Measuring Lagged Economic Effects of Hypoxia with a Bioeconomic Fishery Model

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1 Introduction

Environmental policies to address nutrient pollution require understanding all ecological, biological and economic consequences of hypoxia (Pew oceans Commission 2003, US Commission on Ocean Policy 2004). Though there is more to learn, the ecological dimensions of nutrient pollution are well studied around the world (Rosenberg 1985, Colombo et al. 1992, Nixon 1995, Howarth et al. 1996, Vitousek et al. 1997, National Research Council 2000, Diaz 2001, Paerl 2006, Kemp et al. 2005 and Breitburg et al. 2008). In addition, biological effects of hypoxia on individual growth (Stierhoff et al. 2006), mortality (Miller et al. 2002), movement (Wannamaker and Rice 2000), reproduction (Thomas et al. 2007), species interactions (Breitburg 2002) and food web interactions (Breitburg 2002) have also been well documented for many species. Despite the evidence that hypoxia is becoming more frequent and widespread in coastal and estuarine systems (Diaz 2001, NRC 2000, Boesch et al. 2001), the potential economic effects and their severity have not been thoroughly investigated and the implications of hypoxia for fishery management are largely unknown.

The difficulties of detecting economic effects of hypoxia rely largely on how to isolate the effects of single environmental stressor on fishery harvest from multiple underlying complicated processes which is impacted by environmental, social and economic considerations. The possible factors include spatial and temporal variation in fishing effort, variation in individual vessel catching abilities, and species' growth, natural mortality, reproduction, and emigration rates. In turn, each of these processes may be impacted by hypoxia as well as other factors. Effects of hypoxia on fisherman behavior and catch efficiency are generally less well-known but have been suggested for several commercial fisheries (Martin and Crowder 2005, Baden et al. 1990, Craig and Crowder 2005, Craig 2008). Furthermore, there exist assessments on economic effects of hypoxia based on fisheries aggregated data. However, they have failed to detect economic effects attributable to hypoxia (Zimmerman et al. 1996, Diaz and Solow. 1999). As Diaz and Solow point out in their studies, the limitation of such assessments is the lack of statistical power to make inferences from correlations between aggregate fishery data and coarse indicators of hypoxia severity. These data have integrated out complex information of behavioral, ecological, and climatological processes that operate across multiple spatial and temporal scales. For example, species growth, hypoxia and harvest quite likely occur in different areas and different time, which makes the analysis with aggregate data lack of convincing power. In addition, brown shrimp are able to avoid serious hypoxia situation (Renaud 1986) . Contrarily, Disaggregated fishery data (or 'microdata') consisting of landings and environmental conditions at relatively fine spatial (10-100s km) and temporal (days to weeks) scales offers the possibility to control for some of these effects and thereby make stronger causal inferences about the effects of hypoxia on fishery harvest. The combination of spatial and temporal dynamics of both the productivity of harvested species and commercial fisheries suggests a coupled spatio-temporal bioeconomic modeling framework is appropriate to evaluate the impacts of hypoxia on fisheries. The only studies of which we are aware use bioeconomic model and microdata to detect hypoxia effects are conducted by Massey et al. (2006) and Lipton et al. (2003). However, they have not exploited the spatial and temporal mismatch between harvest and hypoxia which, to our knowledge, are key issues to accurately measure economic effect of hypoxia.

In this paper, we develop and apply a bioeconomic model to identify the effects of hypoxia on commercial harvest in the North Carolina brown shrimp fishery. Similar to other regions in southeast US and Gulf coast estuaries, the shrimp fishery has ranked first or second in terms of economic value among fisheries in North Carolina over the last 30 years[1]. Brown shrimp (Farfantepenaeus aztecus) are subject to harvest during a large portion of their annual life cycle and support important commercial fisheries. Brown shrimp typically start to grow during February-March and return to the ocean shelf during fall and winter to spawn with high fertility. This strong seasonality and high fertility enables shrimp to recruit independent of stock. Since stock decrease could also result from last period's stock decrease which is also a function of last period's water quanlity and harvest, this feature eliminates this possibility which significantly lessens the difficulties of water quanlity analysis. As explained in the model details, our bioeconomic model is tailored to the timing of the shrimp fishery in relation to the life history and migratory timing of brown shrimp.

For the temporal aspect of this model, since hypoxia and fishing jointly affect shrimp populations because they both occur primarily during summer (June-July) and early fall (September-October). Since shrimp can avoid hypoxia by migration, it is conjectured that hypoxia only affects shrimp during their growing time, mostly before July, which creates a lagged hypoxia effects on harvest. Our approach for quantifying the potentially lagged effects of hypoxia on the brown shrimp fishery proceeds in three steps. First, we extend the basic Schaefer model to link the stock of brown shrimp, the commercial fishery and multiple environmental factors. Secondly, shrimp stock dynamics in the extended Schaefer model are decomposed into growth and loss (emigration and natural mortality) processes which are potentially influenced by hypoxia. These effects of hypoxia are accumulated over multiple days by counting how many days are below some dissolved oxygen threshold. Finally, the expanded Schaefer model is linearized and parameters estimated empirically using available harvest and oxygen monitoring data. Although hypoxia in estuarine systems is typically temporally dynamic and can vary over

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[1] The following is summarized from the North Carolina Draft Shrimp Fishery Management Plan (NCDENR-DMF FMP, 2004)

hourly to annual time scales (Fleming and Luetich 19XX), we have detailed water quanlity data which provides fine record scales to 15 minutes.

Besides temporal considerations, because of shrimp's ability to avoid hypoxia, we also account for the effects of hypoxia on the spatial dynamics of harvest by parallel estimation of the model in two adjacent areas: the Neuse River and the Pamlico Sound. Pamlico Sound is a large, open water body (~6000 km^2) that we assume is not strongly influenced by hypoxia directly, but may be influenced indirectly by dissolved oxygen conditions and the potential hypoxia-induced emigration of shrimp from the Neuse River, its major southern tributary. We recover the model parameters using a backward reduction technique to identify the best fit linear model. In order to generalize our models, we compare two alternative versions that assumed the growth dynamics of the shrimp stock are either known or unknown.

This paper makes several contributions. First, we construct the first structural model addressing the spatio-temporal effects of hypoxia on commercial fisheries using fishery-dependent microdata. Our approach can not only be used to investigate the economic consequences of hypoxia, but also applied to other more general water quality effects. Secondly, our approach uses lumped parameters and so does not require information on initial shrimp abundance, which is often not available. Thirdly, we use static analysis to estimate the magnitude of the economic effects of hypoxia thereby providing a valuable economic baseline to inform policy making related to water estuarine quality.

