across a wide variety of terrain were sampled daily, except when conditions made sampling difficult. Control beaches were also monitored, although the low occurrence of dead lobsters made transects unnecessary.

The total estimate of mortality across the entire impacted area was extrapolated from mean quadrat densities (Gibson *et al.,* 1997). The estimated losses were 1.78 million, with a confidence range from 1.28 to 2.28 million lobsters (Gibson *et al.,* 1997). According to transect data, the majority of the 1.78 million were lobsters that were smaller than the contemporary legal size of 82.6 mm in carapace length (Gibson *et al.,* 1997). This suggests that the majority of lobsters impacted were from one to seven years old, because it takes approximately seven years to grow to legal size (Factor, 1995). Once adjustment was made for incompletely sampled small size groups, the total losses were increased to 2.92 million.

Several sources of uncertainty were associated with the mortality extrapolation. These included incomplete accounting (e.g., individuals that did not wash ashore, those that died after one month, etc.), scavenger loss, public interference, misrepresentative samples, underestimation of impact area, double counting, station bias, and statistical problems (i.e., log transformation did not fully normalize the data) (Gibson *et al.,* 1997).

A subsequent study was performed by Cobb and Clancy (1998 a and b), which used dive sampling to estimate mortality in the water column. The focus was on the differences between impacted and non-impacted areas, using data from side-scan sonar to create habitat maps. Twenty-one stations were sampled in both non-impacted and impacted areas, with visual surveys conducted for the larger lobsters (Mauseth *et al.*, 2001). For young-of-the-year or smaller lobsters, both visual identification and airlift sampling (in which a suction system draws small lobsters from complex habitat) were used for separate calculations of abundance. A 20% correction for under-sampling was also included in the estimate of adult lobsters, based on divers' tests with a known number of blue plastic chips. Cobb and Clancy (1998a) verified that smaller lobsters were more susceptible to the oil spill. Calculations from their study estimated total mortality to be nine million individuals, with an uncertainty of plus or minus 30% (French 1999). This uncertainty comes from the lack of a reliable estimate of the pre-spill abundance (French McCay, 2003).

A model was developed to apply oil fates and biological effects to oil spills in varying locations by French-McCay (2003). The model was a practical way to quantify oil impacts when data collection was not possible. This model estimated all of the mortalities for many of the impacted species stated above and estimated total deaths of 8.3 million for the lobster. While this model provides results comparable to the field estimates, a level of uncertainty is associated with both. Uncertainty in the model stems from the toxicity parameter, because there was a discrepancy between the assumed parameter and the samples from bioassays. Imprecision in the estimate of 8.3 million should be considered. The ultimate estimate of total deaths used in the restoration effort was nine million. The North Cape Marine Technical Working Group, which was charged with estimating total lobster mortality, concluded that the estimate by Cobb and Clancy (1998a), of approximately nine million lobsters, was the best estimate (French, 1999). Their decision was based on model estimates, and the approximate extrapolation of around three times those that were estimated to be stranded by Gibson *et al.* (1997).

Long term effects of the oil spill were also considered. In the winter of 1996, directly after the oil spill, a sample of ovigerous females showed no significant differences in egg quality associated with the oil exposure (Mauseth *et al.*, 2001). This observation indicates that despite a high susceptibility to oil exposure, a short period of time was sufficient to allow larvae to disperse and potentially provide viable additions to the population. Planktonic sampling in the summer of that year indicated low abundance, but recruitment was generally weak throughout southern New England (Mauseth *et al.*, 2001).

According to Mauseth *et al.,* (2001), while the population was projected to recover on its own by 2001, the Oil Pollution Act of 1990 required compensation for the lobsters lost that would not be recovered naturally. More specifically, the Act requires that the resources detrimentally affected be returned to a baseline condition, and that interim losses of resources and services be compensated as well. The party responsible for the spill was therefore required to fund a restoration plan that involved restoration, replacement, or acquisition of equivalence to that lost in the spill. A restoration plan was designed by a group of state and federal natural resource Trustees, in conjunction with the responsible party. The National Oceanic and Atmospheric Association (NOAA), one of the Trustees, has Natural Resource Damage Assessment (NRDA) regulations, which outline a process of pre-assessment, restoration planning, and restoration implementation. Coincidentally the NRDA rule for oil spills was published on January 5th, 1996, just prior to the oil spill, making the *North Cape* oil spill the first and largest NRDA case under the Oil Pollution Act NRDA regulations (French McCay, 2003). The Trustees were responsible for documenting the success of the project (Mauseth *et al.*, 2001). The final decisions on restoration were reached and the case successfully settled in 1999 (French McCay, 2003). In this case, the Trustees and Responsible Party agreed to depend on natural restoration to aid in the primary restoration expected by 2001. Compensatory restoration, however, was needed to restore those portions that were lost and would not recover naturally.

The Lobster Resource

Restoration of the lobster population was a priority because it is an important commercial resource (ASMFC, 2006). High fishing mortality rates in the US and Canada have raised concerns about the state of the lobster population in general (Castro *et al.,* 2001). The lobsters affected by the spill are part of the southern New England stock (Figure 2), for which there is particular concern (ASMFC 2006).

The two states involved in the restoration, Rhode Island and Massachusetts, are joined by coastal states from Connecticut to Maryland to comprise the southern New England stock (ASMFC, 2006). Rhode Island and Massachusetts comprise 37% and 14% of the total southern New England stock catch, and 32% and 15% of the traps fished, respectively (ASMFC, 2006). The regional fishery consists mostly of small vessels that make day trips in nearshore waters (75%), but the southern New England fishery also has an offshore component which constitutes 25% of the landings (ASMFC, 2006). The number of traps in the water peaked in 1999, a five fold increase through the 1980's, but a 50% from 2000-2003 (ASMFC, 2006).

Southern New England is the second largest fishery, and accounted for 21% of the total US landings between 1981 and 2003 (ASMFC, 2006). Accordingly, this stock is valuable both economically and socially, supporting a large number of workers. A record increase in landings began in the 1980's and continued on to record highs from 1997 to 1999 (ASMFC, 2006). Landings subsequently declined for the next six years (ASMFC, 2006). In 2003, there were record low landings, comprising only 12% of the total US landings (ASMFC, 2006).

The amount of stock decline attributable to the oil spill and its effects remain unknown. The 2006 assessment for the southern New England stock indicated that a reduction in fishing effort was needed to meet target biomass levels (ASMFC, 2006). Specifically, a 10% reduction in fishing mortality was recommended to achieve the desired fishing rate (Gibson and Angell, 2006). It was suggested that natural mortality has increased since 1996, but the magnitude of the increase was unknown (ASMFC, 2006). Uncertainty in natural mortality confounds the estimates of fishing mortality because both contribute to total mortality. Despite uncertainty in the stock assessment, it is clear that the stock is declining, and a rebuilding plan is needed (ASMFC, 2006).

Restoration Plan

In order to restore the lobster population as per the NRDA regulations, a target number of lobsters to replace the population was required to restore the estimated nine million lost. The North Cape Marine Technical Working Group created a length-based population model to establish these restoration objectives (French, 1999). The total instantaneous rate of mortality for legal-sized lobsters was estimated to be 1.5, with a natural mortality of 0.1 and a fishing mortality of 1.4 (French, 1999). This differs significantly from the 2006 Stock Assessment (ASMFC, 2006), which assumed that legal-sized lobsters experience a natural mortality rate of 0.15 and a fishing mortality of 0.84 during 2001-2003, meaning a total instantaneous rate of 0.99 for legal sized lobsters. The total instantaneous rate of mortality for the juvenile stage, according to French (1999), was 5.0 (from 7mm to 82.6mm in carapace length). This value applies to the time of settlement until reaching legal size.

A mortality schedule was assumed to determine the number of eggs required for restoration (French, 1999). It was estimated that it would take 681 million stage IV lobsters to restore the nine million lost lobsters using Gibson's (1997a) size distribution of post-spill, stranded lobsters. The number of eggs needed to produce that many larvae was estimated using a survival rate of 0.0206; the resulting estimate was 17.2 billion eggs needed to restore the 681 million stage IV lobster (French, 1999). Gibson (1998) used a similar process but estimated around 18 billion eggs were needed. However, the 17.2 billion estimate was used to develop the restoration effort (Mauseth *et al.*, 2001).

The Trustees decided to use V-notching of female lobsters to facilitate the restoration objective. Gibson (1998) subsequently estimated that 0.97 million adult, V-notched females lobsters would be needed to meet that objective, assuming a 5% handling loss, a compliance (by lobstermen) of 50% and a retention time of the V-notch of two years. He based his estimates on survivorship, fecundity, and maturity.

As French (1999) pointed out, however, there would be a differential lag in the restoration of each age class to create the desired full age structured population, meaning this estimate of 0.97 million females would need to be revised further to compensate for the period of missed biological and fishery production. Assuming that the restoration would start in 2000, there would be a seven year lag to restore the 1-2 year olds, an 8 year lag for 2 year olds, and so on. French (1999) used this lag time in conjunction with 3% annual discount rate, applied to the estimates of females needed, to discount the number of egg equivalents for each age class:

$$Discounted\_Value = \left[\frac{1}{(1+d)}\right]^{L} \quad \text{(Equation 1)}$$

where d is the discount of 0.03 and L is the lagged number of years after the spill. This discount rate was then multiplied by the fraction of egg equivalents needed for each age class and summed to create the percent of eggs needed total (78%). This fraction was then divided by 1 (1/.784=1.28) to create an overall expansion factor of 1.28 for lag time.

This expansion factor can then be multiplied by the number of females needed to get the ultimate number needing to be V-notched.

Rather than use the discount value for every age class, (years 1 through 15), however, French (1999) then changed all discount factors for lobsters aged five and older to 1. Her reasoning was that the 1.28 expansion factor assumes that all restocked lobsters would be egg producers, and that they would be replacing ecological and human services immediately. This revision changed the expansion factor to 1.31. The 1.31 rate, multiplied by the number of required restocked females, provided the final number of 1.26 million female lobsters to be V-notched over five years, beginning in 2000, with the provision that the stocking occurred in equal numbers each year.

According to Mauseth *et al.* (2001), once all the calculations had been completed, the Trustees and Responsible Party finally decided on a value of 1.248 million female lobsters needed from the inshore population to restore the 9 million lost. This reduction from the initial estimate of 1.26 million was to account for 12,300 lobsters that were purchased, examined, and returned to the population immediately following the oil spill by the Responsible Party. French (1999) also advised that the females be returned over a wide area, because local female restoration of that magnitude would make it difficult for them to find a male mate.

The V-Notch Program

Many options were considered for restoring the population to its original size, including stocking young lobsters and buying lobsters from fishermen to return to the sea (French, 1999). Other methods considered included transplantation of juvenile lobsters, lobster habitat enhancement or creation, and creation of a sanctuary population (Colburn *et al.*, 2005). V-notching of non-egg bearing females was finally chosen as an appropriate restoration method because logistical, practical, and cost effectiveness made it difficult for the other possibilities to reach the goal of restoring nine million lobsters to the southern New England stock (Mauseth *et al.*, 2001).

A V-notch is cut into the endopodite of the uropod of the lobster using a V-shaped tool, as can be seen in Figure 3. The integument heals within 24 hours while the V-shape remains missing (Getchell, 1987).V-notching has been used for decades to protection mature females from harvest (Daniel *et al*., 1989). The notch indicates to a lobsterman that the lobster is a reproductive female, and she cannot be legally harvested, so long as the notch lasts (Mauseth *et al.*, 2001). The female has the ability to produce one, or sometimes two, clutches of eggs, before molting, over a period of one to three years (Talbot and Helluy, 1995). The molt process results in the loss of the V-notch. Protecting reproductive females from harvest like this is a particularly effective measure to increase reproduction (French, 1999). It also helps increase the yield of larvae per lobster. Most females are harvested soon after the onset of maturity, but by allowing them to grow to a larger size before harvest their reproductive and fishery yield is increased (Mauseth, *et al.* 2001).

The schedules of molting and reproduction have a complex association, particularly for female lobster (Cobb and Phillips, 1980). Mature males typically molt as water warms each spring and mate after the shell hardens (Aiken and Waddy, 1980). Mature females that are not carrying a brood of eggs and are not inseminated also typically molt as water warms (presumably later than males). Females mate while in a soft-shell condition, carry sperm for later extrusion in a hard-shell condition, and carry fertilized eggs until the following spring when eggs hatch. Given this series of events and the timing of initial spring molt and hatch, females are thought to have a two-year molt and reproductive cycle. However, there appear to be exceptions to this typical cycle (e.g., Waddy and Aiken 1990, Castro *et al.*, 2003).

The duration that a V-notch is retained is an important factor for accurately assessing egg production because the retention time of the notch influences the number of eggs that can be produced (Castro *et al.,* 2003). In setting their restoration objectives, the Trustees assumed that nearly all females that were V-notched in the restoration were smaller than 95mm, based on the size of legal catch sampled in Southern New England, These lobster were assumed to have a 2-year molt cycle in the initial calculations of the size of the restoration needed. The few, larger females (up to 105mm) were assumed to have 2-4 year molt frequency. Based on the observed size range of lobsters V-notched in the restoration program, essentially all females were assumed to be mature as well (Mauseth *et al.*, 2001)

A recent study by Castro *et al.* (2003) suggests that retention time may be shorter. Her study, which held 60 V-notched lobsters of legal size, found that 26 did not molt in the first year, but four still lost their mark. Of the 34 that did molt, 56% lost their legal V-notch status when the mark fully healed, but only 19% lost their mark when double-V-notched. Double V-notching involves pulling down the tissue that forms a new exoskeleton and V-notching it as well. The study also tested evidence by Nutting (1991) that showed that some V-notches partially healed within eight to twelve weeks. Castro *et al.* (2003) found evidence of this growth in the four that lost their mark without molting. Several other holding experiments were conducted to assess the retention of V-notches after one to several molts, and the results are in agreement with the results that Castro *et al.* achieved (B. DeAngelis, Northeast Fisheries Science Center, Pers. Comm.).

To be legally protected from harvest, during the duration of the study the V-notch has to be $1/4^{th}$ of an inch in depth and without any setal hairs (hairs that grow at the end of the uropod; Gibson and Angell, 2006). In order to protect the females and make the V-notch effective, regulations were passed making it illegal to harvest a V-notched lobster. The ASMFC's Amendment 3 to the Interstate Fishery Management Plan of Lobster required the Rhode Island Marine Fisheries Council to pass regulations prohibiting possession and harvest of V-notched lobsters in 1998, and Massachusetts, Connecticut and New York followed shortly thereafter. It has been illegal to harvest V-notched lobsters in Federal waters since 1987 (Mauseth *et al.*, 2001). In 2006, extended protection came from the reduction in the V-notch measure from $1/4^{th}$ an inch to $1/8^{th}$ of an inch. This allows lobsters who may have partially re-grown the notch to be protected for a longer time (Gibson and Angell, 2006). After the restoration project ended in 2006, the re-notching of lobsters that lost their marks was continued by a segment of the industry that fishes within the restoration area. It is not known how many lobstermen are implementing this procedure, but sea sampling by both the Rhode Island Department of Fish and Wildlife, and the Massachusetts Department of Marine Fisheries support these claims (Gibson and Angell, 2006).

2000 Restoration Program - The initial V-notching plan in 2000 was to purchase female lobster from wholesalers, V-notch them, and return them back into Rhode Island sound

(Colburn *et al.,* 2005). Dealers sorted and shipped healthy female lobsters to the project holding facility in Point Judith, RI, to be evaluated under a set of criteria to ensure success. Lobsters were held in a recirculation system maintained at 50° F to chill them for at least 6 hours and a maximum of 48 hours, to reduce stress and mortality (Mauseth *et al.*, 2001).

The Ocean Technology Foundation (OTF) executed the initial restocking (Colburn *et al.,* 2005). Crates ensured that the temperature for the lobsters would remain below 60° F as the restocking vessels, holding between 500 and 2,500 lobster each, went along 40 randomly selected compass courses each located 10 miles offshore, as seen in Figure 4 (Mauseth *et al.*, 2001). An additional ring of release sites located 20 miles offshore was added mid-year (B. DeAngelis, Pers. Com.). Lobsters were released at a rate of 10 lobsters per minute, V-notching and removing claw bands as they went (Mauseth *et al.*, 2001).

Approximately 300,000 lobsters were bought, notched, and returned to the sea (Colburn *et al.,* 2005). There were a number of documented technical problems in this program which made modification of this first year of restoration necessary. The source of lobsters and subsequent performance were questioned by an independent fishery monitoring data program (Gibson and Angell*,* 2006). Performance was hindered by the concentration of many of the 300,000 lobsters in a small geographic range and a short period of time. The habitat was believed to be too small for such a large number of lobsters. It also decreased the value of the fishery, because the commercial catch was dominated by un-harvestable lobsters. This initial phase of the project was subsequently terminated (Colburn *et al.,* 2005). The number of V-notched lobster credited towards the 1.24 million goal was only 190,000 lobsters, even though approximately 300,000 were V-notched in the first year (B. DeAngelis, Pers. Comm.).

2001-2006 Restoration Program - A pilot program was implemented in 2001 to address the problems with the previous methodology. After the success of the first year, the program was extended for an additional five years. OTF was again contracted by the Responsible Party to manage this phase of the restoration. The area included in the restoration originally encompassed only Narragansett Bay. After the program was deemed successful, the area was extended to include the western portion of Lobster Management Area 2, which stretched from the Rhode Island/Connecticut border to Martha's Vineyard (Figure 5); this included significant portions of Massachusetts south coast (Colburn *et al.,* 2005).

It was determined that re-stocking would be more effective for egg production if the lobsters came from a local inshore population (Mauseth *et al.*, 2001). Hence, a localized commercial vessel based marking project was developed. Observers were hired to ensure accurate data and compliance to standardized protocols. They were then deployed on boats with Captains who volunteered for the program. Originally there was also an honor program, in which up to 25 lobsters could be V-notched by lobstermen without an observer onboard, but this program was terminated in 2002 (Colburn *et al.,* 2005). Female lobsters caught in traps were deemed eligible by the observer based on a series of selection criteria then V-notched and returned in the same location in which they were caught. Marking criteria dictated that the lobster must:

- be female

- be of legal size (which varied over the period of the study)
- be in good health, including no shell disease,
- have at least one claw (only 15% of the V-notched lobsters were allowed to have only one claw per season),
- not be ovigerous,
- be in hard-shelled condition (i.e., the top of the carapace be hard and not in the inter-molt stage) (B. DeAngelis, Pers. Comm.).

Returning the lobsters to the sea in the location that they came from with the least amount of handling time is believed to have minimized mortality and emigration, as well as ensuring proportional releases to the population densities of capture (Colburn *et al.,* 2005). Scientific investigations were conducted by OTS and found no evidence of increased mortality, onset of shell disease, or negative effects on growth from V-notching (Colburn *et al.,* 2005). On board the boats, observers collected data and the section of the uropd that was cut out by the V-notching (known as a "chad" and used to asses payment to the vessel). The information collected is listed in Table 1. V-notching took place 32 to 38 weeks of the year, from April to December when lobstermen typically fish (B. DeAngelis, Pers. Comm.). Overall, 80 vessels and 91 observers were used for the restoration, for a total of over 9,000 trips.

In addition to promoting the purposes and benefits of the project, OTF compensated lobstermen monetarily for each lobster that was V-notched. A company called TBS Adjusting, Inc. was hired by OTF to assist with accounting and payment to both wholesalers (who in turn rendered payment to lobstermen) and the lobstermen themselves (Colburn *et al.,* 2005). For each V-notch that was provided, lobstermen were paid market price for a 1.25 pound lobster, regardless of the actual size or number of claws (Colburn *et al.,* 2005). The payment was also increased to a 1.35 pound lobster when the minimum legal size increased (Colburn *et al.,* 2005). In 2004, a "Select Lobster" program was established, in which two clawed lobsters having a carapace length of greater than 97 mm were worth more payment for the lobsterman (Colburn *et al.,* 2005). A wholesaler bottom price of $4.25 per pound was also enacted after Sept.11th 2001, when the market fell (Colburn *et al.,* 2005).

Lobstermen were not required to V-notch all eligible lobsters, even when an observer was on the boat. They could choose which lobsters they wanted to bring to market rather than notch (B. DeAngelis, Pers. Comm.). The incentives offered and general promotion of the project lead to most lobstermen V-notching all eligible females possible as the project progressed. One corollary of the effectiveness of the incentives is that most of the harvested lobster were males, and therefore the project had a strong start in supplying the population with a large number of egged females.

In addition to the information collected by observers, program confirmation and payment records were kept by OTF (Colburn *et al.*, 2005). Summary reports were examined weekly by the Trustees, and plans were made for the following week (B. DeAngelis, Pers. Comm.). Particular attention was focused on the recapture rates and proportion carrying eggs. When three recaptures were hauled for every non-marked, legal size lobster within an area, V-notching was temporarily suspended in that area (Colburn *et al.*, 2005).

There was also an ancillary study conducted using arm band tags, which consisted of tie-wraps with individual numbering. The project began in 2004 and continued to

2006, although it did not add to the number V-notched. Instead, lobsters that were V-notched were concurrently banded, and additional information was recorded. Controlled laboratory experiments concluded that the bands did not negatively affect behavior, growth, shell disease or survival (Colburn *et al.,* 2005). The arm bands were typically lost after one molt (B. DeAngelis, Pers. Comm.). The objective was to tag up to 20% of the V-notch releases with bands (Mauseth *et al.*, 2001). The total number banded was 38,787 and the total recaptured bands was 23,097, although many of the recaptured lobsters were recaptured up to eight times. Recaptures were reported by observers and commercial lobstermen (Mauseth *et al.*, 2001). Observers recorded all the information that is outlined in Tables 2 and 3. The size of the recaptured lobster was approximated in the recapture using an interval gauge, in which lobster's carapaces were measured according to the measurement increments.

