Behavioral Response of Fishers to Hypoxia and the Distributional Impact on Harvest

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Behavioral Response of Fishers to Hypoxia and the Distributional Impact on Harvest

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Abstract:

Marine hypoxia, a seasonal phenomenon, adversely affects parts of numerous waterbodies around the world. The effects extend to marine organisms. The objective of this paper is twofold. First, we present a simple theoretical model that can be used to analyze both the aggregate and distributional effects of hypoxia on harvest within an industry. Second, we use temporally and spatially differentiated harvest data for Connecticut Long Island Sound lobster industry, and a set of environmental and economic variables to estimate the *contemporaneous* and *lagged* effects of hypoxia on harvest shares across the three adjacent fishing zones, only one of which faces moderate to severe hypoxic conditions each summer. The key insight from the theoretical model shows that, theoretically, hypoxia can have *an ambiguous effect* on the optimal harvest shares from the hypoxic and non-hypoxic fishing zones. Results from the empirical model indicate that an increase in hypoxic water condition reduces the share of harvest from the hypoxic water zone, compared to the other fishing zones.

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1. Introduction:

A marine ecosystem's ability to provide consistently both ecological and economic benefits depends directly on the water quality. Currently, many aquatic systems worldwide are affected by marine hypoxia, a condition of low dissolved oxygen in the water that makes it difficult for aquatic species to survive. Hypoxia is a seasonal phenomenon caused by both natural and anthropogenic factors. Typically, parts of an aquatic system are affected during specific months each year, which creates a mosaic of hypoxic zones in the water body.

Among other factors, hypoxic conditions can be generated as a result of increase in nutrients, such as nitrates and phosphates, in the water. When nutrients get added to the water body, typically through fertilizers in agricultural runoff and sewage materials, it leads to a response by the ecosystem referred to as eutrophication.[1] Eutrophication can lead to rapid growth in phytoplankton, such as algae. When these organisms die, dissolved oxygen is used up in the bacterial decomposition, thereby reducing the oxygen level in the water. The severity of the hypoxic conditions developed in the water system depends on a number of factors such as the volume of annual nutrient loadings, the specific nature of the aquatic system, the location of the water body, differences in surface and bottom level water temperature and oceanographic phenomenon such as upwelling and down welling etc. Severe hypoxic conditions have resulted in a number of dead zones all over the world (Breitburg, 2002).

In the United States, the northwestern part of the Gulf of Mexico has the largest seasonal hypoxic zone in the western hemisphere, partly because of the agricultural runoff carried into the Gulf by the Mississippi River (Craig, 2012). Hypoxic zones have been identified off the coasts of Oregon and Washington, and in the Long Island Sound system. A 2010 joint study by the U.S. Environmental Protection Agency, U.S. Department of Agriculture, the U.S. Geological Survey and the Virginia Institute of Marine Sciences found that waterbodies with hypoxia in the U.S. increased from 12 prior to 1960 to more than 300 in 2008.[2] This has serious implications for U.S. fishing industries that depend on these aquatic systems.

Hypoxia has been shown to have adverse effects on marine populations through increased mortality (Peterson et al., 2000; Miller et al., 2002), decreased growth (Stierhoff et al., 2009) and reduced reproduction (Thomas et al., 2007). These negative effects are transferred to commercial fisheries through reduced fish stock. Quantifying the effect of hypoxic water conditions on fish stock or commercial harvest has been challenging for a number of reasons. For example, because the size of the fish stock is usually unknown, the exact effects of hypoxia on fish mortality and, hence, the size of fish stock in marine environment cannot be accurately measured. Also, species differ both in their natural ability to survive hypoxic conditions and their behavioral responses to it. For example, hypoxia has been shown to affect the spatial distribution of marine species such as brown shrimp (Craig and Crowder, 2005), sea turtles and marine mammals (Craig et al., 2001). Some species are naturally more adept than others in surviving in low oxygen conditions for considerable lengths of time. Species also tend to move to avoid hypoxic water zones (Craig, 2012). Fast moving species such as finfish or shrimp can escape hypoxic water zones more easily than slow moving species such as large crustaceans like lobster.

When analyzing the effect of hypoxia on harvest, another key point for consideration is the behavioral response of fishers who harvest species that are affected by hypoxia. Fishers involved in commercial harvesting activities are alert to changes in water conditions because they know those changes can have an impact on their daily catch through the effect on fish stock. Hence, these changes can impact their profit earnings for any given level of fishing effort. Thus, given any changes to fishing conditions because of hypoxia, commercial fishers may adjust their harvesting decisions in different ways to account for any harvest and revenue loss that can stem from hypoxic water conditions. For example, they may choose to fish more intensely in the current period if they expect conditions to worsen over time.

They may spend more hours at sea on any given day during months when hypoxic water conditions are present. Also, they may alter their fishing location choices to avoid hypoxic water zones. This further poses a challenge for understanding both the aggregate and distributional effects of hypoxia on commercial harvest and industry profit.