2 Materials and methods

2.1 Basic model

Let C be the harvest of shrimp at particular day *t*, which is a nonlinear function of trip days (K), vessel length *Len* using gear type *m*, gear-specific catchability, and shrimp biomass (X). ε is the error term which is assumed independently and identically distributed (iid) with normal distribution.

$$C_t = q_{t,m} K_t^{\alpha} Len_t^{\beta} X_t e^{\varepsilon_t} \tag{1}$$

This formation of the production function follows the standard Schaefer model but allows α , and β to measure curvature in the relationship between catch and effort. In order to test for the influence of environmental factors on the catchability coefficient q , the equation becomes:

$$C_t = q_{t,m}(O_t^{a_1} T_t^{a_2} S_t^{a_3} P_t^{a_4}) K_t^{\alpha} Len_t^{\beta} X_t e^{\varepsilon_t} \tag{2}$$

Where Ot is dissolved oxygen concentration (mg l^{-1}), Tt is temperature (°C), St is salinity (psu), and Pt is Ph. We assume these environmental factors influence catchability with allometric forms. All these environmental data are collected for Neuse River. Shrimp biomass (X_t) can be decomposed into the total number of shrimp (z_t) and individual shrimp weight (y_t):

$$X_t = z_t y_t \tag{3}$$

The total number of shrimp (z_t) declines over time due to natural mortality and environmental factors:

$$z_t = z_{t-1} e^{-\Delta m_0(t)} e^{b_1 OI_t + b_2 TI_t + b_3 SI_t} \tag{4}$$

Where Δm_0 is the loss rate of shrimp due to mortality and *OI*, *TI*, and *SI* are indices of environmental conditions. While equation (2) incorporates environmental effects on catchability of shrimp, equation (4) incorporates environmental factors that impact the production or migration of the shrimp. Migration effects capture the fact that brown shrimp are able to avoid serious hypoxia situation. The environmental factors in equation (4) are not absolute level but rather are binary indices of critical levels assumed necessary for survival. The laboratory experiments show that brown shrimp avoid areas with dissolved oxygen < 2 mg/L (Renaud 1986). Gunter et. al (1951) found that temperature of 4.4 °C or less may cause 'narcosis and mortality." Kutkuhn (1966) reported that temperature over 32.2°C reduced growth and survival which is also consistent with the findings of Zeineldin and Aldrich (1965). The minimum tolerated salinity has been reported as 0.8 ppt (Gunter et al. 1964), while few shrimp are found in waters of less than 5 ppt (Loesch 1976; Christmas and Langley 1973). These required environmental conditions are summarized in Lassuy (1983). The impacts of hypoxia or other environmental conditions on shrimp growth or migration are captured by these indexes which indicate whether the environmental conditions are within tolerable bounds. Note that b_1, b_2, and b_3 measure the marginal daily effects of environment conditions on growth and migration. Although there is no existing biological literature reporting effects of PH on shrimp growth, we still include it in equation (2) since we want to avoid error from omission variables. Together, equations (2) and (4) allow us to test the effects of environmental conditions on shrimp harvest, growth and migration with commercial fishery data. Equation 4 can be transformed to equation 5 if time is accumulated:

$$z_t = z_0 e^{-m_0(t)} e^{b_1 \sum_{i=\tau - t+1}^{t} OI_i + b_2 \sum_{i=\tau - t+1}^{t} TI_i + b_3 \sum_{i=\tau - t+1}^{t} SI_i} \tag{5}$$

Where τ is the number of days over which the environmental effects are aggregated, the other terms are as defined previously. For example τ =40. We call it 40 moving days. This means we aggregate the marginal effects over 40 days before the harvest. This specification implicitly limits that the water quality only influence brown shrimp in 40 days. For example, occurrence of one day of hypoxia (dissolved oxygen < 2 mg/l) has impacts on followed 40 days' harvest. After 40 days, the influence becomes 0. Substituting equation (2) with equation (3) and (5) provides an extended version of the Schaefer model. In order to simplify the nonlinear estimation, we linearize the whole equation by taking the log of both sides:

$$\begin{aligned}\ln C_t &= \ln q_{t,m} + \ln z_0 + \alpha \ln K_t + \beta \ln Len_t + (\ln y_t - m_0(t)) + a_1 \ln O_t + a_2 \ln T_t \\ &+ a_3 \ln S_t + a_4 \ln P_t + b_1 \sum_{i=\tau-t+1}^{t} OI_i + b_2 \sum_{i=\tau-t+1}^{t} TI_i + b_3 \sum_{i=\tau-t+1}^{t} SI_i + \varepsilon_t\end{aligned} \tag{6}$$

2.2 Data

This model can be applied to the data to test the hypotheses. The harvest data are from the North Carolina Division of Marine Fisheries (NCDMF) trip ticket program (1994-2005). Dealers report commercial landings information for each individual fishing trip including information on the particular vessel, the number of crew, gear type, trip starting and landing date, and price and quantity of each species landed per trip. From 1978 to 1993, North Carolina commercial landings information was collected on a voluntary basis. In 1994, the N.C. General Assembly mandated trip-level reporting of commercially harvested species. The data used in this paper contain shrimp landings in the Neuse River and Pamlico Sound from 1999-2005 since landings in data before 1999 are not classified to species. See figure 2 for map of Neuse River and Pamlico Sound.

On the hypoxia problems, few researches have been done on the Albemarle-Pamlico (A/P) estuarine area compared to the area of the Gulf of Mexico. Hypoxia in A/P has become more serious as population increase. Every year, there will be hypoxia areas in the Gulf of Mexico, which is referred as “Dead zones”. The average size of the dead zones has been 6000 square miles. Compared to Gulf of Mexico, A/P area also find serious hypoxia phenomenon. For example, the Neuse River estuary, experiences severe and recurring hypoxia during the summer months, leading to repeated fish kills and other biological effects (Paerl et al.1998). Unfortunately, we only have water quanlity data for the Neuse River instead of A/P, which are from USGS (The United States Geological Survey) real-time water data. This dataset provide 15 minutes interval water quality including dissolved oxygen, temperature, salinity and PH value from 1999 to 2005. We take the average of the 15 minute values each day as the daily values. The bottom and surface measurements are averaged for dissolved oxygen, temperature, salinity and PH value (DO_average, Temp_average, Sal_average and Ph_average in table 2 respectively).

However we only use bottom value for dissolved oxygen to define “hypoxia” (Bottom DO in table 2). Table 2 presents the days of hypoxia (bottom dissolved oxygen < 2 mg/l) in every year from 1999 to 2005 in A/P area. The average number of hypoxic days for these seven years is 61 days per year.

As is known, brown shrimp are able to avoid serious hypoxia situation. Thus, we hypothesized that severe hypoxia in the Neuse River estuary, which occurs primarily during the summer months, might induce emigration of shrimp in the Neuse to the adjacent Pamlico Sound which rarely experiences severe hypoxia. One of the contributions of this model is that it provides flexibility to test whether there is forced movement due to hypoxia between Neuse River and Pamlico Sound. The monitoring data tell us that the Neuse River encountered moderate or serious hypoxia in the summer each year. On the other hand, Pamlico Sound is relatively offshore and has deep water, thus is assumed to be free of hypoxia. The adjacency of these two areas enables us to conjecture that there might be spatial distributional shift due to hypoxia. We use the fishery dependent data to infer the abundance of brown shrimp and also the environmental impact. The advantage of the fishery dependent data is that we are able to track the stock abundance all though brown shrimp’s life cycle. We apply these models to both Neuse River and Pamlico Sound.