In 2001, a small program was launched to tag 16% of the lobsters released with anchor tags (Castro *et al.,* 2003). The type of anchor tag used is called a sphyrion tag, which has a small metal clip, with a streamer tag hanging off it. These tags are inserted between the carapace and the abdomen with a needle. The study by Castro et al. (2003), in addition to number of other studies, has proved that these tags induce a significant mortality rate. When the anchor is inserted in the space between the carapace and the abdomen it has to pierce through muscle with the hope of anchoring to it and the anchor occasionally goes through the muscle and pierces vital organs inside the carapace.

A considerable portion of lobsters caught in July, August, and September most likely originated from offshore areas (Colburn *et al.,* 2005). Many lobster tagging papers have also documented seasonal immigration and emigration, most likely for the purposes of reproduction (Lawton and Lavalli, 1995). For instance, Cooper and Uzmann (1971) conducted a study that showed lobsters migrating seasonally from offshore southern New England to inshore during the spring and summer, and vice versa for the fall and winter. Long distance movements of both inshore and offshore lobsters have been recorded, with some moving as far as 789 km in three years (Lawton and Lavalli, 1995). Some of the female lobsters tagged in this restoration effort are suspected to migrate inshore during the warm summer months to disperse their eggs into a more facilitating environment than is found offshore (Cooper and Uzmann, 1971; Fogarty et al., 1980). It has also been suggested that as soon as the young have hatched, these females move back offshore to subsist until release of the next batch of young (Lawton and Lavalli, 1995). Although this means that the benefit of the restoration may extend beyond the oil spill area, the migration pattern also suggests an open population that occupies an area that is far bigger than the study area. It is also a problem for the modeling that dictated the numbers killed and the numbers needed to be restored, as there was an assumption made that there was no emigration from the stocking area (Castro *et al.,* 2003).

Objectives - The main purpose of this project was to analyze data from the restoration effort to determine if the restoration was effective. The general hypothesis was:

H_0: The population showed no response to the restoration effort

H_A: The population responded (positively) to the restoration effort

METHODS

Database Development

An Oracle database, which is based on a structured-query-language (SQL), was developed to share and process the V-notch and banding study data. SQL has the advantages of precise data definition, loading protocols, stability for storing large volumes of data, and efficient access to data across many dimensions (time, area, lobster size, band number). The database is located at the Northeast Fisheries Science Center in Woods Hole as part of the Mark-Recapture Database System, which is a compilation of many cooperative tagging projects in the Northeast.

The data were originally entered into Excel by an external company (TBS Adjusting, Inc.) hired by OTF, to help with data management. The data entry was successful, but there were errors that a databasing company could not fix without understanding the project and biology. The data were also stored in a series of Excel files that corresponded to months, years, and project type. This format was not conducive to the large scale queries that need to be performed for tagging analysis. Stability and efficiency were important for constructing the frequency tables of marked and recovered lobsters as well as tag-capture histories necessary for the mark-recapture analysis.

In May of 2007, a federal contractor, Integrated Statistics, was hired to assist in the data migration process from Excel to Oracle. Three separate tables were created for the banding release, recapture and V-notching data. In conjunction with the data migration process, an audit process was performed. This process attempted to identify any data problems before the analysis began. The advantage of auditing data in conjunction with the data migration process was that every datum was audited.

In addition to migration errors, two types of errors were searched for in the data. The first was a true or false search. For instance, any numeric variables had to have valid values. For instance, in the case of the "number of hauls" column, the number had to fall between two and 25, otherwise an error was returned. It could also be a compiled or compared value from other points of data.

Audit procedures were done in conjunction with Bryan DeAngelis (Northeast Fisheries Science Center), who had the necessary institutional knowledge. A value was changed according to the original datasheet from the field component of the study or the program manager's judgment. Otherwise, data values were left as is, but with a note in an added column that the value may be suspicious.

Exploratory analysis of lobster banding data revealed several systematic problems in data entry. The data were therefore re-audited to correct for the errors. When the banding data was first queried for mark-recapture analysis, three major flaws were uncovered (Table 4). The first error was a series of duplicate bands that had been released. Upon further analysis it was revealed that a large number of the errors occurred from poor data quality control or entry errors. Some corrections were able to be made using logic and institutional memory, with the assistance of Northeast Fisheries Science Center personnel. Corrections were recorded in the Oracle database. Although no new entries were created, a number of unique tag numbers were created from resolved duplicates. Other errors, when deemed indeterminable, were identified in the database so that they can be removed from analysis.

In addition to the duplicate band releases, bands were discovered that had been recaptured, but did not have corresponding releases. Once the duplicates had been corrected, a number of these issues were resolved, however some correction and notation was made so that these bands could also be removed from the analysis. The third problem was recaptured bands that had no numbers, typically because the number had been worn off so that some or all of the number was unreadable. These records were noted in the database as well.

Mark-Recapture Analysis

V-Notch Data Analysis

The lack of individually identifiable marks in the V-notch dataset means that many tagging models could not be applied. According to Pine *et al.* (2003), only three common models can be used when individual marks have not been used in a tagging study; the Peterson estimate, the Schnabel model, and the Schumacher and Eschmeyer method. All three also have a closed population assumption; however these models are commonly applied to open populations (Krebs *et al.*, 1989). Out of the three, the Schnabel model was the best starting point for analysis. The basic Peterson method considers only one release and recapture event, and this restoration involves a large number of mark and recapture events.

Although the total number of lobsters V-notched is known, the capture-recapture methodology allows for an estimation of total population size for each year the restoration effort was accomplished. A series of models and methods that have been developed for mark-recapture analysis were applied to the V-notch data. A modification of the notation used in Overton (1965) and Krebs *et al.* (1989) is used throughout, as seen in Table 5.

Schnabel Model - The Schnabel method is an extension of the two-sample Peterson method, in which only one mark and recapture event occurs (Krebs *et al.,* 1989):

$$\frac{r_{t+1}}{c_{t+1}} = \frac{m_t}{N} \qquad \text{(Equation 2)}$$

With simple algebra this equation can be rearranged to yield:

$$\hat{N} = \frac{c_{t+1} m_t}{r_{t+1}} \qquad \text{(Equation 3).}$$

As simple as this model appears, the proportion of recaptured lobster with V-notches (*r/c*) has been used to make population inference for Maine lobster resources (Daniel *et al.*, 1989). The Schnabel model has a similar form, however, m_t is adjusted to M_t (the total marked previous to the *t*-th event) to account for multiple samples (*i* to *k*):

$$\hat{N} = \frac{\sum_{t=1}^{t=k} \left(c_t M_t \right)}{\sum_{t=1}^{k} r_t} \qquad \text{(Equation 4),}$$

according to Krebs *et al.* (1989). The Schnabel model has the following assumptions (Krebs *et al.*, 1989)

- The population is closed (i.e. no mortality, recruitment, death, immigration or emigration)
- The probability of being caught is equal for each animal in the population
- Catchability is not affected by the marks used
- Animals do not lose their marks between sampling periods
- The second sample has all the marks recaptured reported when caught

One way to evaluate the reliability of the estimates is using the variance of the estimate. The variance from the Schnabel model is estimated by inversion of the population estimator:

$$s^2_{\left(\frac{1}{\hat{N}}\right)} = \frac{\sum_{t=1}^{k} r_t}{\sum_{t=1}^{k} (c_t M_t)^2} \qquad \text{(Equation 5)}$$

and the standard error is defined by:

$$s_{\left(\frac{1}{\hat{N}}\right)} = \sqrt{s^2_{\left(\frac{1}{\hat{N}}\right)}} \qquad \text{(Equation 6)}$$

Schumacher and Eschmeyer Method

The Schumacher and Eschmeyer method is similar to the Schnabel model and has the same model assumptions, but has an advantage in that it can be estimated as by linear regression. The Schnabel model (Equation 4) is rearranged as a linear function in which the inverse of the slope becomes the population estimate, allowing an error term to be added, hence:

$$\frac{\sum r}{\sum c} = \frac{\sum M_t}{\hat{N}} = \frac{1}{\hat{N}} \sum M_t + \varepsilon \qquad \text{(Equation 7),}$$

The analytical solution of the Schumacher-Eschmeyer method (Krebs *et al.,* 1989) is:

$$\hat{N} = \frac{\sum_{t=1}^{t=k} c_t M_t^2}{\sum_{t=1}^{t=k} r_t M_t} \qquad \text{(Equation 8).}$$

The variance can be calculated:

$$s^2_{\left(\frac{1}{\hat{N}}\right)} = \frac{\sum \frac{r_t^2}{c_t^2} - \left[\frac{\left(\sum r_t M_t\right)^2}{\sum (c_t M_t)^2} \right]}{k-2} \qquad \text{(Equation 9),}$$

One of the advantages of the Schumacher - Eschmeyer method is that when M_t is plotted against the proportion of r_t/c_t then the points are expected to form a straight line that passes through the origin.

The temporal duration of pooled sampling events was divided into either monthly or weekly increments. Initially, a weekly time step was chosen to match the field protocol (i.e. releases and recaptures were summarized and planned weekly). Weekly summaries were also pooled for monthly analyses to evaluate the optimal sampling period.

Alternative model configurations were developed to account for aspects of the V-notch program (e.g., mark loss, natural mortality, harvest, and remaining marks at large at the start of a new season).

Model modifications – loss of marks: A lobster is assumed to loose its mark when it molts, however there is uncertainty in the literature regarding when molting occurs and exactly how long the duration is between molt cycles. The initial restoration plan assumed molting to occur every two years (French, 1999). To accommodate for molt induced mark-loss, an adjustment was made to the data that removed all marks present in each sampling period which had been at large longer than two years. In other words, starting in 2003 the lobsters that were V-notched in 2001 were removed from the overall summation of the total marks at large. The adjustment was calculated monthly or weekly, depending upon the sampling interval being used. In other words, this loss wan accounted for by using an adjusted *M*. The adjusted *M* is one in which the tags that were marked (M) are modified to account for the *(P)* intermolt period in time *t*:

$$M'_t = \sum M_{t-1} - m_{t-P} \qquad \text{(Equation 10)}$$

where in being consistent with the restoration modeling the 24 accounts for a two-year retention time. Observations labeled as "re-notches", marks that were once marked but no longer retain their legally protected status due to growth of the tail, were treated as new releases.

An experiment conducted as a part of the restoration program suggests a different mark retention time based on a study in which costal Rhode Island lobsters were marked and monitored to determine how long a lobster held a V-notch mark (DeAngelis, pers. com.). The average observed retention time was 258 days. Therefore, it was deemed necessary to assess the sensitivity of abundance estimates to differing mark retention times.

Model modifications – natural mortality

A further violation to the closed population assumption of the models is that natural deaths most likely occurred during the restoration effort. The 2006 stock assessment assumed a natural mortality rate of 0.15 (ASMFC, 2006). This assumed value of natural mortality was used to create a further adjusted cumulative *M*, in which the cumulative marks were discounted by the mortality rate and then the new marks are added in:

$$M'_t = \left(M'_{t-1} - m_{t-P}\right)e^{-X} \qquad \text{(Equation 11),}$$

where *X* is the monthly rate of natural mortality. There is no fishing mortality on the V-notched lobsters, because they are all non-harvestable. This mortality rate was applied in conjunction with both the 258 day and two year mark retention periods.

Model modifications – previous year's marks: The Schumacher and Eschmeyer method assumes that no marks are present in the system at the onset of the study; hence the model uses a regression through the origin approach. Annual abundance estimates were therefore problematic, because many lobsters marked in the previous years retained their marks into the next. To account for marks present from the previous years tagging, an intercept parameter was added in hopes of estimating the discrepancy between the accumulated marks assumed within the system under a closed population assumption (and no mark loss). This was done using an intercept term, to derive estimates of the remaining marks at large from a previous year during a subsequent year of V-notching. Equation 7 can be rearranged to include such an intercept term in the following way:

$$\frac{\sum r}{\sum c} = \frac{1}{\hat{N}}\sum M + \frac{1}{\hat{N}}\hat{M}_0 \qquad \text{(Equation 12),}$$

where M_0 is the number of marks remaining in the population from a previous experiment. This variable creates the latter half of the equation, which is the intercept, as per the standard linear equation $Y = mX + b$. Furthermore, the slope of the regression in an Schumacher and Eschmeyer approach is related to the abundance estimate, thus the abundance estimate under the re-parameterized model was also evaluated.

Model modifications – harvest

Although V-notched females are protected from harvest, the population of inference includes all legal-sized lobster contributing to catch samples (c_t). Overton (1965, reviewed by Seber, 1982) provides a way to account for fishing mortality in the overall estimate of population abundance by modifying the Schnabel estimate. He cautions that the removals accounted for may modify the behavior of those remaining, however, changing the dynamics of the surrounding population and thereby possibly violating further assumptions of the Schnabel estimate.

His method is iterative, and begins with the theoretical equation for the first estimate (1):

$$\hat{N}^{(1)} = N^{(0)} + A^{(1)} \qquad \text{(Equation 13)}$$

in which $N^{(o)}$ is a variation of the Schnabel estimate and A is the adjustment for changing population size. Subsequent calculations can be made using the theoretical form:

$$\hat{N}^{(Subsequent)} = N^{(0)} + A^{(Subsequent)} \qquad \text{(Equation 14)}$$

The analytical solution to both therefore starts with the shared $N^{(0)}$, or variation of the Schnabel estimate:

$$\hat{N}^{(0)} = \frac{\sum_{t=1}^{t=k} c_t M_t}{R_k} \qquad \text{(Equation 15).}$$

Overton's method varies in that the term M_t is modified slightly. It still represents the total marked previous to the t-th event, but this summation is now

$$M_t = \sum_{t=1}^{k-1}\left(m_t - r_t - z_t\right) \qquad \text{(Equation 16)}$$

The assumption is then made that z_t is accounting for all change in the population size, which means it can therefore be assumed that $N_t + Z_t = N^{(1)}$, which leads back to equation

14. The estimations of A, or adjustments for changing population size, as represented in equations 14 and 15 and takes the forms:

$$A^{(1)} = \frac{\sum_{t=1}^{k} Z_t c_t M_t}{\sum_{t=1}^{k} c_t M_t} \qquad \text{(Equation 17)}$$

$$A^{(i)} = \left(\frac{1}{R_k}\right)\sum_{t=1}^{k} \frac{Z_t c_t M_t}{N^{(i)} - Z_t} \qquad \text{(Equation 18),}$$

where *i* refers to the previous iteration. Pulling them together, the first analytical solution is:

$$\hat{N}^{(1)} = \frac{\sum_{t=1}^{k} c_t M_t}{R_k} + \frac{\sum_{t=1}^{k} Z_t c_t M_t}{\sum_{t=1}^{k} c_t M_t} \qquad \text{(Equation 19)}$$

and the second and subsequent analytical solutions can be calculated:

$$\hat{N}^{(Subsequent)} = \frac{\sum_{t=1}^{k} c_t M_t}{R_k} + \left(\frac{1}{R_k}\right)\sum_{t=1}^{k} \frac{Z_t c_t M_t}{N^{(j)} - Z_t} \qquad \text{(Equation 20)}$$

As the computation of $\hat{N}$ is iterated, the values approach the population size. Confidence limits can also be calculated, very similar to the Schnabel estimate, but instead using the equation

$$\lambda * = \sum c_t M_t + \sum \frac{Z_t c_t M_t}{(\hat{N} - Z_t)} \qquad \text{(Equation 21).}$$

95% confidence intervals can then be calculated using this lambda value and the "exact" confidence intervals (as per Overton (1965)):

$$\Pr\left[upper\_CL < \frac{\lambda *}{\hat{N}} < lower\_CL\right] \qquad \text{(Equation 22)}$$

<u>Banding Analysis</u>

Jolly-Seber Method - To properly consider the Jolly-Seber method, the existing notation that was introduced above needs to be modified slightly to account for individual marks (Table 6). The first step in the Jolly-Seber method is to calculate the proportion of marked animals, which is called α (Krebs *et al.,* 1989):

$$\hat{\alpha}_t = \frac{(r_t + 1)}{(c_t + 1)} \qquad \text{(Equation 23).}$$

The addition of 1 is to correct the bias for small sample sizes. The next step is to calculate the size of the marked population prior to the sample *t*, using the equation (Krebs *et al.,* 1989):

$$\hat{P}_t = \frac{(s_t + 1)M_t}{(R_t + 1)} + r_t \qquad \text{(Equation 2410)}$$

The final estimation of the population size can then be derived using $\hat{P}_t$ and $\hat{\alpha}_t$ (Krebs *et al.,* 1989):

$$\hat{N}_t = \frac{\hat{P}_t}{\hat{\alpha}_t} \qquad \text{(Equation 25).}$$

Manly (1984) has derived a method to estimate the confidence limits and variance. It begins with a transform of the estimate (Krebs *et al.,* 1989):

$$\hat{N}_t^{\,*} = Ln(\hat{N}_t) + Ln\left[\frac{\sqrt{1 - \left(\left[c_t / \hat{N}_t\right]/2\right) + \left(1 - \left(c_t / \hat{N}_t\right)\right)}}{2}\right] \qquad \text{(Equation 26)}$$

and the variance can be derived (Krebs *et al.,* 1989):

$$\delta_{\hat{N}_t^*} = \left(\frac{\hat{P}_t - r_t + s_t + 1}{\hat{P}_t + 1}\right)\left(\frac{1}{\hat{R}_t + 1} - \frac{1}{s_t + 1}\right) + \frac{1}{r_t + 1} - \frac{1}{c_t + 1} \qquad \text{(Equation 27).}$$

The variance can then be used to get the 95% confidence limits (*L)*, but for the transformed estimate $\hat{N}_t^{\,*}$, where the upper limit is (Krebs et al., 1989):

$$L_{\hat{N}_t^*(Lower)} = \hat{N}_t^{\,*} - 1.6\sqrt{\delta_{\hat{N}_t^*}} \qquad \text{(Equation 28)}$$

and the lower is:

$$L_{\hat{N}_t^*(Upper)} = \hat{N}_t^{\,*} + 2.4\sqrt{\delta_{\hat{N}_t^*}} \qquad \text{(Equation 29)}$$

These values can be re-transformed to get the non-symmetrical confidence limits around the original population estimate (Krebs et al., 1989):

$$\frac{\left(4e^{L_{\hat{N}_t^*(Lower)}} + c_t\right)^2}{16e^{L_{\hat{N}_t^*(Lower)}}} < \hat{N}_t < \frac{\left(4e^{L_{\hat{N}_t^*(Upper)}} + c_t\right)^2}{16e^{L_{\hat{N}_t^*(Upper)}}} \qquad \text{(Equation 30)}$$

The assumptions of the Jolly-Seber model are (Krebs et al., 1989):

- Every lobster has the same probability (α_t) of being caught in sample *t* (several tests available to test this assumption).
- Every lobster has the same probability of survival from sample *t* to sample *t*+1.
- Sampling time is negligible
- Marks are not lost (an adjustment will be made to account for persistence of V-notches, below).

It is also important to note that population sizes cannot be estimated for the first and last years of the sampling (Krebs et al., 1989). The Jolly-Seber model has been successfully applied to lobster tagging studies before (Dunnington, *et al.*, 2005).

The recapture histories were tabulated in a similar manner to the V-notch study, in monthly time steps. The Jolly-Seber model was run in program MARK using the POPAN formulation to analyze the lobster banding data. Schwarz and Arnason (1996) recognized difficulties in estimating population change using the Jolly-Seber model and developed a likelihood framework that more directly accounted for recruitment. The general conceptual approach that was taken for running the preliminary models follows that of Anderson's (2008) framework of 'Confirmatory Analysis'. As he states, using an *a priori* hypothesis is "good science procedure and it yields a superior result". A set of *a priori* assumptions were therefore created to evaluate the restoration effort.

A priori assumptions were that survival (Φ) and probability of capture (p) could either vary with time or stay constant (Table 7). The Jolly-Seber specific parameter representing the probability of entry (PENT) was expected to vary across time, as animals would be expected to migrate in and out of the area with the seasons (Lawton and Lavalli, 1995; Waddy *et al*. 1995; ASMFC 2006).

Model configurations were evaluated based on five criteria:

1) Whether the model converged and produced a solution
2) How variable or unrealistic the estimates of Φ were. Estimates of Φ that were close to or at 1 were considered problematic.
3) Whether the standard errors could be reliably produced for both the Φ and p parameter estimates. Standard errors that were estimated to be at or near 0 were considered problematic
4) If a considerable percentage of PENT estimates were identical they were considered problematic
5) When the Phi(.) p(.) PENT(.) N(.) model would not converge, the estimates of all the models in that configuration were considered suspect. Although this problem may be a product of heterogeneity, it should still be a model that converges and is considered last in the AIC ranking.

Akaike's Information Criterion (AIC) was considered in choosing the most parsimonious model (Akaike 1973, 1985; Burnham and Anderson 1998). The AIC values were used to help evaluate which model runs within each configuration to consider. Models were ranked based on AIC values. The criterion was then used to choose the most parsimonious models among viable alternatives (Anderson 2008; Cooch and White, 2008).

The program MARK offers a variety of options for analyzing data and configuring models. A combination of model runs with a specific set of data and a specific way of constraining parameters will hitherto be called a "configuration". A set *post hoc* of configurations of data construction and parameter fixing was developed for each model to be run with, once the *a priori* configurations were deemed unusable. Twelve configurations were created, with up to eight distinct Parameter Index Matrices (PIMs) model runs existing under each configuration. All of the models listed in Table 8 were run under the configurations presented in Table 9.