Economic research on hypoxia has primarily developed along two strands; *(i)* analysis of alternative means to control nutrient discharge through agricultural and industrial practices that contribute to the hypoxia level in water bodies (for example, see Wu and Tanaka, 2005, Ribaudo et al., 2005) and *(ii)* analysis of the effect of hypoxia on commercial fisheries (for example, see Diaz and Solow (1999), Knowler, Barbier, and Strand (2001), Huang and Smith (2011), among others). We focus on the second strand to further our understanding of the effects of hypoxic water conditions on the distribution of harvest across fishing zones. There is a growing body of literature that has focused on analyzing and quantifying the effects of hypoxic water conditions on fisheries, mostly focusing on Gulf of Mexico fisheries. Seminal work by Zimmerman et al., (1996) and Diaz and Solow (1999) found little (causal) effect of hypoxia on Gulf of Mexico shrimp harvest. However, in recent years, Huang et al., (2012) found some evidence on an effect of hypoxia on brown shrimp harvest in the Neuse River. Specifically, they found that hypoxic water conditions led to a 12.87% reduction in brown shrimp harvest between 1999 and 2005. Their estimate indicated that the decline in harvest due to hypoxia equated to a $32,000 loss per year in the Neuse River fishery. In Smith et al. (2014), the authors analyze the Gulf of Mexico brown shrimp fishery and the potential impact of a large hypoxic water zone that corresponds with the peak harvesting season. They conduct a series of bioeconomic simulations and compare their findings to aggregate empirical data of the Gulf shrimp fishery. One key finding shows that severity of hypoxia is negatively correlated with total landings.

In this paper we focus on the Long Island Sound (LIS) ecosystem, which experiences hypoxic water conditions every year. The sound is home to a number of New England fisheries where fishers from New York, Connecticut and Rhode Island fish every year. The sound is located in one of the most densely populated regions in the United States, with the coast of Connecticut to its north and Long Island, New York, to its south.[3] It provides numerous economic benefits from activities such as shipping, ferry transportation, electricity power generation and industrial use. It is a highly productive ecological system and serves as a fishing ground for commercially valuable species such as lobster, oyster, flounder and others. Different areas of the sound serve as feeding, breeding, nesting and nursery areas for hundreds of species of plants and animals. The western part of the sound experiences severe hypoxic water conditions every year. Such effects have not been observed in the central and eastern parts. Commercial harvesting activities take place across all three contiguous fishing zones, with lobster being the most commercially valuable species harvested.

In recognition of the critical importance of the Long Island Sound to the region, in 1985 the U.S. Environmental Protection Agency, Connecticut and New York initiated a cooperative Long Island Sound Study (LISS) to identify the key causes that affected the health of the LIS sound system.[3] In 1994, the LISS completed the Comprehensive Conservation and Management Plan that identify low dissolved oxygen (hypoxia) as one of the seven issues that have been plaguing this ecosystem. The effects on water quality are typically observed every summer when the dissolved oxygen level often falls to below 2mg/l generating a hypoxic zone in the western part of the sound.

[3] See http://longislandsoundstudy.net/.

The objective of this paper is twofold. First, we present a simple theoretical model that can be used to analyze the spatial distributional effects of hypoxia on harvest within an industry. Second we use temporally and spatially differentiated data for Connecticut Long Island Sound lobster industry and a set of environmental and economic variables to estimate the contemporaneous and lagged effects of changes in dissolved oxygen level (measure of hypoxic water condition) on aggregate harvest share across the three adjacent fishing zones, only one of which faces moderate to severe hypoxic conditions each summer.

Drawing on Costello and Polasky (2008), Huang and Smith (2011) and an extensive literature on bioeconomic modeling of fisheries **(**such as Wilen and Sanchirico, 1999; Smith and Wilen, 2003; Smith, Sanchirico and Wilen, 2009; Smith and Crowder, 2011), we develop a theoretical model to analyze the spatial effects of hypoxia on fishers' optimal harvest strategy for the season. The model identifies the determinants that are likely to play a key role when fishers adjust their location choices across fishing zones when some zones are affected by hypoxia while others are not. In the absence of zonal restrictions, fishers can choose to allocate fishing effort across hypoxic and non-hypoxic fishing zones that are adjacent to each other. To model the spatial effect of hypoxia on harvest, we incorporate spatial heterogeneity that stems from both species specific biological factors and industry specific economic factors. The biological factors include the effect of hypoxia on growth of species and migration of species away from hypoxic areas. The economic factors include differences in variable costs of harvest across zones. The model illustrates the spatially explicit harvesting strategy when fishers aim to maximize the net present value of profit across seasons while responding to changes in fishing conditions, which stem from the effects of hypoxia on fish stock.

The empirical model uses spatially explicit data on lobster harvest and a group of explanatory variables and estimates zone specific industry supply functions. The model provides estimates of contemporaneous and lagged effect of hypoxic water conditions in western LIS on monthly industry level harvest from each zone, where only one out of three contiguous fishing zones (western LIS) is affected by hypoxia. Our results indicate that over the 1995-2011 time frame, the presence of moderate to severe hypoxic conditions in western LIS had a negative contemporaneous and lagged effect on harvest share from the hypoxic zone. The contemporaneous effect was found to be statistically insignificant whereas the estimated lagged effect is statistically significant. The presence of hypoxic water condition in the hypoxic water zone had a positive contemporaneous and lagged effect on industry harvest share from the non-hypoxic fishing zone. Both effects are statistically significant.

The paper is organized as follows. The following section outlines the theoretical model. Section 3 presents the comparative results derived from the model. In section 4, we state the objective of the econometric study and outline the data structure. The following section outlines the econometric model and provides a description of the variables. Section 6 present the empirical results and provides a discussion of the implications of the results in conjunction with the theoretical findings. Finally, section 7 provides some concluding remarks.