Initial stock? Data source. North Carolina Division of Marine Fisheries Program 120 and 510. Samples collected by this program are used by the NCDMF to assess stock status. Since the samples are taken in different stations and in different time , they are not appropriate for abundance assessment. However, this is the only existing fishery independent data related to shrimp abundance.

2.3 Growth Function

In the basic model (equation (6)), except $m_0(t)$ and y_t , all other variables can be observed in trip ticket program and water quanlity data. For $m_0(t)$ and y_t , we could use available parameter estimations in the literature with the following submodels: the Von Bertalanffy growth function, natural mortality rate and allometric function relating length and weight:

$$L(t) = L\infty(1 - e^{\delta t}) \tag{7}$$

L in this Von Bertalanffy growth function is the total length, while $L\infty$ denotes the terminal length. δ captures the "decay" rate with one unite of time t of length increase.

$$m_0(t) = bL(t)^{\rho} \tag{8}$$

This equation denotes the natural mortality rate of brown shrimp, which we assume decreases over day as shrimp increase in body size.

$$y(t) = \omega L(t)^{\eta} \tag{9}$$

Equation (9) is the allometric function which describes the relationship between shrimp weight and length. All of the parameters take values reported in Table 1.

Since brown shrimp have annual life cycle, besides the curvature of growth, we need to know the starting date of growth each year. After calibrating the growth function with parameters from table 1 to catch observations in the trip ticket data, we specify the 80h day of one year one as the starting point, which is near the time of larval ingress and settlement into juvenile nursery habitats. Figure 1 shows the growth function with no harvest.

Shrimp spawn in offshore shelf waters, typically during February-March and are transported to the upper reaches and tributaries of estuaries where they become demersal, typically during March-May. As juveniles increase in size during the summer months, they gradually immigrate to deeper areas of bays and sounds before returning to the shelf during fall and winter to spawn. Because the fishery occurs mostly in estuarine waters (i.e., within the Albemarle-Pamlico system), there is a close spatial and temporal connection between the estuarine nursery habitats that support the production of shrimp and harvest by the commercial fishery. In North Carolina, peak shrimp landings occur from July to October when shrimp occur primarily in estuarine waters, contributing 72% of the annual harvest, while landings from December to May, when shrimp are either offshore or small in size, only account for 6% of the annual harvest (NCDMF Shrimp Fishery Management Plan)[2].

Using equation (7) to (9) and available parameters to obtain $m_0(t)$ and y_t is one way of estimating the basic model (equation (6)), another more general way is to use second degree polynomial of t to mimic the growth function. This is referred as model with unknown growth function in this paper. Here, t denotes t^{th} day of the harvest in one round of shrimp growth. Thus equation to be estimated becomes:

$$\begin{aligned}\ln C_t = {} & cons + \alpha \ln K_t + \beta \ln Len_t + t + t^2 + a_1 \ln O_t + a_2 \ln T_t \\ & + a_3 \ln S_t + a_4 \ln P_t + b_1 \sum_{i=\tau-t+1}^{t} OI_i + b_2 \sum_{i=\tau-t+1}^{t} TI_i + b_3 \sum_{i=\tau-t+1}^{t} SI_i + \varepsilon_t\end{aligned} \tag{10}$$

These two versions, with known and unknown growth function, of basic model balance trade-off information. Model with known growth function absorbs as much as prior information, while the model with unknown growth function is more general in the sense that it could deal with cases when $m_0(t)$ and y_t is unknown or cannot be obtained (e.g. multiple species are analyzed). In addition, including more known functions means more errors and variations. Thus, comparison of such two versions of estimation verifies and double checks the correctness of the basic model.

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[2] North Carolina Division of Marine Fishery (DMF)'s trip ticket program (1994-2005).

2.4 PDL (Polynomial Distributed Lag) model

PDL (Polynomial Distributed Lag) models are traditional ways to measure lagged effects.

3 Results

3.1 Accumulated effects

For the basic model, we use backward selection method to select appropriate variables. And we do 19 sets[3] of analysis for different moving days (τ in the basic model). The estimation results for 90 days[4] moving models with unknown growth function are reported in table 3 in appendix. The temporal frequency of hypoxia among months lags two to three months after the peak frequency in both river discharge and nitrate flux, which is observed by Justic', Rabalasis, Turner and Wiseman (1993). Although this is reported in the Gulf of Mexico, this could more or less justify that we use 90 days moving effects as the baseline models for Neuse River.

In the result, month is dummy variable while Gear*Month is the interaction term of gear type and month. We only define two types of gear in our model: 'Shrimp Trawl" and 'others" since 91.26% brown shrimp are taken with shrimp trawl. Some indicators of month are omitted because of collinearity problem.

Table 3 contains results of 2X2 models. One dimension is with or without year dummies; another dimension is Neuse River or Pamlico Sound. The table shows that there is no significant hypoxia effect in Neuse River and Pamlico Sound if we include year. If the model does not include year dummies, the hypoxia in Neuse River explains 0.67% in Neuse River. It means that one day of hypoxia in Neuse River explains 0.67% of decrease of harvest if it happens within 40

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[3] These are 10-150 days increasing by 10; 200, 250, 300 and 350 days respectively.

[4] According to AIC, we found 40 days is the best model, while for PDL models, 90 lagged days model is the best. 40 days model result can be requested through the authors. For best comparison results, we only present 90 days moving model here.

days of this low water quality event. With the same logic, the hypoxia in Pamlico Sound explains 0.78% decrease of harvest in this area.

We also run the models with known growth function as we state above (see table 4). In order to check for the lagged effects, all above model are run with alternative 16 different moving days. Comparison of the results of other models to the baseline models provides some interesting insights. All the models with year dummies show lower hypoxia effects than those without year dummies given all other conditions are the same. This can be explained that the year dummies absorb some fluctuation of the brown shrimp harvest. Since we do not have enough information of stock abundance (specifically, z_0), the harvest fluctuation is hard to be distinguished between initial stock abundance effects and hypoxia effects. The best we can say is that the models with and without year dummy quantify the boundary of hypoxia effects from our model. The effects measured by models with 40 days moving are higher than those with 90 days. This is easy to understand, since if we spread the marginal effect to longer period of time, the marginal effects are reduced.

All the hypoxia effects are significantly negative in Pamlico Sound (refer to table 3 and 4). Since there are no serious hypoxia events in Pamlico Sound, these negative effects come from the combination of shrimp immigration and impacts on growth of shrimp in shallow water nurseries. Adversely, the negative effects in Neuse River can be interpreted as migration and impacts on growth of shrimp.

Another advantage of this linear bioeconomic model is that it can avoid initial shrimp abundance assessment. We have some comparison of stock index using different methods presented in table 5. The first column presents the stock index estimated from North Carolina Division of Marine Fisheries Program 120 and 510. Table 5 presents the result of the correlation between abundance predicted from our model and abundance calculated from North Carolina Division of Marine Fisheries Program 120 and 510. The second column uses the direct average harvest from Program 120 and 510. This might also deviates from true initial abundance since environmental conditions take effect on stock growth significantly before June or July. The last two columns use our full model (without backward selection) to predict indexed initial abundance. We calculate the correlations between this stock index and find that abundance index from harvest are correlated with those predicted from our full linear model.