The four configurations that begin with the name "Occasions" had different groupings than the standard, monthly data. Program MARK provides the user with a unique way to circumvent problems with unequal encounter occasions in the data by allowing for variable time steps across the study period. For the restoration data being considered, this meant that the months in which there was no data (recaptures or releases) were grouped together as one with the previous encounter history that had data in the mark-recapture history. The month of December was grouped with the months of January-March or April (Table 10). This unequal time step in the encounter history was then accounted for in the calculations of Φ and λ, so that the parameter estimate for that occasion was divided among the three or four time intervals that were incorporated. The two months of data in 2006 were sparse enough that in two of the configurations the two months were excluded to test the sensitivity of the models to the addition of that data. These configurations are called Occasions_n06 and Occasions_Fixed_n06 (Table 9).

In seven of the configurations certain parameters were fixed to produce better results (Table 9). The months of January, February, and March were months in which there was no fishing effort. These were also months in which it could be presumed little or no emigration or immigration would occur, nor would molting and growing to a legal size (Cooper and Uzmann, 1971). Lobsters are also hard-shelled, and would not be expected to be consumed by predators (Lawton and Lavalli, 1995). As a result, these are months when mortality would be low, and the population size would not be expected to change. The parameter Φ was therefore fixed to 1, because no mortality would be expected, and p and PENT were fixed to 0, as catchability and movement would not be occurring. With an assumption that the population is not changing, the number of gross entrants needs to equal the net entrants. All increases in the population would therefore be new entries, with the assumption that no mortality is occurring. Therefore Φ was fixed to 0.

Another problem was encountered in the months of April-June when there were recaptures being observed, but no new releases were occurring. Further parameter fixing was therefore used on these months to fix the problems, assuming the same biological assumptions of recruitment, emigration and mortality. The parameter p was allowed to vary during those months, to allow the model to accommodate the few recaptures that occurred. The parameter Φ was fixed to 0.99 when there was limited fishing effort in the area, April-June, as evidenced by the low recapture numbers. The parameter PENT was fixed to 0, because immigration and emigration would most likely not begin until the summer (Cooper and Uzmann, 1971). Fixing these parameters resulted in improved model convergence.

The other set of configurations that warrant explanations are occasion records in which only a single year of data were considered. In the configurations 03, 04, and 05 data, only the year's worth of data were considered in the mark-recapture history; this means only the releases that occurred in the year and the recaptures of the same animals that occurred in the same year. In WAYR03, WAYR04, and WAYR05 (Table 14) the mark-recapture histories were created using a years worth of release data in addition to all the subsequent releases over all remaining years.

The Pradel Model - The success of the restoration effort can be indirectly evaluated by the change in lobster abundance during the study period. The conventional Jolly-Seber model derives estimates of abundance ($\hat{N}$), and, indirectly, the change in abundance ($\lambda = N_{t+1}/N_t$) without a likelihood function (Burnham, 2004). Estimates of abundance of are often imprecise and can be severely biased by data that does not conform to the model assumptions. Furthermore, a direct estimation of the rate of change in population abundance would be more suitable for assessing the efficacy of the restoration effort.

Pradel (1996) provided an alternative model formulation of Jolly-Seber population dynamics that derives a likelihood directly from individual capture histories, rather than an estimate of initial population size (Williams *et al*., 2002; Cooch and White, 2008). The Pradel model is therefore conditional upon events that occur since marking, rather than upon an absolute estimate of initial population abundance, which requires trying to model events prior to the first encounter (Sanathanan, 1972). This allows for more statistically sound estimates of apparent survival (Φ), recapture probability (p), the change in abundance (λ) (Cooch and White 2008).

The Jolly-Seber and Pradel models assume the same basic model of population dynamics. Let N_t equal the population abundance at time i, Φ equal the probability of survival at time t and B_t is equal to the population recruitment at time t, Equation 31 shows the population abundance at time t+1.

$$N_{t+1} = N_t \phi_t + B_t \qquad \text{(Equation 31)}$$

It is also intuitive that the rate of population change is determined by the quotient of the future population size and current population size, or:

$$\lambda_t = N_{t+1} / N_t \qquad \text{(Equation 32)}$$

To simplify Equation 32 can be combined with Equation 31:

$$\lambda_t = \frac{B_t}{N_t} + \phi_t \qquad \text{(Equation 33)}$$

B_t / N_t, is the marginal change in abundance, conditional upon absolute population abundance. This can also be called the recruitment rate, or f_t. Substituted into Equation 33:

$$\lambda_t = f_t + \phi_t \qquad \text{(Equation 34)}$$

where the change in population abundance is a linear combination of recruitment and survival. In practice the parameter f_t is difficult to estimate with any precision, due to the difficulties in estimating population size. Pradel (1996) showed that by reversing the encounter histories, and introducing a new parameter, γ, to represent the probability that animals had not entered the population, statistically sound estimates of f and λ could be made. In other words, γ represents the probability that that an animal was alive and in the population at time i-1, and is often referred to as the seniority parameter (Williams *et al*., 2002; Cooch and White, 2008).

A reversal of encounter histories can be seen with a schematic of the encounter probabilities, seen in Figure 6. A typical encounter history for the Jolly-Seber model is 101110 meaning that the lobster was tagged during the first period, not recaptured in the second period, recaptured and released in the third, fourth, and fifth periods, and then not recaptured in the last period. The same capture/recapture history would be represented with a probability expression:

$$\phi_1(1-p_2)\phi_2 p_3\phi_3 p_4\phi_4 p_5\phi_5(1-p_6) \qquad \text{(Equation 35)}$$

With the reversal of the encounter histories and the addition of the parameter γ , however, the probability expression can now be seen in pink and written as

$$\gamma_5 p_4\gamma_4 p_3\gamma_3(1-p_2)\gamma_2 p_1 \qquad \text{(Equation 36)}$$

So that γ_{i+1} represents the probability that the lobster was not recruiting to the population, or

$$\gamma_{t+1} = 1 - \frac{B_t}{N_{t+1}} \qquad \text{(Equation 37)}$$

Equation 37 can then be manipulated using Equations 32-34 so that

$$\gamma_{t+1} = 1 - \frac{(N_{t+1} - N_t\phi_t)}{N_{t+1}} = \frac{N_t\phi_t}{N_{t+1}} = \frac{\phi_t}{\lambda_t} \qquad \text{(Equation 38)}$$

and

$$\lambda_t = \frac{\phi_t}{\gamma_{t+1}} \qquad \text{(Equation 39)}$$

The Pradel estimates the change in population abundance, and the estimates are conditioned upon encounter histories rather than absolute population abundance. Program MARK can fit the Pradel model according to three parameterizations: (Φ, p, γ), (Φ, p, λ), or (Φ, p, f). Once an estimate of either parameterization occurs the other two parameters can be derived (Cooch and White 2008). Recruitment, shown in Equation 34 can now be re-written as

$$f_t = \phi_t\left(\frac{1-\gamma_{t+1}}{\gamma_{t+1}}\right) \qquad \text{(Equation 40)}$$

Therefore, estimates of population growth, the primary objective of this research, can both be obtained, without having to estimate the actual population size. These estimations will greatly benefit the evaluation of the restoration effort.

The Pradel model was run in program MARK utilizing the lobster banding data, which had been grouped similar to the V-notching analysis. A series of model formulations were developed by hypothesis-driven intuition and utilizing the aforementioned *a priori* assumptions (Table 12). For the consideration of Φ, or the survival probability, it was hypothesized that survivability would vary with time (denoted as (t) in Table 13), as the 2006 stock assessment suggests (ASMFC 2006), with the influence of increased mortality during molting periods and the fishing season (Fogarty, 1995). The alternative hypothesis was constant survival (denoted as (.) in Table 13). This means that as a parameter, Φ could either vary with time or stay constant, depending on the hypothesis that was confirmed. Similarly, the capture probability, p was expected to vary across time as the fishing season developed, and lobster went into ecdysis and therefore hid, or possibly as they seasonally migrated in and out of the study area (Lawton and Lavalli, 1995). The seasonally variable capture probability may be masked by co-occurring groups of molting lobsters, as hypothesized by Waddy *et al*. (1995). Therefore p would alternatively be expected to remain constant across time. Finally, population growth rate between observations λ would be expected to change throughout the year, with variable emigration, immigration, death and recruitment. Therefore λ should ideally be considered a time varying parameter. When data were not sufficient to support the a priori expectations of time-varying parameter estimates, a series of *post hoc* analyses were developed, that may be less objective than *a priori* objectives (Anderson 2008).

In all, 12 configurations were developed, the same as those used with the Jolly-Seber, with up to eight differing Parameter Index Matrices (PIMs). Table 14 shows the different configurations listed with the differing types of data and fixed parameters. As was the case with the Jolly-Seber, the four configurations that begin with the name "Occasions," the month of December was grouped with the months of January-March or April (Table 10). This unequal time step in the encounter history was then accounted for in the calculations of Φ and λ, so that the parameter estimate for that occasion was divided among the three four time intervals that were incorporated. The two months of data in 2006 were sparse enough that in two of the configurations the two months were excluded to test the sensitivity of the models to the addition of that data. These configurations are called Occasions_n06 and Occasions_Fixed_n06 (Table 14).

Parameters were fixed (i.e., set at a default value with no variance) in seven of the configurations, all based on biologically reasonable assumptions. In configurations NEF, WAYR03, WAYR04, and WAYR05 (see Table 14 for data details) the parameters Φ, p, and λ were all fixed for the months when there was no fishing effort to inform the model. The assumption was that Φ would be 0.99 when there was no fishing. Few predators threaten full grown, hard shelled, harvestable lobster during the winter (Lawton and Lavalli, 1995). Therefore survivability would be expected to be high during winter months when there was no fishery and lobsters were hard-shelled. The second assumption was that p would be zero when there was no fishing (i.e. there ought to be no lobster caught when there is no effort). The third parameter, λ, was fixed to 1 during those months to represent no population change. The three months that did not typically experience fishing were January, February and March, in which little emigration or migration would occur (Cooper and Uzmann, 1971). Mortality would therefore be low, and no new recruits would molt into the legal-size range, meaning the population size would not be expected to change.

In configurations NEF2, Occasions_Fixed, and Occasions_Fixedn06, parameters were also fixed based on the same biological assumptions mentioned above, but more parameters were fixed during the months when there were recaptures but no releases, typically the months of April-June. During these months, λ was fixed to 1; fishing effort was presumably low during these months, and immigration and emigration likely had not started (Cooper and Uzmann, 1971). Likewise, Φ was fixed to 0.99 when there was limited fishing effort in the area, as evidenced by the low recapture numbers. The parameter p, however, was allowed to vary during those months. This was to allow the model to accommodate the few recaptures during those months. Fixing these parameters resulted in improved model convergence and solutions.

Numerical optimization algorithms may have fewer convergence issues when estimating γ instead of λ (Williams et. al 2002). The parameter γ can easily be transformed into estimates of λ using Equation 39. Due to difficulties with convergence that were encountered with the λ parameterization, several models that did not converge were also re-run using this technique.

Model configurations were evaluated based on three criteria:

1) The model converged and produced a solution.
2) Estimates of Φ and its variance are realistic. Estimates of Φ that were close to or at 1 with near-zero variance were indicative of the likelihood search not adjusting the starting values.
3) Estimates of λ and its variance were realistic. Estimates that were greater than 3 or less than .001, were considered to be unrealistic. Anything within that range was considered a reasonable estimate for a rate of increase or decrease during the duration of the study.

For all model configurations that met these criteria, Akaike's Information Criterion (AIC) was used to determine the optimal model (Akaike 1973, 1985; Burnham and Anderson 1998). AIC values indicate the most parsimonious models among viable alternatives (Anderson 2008; Cooch and White, 2008). The AIC values were used to help evaluate which model runs within each configuration to consider. The model runs that are highlighted in blue in Table 14 meet both AIC and the previously explained criterion (Table 15).

RESULTS

V-Notch Analysis

More than 3.6 million lobster were sampled during the V-notch program, but sampling was not evenly distributed temporally or spatially (Figure 7). V-notching effort had to be focused where and when lobstermen fished (Figures 8-10). V-notch releases and recaptures were concentrated in these areas and seasons of most fishing effort, particularly in the areas in and around Narragansett Bay and Block Island Sound. For certain areas the recurrence of recapture is far higher than releases. This could be due to emigration or immigration, but is most likely due to multiple recaptures of the same animals due to intense fishing effort.

In total 33 sets of population estimates were created, with an individual abundance estimate for all of the six years. However, statistical diagnostics indicate that all analyses of V-notch data substantially violated model assumptions. The first evaluations to be considered are the confidence limits of the estimates. The Schumacher and Eschmeyer, Schnabel, and Oveton have analytically calculated confidence limits (Figure 11). From these confidence intervals, it appears that the data are sensitive to the temporally based sampling interval (i.e., monthly or weekly pooling). The confidence intervals indicate that the monthly groupings are more precise than weekly. The weekly sampling periods increase the overall number of events (i.e. sample size), but add variance from the expected linear relationship, producing wider confidence limits. However, the power of the analyses was much less in the monthly grouping than in the weekly groupings for 2001 and 2006 because the first and last years had only four months and two months of data, respectively. It is also interesting to note that the confidence intervals for Overton's method were, in contrast to the other models, remarkably precise to the population estimations. However, estimates are from an analytical solution based on a Poisson distribution.

An advantage of the Schumacher and Eschmeyer method is that it provides model residuals, which can be used to validate that the model is appropriate for the data. Trends in residuals indicate violations of the assumptions of the model. For this application, regressions should not go through the origin, because marks were at large from previous years of V-notching. Residual analysis revealed a series of trends in the data (Figure 12). The pattern of recapture rate as a function of marks at large shows the subtractions made by the periodic, 2 year or 258 day removals for loss of marks.

A second evaluation tool for the Schumacher and Eschmeyer method is that of R^2 values which evaluate the goodness of fit of the regression. The conventional Schumacher and Eshmeyer method produced the worst R^2 values (Table 16), with the two year mark loss combined with mortality considerations coming in a close second. The modified models that accounted for mark loss with two-year or 258-day mark retention produced better results, and the best set of R^2 values came from the model modified to include both a 258 day mark retention period and natural mortality. When the regressions were forced through the origin, the R^2 values did not improve. The estimates from the Schumacher and Eschmeyer method, the Schnabel model, and the Overton (which includes the Schnabel model) method all assume a linear relationship that originates at 0,0 (i.e., no recaptures when there are no marks at large), which was not the case when there were remaining marks at large from the previous year.

Banding Analysis

Jolly-Seber Analysis

All four of the Jolly-Seber models described in Table 7 produced imprecise and unreliable results. Model 1 had two errors; estimates of Φ were estimated at 1 for 30.3% of the estimates, and the standard errors for Φ and *p* were estimated to be 0 for 29.85% of the estimates. Model 2 had greater than 60% error rate for both estimates of Φ and estimates of PENT. Model 3 had a 58% error rate for estimates of PENT but Model 4 had a 67% error rate. The basic model [*Φ* (.) *p*(.) PENT(.) *N*(.)] would not converge for all four models, suggesting that the data were not sufficient to support the complexity of the model. Due to the inability of the models to perform based on this data, the *a priori* hypotheses were unable to be tested.

Nine other model configurations were developed for *post hoc* analysis, the results and tradeoffs of each can be seen in Table 11. The basic *Φ* (.) *p*(.) PENT(.) N(.) model did not converge for four *post hoc* configurations: 'NEF', 'NEF2', 'Occasions' and 'Occasions_Fixed'.

Results from the models described in Table 17 indicate that there may be a surge of recruitment or immigration during the months of September and October for the years 2003 and 2004, and the months of July and August for 2005. Among the five remaining configurations, most of the models did not produce precise results (Table 11). Using a threshold of 20% viability for each model run between the three possible technical problems (*Φ*'s of 1, standard errors of 0, and identical PENT estimates) and a requirement that the model converged, 24 other model runs under the various configurations could be removed from consideration. The five remaining successful model runs were evaluated in a sensitivity analysis (Table 18). From these remaining configurations, it is clear that removing the 2006 data from the analysis was beneficial, and allowed for more precise model results.

Fixing parameters allows for model convergence, but there is assumed to be no uncertainty in the parameter. These fixed parameters can have effects on the surrounding parameters. In other words, the parameters being estimated around the fixed estimate are conditioned on the fixed value being correct. Additionally, fixed parameters may affect the AIC estimates, because the total variance of the model is assumed to be much lower than it actually may be. Fixed parameter configurations were therefore removed from consideration. This resulted in the model runs from the configurations Occasions_Fixed_n06 and 05 WAYR being removed from the model ranking, despite having the lowest AIC values.

That leaves two models from the Occasions_n06 assemblage from which to choose the best model. Estimates of abundance were sensitive to model choice. The best model was the *Φ* (.) *p*(t) PENT(t) N(.) model in the Occasions_n06 assemblage. This model yielded a time-constant survival probability, estimated to be 0.879, (95% CI: 0.875, 0.882). The super-population size, or N, which represents the total number of all animals that entered study site was estimated to be 67,351 lobsters (95% CI: 66,266; 68472). The capture probability, *p*, and the probability of entry, or PENT, were both estimated across time (Figures 13 and 14). Cooch and White (2008) point out that the first and last parameter estimates are imprecisely estimated and often confounded.

Specifically, p is confounded with the first estimate of PENT, and the last estimate of p is confounded with Φ. The first PENT is also untrustworthy because the first and second occasions cannot be estimated separately, as is the last PENT which is not estimated correctly. Program MARK reports estimates of these parameters in all occasions although their interpretation should be tentative.

Gross population size, N^*, was estimated to be 71,804 lobsters (95% CI: 70,630; 72,979). Abundance at time of sampling at the i^{th} occasion, or N_i, increased during the study period (Figure 15). The two parameters, N^* and N_i are both derived estimates without a direct measure of precision, therefore program MARK employs the Delta method to estimate precision (Cooch and White 2008). Estimates of population increase can be evaluated for significance, although conclusions from such test should be tentative.

<u>Pradel Model</u>

Of the alternative, exploratory Pradel model configurations, ten produced results that had parameter estimates that were biologically feasible, none of which could confirm the *a priori* assumptions. The results from the best models and the tradeoffs of each can be seen in the Table 15. This sensitivity analysis shows that the majority of estimates were similar among alternative models. For example, the greatest range of estimates for Φ was 0.119, 0.093 for p, and 0.27 for λ.

As was previously described, even though fixing parameters allowed for increased convergence and precision, estimates with fixed parameters were subsequently removed from consideration. Fixing parameters influences surrounding, freely estimated, parameters, can introduce bias. This leads us to reject those models from the assemblages NEF2 and 05WAYR, because all of the model runs have a large number of fixed parameters. The solution is to look at the simpler models, which come from the Occasions_Fixed and Occasions_Fixed_no06. These models have parameter estimates with less variable and unrealistic standard errors and less fixed parameters.

The assemblage Occasions_Fixed_no06 had all recaptures and releases from 2006 removed initially to test how sensitive the results were to having the possibly extraneous data in the model. However, the influence of the 2006 data was insignificant on the results. That leaves the three models from the Occasions_fixed group, two of which had no fixed parameters, but time varying p. The model in which p and Φ vary with time while λ is constant may be the best model that the data support, but is inconsistent with our expectations of the lobster population. If survival is varying monthly, but overall the population growth rate is constant, then recruitment (or migration) must be in balance with survival. The next best AIC ranking model is that which Φ was constant, p varied with time, and λ stayed constant. While this model has a lower AIC ranking, it is only second out of eight models and the results of both the top model and it are so similar that model choice doesn't make an appreciable difference (Table 19).

The parameter Φ, or the survival probability, was therefore estimated to be 0.916, (95% CI: 0.913, 0.918) while the population growth rate between observations, or λ, was estimated to be 1.06 (95% CI: 1.058, 1.062). The capture probability, p, was estimated across time and was generally and consistently low across the study period (Figure 16). Cooch and White (2008) point out that typically the first estimate of p is confounded with λ, and the last estimate of p is confounded with Φ.

For the purposes of testing the general hypothesis (H_0: The population showed no response to the restoration effort; H_A: The population responded (positively) to the restoration effort) a *t*-ratio test was performed on the λ parameter result to determine significant difference from 1.0, which would mean the population was not showing a positive response to the restoration effort. With 871 degrees of freedom, the result was a t value of 61.420 and a subsequent P value of <0.001. This highly significant result indicates that the null hypothesis can be rejected, and that the population showed a significant increase during the duration of the restoration effort.

Model diagnostic plots for the best model can be found in Figures 17-21 and the MARK output for the best model can be found in Appendix A. While it is clear that October of 2003 has a problematic standard error, the CV's suggest that the problem lies with September of 2003, which according to Cooch and White (2008) is typically a confounded parameter.

As for the model runs that estimated γ instead of λ, each run that would not converge while estimating λ did so for estimations of λ. No model had problems converging using this parameterization. Although there were fewer convergence issues, the results of all the models had far more problems than those of models estimating λ. A similar exploratory approach was taken with the model results, however very few of the models produced feasible results. These model runs and associated results can be seen in Table 20**.** The only result of note was that the models performed better with the 2006 data removed. Even with unreliable estimates, the top model came from the Occasions_n06 assemblage, had a constant Φ and γ , and a time-varying p, and most importantly, had γ estimate of 0.850 (95% CI: 0.847, 0.852), which gives an approximate λ estimate of 1.069. This is similar enough to the estimate that came from solving for λ (1.06) that it supports the prior result.