2. The Model:

To motive our empirical analysis, which is based on aggregate harvest shares, we present a simplified theoretical model that treats the industry as a single, aggregate firm. We recognize that this abstracts from many potentially important intra-industry issues (such as incentives to race-to-fish), but it suffices to demonstrate the basic result that the effect of hypoxia on harvest shares in different zones is theoretically ambiguous and hence ultimately an empirical question. We assume the fishing area is comprised of two adjacent fishing zones denoted by $k = A, B$ that differ in their levels of water quality. Specifically, fishing zone A typically experiences hypoxic water conditions during summer months every year, which corresponds to the fishing season. Fishing zone B is assumed to experience no impact of hypoxia each year.

As noted, for simplicity, we treat the industry as a single firm (essentially, a sole owner) that is subject to a total allowable harvest, which we normalize to one. Absent any zonal restrictions, the firm can fish in either zone, and we assume throughout that it in each period it harvests from both zones (implying an interior solution for the optimal allocation of harvest across zones). The amount of fish harvested in zone k at time t is given by $y_k(t)$. The firm maximizes total discounted net profits over the period from $t = [0, T]$, by choosing the share of total allowable catch to be harvested from zone *A*, denoted by *s*, which in turn determines the share harvested from zone *B*, $(1-s)$. Harvest from the two zones are sold in a competitive market at constant prices given by P_A and P_B, respectively.

Following Costello and Polasky (2008), Huang et al. (2010) and Huang and Smith (2011) we adopt a bioeconomic structure to specify the equation of motion for the fish stocks in each zone. The change in stock in zone A is given by $\dot{X}_A = X_A[g_A(t) - h_A(t)\theta - h_A(t)\gamma - m_A(t)] - y_A(t)$, where $h_A(t)$ is a time dependent variable that measures the presence of hypoxic water conditions in zone A at time t. In empirical applications this variable can be an indicator variable that would take the value of 1 at time t if the level of dissolved oxygen in the water is below 2mg/l and 0 if the level is above that threshold. The two time independent constants (θ, γ) show the effect of hypoxia on fish stock. The fraction of stock, $X_A(t)$, that migrates from zone A to B in response to hypoxic conditions in A is given by $\theta h_A(t)$, where θ is a constant. Typically unobservable to resource managers and researchers, this constant is species-specific, given that species vary in their natural ability to avoid hypoxic water conditions. The fraction of the stock that succumbs to hypoxic water conditions at any given time is given by $\gamma h_A(t)$, where γ is a constant. In general, fast moving species that are able to respond to hypoxia in a timely way by migrating to non-hypoxic water zones are likely to have a higher proportion of fish migrating to better aquatic environment than those that perish. Note that in empirical applications we cannot distinguish between the two effects given by θ and γ. However, in reality, different values of θ

and γ can have different impact on aggregate industry output. For example, the net effect of hypoxia on total stock across zones will be different for a species with a high θ and a low γ value than another species that has a low θ and a high γ value.

Let $g_A(t)$ denote the natural growth rate of the species at time t and $m_A(t)$ be its natural mortality rate in zone A. They are determined by factors other than hypoxia that contributes to mortality within a season. For example, these factors, mostly unobservable to resource managers and fishers, could be intra-species competition, predation, age, diseases and infections etc. Let the change in stock in zone B be given by $\dot{X}_B = X_B\left[g_B(t) - m_B(t)\right] + h_A(t)\theta X_A(t) - y_B(t)$, where $g_B(t)$ and $m_B(t)$ are the respective growth and mortality rates of the stock in zone B. The term $h_A(t)\theta X_A(t)$ shows the proportion of total population in zone A that migrates to zone B in response to hypoxic water conditions.

Similar to Huang and Smith (2011), we assume a cost function that is linearly separable in harvest and stock, *i.e.*, $C_{yX}(.) = 0.$, which means marginal cost of harvest does not depend on the level of stock. We acknowledge this is a restrictive assumption but it simplifies the mathematics to a considerable extent without major loss of insight. The total cost function for zone A is given by $C_A = c_o + \frac{c_A}{2} y_{At}^2 - \alpha X_{At}$ for $y_A > 0$ and 0 otherwise. Similarly, the total cost function for zone B is given by $C_B = c_o + \frac{c_B}{2} y_{Bt}^2 - \beta X_{Bt}$ for $y_B > 0$ and 0 otherwise. The coefficients c_0, c_k, α, β are all positive, where $k = A, B.$ The coefficient c_o is a fixed cost coefficient. In fisheries, the fixed cost can include the number of crew members hired by the captain. The variable cost coefficient, c_k , affects the marginal cost of harvest in zone k , given by $c_k y_k$. The coefficients α and β indicate the marginal impacts on total cost given a unit increase in fish stock in zones A and B respectively. Hence, ceteris paribus, for a unit increase in stock, the cost of fishing is reduced by α in zone A and β in zone B.