3.2 PDL model results

We run the PDL models in 2X2 dimensions (Table 8). Dependent variable is logged shrimp weight which is aggregated to daily level from year 1999 to 2005. 'do_{ind}' and 'sal_{ind}' are the same indicators of low water quality defined above. Using AIC, we find that for Neuse River, the best degree of polynomial for 90 days moving PDL models is 4 for both models with and without year dummies, while 3 for Pamlico Sound. Figure 2 describes the lagged effects graphically. It shows that all lagged effects for Neuse River are negative while the models without year dummies yield higher negative hypoxia effects than that with year dummy, which is consistent with what we find in the linear bioeconomic model. As for the Pamlico Sound, models with or without year dummies also present negative effects during most of the lags. However, as we explain before, the economic effects are within the boundaries defined by these two models.

3.3 Total economic effect of hypoxia

For both linear models and PDL models with 90 days moving, we calculate the range of percentage change to the original harvest if we close down the hypoxia effects (See Figure 3). Linear models without growth function for Neuse River and Pamlico Sound haven't detected hypoxia effects if we include year dummy in the estimation, thus the changes of harvest due to cleaning of hypoxia are both zeros. Linear models without year dummy for the Neuse River show that, if decreasing hypoxia to zero for the whole year, the yield will increase 19.03%, while Pamlico Sound will increase 26.78% in yield. Due to the parameters uncertainty, these changes also have uncertainties. 95% confidence interval for Neuse River is 10.68% to 28.25%, while for Pamlico Sound is from 22.35% to 31.42%. Table 10 presents the percentage changes and 95% confidence intervals for linear models with growth function. It shows higher percentage harvest changes due to higher marginal hypoxia effects. Using the same logic, we calculate economic effects according to estimates of the PDL models, which provide some useful comparison to the results of linearized models. The change of harvest for Neuse River is 22.87% and 28.87% in corresponding scenarios with year dummies and no year dummies. Similarly, Pamlico Sound has changes of 8.13% and 56.8%. However, since most of the PDL lagged effects are not significant, the uncertainties are quite large. Thus 95% confidence intervals for the changes are pretty broad. For example, Pamlico Sound will have a range of -26.72% to 66.48% if year dummies are included.

4 Discussions

According to the estimates of this model, we find significant economic effects of hypoxia in both Neuse River and Pamlico Sound. So as to clearly show the total effects instead of the marginal effect, the total harvest changes due to hypoxia effects are calculated. It turns out that in average there will be 0 to 30% increase of the brown shrimp harvest change in Neuse River if there is no hypoxia in the same area at all. For Pamlico Sound, the brown shrimp harvest effects from Neuse river hypoxia will be 0 to 31% in average depending on different scenarios. We conclude by comparing the linearlized lagged effects to Polynomial Distributed Lags (PDL) model. Using PDL models, the total effects will be 23% to 29% for Neuse River approximately, while approximate 8% to 57% for Pamlico Sound in different cases. Statistic test shows that the linearlized lagged models developed in this paper give more accurate answers than PDL models. In other words, PDL models have far less significant estimators.

It is important to note that this analysis assumes a scenario that there is no hypoxia for one whole year, which is hard to achieve in reality. And also the hypoxia might have dynamic effects on the growth and harvest of species. But we can safely inference that cleaning significant part of hypoxia will have significant influences on the shrimp industry.

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Figure 1: Biomass over time

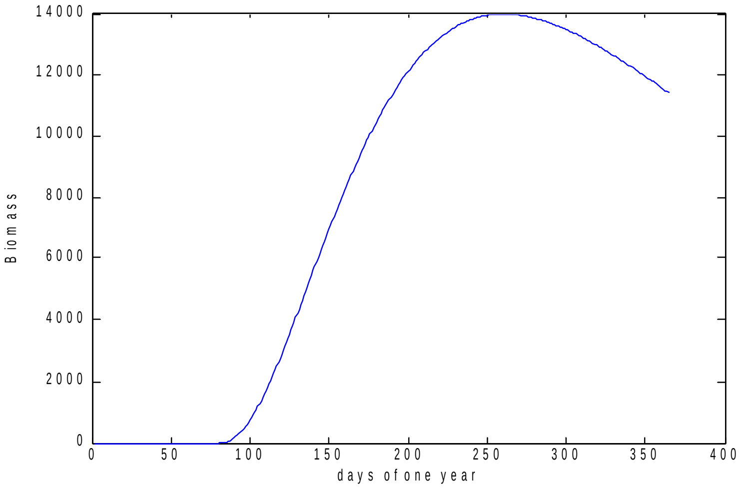


Table 1: Parameter sources

Parameter	Value	Function	Parameter source
$L\infty$	177.7	Von Bertalanffy growth function	McCoy 1968
δ	-0.0104	Von Bertalanffy growth function	McCoy 1968
ϕ	1.4866	natural mortality rate	Minello et. al. 1989 & Heather et. al 2004
ρ	-1.1163	natural mortality rate	Minello et. al. 1989 & Heather et. al 2004
α	10.52*10(-6)	allometric function(weight(pound)	Fontaine and Neal 1971
τ	2.94	allometric function(weight(pound)	Fontaine and Neal 1971