There is congruence between the best model parameterization of both the Pradel and Jolly-Seber analysis. In both the Pradel analysis and Jolly-Seber analysis Φ was estimated as a time invariant and p was estimated as a time variant parameter. In the Pradel analysis, the rate of population change (λ) was chosen to be a temporally-constant parameter while in the Jolly-Seber analysis, the PENT parameter was time-varying. This indicates that the change in population size did not vary significantly across months, although the population was constantly increasing, and that the probability of new entries did vary with time. If that is indeed the case, then the mortalities accrued from the fishing season are most likely canceling out the effect of new animals that are entering the population during those months, be they new recruits or migrating larger lobsters. This keeps the population rate of change constant, but the pulses of entrants into the population must be enough over time to be causing the steady increase in population size.

Combined Analyses

Estimates of abundance from analysis of V-notch data, adjusted for mortality and 258 day mark retention time, indicate a slight increase in the legal-sized lobster population from 2001 to 2002 , a more substantial increase in 2003, a decline in 2004 and another slight increase in 2005 (Figure11). These estimations indicate a general increase in population abundance during the restoration program. The Overton method, which incorporates removals from the population indicates a large population increase from 2001 to 2005. Although these model applications were considered the best among all alternatives, each has substantial statistical problems and model violations. Therefore, results from V-notch analyses may not be reliable.

Analyses of banding data were much more consistent, and model diagnostics suggest that they are reliable. A wide variety of data and model configurations support the conclusion that the population of legal-sized lobsters increased during the restoration program. The optimal model indicates that the general rate of change was significantly positive, at approximately 6% per month (Figure 16).

DISCUSSION

A population increase of 1.06 per month, as indicated by the best Pradel model of the banding data, means that the population is increasing by 6% each month. These general results are corroborated by the best Schumacher and Eschmeyer model of V-notch data. Some of the increase, however, could have been a natural process, and it is difficult to determine how much of the increase resulted from the restoration program.

A number of violations to the V-notch models make the results somewhat suspect. Despite extensive efforts to adjust data and modify models to reflect the population of inference, apparently the assumption of a closed population could not be adequately addressed. Lobsters can be highly mobile and most likely moved in and out of the recovery area during the restoration effort. A study by Fogarty *et al.* (1980) found that while 74.5% stayed within 60km of the release site lobsters released off Cox Ledge moved, on average, 41.6km, with lone lobster travelling as far as 173 km southeast, in an offshore direction. Inshore locations off of Rhode Island saw less movement, with averages between 5.5 to 10.4 km at different release sites; however, a portion of the lobsters moved great distances, one travelling as far as 184.2 km southwest in an offshore direction. These distances certainly indicate that lobsters were most likely moving out and possible others moving back in to the population during the time period studied. This is a clear violation of the closed population assumption of all of tagging models being used except for the Jolly-Seber family of models (Krebs *et al.*, 1989). This problem would be compounded further if the models are run on smaller portions of the gridded study area, as suggested in the proposed methods, as the likelihood of lobsters moving between grid squares is highly likely given Fogarty *et al.*'s study. (1980).

For the purposes of confirming the hypothesis of a population increase during the restoration program, it is more appropriate to rely on the results of the Pradel over the Jolly-Seber model. Abundance at time can be calculated from the Jolly-Seber model, but the calculations are derived from estimated parameters rather than being directly estimated. The Pradel model directly estimates a parameter of population change, conditional upon recapture histories. Therefore the rate of population change estimated from this model may be more reliable for population level inference.

There are some technical problems with Jolly-Seber analysis. The sensitivity analysis (Table 18) shows large discrepancies among results from alternative model runs, and the removal of the two months of 2006 data is necessary for producing valid results. Testing significance of abundance change is also difficult, because abundance is a derived variable rather than an estimated parameter. Results from the Pradel model are more appropriate for evaluating the results of the restoration effort.

This review of the restoration program and the database development allow confirmation that the target number of V-notches, and the intended egg production, were achieved. Some details of the restoration plan were not implemented. For example, the plan was to begin V-notching in 2000, and V-notch an equal number in each of the next five years (French, 1999). Although the restoration effort did begin in 2000, operational procedures weren't resolved until 2001, meaning it took six years to finish the effort; furthermore the numbers released varied widely among years (see Figures 7-10). It is therefore important to review, the process that went into creating the initial estimates to evaluate if the intended egg production was achieved. The success of the V-notching project can help shape future efforts to restore lobster populations, from both oil spills and from other problems.

Although the V-notch data effectively monitored the restoration, and the banding data offer valuable information for studying the local lobster population, neither was designed to evaluate egg production or recruitment, nor are the mark-recapture analyses robust enough to estimate ancillary population parameters (e.g., intermolt period and reproductive cycles). Future restoration efforts that rely on V-notching should consider monitoring egg production and recruitment more directly. The banding data were valuable for population modeling, but a more effective design would include releasing a more balanced number of tagged lobster in each time step.

The restoration program has been considered in lobster stock assessment and management. The 2006 Stock Assessment concluded that the lobster resource in southern New England had been declining and recommended fishery management actions to promote stock rebuilding (ASMFC 2006). Gibson and Angell (2006) challenged the stock status and the fishing mortality rates used in the stock assessment, which came from the years 2001-2003; they challenge that these rates do not reflect those seen in the more recent years, from 2004-2006. They proposed that abundance had increased, fishing effort had declined, and that subsequently egg production had been increased. Gibson and Angell (2006) based their claims on the potential that the restoration effort from the North Cape oil spill changed the population dynamics of female lobsters in the area. This was a direct result of the V-notching effort, protecting mature female lobsters from being harvested. Recent reductions by both Massachusetts and Rhode Island to the minimum legal size of a V-notch from 1/4th an inch to 1/8th of an inch has furthered the protection and likely the egg production of mature, V-notched females.

More specifically, Gibson and Angell (2006) showed that the correlation between independent sampling Catch Per Unit of Effort (CPUE) and the number of V-notches released by the program was strong. They also demonstrated that the abundance of female V-notched lobsters has increased substantially, although the abundance of marketable females has declined. While the abundance of males, both legal and sub-legal, has been decreasing slightly, the restoration program effectively increased abundance (Gibson and Angell, 2006). The ratio of recruits to legal sized decreased, but the male ratio was constant, and abundance of legal sized females increased. Apparently, the restoration program substantially reduced mortality of females (Gibson and Angell, 2006).

The suggested mortality reduction required in the 2006 stock assessment, according to Gibson and Angell's (2006) quantitative analysis, has already been achieved. Fishery dependent monitoring and fishery independent trawl data further support the claims. The correlation also proved that this reduction has come about as a result of the restoration efforts for the oil spill. Similarly, fishing effort has recently decreased, with fewer pots fished in both Massachusetts and Rhode Island waters. While the restoration has helped the female population, the male population has not been improved and perhaps the biased ratio will have other, unintended biological or ecological consequences.

In the context of an overall decreasing trend in the southern New England lobster stock (ASMFC, 2006), the conclusion of a significant population increase during the restoration program suggests that the restoration program was effective. The anticipated natural recovery of the lobster population by 2001 (Mauseth, 2001) did not occur. Therefore, the effect of the oil spill was exacerbated by other regional impacts on the population, and the restoration program was needed to produce a positive impact on the resource.

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Table 1. Data recorded by observers when V-notching. The "select" size in the "large" category refers to lobsters of a certain length that were credited for extra money for the lobstermen.

V-Notch Data

Data Taken	Trip Date	Traps Per Haul	Haul Number	Notched This Haul	Large	Release Area
Explanation	When the haul occurred	Number of traps on string	Which haul for that day	The number notched, includes re-notches, and culls notched as well as those not fitting in those categories	How many were of a "select" size?	See Figure 5 for map divided by areas
Data Taken	Re-Notched	Culls Notched	Previously Notched	Previously Notched with Eggs	Harvested	
Explanation	How many were re-notched	How many had only one claw	How many had a notch that didn't need re-notching, includes previously notched with eggs	How many of the previously notched were egg bearing	How many were harvested	

Table 2. Data recorded by observers upon a banded lobster's release.

Releases

Data Taken	Release Date	Band Number	Release Area	Vessel Name	Observer Number
Explanation	The date it was released	The specific number on the band	See Figure 5 for map divided by areas	The vessel releasing the lobster	Specific to each observer

Table 3. Data recorded upon a banded lobster's recapture.

Recaptures

Data Taken	Recapture Date	Band Number	Recapture Area	Interval Gauge	Eggs	Shell Disease	Vessel Name	Observer Number
Explanation	The date it was recaptured	The specific number on the band	See Figure 5 for map divided by areas	Size of lobster	If the lobster had eggs (Y/N)	Presented symptoms (Y/N)	The vessel recapturing the lobster	Specific to each observer

Table 4. Summary of Problems Encountered and Subsequent Corrections in the Lobster Banding Database

Duplicate Bands		**Recaptured Bands Without Releases**		**Unreadable Bands**
Unresolvable	136	Unresolvable	378	
Observer Mistake	108	Fixed	179	
Entry Mistake	524			
Total	768		557	372

Table 5. Notation used for the Schnabel model (Krebs *et al.* 1989), the Schumacher and Eschmeyer method (Krebs *et al.* 1989), and Overton's (1965) method.

Variable	Explanation
t	Event number
j	Previous calculation
k	Number of events total
c_t	Number caught in t-th event
r_t	Number recaptured (already marked) in t-th event
m_t	Number marked on t-th event
Z_t	Number removed from population on t-th event
R_t	Total recaptures up to and including t-th event
M_t	Total marked previous to t-th event
Z_t	Total removed previous to t-th event
n	Number of samples in a summation

Table 6. Notation used for the explanation of the Jolly-Seber method (Krebs *et al.*, 1989).

Variable	Explanation
t	Event number
r_t	Number marked caught in t-th sample
c_t	Total number caught in t-th sample (r_t plus unmarked animals)
s_t	Total number marked and released after t-th sample (c_t-deaths, removals)
R_i	Number released in t-th sample but caught again in later sample
M_i	Number marked before t-th sample, not caught in sample t, but caught in later sample

Table 7. Jolly-Seber models that correspond to the a priori hypothesis.

MODEL	Phi	*p*	PENT	N
1	(t)	(t)	(t)	(.)
2	(t)	(.)	(t)	(.)
3	(.)	(t)	(t)	(.)
4	(.)	(.)	(t)	(.)

(.) = constant (t) = varies w/time

Table 8. Parameter Index Matrices for the Jolly-Seber model with the typical notation used to indicate the type of model run

Possible PIMs for the Jolly Seber Model

	Phi	p	PENT	N	Annotation
1	Time - Varying	Time - Varying	Time - Varying	Constant	(t)(t)(t)(.)
2	Constant	Constant	Time - Varying	Constant	(.)(.)(t)(.)
3	Constant	Time - Varying	Constant	Constant	(.)(t)(.)(.)
4	Time - Varying	Constant	Constant	Constant	(t)(.)(.)(.)
5	Time - Varying	Time - Varying	Constant	Constant	(t)(t)(.)(.)
6	Constant	Time - Varying	Time - Varying	Constant	(.)(t)(t)(.)
7	Time - Varying	Constant	Time - Varying	Constant	(t)(.)(t)(.)
8	Constant	Constant	Constant	Constant	(.)(.)(.)(.)

Table 9. Jolly-Seber model configurations. Those in light blue are the models that are considered in the evaluation, those in dark blue are the most successful.

Model Configurations - Jolly Seber

Configuration Name	Data Type	Parameters fixed	When
Original	All releases and recaptures together	None	N/A
No Effort Fixed (NEF)	All releases and recaptures together	phi (1) PENT (0) p (0)	months with no effort
No Effort Fixed 2 (NEF2)	All releases and recaptures together	phi (1) PENT (0)	constrained all months w/o releases; p only to 0 when no effort
Occasions	Those years with no effort grouped with last month of releases/recaptures	None	N/A
Occasions_n06	Those years with no effort grouped with last month of releases/recaptures, no 2006 data	None	N/A
Occasions_Fixed	Those years with no effort grouped with last month of releases/recaptures	phi (1) PENT (0)	constrained all months w/o releases; p only to 0 when no effort
Occasions_Fixed_n06	Those years with no effort grouped with last month of releases/recaptures, no 2006 data	phi (1) PENT (0)	constrained all months w/o releases; p only to 0 when no effort
03 data	One year of releases, same year of recaptures from those releases	None	N/A
04 data	One year of releases, same year of recaptures from those releases	None	N/A
05 data	One year of releases, same year of recaptures from those releases	None	N/A
03 With All Years Reacaps (WAYR03)	One year of releases, same year and all subsequent years of recaptures	phi (1) PENT (0) p (0)	months with no effort
04 With All Years Reacaps (WAYR04)	One year of releases, same year and all subsequent years of recaptures	phi (1) PENT (0) p (0)	months with no effort
05 With All Years Reacaps (WAYR05)	One year of releases, same year and all subsequent years of recaptures	phi (1) PENT (0) p (0)	months with no effort

Table 10. An example of the encounter histories and how they can be grouped together to create occasions. The yellow block represents those months being joined together.

Encounter occasion		1		2		3					4					5	
Number of time steps in occasion		1		1		1					4					1	
Corresponding months	Sep-03		Oct-03		Nov-03		Dec-03		Jan-04		Feb-04		Mar-04		Apr-04		May-04

Table 11. Jolly-Seber configurations with their differing model runs and the success and failure of each. The percentage was calculated by dividing the number of problems by the total estimable parameters, which had the number of fixed parameters subtracted from it, if applicable.

	phi(t) p(t) PENT(t)			phi(.) p(t) PENT(t)			phi(t) p(t) PENT(.)			phi(t) p(.) PENT(t)		
	Phi problem	PENT Problem	SE Problem (phi and p)	Phi problem	PENT problem	SE Problem (phi and p)	Phi problem	PENT problem	SE Problem (phi and p)	Phi problem	PENT problem	SE Problem (phi and p)
Original	30.30%	18.18%	29.85%	n/a	57.58%	13.16%	69.70%	n/a	56.72%	69.70%	63.64%	34.33%
No Effort Fixed (NEF)	26.09%	52.17%	12.77%	n/a	0.00%	0.00%	60.87%	n/a	29.79%	65.22%	69.57%	31.91%
No Effort Fixed 2 (NEF2)	12.50%	12.50%	10.00%	n/a	31.25%	7.50%	37.50%	n/a	30.00%	56.25%	43.75%	25.00%
Occasions	21.74%	0.00%	17.02%	n/a	0.00%	4.26%				52.17%	0.00%	25.53%
Occasions_n08	23.81%	0.00%	16.25%	n/a	0.00%	4.65%				47.62%	0.00%	25.58%
Occasions_Fixed	17.65%	52.94%	19.51%	n/a	17.65%	7.32%				35.29%	11.76%	14.63%
Occasions_Fixed_n08	33.33%	20.00%	29.73%	n/a	13.33%	8.11%	40.00%	n/a	29.73%	46.67%	0.00%	21.62%
03 WAYR	26.09%	56.52%	29.79%	n/a	56.52%	6.41%				4.35%	8.70%	34.04%
04 WAYR	37.50%	0.00%	12.12%	n/a	30.30%	0.00%	31.25%	n/a	21.21%	31.25%	0.00%	18.18%
05WAYR	0.00%	0.00%	6.67%	n/a	0.00%	0.00%	0.00%	n/a	20.00%	14.29%	28.57%	6.67%

	phi(.) p(.) PENT(t)			phi(t) p(.) PENT(.)			phi(.) p(t) PENT(.)			phi(.) p(.) PENT(.)		
	Phi problem	PENT Problem	SE Problem (phi and p)	Phi problem	PENT Problem	SE Problem (phi and p)	Phi problem	PENT Problem	SE Problem (phi and p)	Phi problem	PENT Problem	SE Problem (phi and p)
Original	n/a	66.67%	n/a	27.27%	n/a	14.93%	n/a	n/a	17.91%			
No Effort Fixed (NEF)	n/a	43.48%	n/a				n/a	n/a	36.17%			
No Effort Fixed 2 (NEF2)	n/a	31.25%	n/a	43.75%	n/a	20.00%	n/a	n/a	42.50%			
Occasions	n/a	0.00%	n/a				n/a	n/a	6.38%			
Occasions_n08				47.62%	n/a	25.58%	n/a	n/a	2.33%			
Occasions_Fixed	n/a	17.65%	n/a	23.53%	n/a	12.20%						
Occasions_Fixed_n08	n/a	40.00%	n/a	26.67%	n/a	13.51%	n/a	n/a	2.70%			
03 WAYR	n/a	91.30%	n/a	52.17%	n/a	27.36%	n/a	n/a	53.19%			
04 WAYR	n/a	0.00%	n/a	43.75%	n/a	21.21%	n/a	n/a	75.76%			
05WAYR	n/a	28.57%	n/a	14.29%	n/a	6.67%	n/a	n/a	6.67%			

- # of Phi's of 1
- SE of 0 or close to (within three decimal places)
- # of same estimates
- (.,t,t,t,.) model would not run
- did not converge
- being considered in text

Table 12. Alternative Pradel models with constant (.) or time varying (t) parameters.

	VARIABLE		
MODEL	phi	p	lambda
1	(t)	(t)	(t)
2	(t)	(.)	(t)
3	(.)	(t)	(t)
4	(.)	(.)	(t)

(.) = constant (t) = varies w/time

Table 13. All possible Parameter Index Matrices for the Pradel model with the typical notation used to indicate the type of model run.

Possible PIMs for the Pradel Model

	Phi	p	Lambda	Annotation
1	Time - Varying	Time - Varying	Time - Varying	(t)(t)(t)
2	Constant	Constant	Time - Varying	(.)(.)(t)
3	Constant	Time - Varying	Constant	(.)(t)(.)
4	Time - Varying	Constant	Constant	(t)(.)(.)
5	Time - Varying	Time - Varying	Constant	(t)(t)(.)
6	Constant	Time - Varying	Time - Varying	(.)(t)(t)
7	Time - Varying	Constant	Time - Varying	(t)(.)(t)
8	Constant	Constant	Constant	(.)(.)(.)

Table 14. Pradel model configurations. Those in light blue are the models that are considered in the evaluation, those in dark blue are the most successful.

Model Configurations

Configuration Name	Data Type	Parameters fixed	When
Original	All releases and recaptures together	None	N/A
No Effort Fixed (NEF)	All releases and recaptures together	phi (0.99) lambda (1) p (0)	months with no effort
No Effort Fixed 2 (NEF2)	All releases and recaptures together	phi (0.99) lambda (1)	constrained all months w/o releases; p only to 0 when no effort
Occasions	Those years with no effort grouped with last month of releases/recaptures	None	N/A
Occasions_n06	Those years with no effort grouped with last month of releases/recaptures, no 2006 data	None	N/A
Occasions_Fixed	Those years with no effort grouped with last month of releases/recaptures	phi (0.99) lambda (1)	constrained all months w/o releases; p only to 0 when no effort
Occasions_Fixed_n06	Those years with no effort grouped with last month of releases/recaptures, no 2006 data	phi (0.99) lambda (1)	constrained all months w/o releases; p only to 0 when no effort
03 data	One year of releases, same year of recaptures from those releases	None	N/A
04 data	One year of releases, same year of recaptures from those releases	None	N/A
05 data	One year of releases, same year of recaptures from those releases	None	N/A
03 With All Years Reacaps (WAYR03)	One year of releases, same year and all subsequent years of recaptures	phi (0.99) lambda (1) p (0)	months with no effort
04 With All Years Reacaps (WAYR04)	One year of releases, same year and all subsequent years of recaptures	phi (0.99) lambda (1) p (0)	months with no effort
05 With All Years Reacaps (WAYR05)	One year of releases, same year and all subsequent years of recaptures	phi (0.99) lambda (1) p (0)	months with no effort

Table 15. Pradel model configurations with their differing model runs and the success and failure of each. The percentage was calculated by dividing the number of problems by the total estimable parameters, which had the number of fixed parameters subtracted from it, if applicable.

Assemblage	phi(t) p(t) lambda(t)		phi(.) p(t) lambda(t)		phi(t) p(t) lambda(.)		phi(t) p(.) lambda(t)	
NEF	39.13%	34.78%			56.52%		4.35%	39.13%
NEF2					25.00%		6.25%	12.50%
Occasions					56.52%		34.78%	30.43%
Occasions_no06					47.62%		23.81%	42.86%
Occasions_fixed							29.41%	23.53%
Occasions_fixed_no06							46.67%	26.67%
03 WAYR	56.52%	60.87%		47.83%	65.22%		56.52%	47.83%
04 WAYR					50.00%		68.75%	56.25%
05 WAYR								

Assemblage	phi(.) p(.) lambda(t)		phi(t) p(.) lambda(.)		phi(.) p(t) lambda(.)	phi(.) p(.) lambda(.)
NEF		34.78%	39.13%		ranked 5/7	at bottom
NEF2		18.75%	12.50%		ranked 4/8	at bottom
Occasions			43.48%		ranked 3/5	at bottom
Occasions_no06		47.62%	42.86%		ranked 4/6	at bottom
Occasions_fixed		23.53%	17.65%			at bottom
Occasions_fixed_no06		26.67%	26.67%			at bottom
03 WAYR			73.91%		ranked 5/7	ranked 6/7
04 WAYR		68.75%	37.50%			at bottom
05 WAYR			14.29%		ranked 3/5	at bottom

model would not converge
number of absurd lambda parameter estimates (over 3 or under .001)
# of Phi's of 1
being considered in sensitivity analysis

Table 16. R^2 values from Schumacher-Eschmeyer regressions of V-notch data. The ten regressions correspond to the different treatments and groupings that were mentioned in the text.