Given this specification, the optimal allocation of harvest across the two zones solves:

$$\underset{\{s(t)\}}{Max} \int_0^T e^{-rt}\left[P_A s + P_B(1-s) - 2c_0 - \frac{c_A}{2}s^2 - \frac{c_B}{2}(1-s)^2 + \alpha X_A + \beta X_B\right]dt$$

s.t $\quad \dot{X}_{At} = X_A[g_A(t) - m_A(t) - h_A(\theta+\gamma)] - y_A,$

$$\dot{X}_{Bt} = X_{Bt}\left[g_B(t) - m_B(t)\right] + h_{At}\theta X_{At} - y_B,$$

$$X_A(0) = \bar{X}_{A0} \ ,$$

$$X_B(0) = \bar{X}_{B0} \ ,$$

where r is the discount rate. Assuming that $\left[g_A(t) - m_A(t)\right] = \left[g_B(t) - m_B(t)\right] = \phi(t)$, we can rewrite the co-state equations in terms of s as follows:

$$\dot{X}_A = X_A\left[\phi - h(\theta+\gamma)\right] - s, \tag{1}$$

$$\dot{X}_B = X_B\phi + h\theta X_A - (1-s), \tag{2}$$

where we assume $r > \phi$.[4]

The current value Hamiltonian for this problem is:

$$H = P_A s + P_B(1-s) - 2c_0 - \frac{c_A}{2}s^2 - \frac{c_B}{2}(1-s)^2 + \alpha X_A + \beta X_B + \lambda\left[X_A\{\phi - h(\theta+\gamma)\} - s\right] + \mu\left[\phi X_B + h\theta X_A - (1-s)\right].$$

In the above Hamiltonian, λ and μ are the shadow values or co-state variables for the two equations of motion. They denote the marginal increase in the objective function given an increase in the state variables, X_A and X_B, respectively.

The first order necessary conditions for an optimal interior solution for the above optimization problem include the following:

$$\frac{\partial H}{\partial s} = 0 \qquad \Rightarrow \qquad (P_A - P_B) - c_A s + c_B(1-s) - \lambda + \mu = 0, \tag{3}$$

$$\frac{\partial H}{\partial X_A} = -(\dot{\lambda} - r\lambda) \qquad \Rightarrow \qquad \alpha + \lambda[\phi - h(\theta+\gamma)] + \mu h\theta = -(\dot{\lambda} - r\lambda), \tag{4}$$

$$\frac{\partial H}{\partial X_B} = -(\dot{\mu} - r\mu) \qquad \Rightarrow \qquad \beta + \mu\phi = -(\dot{\mu} - r\mu). \tag{5}$$

3. Comparative Statics

In this section, we derive some comparative results to illustrate the effect of hypoxia on the optimal allocation of harvest across zones. We focus on the steady state solutions where $\dot{\lambda} = \dot{\mu} = 0$ and $\dot{X}_A = \dot{X}_B = 0$. In steady state, equation (5) implies:

$$\tilde{\mu} = \frac{\beta}{(r-\varphi)}, \tag{6}$$

which gives the steady state value of this multiplier, $\tilde{\mu}$. Note that $\tilde{\mu} > 0$ if $r - \phi > 0$, implying that in the steady state an increase in the stock in zone *B* is beneficial. In addition, equation (4) gives the steady state value of an increase in the stock in zone *A*, $\tilde{\lambda}$:

$$\tilde{\lambda} = \frac{\alpha + \tilde{\mu}h\theta}{r - \varphi + h(\theta+\gamma)} = \frac{\alpha + \dfrac{\beta h\theta}{(r-\varphi)}}{r - \varphi + h(\theta+\gamma)}. \tag{7}$$

Note that from equations (6) and (7) we are able to derive the difference between the steady state shadow values of the two constraints, given in the following equation,

$$\tilde{\mu}-\tilde{\lambda}=\frac{\beta}{(r-\varphi)}-\left\{\frac{\alpha+\frac{\beta h\theta}{(r-\varphi)}}{r-\varphi+h(\theta+\gamma)}\right\}=\frac{(\beta-\alpha)(r-\varphi)+\beta h\gamma}{(r-\varphi)\left[r-\varphi+h(\theta+\gamma)\right]} \quad . \tag{8}$$

Furthermore, equation (3) implies:

$$s^{*}=\frac{P_A-P_B+c_B+(\tilde{\mu}-\tilde{\lambda})}{c_A+c_B}, \tag{9}$$

where s^{*} is the optimal harvest share for zone A. If $\tilde{\mu}=\tilde{\lambda}$ [5], this reduces to:

$$P_A-c_A s=P_B-c_B(1-s),$$

which simply states that the optimal allocation of harvest equates the static marginal returns across the two zones. However, in general $\tilde{\mu}\neq\tilde{\lambda}$. In this case, the optimal allocation depends not only on the prices and cost coefficients, but also on $(\tilde{\mu}-\tilde{\lambda})$, which is the (steady state) *stock effect*. Note that this stock effect can be either positive or negative. If $\alpha<\beta$, it will be strictly positive, implying that more should be harvested from zone *A* and less from zone *B* than would be warranted in the absence of any stock effect. The intuition is that leaving behind an additional unit of stock in zone *B* reduces cost by more than leaving behind an additional unit in zone *A*. However, if $\alpha\geq\beta$, the stock effect could be negative, which would imply allocating less harvest to zone *A*.