Figure 2: Waterbodies and water quanlity monitoring sites

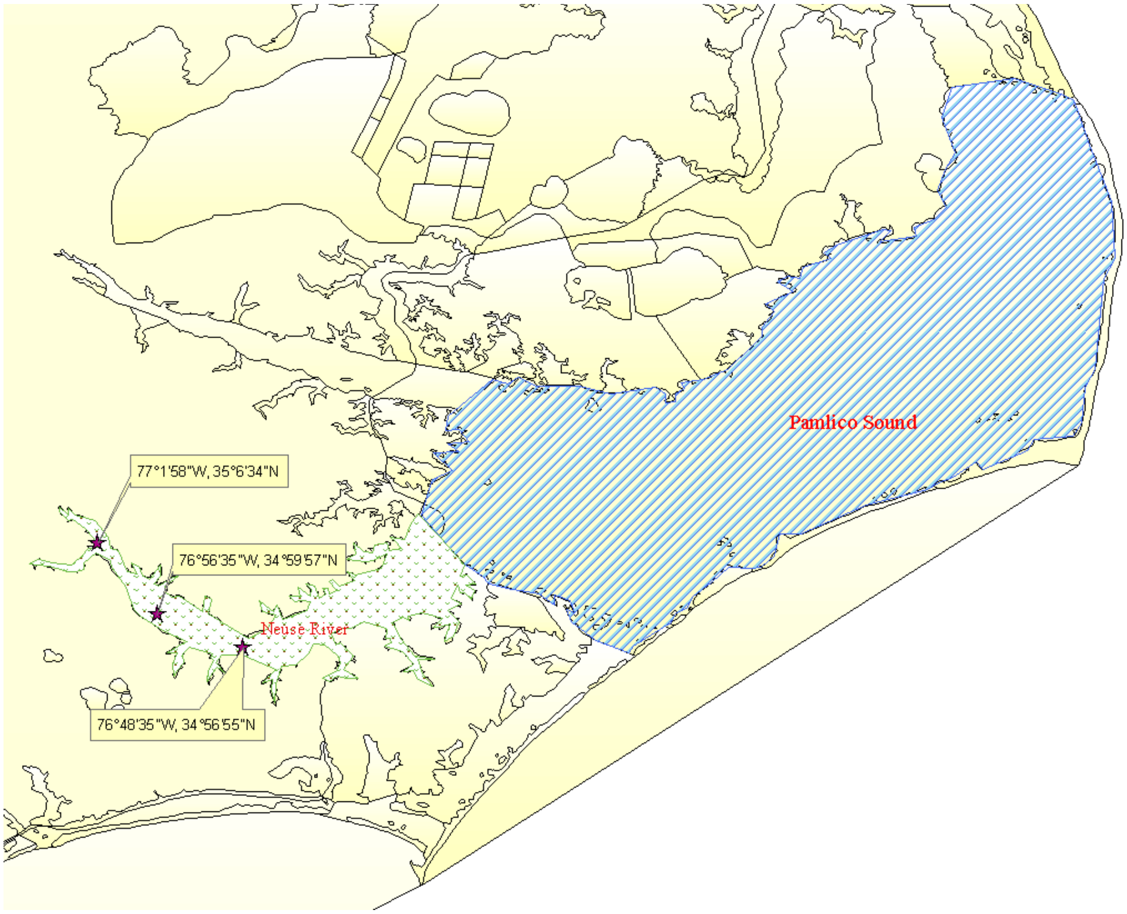


Table 2: Summary statistics

Neuse River Harvest Data

Variable	Obs.	Mean	Std. Dev	Minimum	Maximum			
Catch/trip(pound)	2245	308.4	579.1	4.0	7985.6			
Trip days	2245	1.9	1.3	1.0	10.0			
Vessel Length	2211	37.0	13.6	15.0	80.0			
year	1999	2000	2001	2002	2003	2004	2005	Mean
Annual Catch(Pound)	17915	193960	18063	162860	99077	73550	108228	96236

Pamlico Sound Harvest Data

Variable	Obs.	Mean	Std. Dev	Minimum	Maximum
Catch/trip(pound)	11690	1524.7	1808.7	1.0	22097.0

Trip days	11690	3.5	3.9	1.0	366.0			
Vessel Length	11651	51.9	18.1	12.0	91.0			
year	1999	2000	2001	2002	2003	2004	2005	Mean
Annual Catch(Pound)	1208294	5096432	2495106	4618086	1991780	1602778	547580	2508579

Water quality

Variable	Obs.	Mean	Std. Dev	Minimum	Maximum
Bottom DO (%)	2301	5.9	3.5	0.0	13.6
DO_average (%)	2301	74.9	20.4	0.4	129.2
Temp_average(ºC)	2301	18.3	7.6	1.5	30.2
Salinity_average(ppt)	2301	8.1	5.0	0.0	22.6
PH_average	2301	7.6	0.4	5.7	8.9

Annual intolerable days

Year	1999	2000	2001	2002	2003	2004	2005	Mean
Bottom DO<=2(days)	50	38	80	43	69	87	57	61
Temp_ave<4.4 or>32.2(days)	0	0	0	0	0	0	0	0
Salinity_ave<5	76	51	26	2	224	100	80	80

Table 3: 90 days moving models with unknown growth function

90 days moving effects	Backward-selection model for Neuse River				Backward-selection model for Pamlico Sound			
Year specific								
Variable	Parameter Estimate	Std. Error.	F value	Pr > F	Parameter Estimate	Std. Error.	F value	P value
Month5	-2.54378	0.42219	36.3	<.0001	-1.56636	0.12499	157.06	<.0001
Month6	-	-	-	-	-	-	-	-
Month8	0.30283	0.13728	4.87	0.0275	-	-	-	-
Month9	-	-	-	-	0.26568	0.06539	16.51	<.0001
Month10	-	-	-	-	0.39107	0.07955	24.17	<.0001
Gear*Month6	-	-	-	-	-	-	-	-
Gear*Month7	0.28004	0.05724	23.94	<.0001	0.45349	0.04736	91.67	<.0001
Gear*Month8	-0.41556	0.12707	10.7	0.0011	0.13198	0.05813	5.15	0.0232
Gear*Month9	-	-	-	-	-	-	-	-
Year1999	-	-	-	-	-	-	-	-
Year2000	6.54608	1.55463	17.73	<.0001	-1.08691	0.19127	32.29	<.0001
Year2001	-1.98829	0.25394	61.3	<.0001	-1.26452	0.15387	67.54	<.0001
Year2002	4.64022	1.14965	16.29	<.0001	0.64275	0.32264	3.97	0.0464
Year2003	10.21369	1.78796	32.63	<.0001	-5.49733	0.86256	40.62	<.0001
Year2004	-	-	-	-	-7.91669	0.69988	127.95	<.0001
Year2005	0.90439	0.45652	3.92	0.0477	-6.46065	1.27962	25.49	<.0001
t1999	-0.01245	0.00183	46.34	<.0001	-0.02115	0.00164	166.28	<.0001
t2000	-0.1108	0.02453	20.4	<.0001	-0.00566	0.00101	31.51	<.0001
t2001	-	-	-	-	-0.00692	0.000857	65.27	<.0001
t2002	-0.07862	0.01813	18.81	<.0001	-0.02628	0.00463	32.18	<.0001
t2003	-0.17807	0.02868	38.55	<.0001	0.0442	0.01141	15	0.0001
t2004	-0.01487	0.00195	58.19	<.0001	0.07588	0.00893	72.25	<.0001
t2005	-0.0188	0.00305	37.89	<.0001	0.06099	0.01691	13.01	0.0003
t1999 squared	-	-	-	-	4.9E-05	7.19E-06	46.52	<.0001
t2000 squared	0.000365	9.56E-05	14.57	0.0001	-	-	-	-
t2001 squared	-	-	-	-	-	-	-	-
t2002 squared	0.000224	7.02E-05	10.16	0.0015	4.99E-05	1.56E-05	10.26	0.0014
t2003 squared	0.00066	0.000113	34.41	<.0001	-0.00016	3.86E-05	16.66	<.0001
t2004 squared	-	-	-	-	-0.00025	2.88E-05	72.8	<.0001
t2005 squared	-	-	-	-	-0.00021	5.61E-05	13.94	0.0002
Log of trip days	0.96765	0.03453	785.25	<.0001	0.63783	0.01473	1875.53	<.0001
Log of vessel length	1.24755	0.05205	574.51	<.0001	1.96435	0.02578	5804.12	<.0001