	2 Yr. Mark Loss		2 yr. Mark Loss and Mortality		Regular	
	Monthly	Weekly	Monthly	Weekly	Monthly	Weekly
2001	**0.7247**	**0.9214**	0.6887	**0.9166**	**0.8764**	**0.9**
2002	0.0414	1.00E-05	0.1256	0.2154	**0.913**	**0.8909**
2003	**0.917**	**0.7367**	**0.9158**	**0.7533**	0.5005	0.3639
2004	0.0346	0.1076	0.2898	0.5204	0.3542	0.2842
2005	**0.93**	**0.9948**	**0.9325**	**0.9957**	**0.7307**	0.5411
2006	**N/A**	**0.9119**	**N/A**	**0.841**	**N/A**	0.0647
All	**0.8566**	**0.7676**	0.6841	**0.7972**	**0.7852**	**0.7276**

	258 Day Mark Loss		258 Day Mark Loss and Mortality	
	Monthly	Weekly	Monthly	Weekly
2001	**0.7247**	**0.9214**	**0.7264**	**0.9235**
2002	**0.9739**	**0.9487**	**0.9758**	**0.9377**
2003	0.0334	**0.9573**	0.0517	**0.9532**
2004	**0.8613**	**0.9498**	**0.8772**	**0.9515**
2005	**0.7655**	**0.8879**	**0.7893**	**0.8931**
2006	**N/A**	0.5851	**N/A**	0.5761
All	0.4165	0.5084	0.4546	0.5099

R^2 Value:

under 0.5

under 0.7

Table 17. A list of PENT estimates from Jolly Seber models that were skewed strongly towards one or two months in which a large amount of the total recruits entered the population.

Model Configuration	Model Run	Problem Month(s)	PENT Estimate (Out of 1 total)	AIC Rank
03 WAYR	Phi(t) p(t) PENT(t) N(.)	Sept. 03	0.80	top
	Phi(.) p(t) PENT(t) N(.)	Sept. 03	0.81	2nd
04 WAYR	Phi(.) p(t) PENT(t) N(.)	Sept. 04	0.89	3rd
	Phi(t) p(.) PENT(t) N(.)	Sept. 04	0.79	4th
	Phi(.) p(.) PENT(t) N(.)	Sept./Oct. 04	0.53 and 0.29	5th
05 WAYR	Phi(t) p(t) PENT(t) N(.)	July/Aug. 05	0.20 and 0.50	top

Table 18. Model sensitivity analysis for the top ten Jolly Seber models with corresponding configurations and potential problems.

		N	Phi	p Estimates			PENT Estimates			Comments	
Assmeblage	model (, p, PENT, N)	Estimate	Estimate	mean p	p min	p max	mean p	p min	p max	AIC rank	Fixed Params ?
Occasions_no06	(.)(t)(t)(.)	71804	0.879	0.205	0.006	1.000	0.048	0.000	0.336	3rd	no
Occasions_no06	(.)(t)(.)(.)	229141	0.671	0.462	0.000	0.937	1.000	-	-	6th	no
Occasions_Fixed_no06	(.)(t)(.)(.)	229141	0.671	0.462	0.000	0.937	1.000	-	-	last	no
Occasions_Fixed_no06	(.)(t)(t)(.)	83158	0.900	0.144	0.000	0.999	0.046	0.000	0.309	3rd	yes
05 WAYR	(.)(t)(t)(.)	46767	0.788	0.175	0.000	0.751	0.074	0.000	0.493	2nd	yes
05 WAYR	(.)(t)(.)(.)	65166	0.700	0.184	0.000	0.281	0.000	-	-	3rd	yes

*(t)(.)(.)(.) model not shown due to 7th ranking

Table 19. Sensitivity analysis for the top ten Pradel models with corresponding configurations and potential problems.

		Lambda Estimates			Phi estimates			p Estimates			Comments			
Assmeblage	model (Φ p λ)	mean lambda	lambda min	lambda max	mean phi	phi min	phi max	mean p	p min	p max	AIC rank	Fixed Params?	# SE unusual/ problems	other comments
Occasions_fixed	(t)(t)(.)	1.04	-	-	0.896	0.433	1.000	0.125	0.000	0.610	top	6	1	a few wide CI's
Occasions_fixed	(.)(t)(.)	1.06	-	-	0.916	-	-	0.098	0.000	0.266	second	0	2	Oct. 03 an issue
Occasions_fixed	(.)(.)(.)	1.03	-	-	0.898	-	-	0.091	-	-	last	0	0	very simple
Occasions_Fixed_no06	(t)(t)(.)	1.05	-	-	0.877	0.445	1.000	0.143	0.000	0.700	top	6	8	SE's all over the place
Occasions_Fixed_no06	(.)(t)(.)	1.07	-	-	0.908	-	-	0.108	0.000	0.628	second	0	2	Oct. 03 an issue
Occasions_Fixed_no06	(.)(.)(.)	1.06	-	-	0.904	-	-	0.098	-	-	last	0	0	very simple
NEF 2	(.)(t)(t)	1.12	0.29	3.73	0.895	-	-	0.079	0.007	0.369	top	26	3	very wide CI's, bad SE problems
NEF 2	(t)(t)(t)	1.07	0.14	3.63	0.881	0.401	0.951	0.084	0.006	0.424	second	44	8	very wide CI's, bad SE problems
05 WAYR	(t)(.)(t)	0.84	0.12	1.25	0.957	0.811	1.000	0.172	-	-	top	8	5	low lambda estimates, little info
05 WAYR	(.)(.)(t)	0.80	0.09	1.54	1.000	-	-	0.104	-	-	second	4	5	few estimates, little info

Table 20. Gamma model configurations with their differing model runs and the varying failures of each, represented by percent. The percentage was calculated by dividing the number of problems by the total estimable parameters, which had the number of fixed parameters subtracted from it, if applicable.

	phi(t) p(t) Gamma(t)			phi(.) p(t) Gamma(t)			phi(t) p(t) Gamma(.)			phi(t) p(.) Gamma(t)		
	Phi problem	Gamma Problem	SE Problem (phi and p)	Phi problem	Gamma problem	SE Problem (phi and p)	Phi problem	Gamma problem	SE Problem (phi and p)	Phi problem	Gamma problem	SE Problem (phi and p)
Original	21.21%	75.76%	41.79%	n/a	78.79%	13.16%	9.09%	n/a	43.28%	75.76%	81.82%	25.37%
No Effort Fixed (NEF)	21.74%	65.22%	0.00%	n/a	73.91%	0.00%	13.04%	n/a	12.77%	60.87%	60.87%	29.79%
No Effort Fixed 2 (NEF2)	31.25%	43.75%	22.50%	n/a	56.25%	7.50%	12.50%	n/a	5.00%	56.25%	62.50%	25.00%
Occasions	39.13%	69.57%	21.28%	n/a	65.22%	4.26%	39.13%	n/a	27.66%	60.87%	73.91%	31.91%
Occasions_n06	14.29%	57.14%	2.33%	n/a	66.67%	6.98%	42.86%	n/a	27.91%	47.62%	61.90%	23.26%
Occasions_Fixed	52.94%	64.71%	29.27%	n/a	70.59%	2.44%	17.65%	n/a	17.07%	58.82%	64.71%	24.39%
Occasions_Fixed_n06	33.33%	40.00%	16.22%	n/a	60.00%	5.41%	26.67%	n/a	16.22%	53.33%	60.00%	18.92%
03 WAYR	56.52%	95.65%	40.43%	n/a	82.61%	6.38%	52.17%	n/a	27.66%	60.87%	86.96%	34.04%
04 WAYR	37.50%	81.25%	15.15%	n/a	87.50%	3.03%	56.25%	n/a	27.27%	43.75%	87.50%	21.21%
05WAYR	28.57%	57.14%	26.67%	n/a	42.86%	6.67%	42.86%	n/a	26.67%	28.57%	57.14%	13.33%
03 WAYR no fixing	66.67%	87.88%	53.73%	n/a	78.79%	31.34%	57.58%	n/a	44.78%	69.70%	93.94%	40.30%

	phi(.) p(.) Gamma(t)			phi(t) p(.) Gamma(.)			phi(.) p(t) Gamma(.)			phi(.) p(.) Gamma(.)		
	Phi problem	Gamma Problem	SE Problem (phi and p)	Phi problem	Gamma problem	SE Problem (phi and p)	Phi problem	Gamma problem	SE Problem (phi and p)	Phi problem	Gamma problem	SE Problem (phi and p)
Original	n/a	78.79%	n/a	72.73%	n/a	35.82%	n/a	n/a	25.37%		Ranked last	
No Effort Fixed (NEF)	n/a	73.91%	n/a	60.87%	n/a	29.79%	n/a	n/a	14.89%		Ranked last	
No Effort Fixed 2 (NEF2)	n/a	75.00%	n/a	43.75%	n/a	17.50%	n/a	n/a	17.50%		Ranked last	
Occasions	n/a	69.57%	n/a	56.52%	n/a	27.66%	n/a	n/a	14.89%		Ranked last	
Occasions_n06	n/a	71.43%	n/a	57.14%	n/a	27.91%	n/a	n/a	13.95%		Ranked last	
Occasions_Fixed	n/a	64.71%	n/a	41.18%	n/a	17.07%	n/a	n/a	17.07%		Ranked last	
Occasions_Fixed_n06	n/a	66.67%	n/a	53.33%	n/a	18.92%	n/a	n/a	24.32%		Ranked last	
03 WAYR	n/a	95.65%	n/a	73.91%	n/a	36.17%	n/a	n/a	19.15%		second to last	
04 WAYR	n/a	87.50%	n/a	50.00%	n/a	24.24%	n/a	n/a	15.15%		Ranked last	
05WAYR	n/a	57.14%	n/a	42.86%	n/a	20.00%	n/a	n/a	20.00%		Ranked last	
03 WAYR no fixing	n/a	100.00%	n/a	78.79%	n/a	40.30%	n/a	n/a	28.36%		second to last	

(yellow)	# of Phi's of 1
(pink)	SE of 0 or close to (within three decimal places)
(brown)	Gamma of 1 or .999
(teal)	being considered in sensitivity analysis

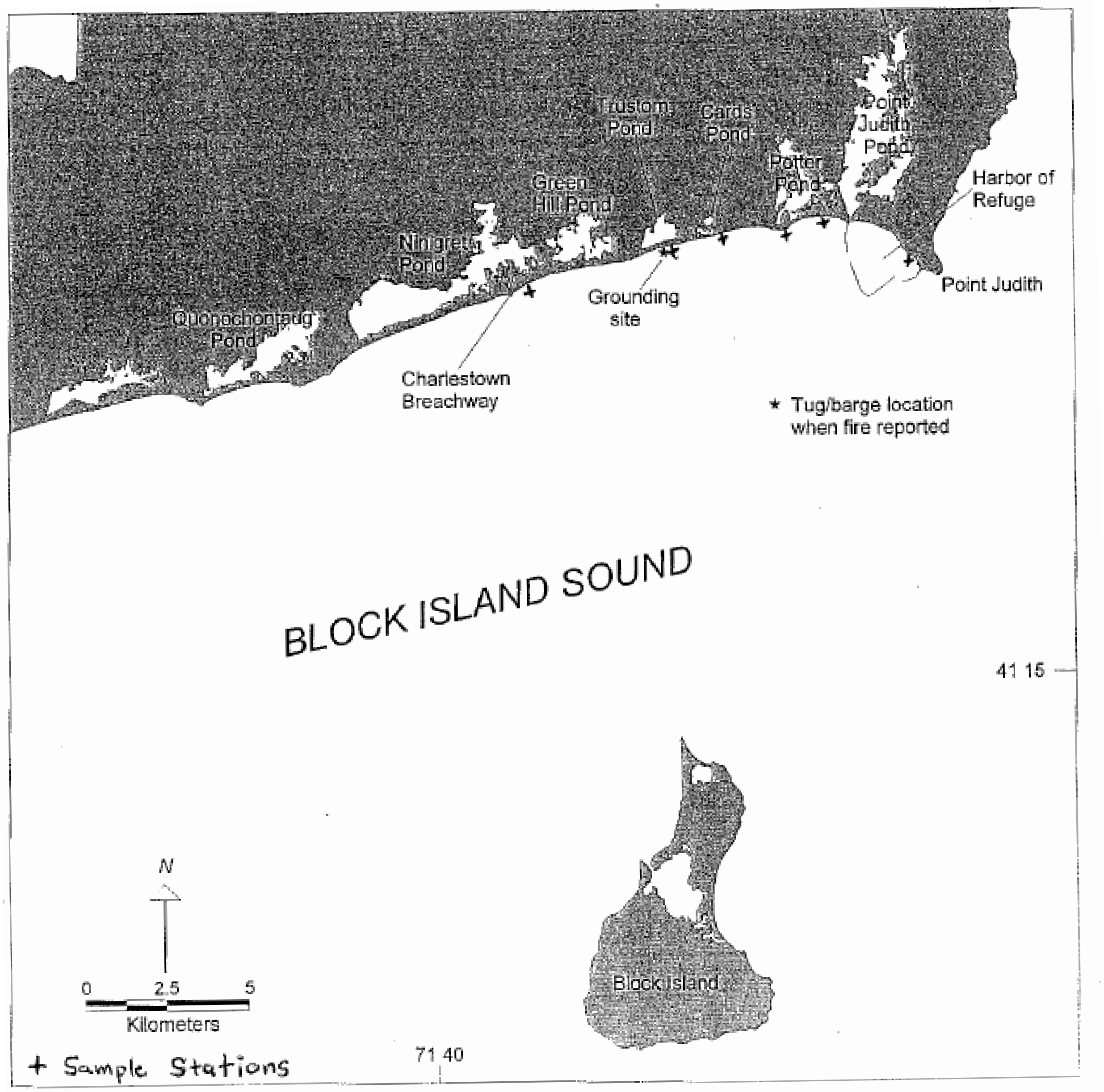


Figure 1. The site of the *North Cape* grounding off the south shore of Rhode Island (from Gibson *et al.*, 1997)

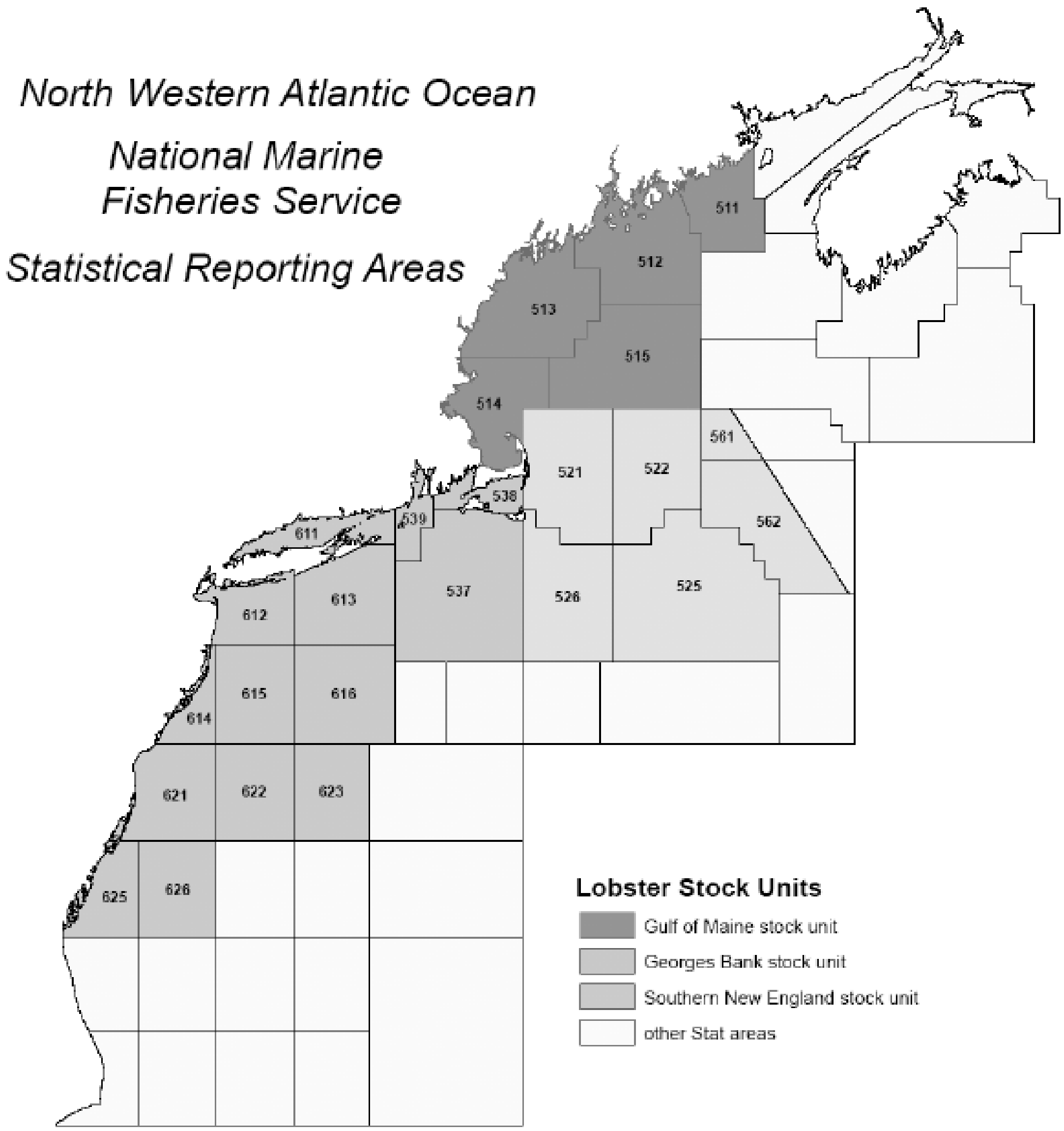


Figure 2. Statistical reporting areas on Northeast coast for American lobster; shading denotes new stock boundaries for 2006 Stock Assessment (from ASMFC, 2006)

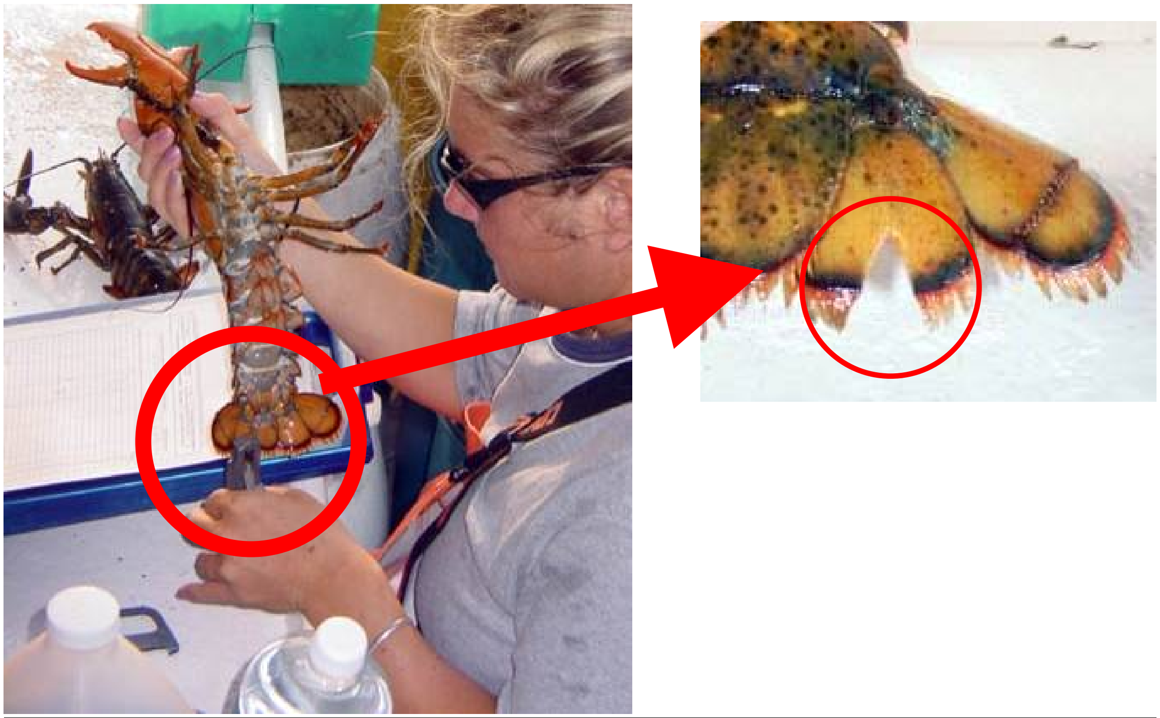


Figure 3. Images of V-notching. Left is a woman using the V-notch tool on a lobster, right is the resulting V-notch (from Bryan DeAngelis, Northeast Fisheries Science Center)