Since $\tilde{\mu}$ is independent of h, the effect of an increase in hypoxia on the optimal allocation of harvest is simply given by:

$$\frac{\partial s^{*}}{\partial h}=\frac{-1}{c_A+c_B}\frac{\partial\tilde{\lambda}}{\partial h}=\frac{-1}{c_A+c_B}\cdot\frac{[(\beta-\alpha)\theta-\alpha\gamma]}{[(r-\phi)+h(\theta+\gamma)]^{2}}\ . \tag{10}$$

Thus, the sign of (10) is inversely related to the sign of $(\beta-\alpha)\theta-\alpha\gamma$ .The first term, $\theta(\beta-\alpha)$, reflects the "migration" effect. Its sign depends on the relative magnitudes of α and β . Note that, in the absence of any hypoxia-induced mortality, i.e., if $\gamma=0$, then the migration effect implies that an increase in hypoxia will decrease harvest in zone A if $\beta>\alpha$ and increase harvest in zone A if $\alpha>\beta$. When $\beta>\alpha$, then $\tilde{\mu}>\tilde{\lambda}$, implying that, all else equal, a shift in stock from zone *A* to zone *B* through migration will reduce costs. Because migration is proportional to the stock in zone *A*, an increase in migration induced by increased hypoxia increases the marginal value of stock in zone *A*, implying $\partial\tilde{\lambda}/\partial h>0$. This, in turn, reduces the optimal steady state harvest in zone *A*. On the other hand, if there is no migration, i.e., $\theta=0$, then an increase in hypoxia will unambiguously increase optimal harvest in zone A because of the "die-off" effect, reflected in the second term $-\alpha\gamma$. As a result of the die-off effect, an increase in hypoxia will lead to greater mortality in zone A , implying that the marginal gain from leaving stock behind in zone A is reduced and hence optimal harvest in zone A is increased. When both migration and die-off occur ($\theta\neq0$ and $\gamma\neq0$) and an increase in the stock reduces costs more in zone B than in zone A ($\beta>\alpha$), then the effect of an increase in hypoxia on the allocation of harvest between the two zones is ambiguous. We summarize these findings in the proposition below.

Proposition 1:

(i) The net effect of change in the level of hypoxia on the optimal harvest share from the hypoxic zone, $\frac{\partial s^*}{\partial h}$, depends on the migration effect (reflected by $\theta(\beta-\alpha)$) and the die-off effect (reflected by $\alpha\gamma$).

(ii) In absence of the die-off effect, the migration effect implies $\frac{\partial s^*}{\partial h}<0$ if $\beta>\alpha$ and vice versa if $\beta\leq\alpha$.

(iii) If there is no migration effect, *i.e.,* $\theta=0$, then an increase in hypoxia will unambiguously increase optimal harvest in zone A because of the "die-off" effect.

(iv) When both migration and die-off effects occur and $\beta > \alpha$, the effect of an increase in hypoxia on the allocation of harvest between the two zones is ambiguous.

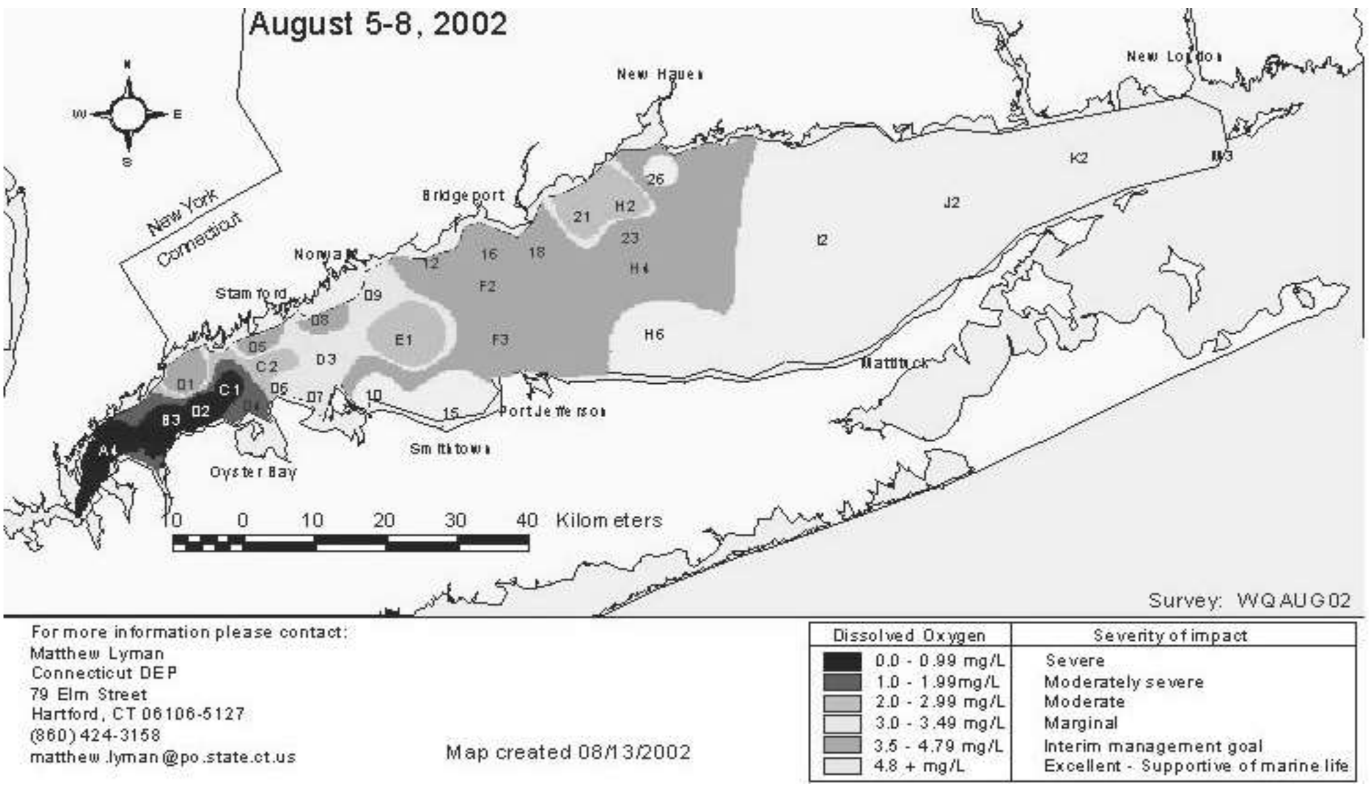
Equation (10) and the analysis that leads to it illustrates that when hypoxia is present, the optimal harvest share in each fishing zone depends on hypoxia along with the usual economic variables, price and cost parameters. However, the direction of that effect is ambiguous and depends on the effect of hypoxia on the stock effect, which in turn depends on: (i) die-off effect (positive), (ii) migration effect (zero or positive) and (iii) the relationship between α and β , where α and β are the marginal impact of a change in fish stock on cost of fishing in zone *A* and *B* respectively.