Aggregated oxygen index	-	-	-	-	-	-	-	-
Aggregated salinity index	-	-	-	-	0.00631	0.00229	7.58	0.0059
Log of oxygen	0.08488	0.03556	5.7	0.0171	-	-	-	-
Log of temperature	1.20735	0.34636	12.15	0.0005	-	-	-	-
Log of salinity	-	-	-	-	-	-	-	-
Log of PH value	-1.38963	0.58649	5.61	0.0179	-	-	-	-
Obs.	2187	R-square	0.4956	Obs.	11504	R-square	0.6230	
	Backward-selection model for Neuse River				Backward-selection model for Pamlico Sound			
Non-year specific								
Variable	Parameter Estimate	Std. Error.	F value	Pr > F	Parameter Estimate	Std. Error.	F value	P value
Intercept	0.74229	2.02023	0.14	0.7133	Intercept	-0.07369	0.48157	0.02
Month5	-1.7239	0.39607	18.94	<.0001	month5	-1.65357	0.11923	192.34
Month6	-	-	-	-	-	-	-	-
Month8	0.43575	0.15708	7.7	0.0056	-	-	-	-
Month9	0.48614	0.18381	6.99	0.0082	0.27872	0.05181	28.94	<.0001
Month10	-	-	-	-	0.35905	0.07351	23.86	<.0001
Gear*Month6	-	-	-	-	-	-	-	-
Gear*Month7	0.20462	0.06367	10.33	0.0013	0.40197	0.0375	114.9	<.0001
Gear*Month8	-0.43636	0.12807	11.61	0.0007	0.17063	0.04066	17.61	<.0001
Gear*Month9	-	-	-	-	-	-	-	-
t	-0.01685	0.00202	69.86	<.0001	-	-	-	-
t squared	-	-	-	-	-2.4E-05	1.85E-06	168.59	<.0001
Log of trip days	0.99419	0.03482	815.34	<.0001	0.61976	0.01479	1754.93	<.0001
Log of vessel length	1.23422	0.05333	535.54	<.0001	2.00035	0.02625	5808.71	<.0001
Aggregated oxygen index	-0.00672	0.00141	22.75	<.0001	-0.00782	0.000582	180.46	<.0001
Aggregated salinity index	-	-	-	-	-0.00108	0.00042	6.63	0.01
Log of oxygen	0.16224	0.03227	25.28	<.0001	0.05575	0.01385	16.19	<.0001
Log of temperature	1.6696	0.54657	9.33	0.0023				
Log of salinity					-0.08975	0.01874	22.93	<.0001
Log of PH value	-2.2894	0.54735	17.49	<.0001	-0.63008	0.24431	6.65	0.0099
Obs.	2187	R-square	0.4670	Obs.	11504	R-square	0.6078	

Table 4: 90 days moving models with known growth function

90 days moving effects	Backward-selection model for Neuse River				Backward-selection model for Pamlico Sound			
Year specific								
Variable	Parameter Estimate	Std. Error.	F value	Pr > F	Parameter Estimate	Std. Error.	F value	P value
Month5	-	-	-	-	1.49107	0.15788	89.19	<.0001
Month6	0.92418	0.10552	76.71	<.0001	1.77416	0.13292	178.15	<.0001
Month8	-0.375	0.15815	5.62	0.0178	0.76503	0.1363	31.51	<.0001
Month9	-	-	-	-	0.46798	0.12897	13.17	0.0003
Month10	-1.83116	0.54643	11.23	0.0008	0.3407	0.11112	9.4	0.0022
Gear*Month6	-	-	-	-	-	-	-	-
Gear*Month7	0.33588	0.09816	11.71	0.0006	1.52604	0.13437	128.99	<.0001
Gear*Month8	-0.36798	0.13186	7.79	0.0053	-	-	-	-
Gear*Month9	-1.06131	0.13668	60.3	<.0001	-	-	-	-
Year1999	3.40102	0.21573	248.54	<.0001	-1.70075	0.55185	9.5	0.0021
Year2000	3.51227	0.2047	294.39	<.0001	-1.50196	0.54426	7.62	0.0058
Year2001	2.93839	0.22313	173.42	<.0001	-1.8253	0.53795	11.51	0.0007
Year2002	3.42866	0.2074	273.31	<.0001	-1.73561	0.55472	9.79	0.0018
Year2003	3.53936	0.21039	283.01	<.0001	-1.3042	0.53799	5.88	0.0154
Year2004	3.04114	0.21052	208.69	<.0001	-1.66798	0.53728	9.64	0.0019
Year2005	3.46077	0.21401	261.51	<.0001	-1.61112	0.55209	8.52	0.0035
Log of trip days	0.98771	0.03604	751.03	<.0001	0.62934	0.0151	1736.88	<.0001
Log of vessel length	1.24688	0.05509	512.32	<.0001	1.96765	0.02654	5496.53	<.0001

Aggregated oxygen index	-	-	-	-	-0.00615	0.00189	10.53	0.0012
Aggregated salinity index	-	-	-	-	-0.00619	0.00165	13.98	0.0002
Log of oxygen	-	-	-	-	0.0336	0.01341	6.28	0.0122
Log of temperature	-	-	-	-	0.73676	0.19054	14.95	0.0001
Log of salinity	-	-	-	-	-0.08659	0.01982	19.08	<.0001
Log of PH value	-	-	-	-	-	-	-	-
Obs.	2187	R-square	0.5212	Obs.	11504	R-square	0.6218	
	Backward-selection model for Neuse River				Backward-selection model for Pamlico Sound			
Non-year specific								
Variable	Parameter Estimate	Std. Error.	F value	Pr > F	Parameter Estimate	Std. Error.	t statistics	P value
Intercept	6.48468	1.27358	25.93	<.0001	-1.72049	0.49596	12.03	0.0005
Month5	-	-	-	-	1.34748	0.15208	78.51	<.0001
Month6	0.84835	0.09221	84.64	<.0001	1.80554	0.12765	200.06	<.0001
Month8	-	-	-	-	0.95093	0.12821	55.01	<.0001
Month9	-	-	-	-	0.67023	0.12041	30.98	<.0001
Month10	-1.89913	0.54341	12.21	0.0005	0.46494	0.10794	18.55	<.0001
Gear*Month6	-	-	-	-	-	-	-	-
Gear*Month7	0.40824	0.08104	25.37	<.0001	1.62374	0.12658	164.56	<.0001
Gear*Month8	-0.49697	0.08697	32.65	<.0001	-	-	-	-
Gear*Month9	-0.79623	0.12946	37.82	<.0001	-	-	-	-
Log of trip days	1.0068	0.03574	793.57	<.0001	0.61403	0.01496	1685.44	<.0001
Log of vessel length	1.24164	0.05478	513.75	<.0001	1.98599	0.02656	5592.28	<.0001
Aggregated oxygen index	-0.0099	0.00138	51.41	<.0001	-0.0088	0.00059	222.42	<.0001
Aggregated salinity index	0.00338	0.00108	9.86	0.0017	-	-	-	-
Log of oxygen	0.12968	0.03531	13.49	0.0002	0.05319	0.01316	16.35	<.0001
Log of temperature	-	-	-	-	0.66673	0.16883	15.6	<.0001
Log of salinity	0.14111	0.05223	7.3	0.0069	-0.0736	0.01533	23.04	<.0001
Log of PH value	-1.89482	0.64377	8.66	0.0033	-	-	-	-
Obs.	2187	R-square	0.5161	Obs.	11504	R-square	0.6182	