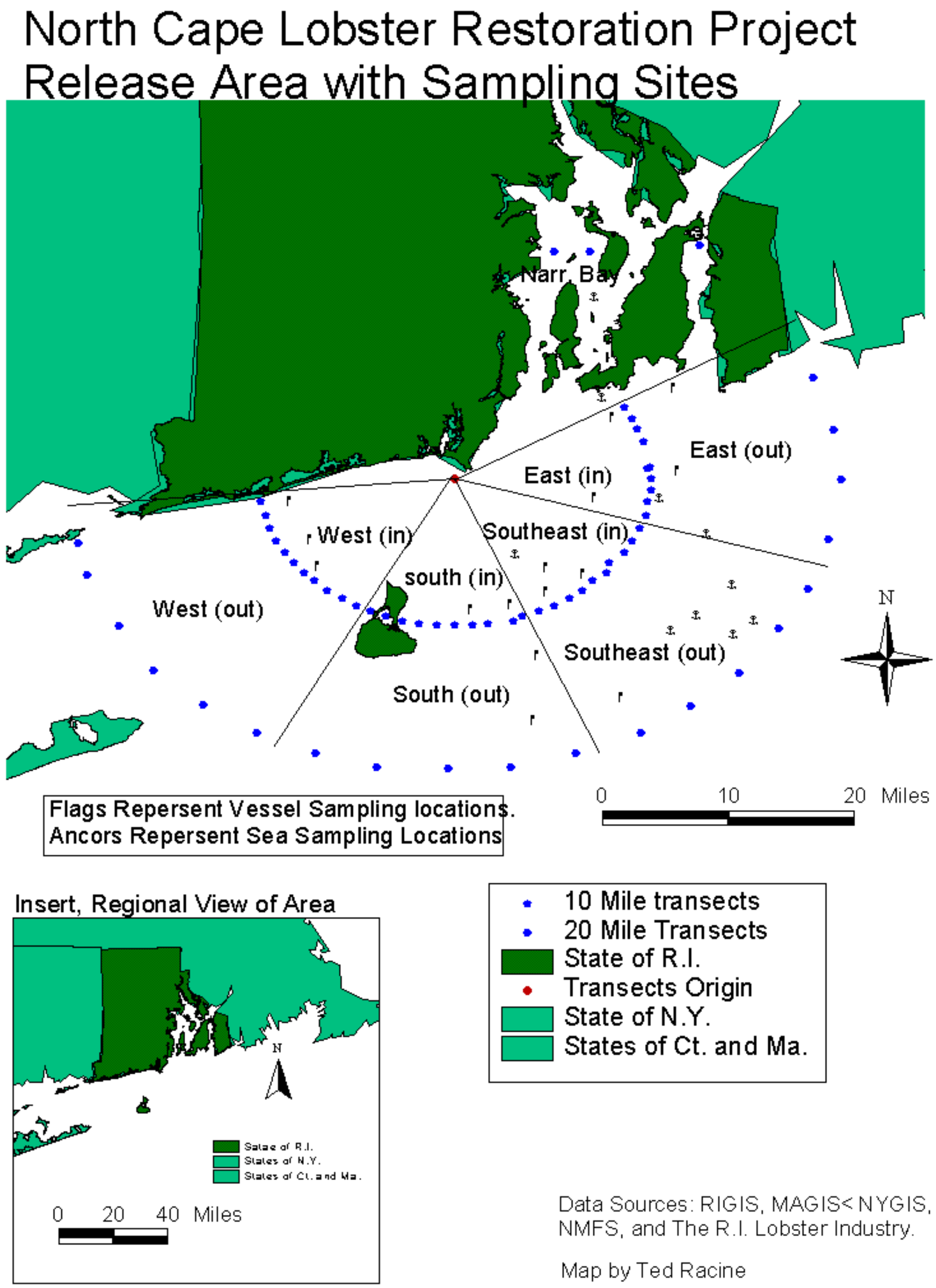


Figure 4. Release areas for the lobsters V-notched in the year 2000, where the blue dots denote release areas. The small flags and anchors represent vessel sampling and sea sampling locations, respectively (from Bryan DeAngelis, Northeast Fisheries Science Center)

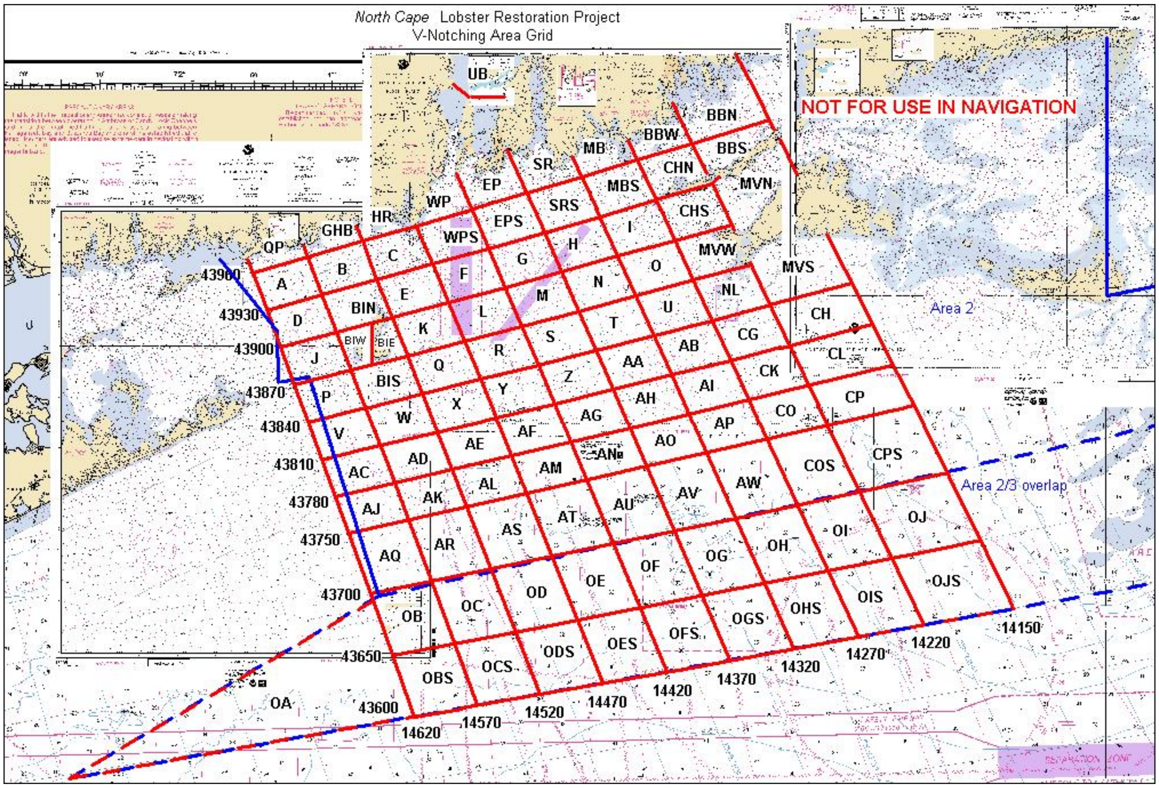
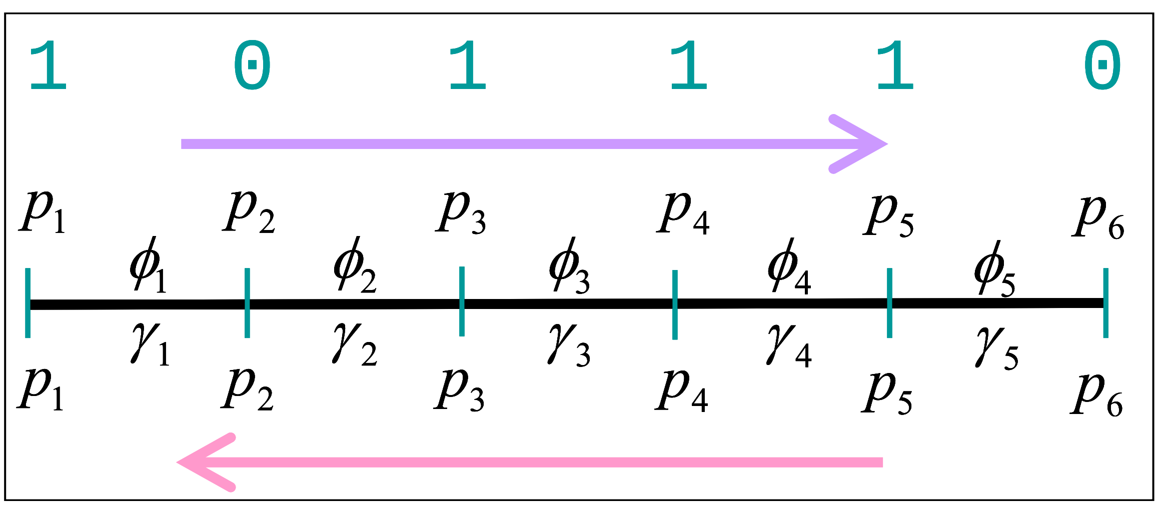


Figure 5. Areas in which V-notching took place for the years 2001-2006. Letter labels and the red borders are used as statistical areas. Blue lines denote boundaries for the ASMFC. There is also an offshore grid which is missing, notated "OFF" (Bryan DeAngelis, Northeast Fisheries Science Center)

Figure 6. A schematic of encounter probabilities and how they are reversed



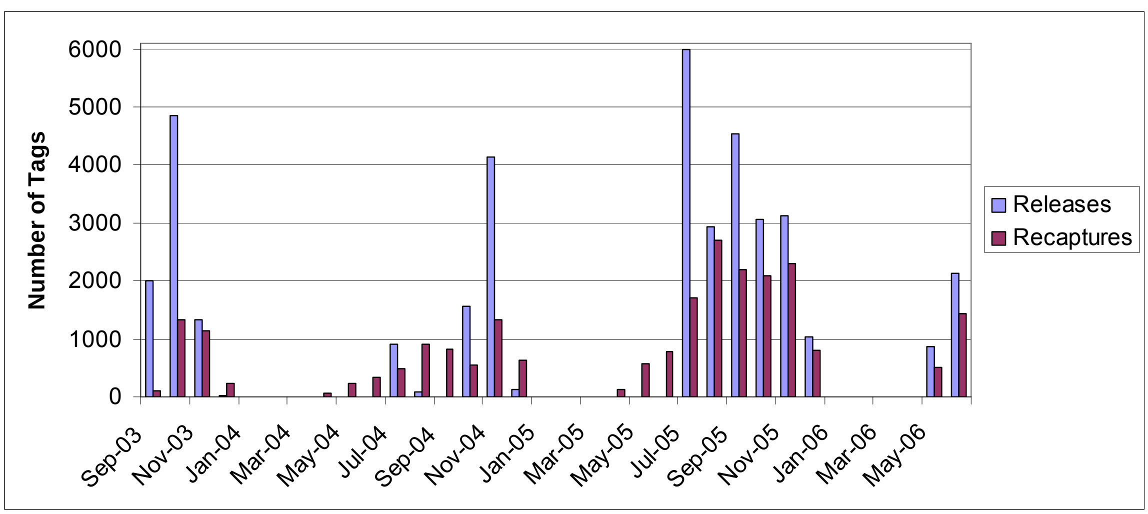


Figure 7. Annual summary V-notching Program. Upper Panel: total catch, by new, V-notches, renotches, recaptures of V-notches, and those that were harvested. Lower Panel: releases and recaptures by month.

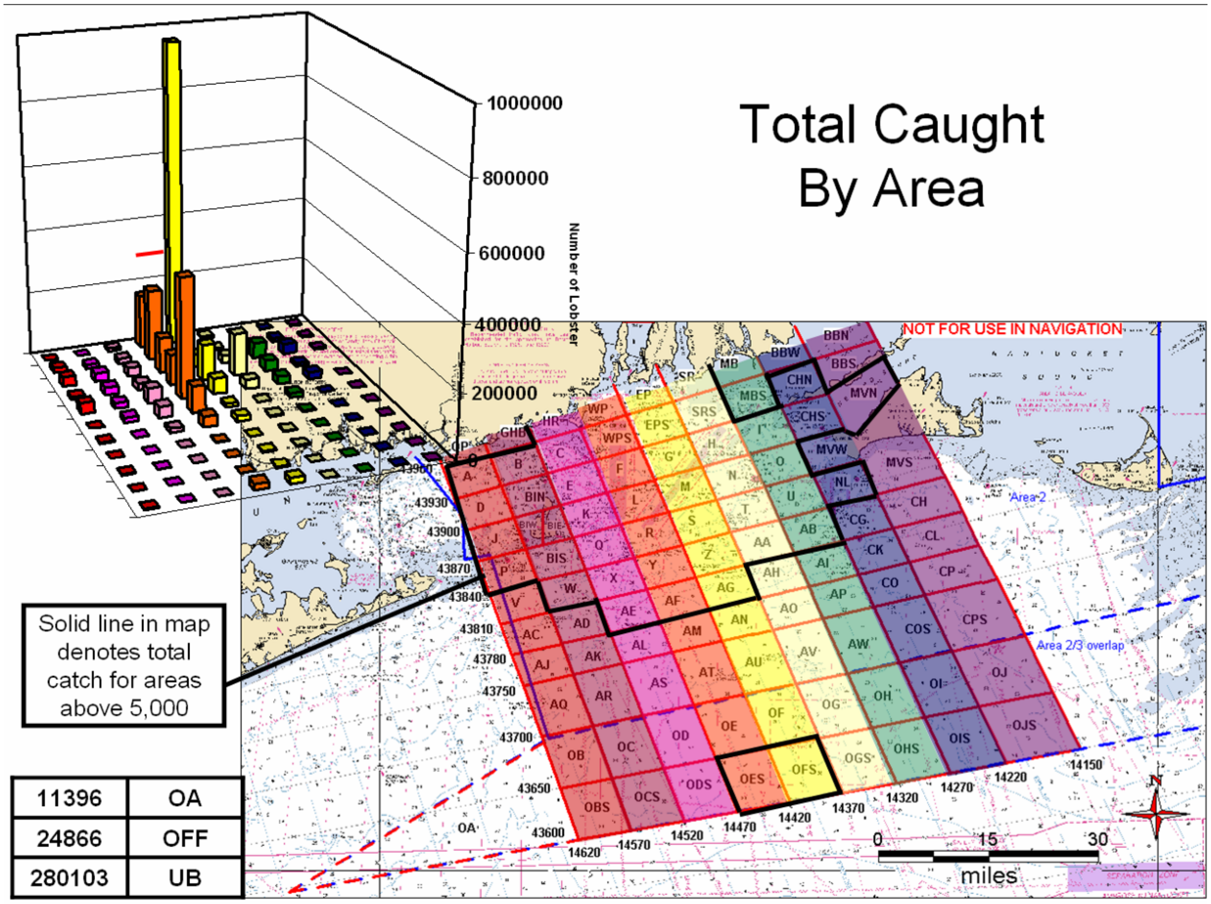


Figure 8. Summary of the total lobsters caught by area in the grid over the entirety of the restoration effort. The colored grid corresponds to the color of the graph in the upper left hand corner. The red line in the upper corner designates where the OA area would fall if it was graphed. The three areas in the lower left (OA, OFF, and UB) were not graphed because they did not fit in with the grid. Offshore denotes the areas S-SE of the grid, whereas UB denotes the Upper Bay area, located in Narragansett Bay, north of the grid.

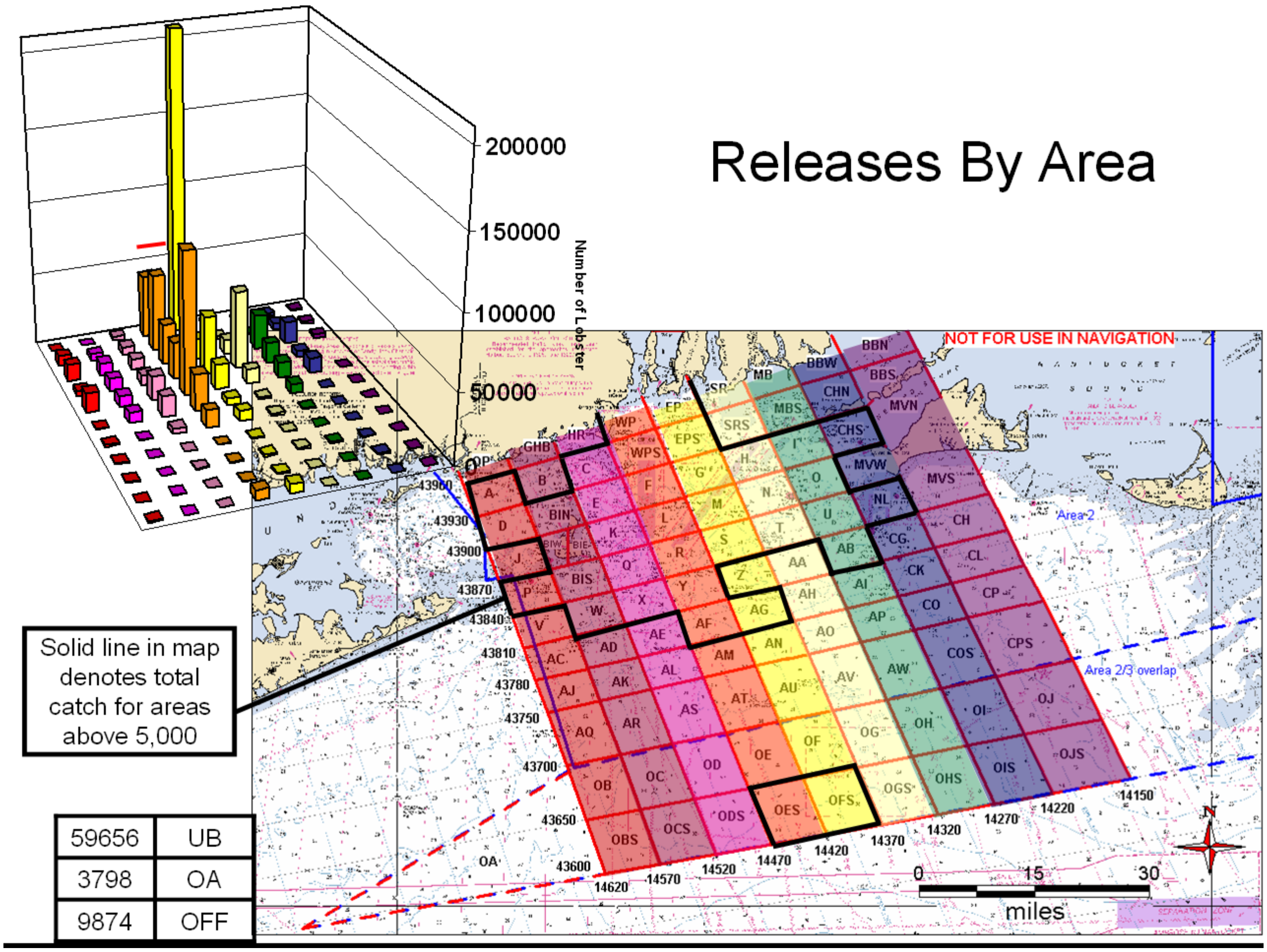


Figure 9. Summary of the total lobsters released by area in the grid over the entirety of the restoration effort. The colored grid corresponds to the color of the graph in the upper left hand corner. The red line in the upper corner designates where the OA area would fall if it was graphed. The three areas in the lower left (OA, OFF, and UB) were not graphed because they did not fit in with the grid. Offshore denotes the areas S-SE of the grid, whereas UB denotes the Upper Bay area, located in Narragansett Bay, north of the grid.

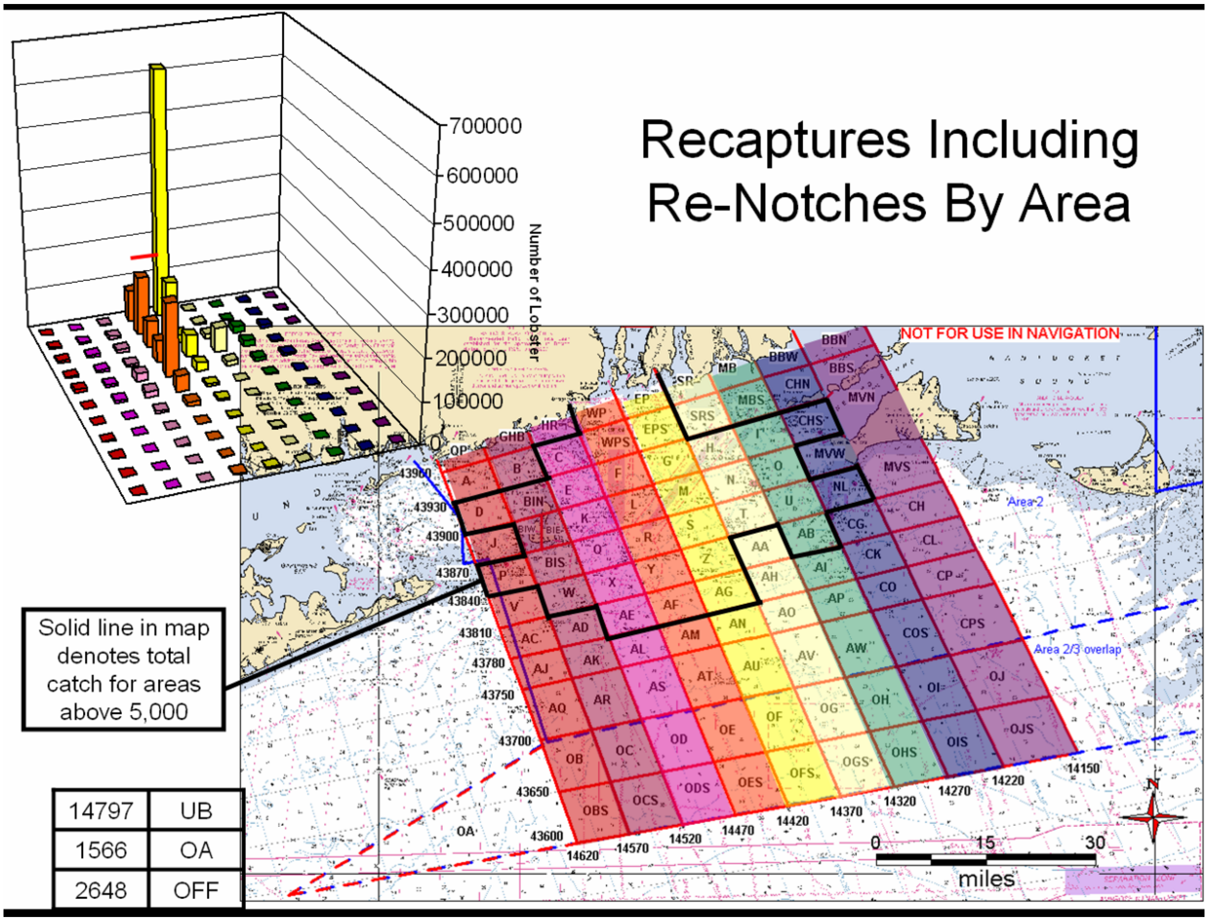


Figure 10: A statistical summary of the recaptures caught by area in the grid, which includes the "re-notch" category (those which were previously marked but had lost their legal status). This is a summation over the entirety of the restoration effort. The colored grid corresponds to the color of the graph in the upper left hand corner. The red line in the upper corner designates where the OA area would fall if it was graphed. The three areas in the lower left (OA, OFF, and UB) were not graphed because they did not fit in with the grid. Offshore denotes the areas S-SE of the grid, whereas UB denotes the Upper Bay area, located in Narragansett Bay, north of the grid.