4. Empirical Model –

In this section, we specify and estimate an econometric model using data on Connecticut lobster harvest and a set of environmental and economic variables that affect harvest. We draw upon the insights from the theoretical model to obtain estimates of the effects of hypoxia on contiguous fishing zones in the Long Island Sound (LIS). Of the three fishing zones where CT fishers harvest their target species, only western LIS experiences moderate to severe hypoxic water conditions during summer months. When dissolved oxygen in the water is between 4 mg/l and 2 mg/l, the west zone experiences moderate hypoxic water conditions. Severe hypoxic conditions exist when the oxygen level further falls below 2mg/l.

Data:

Our dataset contains monthly observations from 1995 - 2011 for each of the three fishing zones – western LIS, central LIS and eastern LIS. The data for the lobster harvest, price and all environmental variables used in the study have been collected and provided by the Connecticut Department of Energy and Environmental Protection (CT DEEP). The monthly average price data for No. 2 diesel fuel for the U.S. east coast, series WPU057303, are from the Energy Information Administration. The environmental data have been collected at various stations in the sound where monitoring stations are located. The map below shows the various locations where the data are collected.[6]



Source: Connecticut Department of Energy and Environmental Protection

Stations 9, 15, A4, B3, C1, C2, D3, E1, F2 and F3 comprise western LIS and stations H2, H4, H6, I2, J2 and J4 are part of central LIS. Eastern LIS has only two stations - K2 and M3. Data for the environmental variables are typically collected once every month. Sometimes during the summer months, data were collected twice with a gap of 15 days in the same month. For those months the average of the two observations was used. The complete list of zone specific data series used in the study are listed as follows: (i) harvest (industry aggregate), (ii) price of lobster, (iii) bottom level dissolved oxygen, (v) bottom level dissolved nitrogen, (vi) bottom level water temperature and (vii) bottom level salinity. We include the diesel data for U.S. east coast as an explanatory variable, given diesel is a key input for lobster fishers. Each data point corresponds to a fishing zone (western, central or eastern LIS) and a particular month in the chosen time period.

5. Econometric Model:

To obtain estimates for the effect of hypoxic water conditions in west LIS on lobster harvest from the three adjacent fishing zones, we specify the econometric model as a system of equations where the dependent variable in each equation is the harvest share from each zone, *i.e.*, harvest from each zone enters the model as a fraction of total harvest from all three zones in any given month. Each of the three harvest-share equations is a function of a set of independent variables and a random error term, which captures the unobservable factors that can affect the dependent variables in any given time period. Since we use monthly observations for estimating the model, t would indicate any given month in any year.

The following system of equations specifies the industry level model we estimate to find evidence of *(i)* any direct effect of hypoxia in western LIS on industry output in western LIS, which is the hypoxic fishing zone, and, *(ii)* indirect effect of hypoxia in west zone on aggregate monthly landings from central and eastern LIS.

$$Share_{kt} = \alpha_{0k} + \alpha_{1k} Share_{k(t-1)} + \alpha_{2k} \left(\frac{P_k}{P_{\neq k}} \right)_{t-1} + \alpha_{3k} dob\_k_t$$
$$+ \alpha_{4k} nb\_k_t + \alpha_{5k} tempb\_k_t + \alpha_{6k} salb\_k_t + \alpha_7 diesel_t + \alpha_8 H\_dummy_t$$
$$+ \alpha_9 H\_dummy_{t-1} + u_{kt}$$

(11)

Equation (11) represents the system of equations we will estimate for the econometric analysis. The dependent variable in each equation, is the contemporaneous harvest share is zone k at time t, where k is west LIS, central LIS and east LIS respectively. We include a one period lag value of the dependent variable, $Share_{k(t-1)}$ as an explanatory variable in each equation. Since we are interested in estimating the effect of hypoxia of the share of harvest from each zone, we assume the harvest share depends on the relative prices of lobster across zones. Because harvest share and contemporaneous price ratios are endogenously determined, we include one period lagged values of the price ratios. The one period lagged ratio of prices for two zones is denoted by the variable $\left(\frac{P_k}{P_{\neq k}}\right)$ in the model. It must be noted that the price data indicates there is a very small amount of variation in lobster prices across of the three zones.