Table 5: PDL models

	PDL in Neuse river with 90 lags					**PDL in Pamlico with 90 lags**			
Year specific									
Variable	Parameter Estimate	Std. Error.	t statistics	Pr > |t|		Parameter Estimate	Std. Error.	t statistics	Pr > |t|
do_ind**0	-0.0674	0.0782	-0.86	0.3892		0.000266	0.0455	0.01	0.9953
do_ind**1	0.02	0.0466	0.43	0.6677		0.1296	0.0324	3.99	<.0001
do_ind**2	0.0214	0.048	0.45	0.6557		0.02	0.0304	0.66	0.51
do_ind**3	0.0345	0.0352	0.98	0.3278		-0.016	0.0266	-0.6	0.5464
do_ind**4	-0.0134	0.0436	-0.31	0.7589		-	-	-	-
sal_ind**0	-0.065	0.0646	-1	0.3156		0.0476	0.0394	1.21	0.2277
sal_ind**1	0.0961	0.0431	2.23	0.0263		0.0238	0.0262	0.91	0.3637
sal_ind**2	-0.0397	0.0528	-0.75	0.4528		0.0255	0.0328	0.78	0.4372
sal_ind**3	0.0701	0.0515	1.36	0.1742		0.0913	0.0378	2.42	0.0158
sal_ind**4	0.0571	0.0531	1.08	0.2829		0.0684	0.0425	1.61	0.1079
year1999	1.5867	0.5289	3	0.0029		-0.5566	0.4548	-1.22	0.2213
year2000	1.4613	0.5476	2.67	0.0079		-0.3815	0.452	-0.84	0.399
year2001	0.9728	0.6086	1.6	0.1107		-0.908	0.447	-2.03	0.0426
year2002	1.1123	0.5329	2.09	0.0374		-0.5536	0.4437	-1.25	0.2125
year2003	2.0734	0.8373	2.48	0.0137		-1.0062	0.5665	-1.78	0.0761
year2004	1.375	0.7317	1.88	0.0609		-0.9024	0.5084	-1.78	0.0763
year2005	1.7114	0.6333	2.7	0.0071		-0.7811	0.4834	-1.62	0.1065
month5	-0.0893	0.3182	-0.28	0.7791		0.6847	0.1808	3.79	0.0002
month6	1.0443	0.15	6.96	<.0001		1.1281	0.1525	7.4	<.0001
month7	0.8064	0.1022	7.89	<.0001		1.8528	0.1495	12.39	<.0001
month8						1.2456	0.1605	7.76	<.0001
month9	-0.0806	0.1206	-0.67	0.5045		0.818	0.1538	5.32	<.0001
month10	-0.1766	0.3651	-0.48	0.6289		0.5396	0.1348	4	<.0001
k_l	1.0028	0.0302	33.26	<.0001		0.8952	0.0193	46.42	<.0001
len_l	0.7404	0.1347	5.5	<.0001		1.1833	0.1143	10.35	<.0001
Obs.	2555	AIC	995.48			Obs.	2555	AIC	1710.94

	PDL in Neuse river with 90 lags					PDL in Pamlico with 90 lags			
					Non-year specific				
do_ind**0	-0.0823	0.0269	-3.05	0.0024		-0.112	0.0216	-5.19	<.0001
do_ind**1	0.0268	0.0415	0.64	0.5197		0.1341	0.0299	4.48	<.0001
do_ind**2	-0.00804	0.0475	-0.17	0.8657		0.0198	0.0299	0.66	0.5083
do_ind**3	0.0496	0.0348	1.42	0.1555		-0.0161	0.0266	-0.6	0.5459
do_ind**4	-0.0349	0.043	-0.81	0.4174		-	-	-	-
sal_ind**0	0.0394	0.013	3.04	0.0025		0.001023	0.0117	0.09	0.9305
sal_ind**1	0.1013	0.0386	2.63	0.0089		0.0417	0.0249	1.68	0.0941
sal_ind**2	-0.00675	0.0513	-0.13	0.8955		0.0481	0.0308	1.56	0.118
sal_ind**3	0.0594	0.0506	1.17	0.241		0.0907	0.0377	2.4	0.0164
sal_ind**4	0.0886	0.0523	1.7	0.0907		0.0782	0.0425	1.84	0.0659
month5	1.2285	0.5877	2.09	0.0371		0.4473	0.1716	2.61	0.0093
month6	2.3295	0.488	4.77	<.0001		1.1285	0.1402	8.05	<.0001
month7	2.2325	0.4954	4.51	<.0001		1.9081	0.1339	14.25	<.0001
month8	1.6487	0.4985	3.31	0.001		1.3918	0.1397	9.96	<.0001
month9	1.5801	0.5116	3.09	0.0021		0.9619	0.1363	7.06	<.0001
month10	1.2015	0.6078	1.98	0.0487		0.5767	0.125	4.61	<.0001
k_1	1.0356	0.0303	34.23	<.0001		0.9057	0.0171	52.83	<.0001
len_1	0.6475	0.1312	4.94	<.0001		1.0841	0.0314	34.52	<.0001
Obs.	2555	AIC	1768.03			Obs.	2555	AIC	1722.16