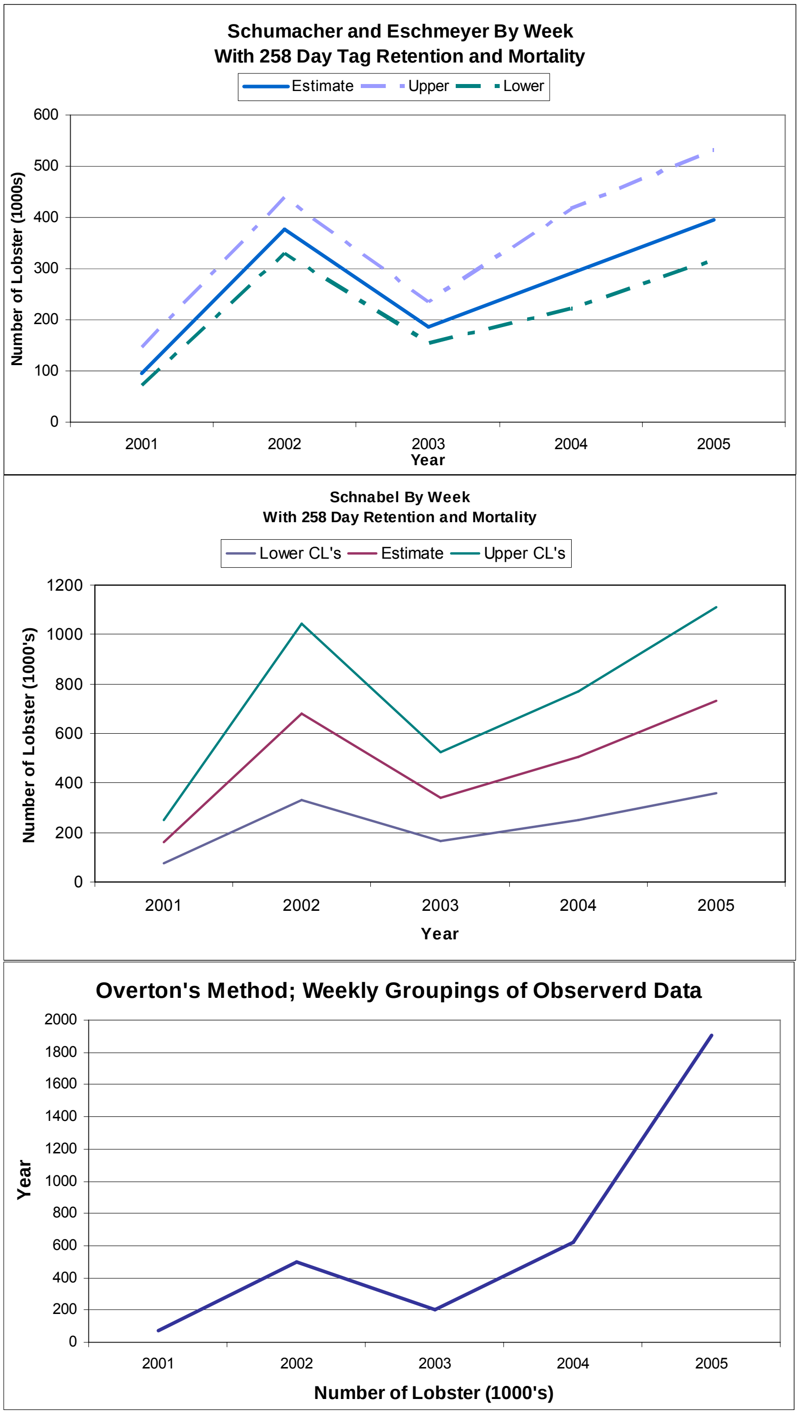


Figure 11. Estimates of abundance from alternative models of V-notch data.

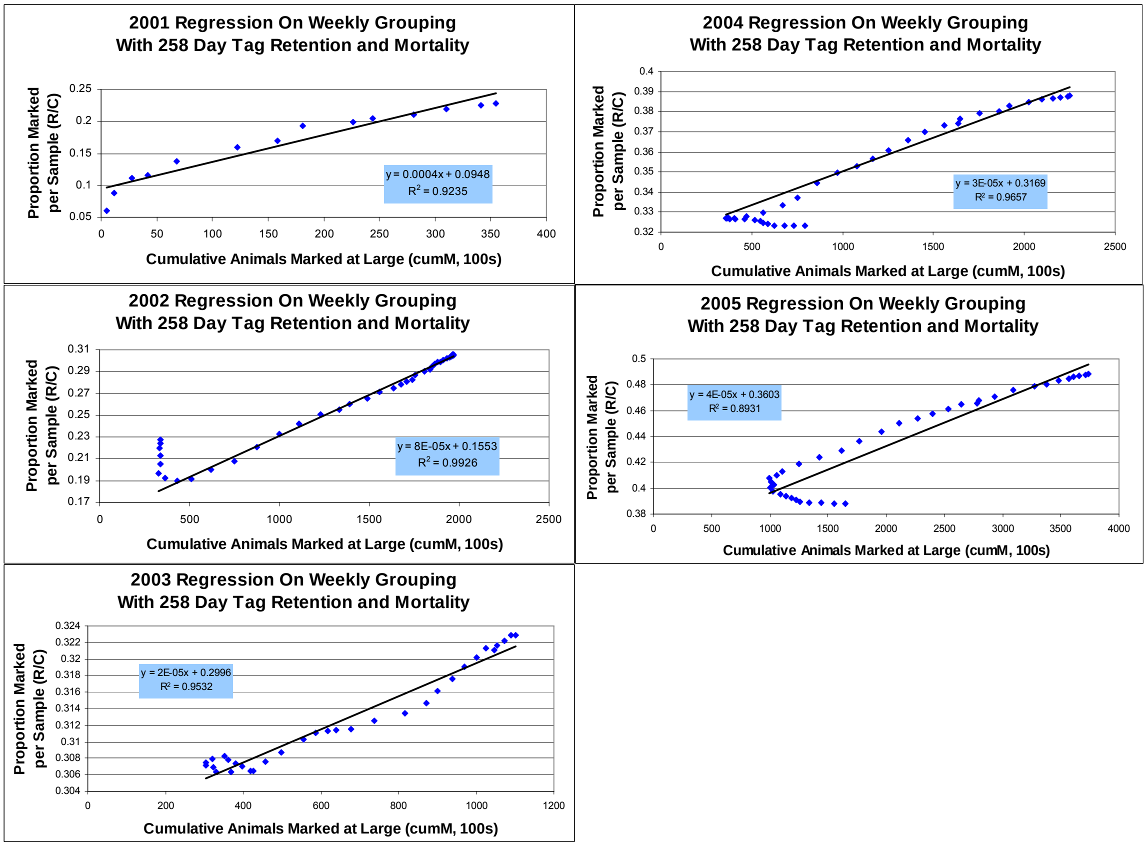


Figure 12. Regression used to derive the Schumacher and Eschmeyer population estimates from V-notch data. Regressions and corresponding statistics were of V-notch releases and recaptures grouped by week, assuming a mark retention time of 258 days.

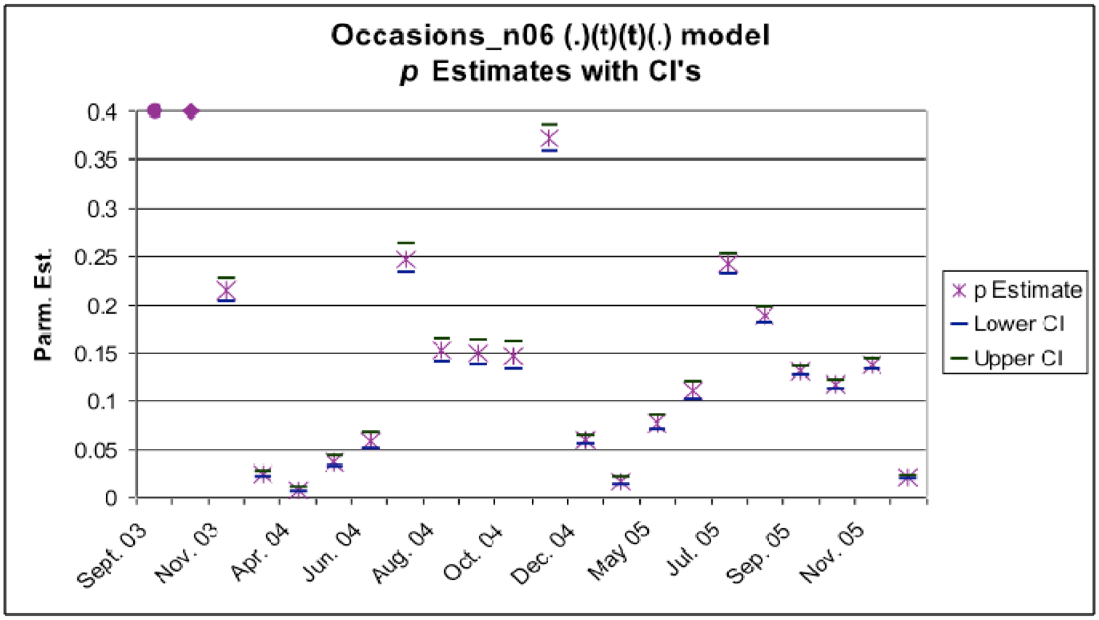


Figure 13. Results for p of the Jolly Seber model where Φ was constant, p varied with time, and PENT varied with time, under the Occasions_n06 model. The first estimate of p is typically confounded with PENT, and the last estimate of p is typically confounded with Φ (Cooch and White, 2008). The circle denotes the September 2003 estimated to be 1 (CI's: 0, 1) and the diamond denotes the October 2003 estimate, estimated to be 0.991 (CI's: 0, 1)

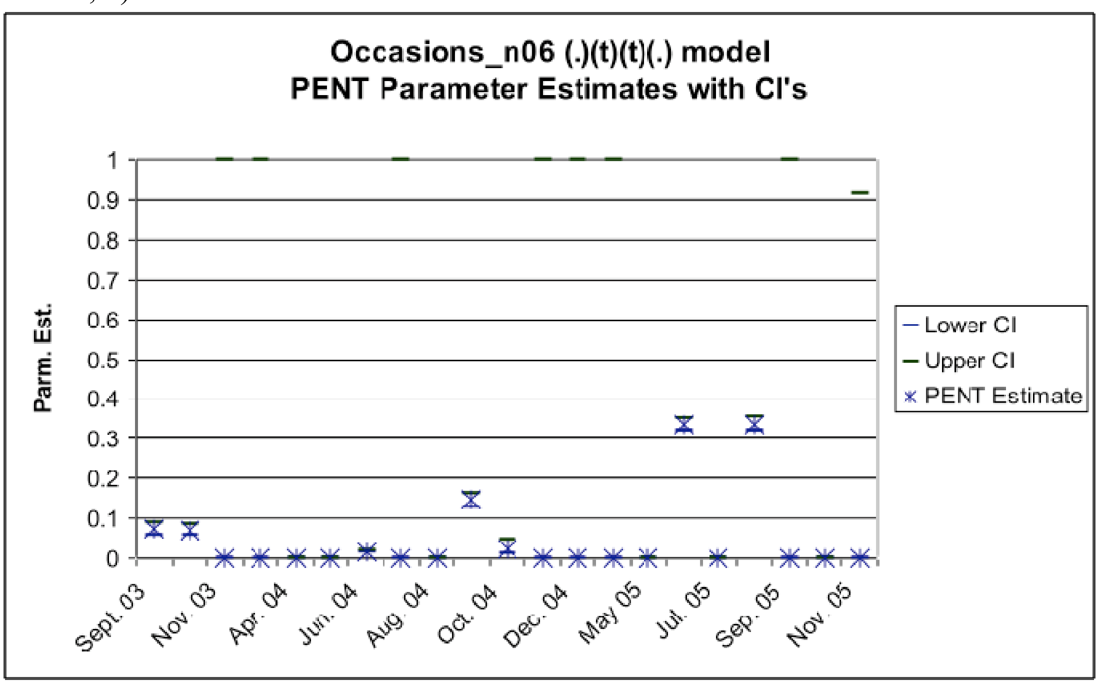


Figure 14. Results for PENT of the Jolly-Seber model run where Φ was constant, p varied with time, and PENT varied with time, under the Occasions_n06 model. The first estimate of p is typically confounded with PENT, and the last estimate of PENT is not reliable (Cooch and White, 2008).

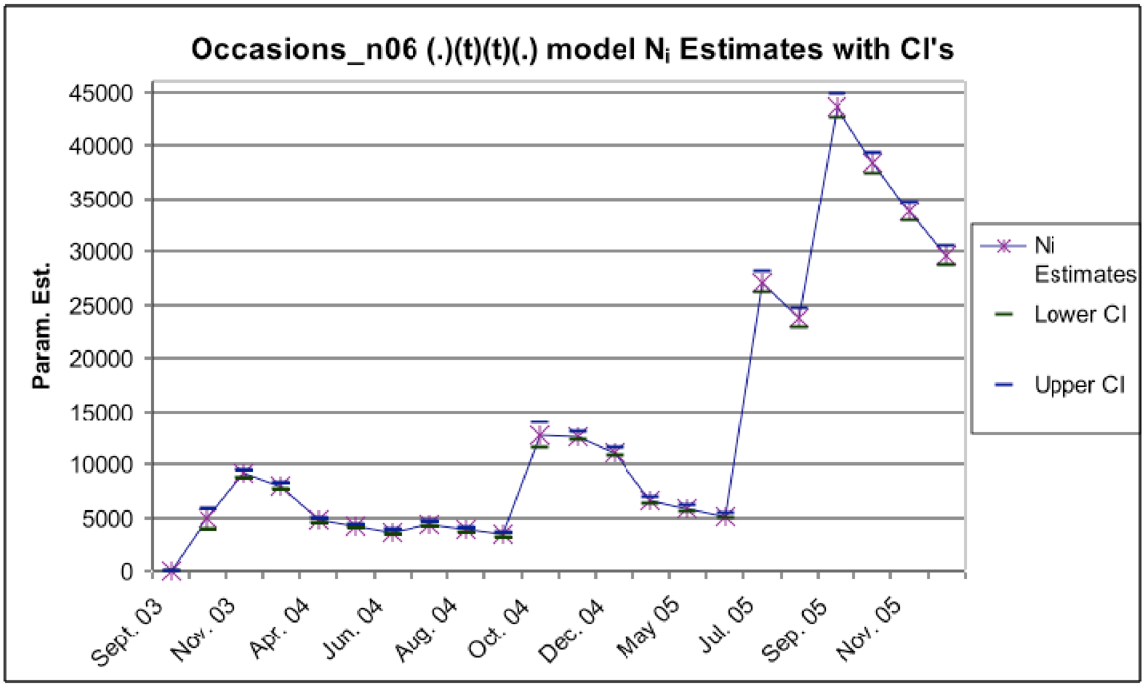


Figure 15. Population estimates by month of the Jolly Seber model run where Φ was constant, p varied with time, and PENT varied with time, under the Occasions_n06 model. All estimates in are derived.

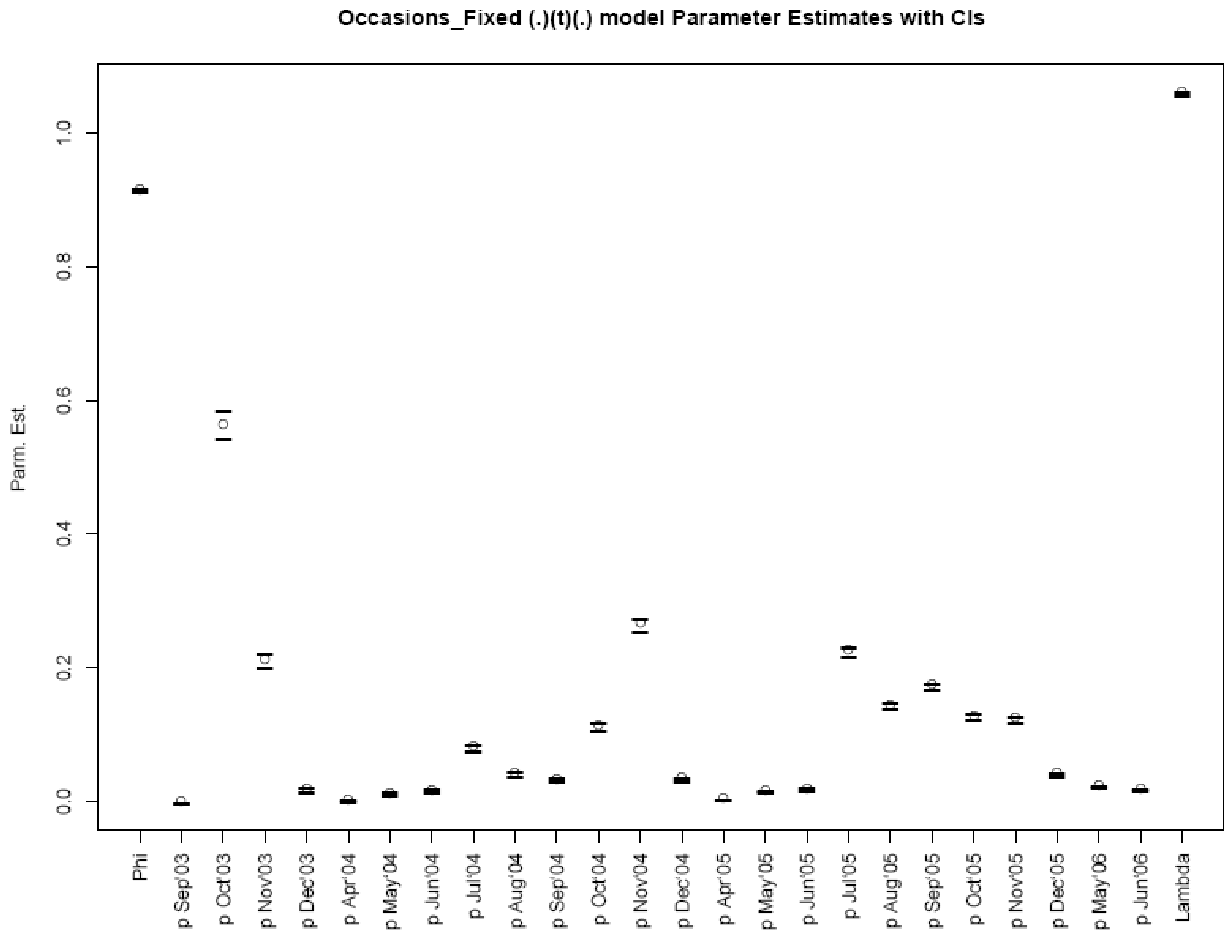


Figure 16. Results of the Pradel model, where Φ was constant, *p* varied with time, and λ was constant, under the Occasions_Fixed model. The first estimate of *p* is typically confounded with Lambda, and the last estimate of *p* is typically confounded with Phi (Cooch and White, 2008).

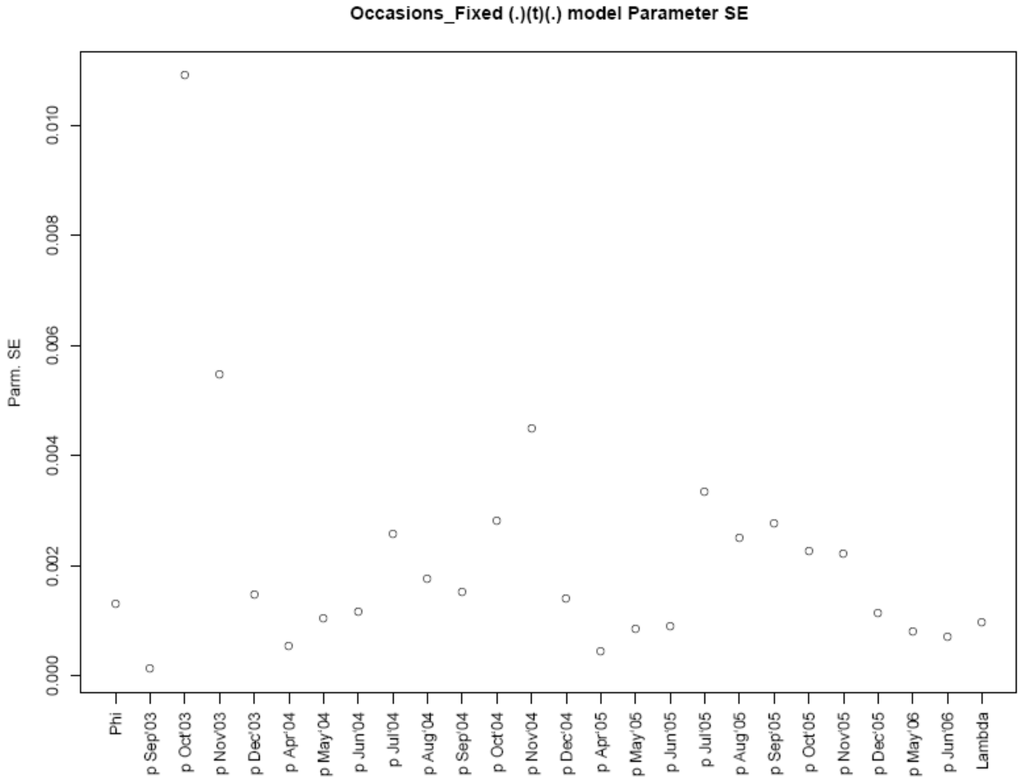


Figure 17. Parameter Standard Errors from the Pradel model.