As lobster is a bottom dwelling species, data included for all the environmental variables in the model for each zone – dissolved oxygen (dob_k_t), nitrogen (nb_k_t), water temperature ($tempb\_k_t$) and salinity ($salb\_k_t$) are bottom level data for each zone k. The coefficient for the variable dob_k_t shows the marginal impact of a change in the bottom level dissolved oxygen in the current month on the harvest share from zone k.

The variable H_dummy_t is a dummy variable that is of key interest in this study. It takes a valuable of 1 when the dissolved oxygen level falls below 4mg/l and 0 when the level remains above that threshold. A key question arises at this point about the choice of threshold. We chose 4mg/l as the cutoff point even though severe hypoxic conditions are said to set in only when the dissolved oxygen level drops to 2mg/l or below. This is because even though 2mg/l is the level that is known to be a serious threat to marine species such as having an impact on the mortality rate, the threshold when the species perceives an adverse change in its natural habitat in terms of a gradual drop in the oxygen level and starts responding to that change (through migration) might be higher than 2mg/l. Note this trigger point will possibly depend on the oxygen requirement of the species, the adaptive capability of the species, and the speed with which it can migrate out of the hypoxic zone. Since lobster is a relatively large slow moving species with a life cycle that spans over years, we chose a threshold sufficiently higher than 2mg/l. Typically, moderate hypoxic water conditions persist when the dissolved oxygen level is 2mg/l and 4mg/l. We include a one period lag of the H_dummy_t variable denoted by H_dummy_{t-1}, which shows whether hypoxic water conditions was present in the west zone in the previous period. The corresponding coefficient shows the impact of hypoxic condition in the previous month on the harvest share this month.

The variable for diesel price is given by $diesel_t$. The diesel price data was found to be non-stationary. Since including variables that follow non-stationary data processes will result in spurious regression results, we include diesel price in the first difference order so that it is included in the model as a stationary variable. We also include a dummy variable, $Die-off\_dummy_t$, to control for the major lobster die-off that took place in the summer and fall of 1999 in western LIS (Balcom and Howell, CT Sea Grant Report, 2006). The variable takes the value 1 for all months throughout which the mortality event took place.

The zone specific error term is given by the variable u_{kt}. To estimate the model, we follow Smith (2002) and treat our system of equations as a seemingly unrelated regression (SUR) model. The SUR model, first proposed in Zellner (1962), is a generalization of the standard linear regression model that allows the error terms across equations to be correlated. Hence, in our case, it accounts for the possibility that unobserved zone specific factors can be correlated with each other.

The data consists of a weakly unbalanced panel, which implies we have a few missing observations for some variables. We account for this issue in the econometric analysis. Note, our model is essentially three share equations where the harvest shares for each month add up to one. Because the variance covariance matrix of error terms for the complete set of equations will be singular due to the adding-up property, we drop one equation (center LIS - $Share_{ct}$) since we can compute the parameters residually using the estimates from the other two equations.

6. Results and discussion:

Tables 1 and 2 in the appendix report the estimation results for the SUR model specified in equation 11. Table 1 shows the results for western LIS harvest share. In table 1, the coefficients for lagged share variable, temperature variables for west and central zones, diesel fuel and the lagged hypoxia dummy variable are significant at 5% level of significance. The coefficient for the nitrogen variable for the west zone is at 10% level of significance. Table 2 shows the results for eastern LIS harvest share. In table 2, the lagged share variable, the temperature variables for west and central zone, the diesel variable and both the hypoxia dummy variables are significant at 5% level of significance. The *Die_off* dummy variable is positive and significant at 10% level of significance. The hypoxia dummy variables are our key variables of interest because they capture the contemporaneous and lagged effect of hypoxia on harvest shares in each zone.

The theoretical findings can be used to understand the empirical results on the effect of hypoxia on harvest from each zone. The key insight from the theoretical model shows that hypoxia can have an ambiguous effect on the optimal harvest zones from hypoxic and non-hypoxic zones and the net effect at any time would depend on the effect of hypoxia on stock from each zone (through migration and die-off effects). In the empirical model, we find that the presence of contemporaneous and lagged harvest hypoxia in the west zone reduces harvest share in that zone, though the contemporaneous effect turns out to be statistically insignificant. In the east zone, we find presence of hypoxia in the west zone leads to a rise in the share of harvest. Both the coefficients for the hypoxia variables are statistically significant. Though we are unable to identify whether this redistribution of harvest across the sound happened because of the impact of hypoxic on the stock (*i.e.*, through die-off or migration of species) from each zone or through a behavioral response from fishers through a reallocation of effort across time and space, our empirical findings provide a basis for the insights illustrated through the theoretical model.

7. Conclusion:

The objective of this paper is twofold. First, we present a simple theoretical model that can be used to analyze the distributional effects of hypoxia on harvest within an industry. Second, we use temporally and spatially differentiated data for Connecticut Long Island Sound lobster industry and a set of environmental and economic variables to estimate the effect of changes in hypoxic conditions on harvest across the three adjacent fishing zones, only one of which faces moderate to severe hypoxic conditions each summer.

We develop a theoretical model to analyze the spatial effects of hypoxia on fishers' optimal harvest strategy for the season. In the absence of zonal restrictions, fishers can choose to allocate fishing effort across contiguous hypoxic and non-hypoxic fishing zones. To model the spatial effect of hypoxia on harvest, we incorporate spatial heterogeneity that stems from both species specific biological factors and industry specific economic factors. The biological factors include effect on growth and number of species, natural dispersal rate across zones and migration of species across away from hypoxic areas. The economic factor includes differences in variable costs of harvest across zone. The model illustrates the spatially explicit harvesting strategy when fishers respond to hypoxic water conditions.