Figure 3: Hypoxia effects using PDL model

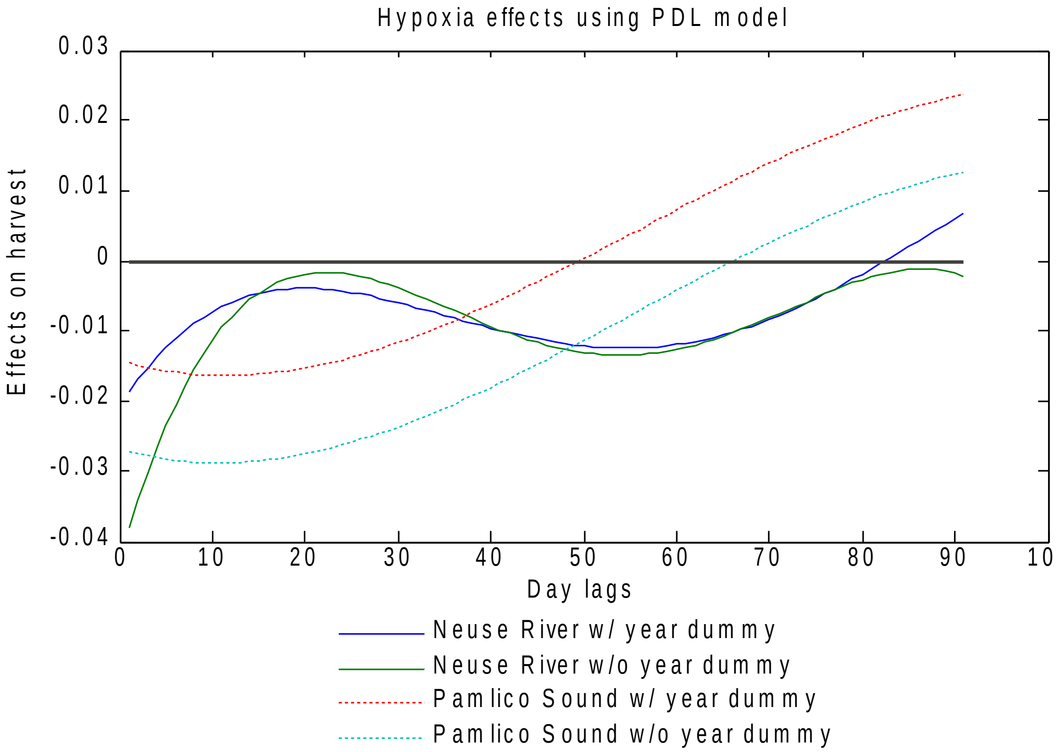
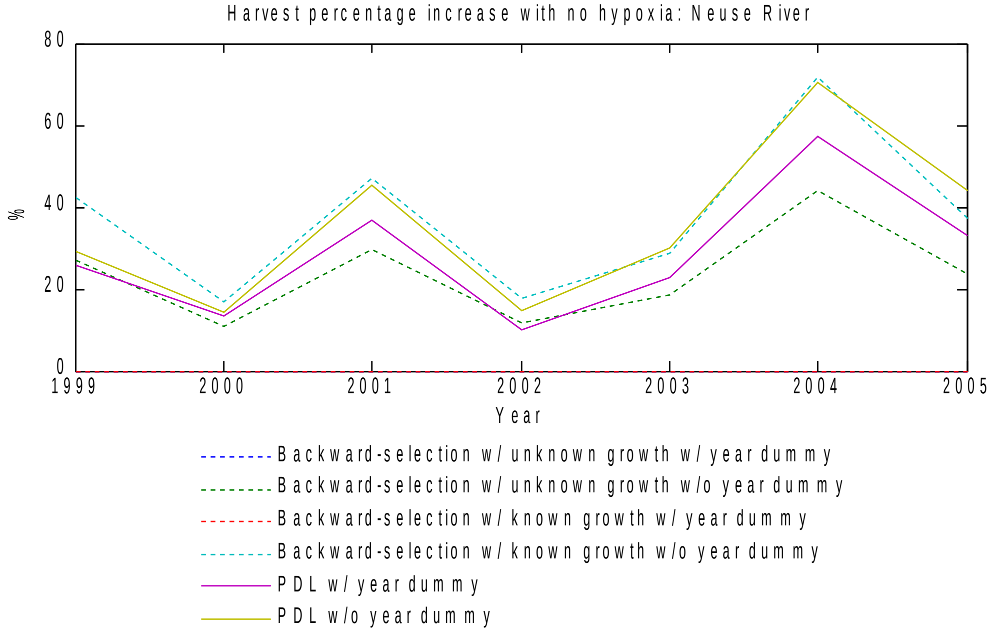


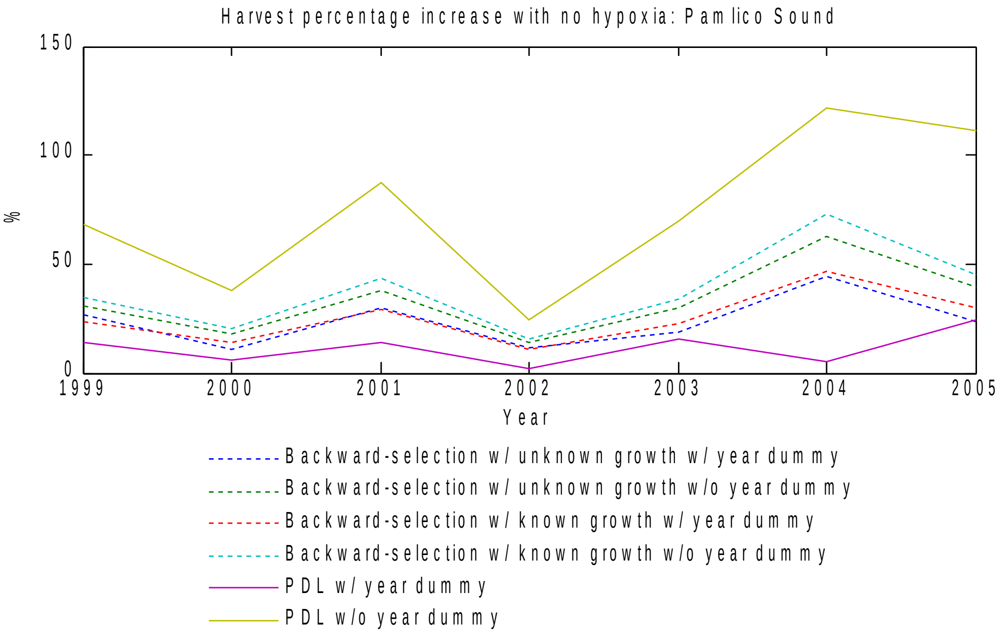
Table 6: Stock Index from full model

Neuse river				
Year	Stock index (from survey)	Stock index (from harvest)	Unknown Growth function	Known Growth function
1999	18788358.64	216922.1	0.54423	6.53157
2000	29233528.48	210969.7	7.63298	6.45547
2001	24431351.49	19941.82	-0.68727	6.09763
2002	27407293.15	213696.7	5.57852	6.28732
2003	11028119.19	102365.7	11.22967	7.08601
2004	23662494.45	87384.05	0.42537	6.30252

2005	30415641.36	110286.5	2.23471	6.64131
Correlation with stock index from survey	1	0.152159	-0.35599	-0.61502
Correlation with stock index from harvest	0.152159	1	0.310258	0.106667
Pamlico sound				
Year	Stock index (from survey)	Stock index (from harvest)	Unknown Growth function	Known Growth function
1999	17050137.9	3876339	1.86787	-2.3082
2000	15974454.69	6708334	-0.6833	-2.23577
2001	20273098.23	2890943	-0.93727	-2.45666
2002	22167886	6147806	0.04857	-2.4017
2003	16830229.67	2023826	-5.62485	-2.19195
2004	17958178.14	2104690	-6.49259	-2.38726
2005	16140737.33	552302.8	-6.86648	-2.30986
Correlation with stock index from survey	1	0.319994	0.370436	-0.75895
Correlation with stock index from harvest	0.319994	1	0.75277	0.011814

Figure4: Comparison of predicted harvest between status quo and no hypoxia scenario




Harvest percentage increase with no hypoxia: Pamlico Sound
150
100
50
0
%
1999
2000
2001
2002
2003
2004
2005
Year
Backward-selection w/ unknown growth w/ year dummy
Backward-selection w/ unknown growth w/o year dummy
Backward-selection w/ known growth w/ year dummy
Backward-selection w/ known growth w/o year dummy
PDL w/ year dummy
PDL w/o year dummy