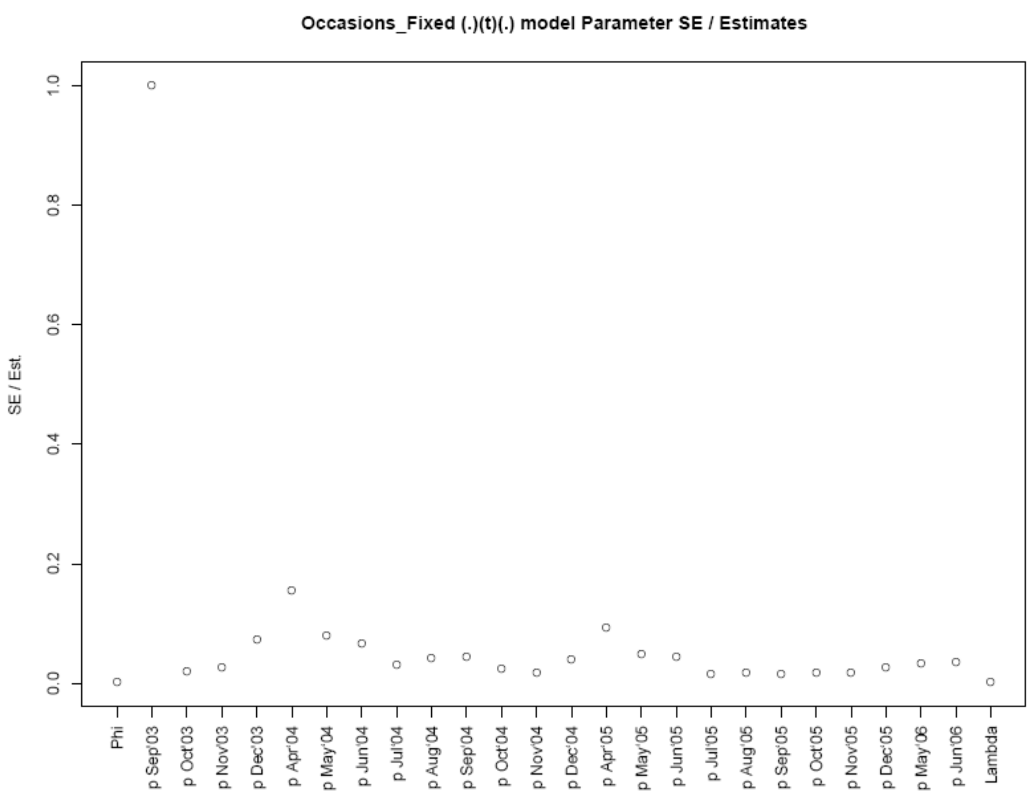


Figure18. Parameter CV's from the Pradel model.

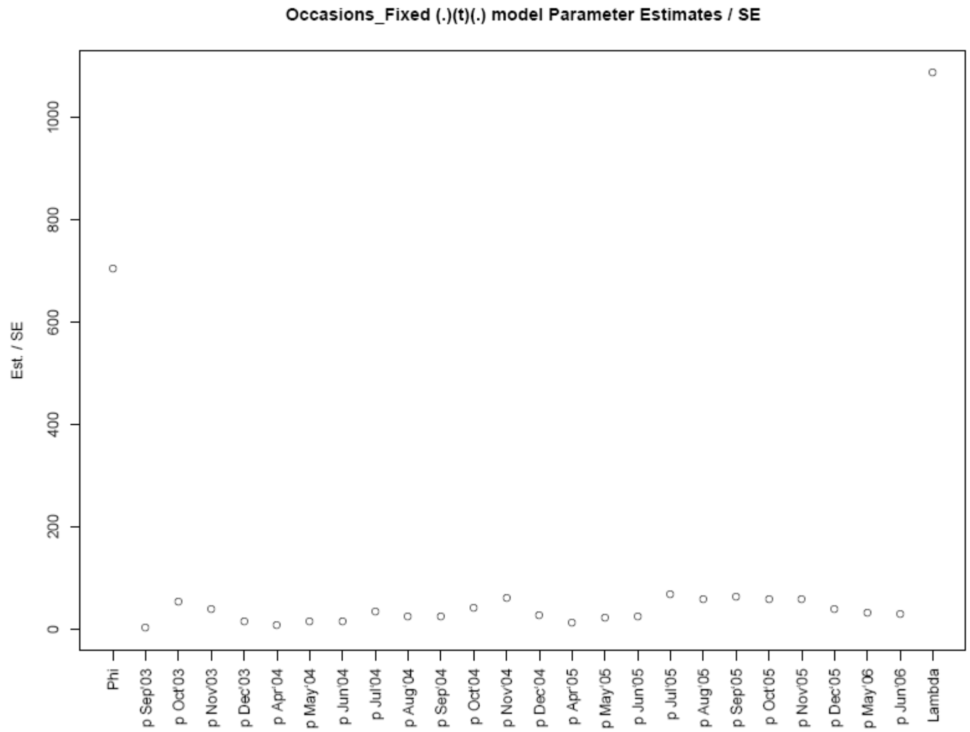


Figure 19. Parameter *t* values from the Pradel model.

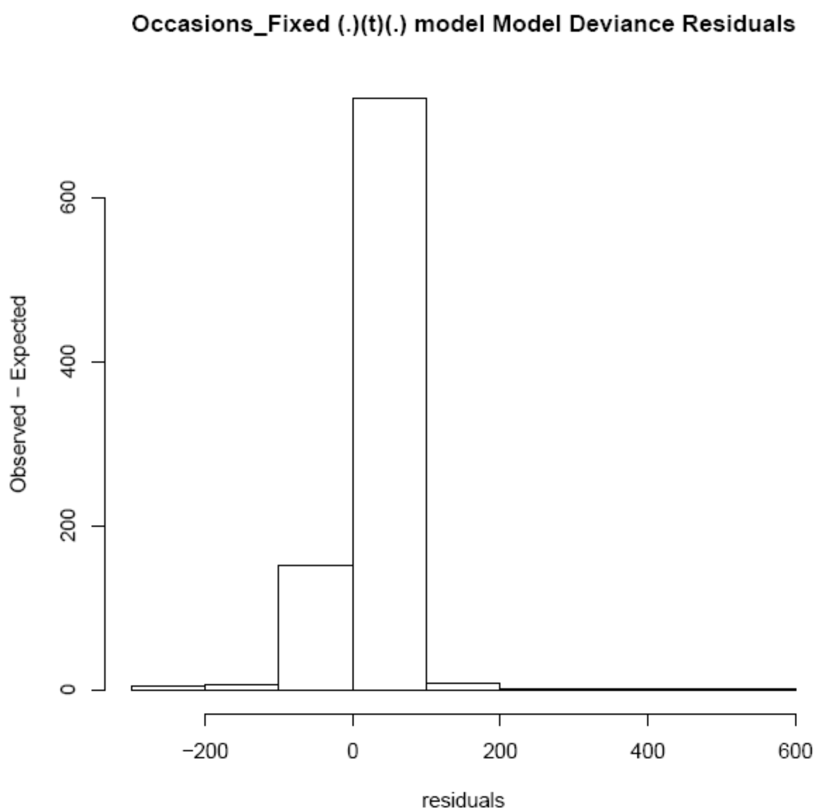


Figure 20. The deviance residuals from the Pradel model.

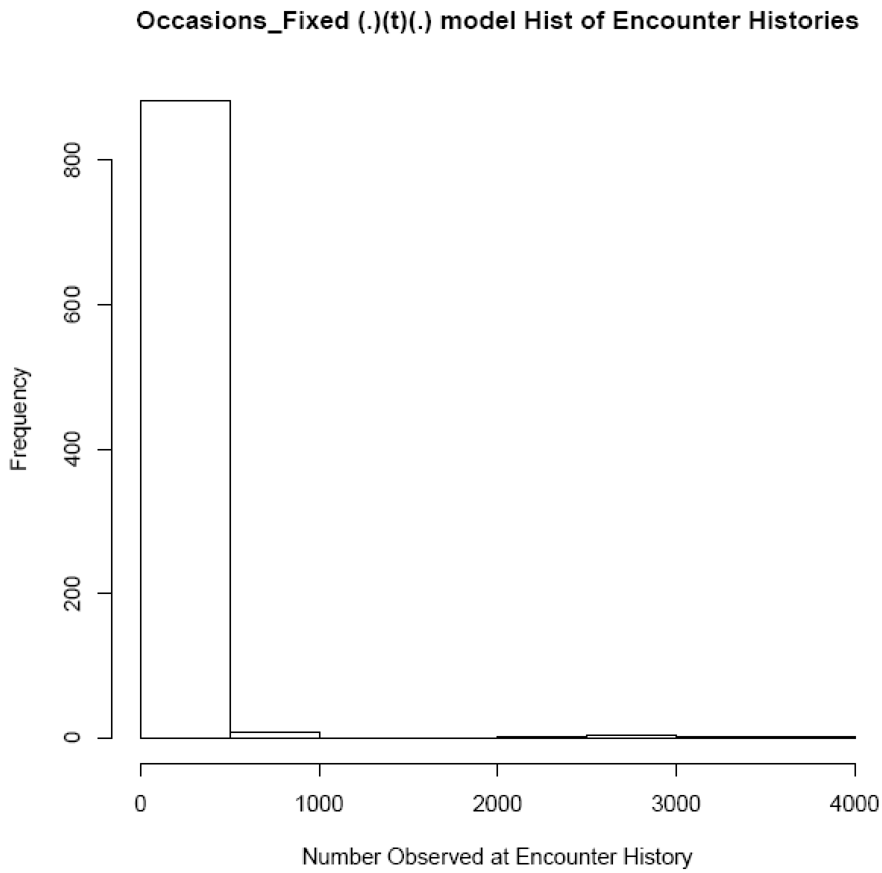


Figure 21. A histogram of the initial encounter histories from the Pradel model

APPENDIX A

Mark output for the best Pradel model {Φ(.) p(t) λ(.)} from the Occasions_Fixed assemblage:

```
   Program  MARK  - Survival Rate Estimation with Capture-Recapture Data
   Compaq(Win32) Vers. 5.1 Apr 2007     20-Nov-2008 02:35:55    Page  001
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
  INPUT --- proc title Lobster Banding, Grouped by Month, Occasions,
  INPUT --- Parms Fixed;
     Time in seconds for last procedure was 0.02

  INPUT --- proc chmatrix occasions=24 groups=1 etype=PradLambda NoHist
  INPUT --- hist=897;
  INPUT ---    glabel(1)=Group 1;
  INPUT ---    time interval  1 1 1 4 1 1 1 1 1 1 1 1 4 1 1 1 1 1 1 1 1 5
  INPUT ---    1;
      Number of unique encounter histories read was 897.
      Number of individual covariates read was 0.
      Time interval lengths vary and/or not equal to 1.
      Data type is Pradel Survival and Lambda
     Time in seconds for last procedure was 0.53

  INPUT --- proc estimate link=Logit varest=2ndPart ;
  INPUT --- model={phi(.) p(t) lambda(.)};
  INPUT ---    group=1 Phi rows=1 cols=23 Square Constant=1;
  INPUT ---    group=1 p rows=1 cols=24 Square Time=2;
  INPUT ---    group=1 Lambda rows=1 cols=23 Square Constant=26;
  INPUT ---    design matrix constraints=26 covariates=26 identity;
  INPUT ---    blabel(1)=Phi;
  INPUT ---    blabel(2)=p;
  INPUT ---    blabel(3)=p;
  INPUT ---    blabel(4)=p;
  INPUT ---    blabel(5)=p;
  INPUT ---    blabel(6)=p;
  INPUT ---    blabel(7)=p;
  INPUT ---    blabel(8)=p;
  INPUT ---    blabel(9)=p;
  INPUT ---    blabel(10)=p;
  INPUT ---    blabel(11)=p;
  INPUT ---    blabel(12)=p;
  INPUT ---    blabel(13)=p;
  INPUT ---    blabel(14)=p;
  INPUT ---    blabel(15)=p;
  INPUT ---    blabel(16)=p;
  INPUT ---    blabel(17)=p;
  INPUT ---    blabel(18)=p;
  INPUT ---    blabel(19)=p;
  INPUT ---    blabel(20)=p;
  INPUT ---    blabel(21)=p;
  INPUT ---    blabel(22)=p;
  INPUT ---    blabel(23)=p;
  INPUT ---    blabel(24)=p;
  INPUT ---    blabel(25)=p;
  INPUT ---    blabel(26)=Lambda;
  INPUT ---    rlabel(1)=Phi;
  INPUT ---    rlabel(2)=p;
  INPUT ---    rlabel(3)=p;
  INPUT ---    rlabel(4)=p;
  INPUT ---    rlabel(5)=p;
  INPUT ---    rlabel(6)=p;
  INPUT ---    rlabel(7)=p;
  INPUT ---    rlabel(8)=p;
  INPUT ---    rlabel(9)=p;
  INPUT ---    rlabel(10)=p;
  INPUT ---    rlabel(11)=p;
  INPUT ---    rlabel(12)=p;
  INPUT ---    rlabel(13)=p;
  INPUT ---    rlabel(14)=p;
```

```
 INPUT ---    rlabel(15)=p;
 INPUT ---    rlabel(16)=p;
 INPUT ---    rlabel(17)=p;
 INPUT ---    rlabel(18)=p;
 INPUT ---    rlabel(19)=p;
 INPUT ---    rlabel(20)=p;
 INPUT ---    rlabel(21)=p;
 INPUT ---    rlabel(22)=p;
 INPUT ---    rlabel(23)=p;
 INPUT ---    rlabel(24)=p;
 INPUT ---    rlabel(25)=p;
 INPUT ---    rlabel(26)=Lambda;
Link Function Used is LOGIT
Variance Estimation Procedure Used is 2ndPart
-2logL(saturated) = 255989.76
Effective Sample Size = 48136

Number of function evaluations was 59 for 26 parameters.
Time for numerical optimization was 560.95 seconds.

-2logL {phi(.) p(t) lambda(.)} = 276384.92
Penalty {phi(.) p(t) lambda(.)} = 0.0000000
Gradient {phi(.) p(t) lambda(.)}:
-0.1719242E-01 0.4656605E-02 0.5086808E-01-0.1516605E-01 0.4763074E-02
 0.3505547E-02 0.6577704E-02-0.2319287E-02 0.2907896E-01-0.8498082E-02
 0.4039588E-02 0.2099173E-01 0.2602657E-01  0.000000     0.2757453E-02
 0.3482856E-02 0.2039417E-01-0.1305669E-01 0.2940902E-01 0.1366995E-01
 0.2799764E-01 0.5338075E-01 0.1981463E-01-0.3751424E-02 0.1195118E-02
 0.1430223
S Vector {phi(.) p(t) lambda(.)}:
  3368361.      5612.242      4648.162      4287.378      3909.659
  3671.492      2826.806      1981.265      1567.744      1516.980
  1378.983      1155.221      1018.969      706.2559      615.4979
  583.5706      537.1938      478.8227      401.1502      330.4945
  216.5707      177.3031      150.6649      112.4573      41.42416
  1.000537
Time to compute number of parameters was 406.50 seconds.
  Threshold =  0.5400000E-06     Condition index =  0.2970398E-06

Conditioned S Vector {phi(.) p(t) lambda(.)}:
  1.000000     0.1666164E-02 0.1379947E-02 0.1272838E-02 0.1160701E-02
 0.1089993E-02 0.8392228E-03 0.5881984E-03 0.4654322E-03 0.4503615E-03
 0.4093929E-03 0.3429622E-03 0.3025119E-03 0.2096734E-03 0.1827292E-03
 0.1732506E-03 0.1594822E-03 0.1421530E-03 0.1190936E-03 0.9811730E-04
 0.6429555E-04 0.5263779E-04 0.4472943E-04 0.3338635E-04 0.1229801E-04
 0.2970398E-06
Number of Estimated Parameters {phi(.) p(t) lambda(.)} = 25
DEVIANCE {phi(.) p(t) lambda(.)} = 20395.157
DEVIANCE Degrees of Freedom {phi(.) p(t) lambda(.)} = 872
c-hat {phi(.) p(t) lambda(.)} = 23.388942
AIC {phi(.) p(t) lambda(.)} = 276434.92
AICc {phi(.) p(t) lambda(.)} = 276434.95
BIC {phi(.) p(t) lambda(.)} = 276654.46
Pearson Chisquare {phi(.) p(t) lambda(.)} = 21167600.
```

LOGIT Link Function Parameters of {phi(.) p(t) lambda(.)}

Parameter	Beta	Standard Error	95% Confidence Interval Lower	Upper
1:Phi	2.3856579	0.0168240	2.3526828	2.4186330
2:p	-9.0000166	0.9997310	-10.959489	-7.0405438
3:p	0.2587151	0.0443103	0.1718669	0.3455634
4:p	-1.3028136	0.0325672	-1.3666454	-1.2389818
5:p	-3.8882431	0.0744838	-4.0342314	-3.7422549
6:p	-5.6417774	0.1552767	-5.9461197	-5.3374351
7:p	-4.3095420	0.0794637	-4.4652909	-4.1537932
8:p	-4.0194451	0.0675842	-4.1519102	-3.8869800
9:p	-2.4029080	0.0339696	-2.4694884	-2.3363276
10:p	-3.1097032	0.0429030	-3.1937931	-3.0256133
11:p	-3.3227918	0.0454605	-3.4118944	-3.2336891
12:p	-2.0501741	0.0277638	-2.1045912	-1.9957570
13:p	-1.0128234	0.0229245	-1.0577555	-0.9678914
14:p	-3.3059418	0.0411072	-3.3865119	-3.2253717
15:p	-5.3327632	0.0940536	-5.5171082	-5.1484182
16:p	-4.0137869	0.0486414	-4.1091242	-3.9184497
17:p	-3.8520249	0.0438269	-3.9379256	-3.7661242
18:p	-1.2290360	0.0191062	-1.2664842	-1.1915878
19:p	-1.7709434	0.0200410	-1.8102238	-1.7316630
20:p	-1.5548444	0.0191791	-1.5924355	-1.5172533
21:p	-1.9106279	0.0201757	-1.9501723	-1.8710835
22:p	-1.9441451	0.0203240	-1.9839801	-1.9043102
23:p	-3.1126550	0.0280110	-3.1675567	-3.0577534
24:p	-3.6548455	0.0324993	-3.7185442	-3.5911468
25:p	-3.8704536	0.0347778	-3.9386181	-3.8022892
26:Lambda	0.0581562	0.9198574E-03	0.0563533	0.0599591

Real Function Parameters of {phi(.) p(t) lambda(.)}

Parameter	Estimate	Standard Error	95% Confidence Interval Lower	Upper
1:Phi	0.9157271	0.0012983	0.9131472	0.9182372
2:p	0.1233925E-03	0.1233441E-03	0.1739189E-04	0.8748842E-03
3:p	0.5643204	0.0108943	0.5428613	0.5855413
4:p	0.2136919	0.0054722	0.2031624	0.2246133
5:p	0.0200702	0.0014649	0.0173915	0.0231519
6:p	0.0035340	0.5468125E-03	0.0026091	0.0047852
7:p	0.0132615	0.0010398	0.0113706	0.0154619
8:p	0.0176460	0.0011715	0.0154906	0.0200951
9:p	0.0829512	0.0025841	0.0780250	0.0881587
10:p	0.0427088	0.0017541	0.0394000	0.0462821
11:p	0.0347975	0.0015269	0.0319258	0.0379174
12:p	0.1140348	0.0028050	0.1086514	0.1196491
13:p	0.2664277	0.0044805	0.2577386	0.2753010
14:p	0.0353679	0.0014025	0.0327197	0.0382220
15:p	0.0048075	0.4499869E-03	0.0040014	0.0057750
16:p	0.0177443	0.8477934E-03	0.0161568	0.0194847
17:p	0.0207951	0.8924308E-03	0.0191161	0.0226182
18:p	0.2263502	0.0033458	0.2198597	0.2329751
19:p	0.1454250	0.0024906	0.1406111	0.1503750
20:p	0.1743877	0.0027613	0.1690415	0.1798663
21:p	0.1289103	0.0022656	0.1245346	0.1334164
22:p	0.1251932	0.0022259	0.1208952	0.1296214
23:p	0.0425883	0.0011421	0.0404050	0.0448839
24:p	0.0252133	0.7987560E-03	0.0236942	0.0268272
25:p	0.0204231	0.6957646E-03	0.0191031	0.0218323
26:Lambda	1.0598806	0.9749390E-03	1.0579714	1.0617932

```
Attempted ordering of parameters by estimatibility:
 26  1 18 20 22 21 19 13 12  4 23 24  9 25 14 10 17  3 11 16  8  5  7 15  6
  2
Beta number 2 is a singular value.
    Time in seconds for last procedure was 967.89
 INPUT --- proc stop;
    Time in minutes for this job was 16.14

         E X E C U T I O N   S U C C E S S F U L
```