The empirical model provides estimates of the contemporaneous and lagged effect of hypoxia on lobster harvest using data from three adjacent fishing zones or patches in the Long Island Sound (LIS). Every summer the western section of Long Island Sound is affected by moderate to severe hypoxic water conditions. Using monthly data for seventeen years (1995-2011) and a large set of environmental and economic variables for the three fishing zones, we run two alternative specifications of the empirical model to obtain estimates of contemporaneous and lagged effects of hypoxia of lobster harvest from the sound.

The key insight from the theoretical model illustrates that the effect of hypoxia on harvest shares from different fishing zones is theoretically ambiguous. Results from our empirical model indicate that an increase in hypoxic water condition reduced the share of harvest from the hypoxic water zone, compared to the other fishing zones, between the 1995 and 2011.

These results have practical policy implications, particularly for fisheries that are regulated using zonal restrictions. The presence of zonal restrictions can prevent fishers from fishing in non-hypoxia zones to offset the loss in individual profit, which can lead to a more unequal distribution of earnings over time across the industry. In contrast, in fisheries without zonal restrictions, fisheries can choose to fish in non-hypoxic water zones to prevent loss in harvest share and profit, which can lead to a more equitable distribution of profit earnings over time.

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Appendix:

Table 1: Results for – $Share_{wt}$ - west LIS

Dep Var: $Share_{wt}$	**Coefficient**	**Robust Standard Error**	***t*-statistic**
$Share_{w(t-1)}$	.6186883	.0776405	7.97**
$\left(\frac{P_w}{P_e}\right)_{t-1}$	.0010204	.0071241	0.14
$\left(\frac{P_c}{P_e}\right)_{t-1}$	.0223856	.2202025	0.10
dob_w_t	-.0255431	.021333	-1.20
nb_w_t	.3937422	.2050277	1.92*
$tempb\_w_t$	-.0467469	.0133217	-3.51**
$salb\_w_t$	.0201623	.0302819	0.67
dob_c_t	.0441606	.0355131	1.24
nb_c_t	-.174476	.2925611	-0.60
$tempb\_c_t$	.0631541	.0249492	2.53**
$salb\_c_t$	-.0034761	.0412874	-0.08
dob_e_t	-.0024689	.030048	-0.08
nb_e_t	-.3270572	.2101516	-1.56
$tempb\_e_t$	-.0120697	.0191843	-0.63
$salb\_e_t$	-.0258901	.0266293	-0.97
$diesel_t$	-.0320052	.0137126	-2.33**
H_dummy_t	-.0079586	.0362946	-0.22
H_dummy_{t-1}	-.0810381	.0350461	-2.31**
$Die-off\_dummy_t$	-.0388874	.0277835	-1.40
Constant	.294534	.779944	0.38

** - statistically significant at 5% level of significance

* - statistically significant at 10% level of significance

R square: 0.61

Adjusted R square: 0.55

Table 2: Results for $Share_{et}$ – east LIS

Dep Var: $Share_{et}$	**Coefficient**	**Robust Standard Error**	***t*** **- statistic**
$Share_{e(t-1)}$	.4933892	.0659973	7.48**
$\left(\frac{P_w}{P_e}\right)_{t-1}$	-.0086891	.0087499	-0.99
$\left(\frac{P_c}{P_e}\right)_{t-1}$	.3212403	.2256131	1.42
dob_w_t	.0337298	.0309079	1.09
nb_w_t	-.3386238	.2236947	-1.51
$tempb\_w_t$	.0303277	.0148056	2.05**
$salb\_w_t$	-.0258092	.0380075	-0.68
dob_c_t	-.0856452	.0528002	-1.62
nb_c_t	.4499893	.344003	1.31
$tempb\_c_t$	-.0635245	.0236237	-2.69**
$salb\_c_t$	.0400594	.0539475	0.74
dob_e_t	.0563095	.0400215	1.41
nb_e_t	.1925253	.2545393	0.76
$tempb\_e_t$	.0278792	.0213515	1.31
$salb\_e_t$	.0079507	.028551	0.28
$diesel_t$	.0622995	.0136768	4.56**
H_dummy_t	.0907566	.0361062	2.51**
H_dummy_{t-1}	.1521166	.0446115	3.41**
$Die-off\_dummy_t$	.0577684	.0343353	1.68*
Constant	-.9120786	.7373534	-1.24

R square: 0.59

Adjusted R square: 0.53

[1] For definitions of eutrophication, see http://toxics.usgs.gov/definitions/eutrophication.html

[2] Source: http://www.whitehouse.gov/sites/default/files/microsites/ostp/hypoxia-report.pdf (page 11)

[3] Source: The Long Island Sound Study – The Comprehensive Conservation and Management Plan, March 1994

[4] This ensures that in a steady state $\mu > 0$ (see equation (6)).

[5] This would be true, for example, if $h = 0$ and $\alpha = \beta$.

[6] The map with the station locations and the data for all environmental variables were provided by Matthew Lyman at CT Department of Energy and Environmental Protection. The fisheries data were provided by Matthew Gates at CT DEEP. The authors are very grateful for the support they received from CT DEEP.