# FISHING WITHIN THE LIMITS:
# A SUSTAINABLE FISHING MODEL

Brett Alexander Leibowitz

Advisor: Philippe Rigollet

June 2013

I hereby declare that I am the sole author of this thesis.

I authorize Princeton University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

<div align="right">Brett Leibowitz</div>

I further authorize Princeton University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

<div align="right">Brett Leibowitz</div>

# Table of Contents

# List of Tables

# List of Figures

# List of Equations

# List of Terms and Abbreviations

**Annual Catch Limit (ACL):** The annual catch limit refers to the total number of fish from the targeted population that are allowed to be caught in a given year.

**Catch per Unit Effort (CPUE):** The catch per unit effort refers to the average amount of targeted fish caught during one vessel deployment.

**Ecologically Sustainable Yield (ESY):** The ecologically sustainable yield refers to the amount of fish that can be harvested without overfishing the target population or causing irrevocable harm to other populations or the habitat.

**Ecosystem Based Fishery Management (EBFM):** Ecosystem based fishery management takes into account all aspects of an ecosystem, including multiple species and the habitat as opposed to just the targeted species.

**Essential Fish Habitats (EFH):** Essential fish habitats are the environments necessary for marine life to thrive.

**Fishery Management Plan (FMP):** Fishery management plans are the reports created by the Regional Fishery Management Councils detailing the necessary steps for preventing overfishing in future years.

**Habitat Impact Units (HIU):** Habitat impact units are a measure of how healthy the habitat is in a given cell.

**Individual Habitat Quota (IHQ):** The individual habitat quota refers to the amount of habitat damage a fishery is permitted to cause in a given year.

**Magnuson-Stevens Fishery Conservation and Management Act (MSA):** This act was the first piece of legislation that regulated fishing practices on the national scale.

**Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006 (FCMRA):** This reauthorization updated the MSA to require regional councils to set annual catch limits (ACL) as part of their fishery management plans (FMP) and called for further research regarding specific fishing practices and the life histories of fish populations.

**Maximum Sustainable Yield (MSY):** The maximum sustainable yield refers to the amount of fish that can be harvested without overfishing the population.

**National Oceanic and Atmospheric Association (NOAA):** The NOAA is a scientific agency within the US Department of Commerce dedicated to the study of the oceans and the atmosphere.

**New England Fishery Management Council (NEFMC):** The NEFMC is the regional fishery council in charge of regulating fishing practices in New England.

**Regional Fishery Management Councils (RFMC):** These councils were set up by the MSA to oversee fishing practices in a given region.

**Swept Area Seabed Impact (SASI) Database:** This database, which was set up by the NEFMC, compiled the effects of different gear types on essential fish habitats.

**Sustainable Fisheries Act of 1996 (SFA):** The SFA is an amendment to the MSA that suggested further research be done to find and protect essential fish habitats.

**Total Allowable Bycatch (TAB):** The total allowable bycatch refers to the total amount of bycatch that can be caught by a fishery in a given year.

**Total Allowable Catch (TAC):** The total allowable catch refers to the total amount of the targeted species that can be harvested by a fishery in a given year.

**Total Habitat Quota (THQ):** The total habitat quota is the maximum amount of habitat damage that is permitted to occur in a specific region in a given year.

**Vessel Monitoring System (VMS):** A vessel monitoring system refers to a fleet of ships that observes and records the distribution of fish populations and habitat quality in a specific region.

# Abstract

The understanding and regulation of fisheries is continually evolving. Typically, previous regulation has only focused on the targeted species population, however this does not account for the destruction of the surrounding marine habitats or the depletion of other species caught as bycatch. This thesis takes a holistic approach by implementing a sustainable fishing system that minimizes the habitat damage as well as the amount of bycatch caught, while maximizing the amount of the targeted species that can be harvested without depleting the population over time.

# Chapter One: Background

## Introduction:

Ever since I was a young child, I have traveled with my family to Alaska. Throughout the years, we have toured Denali State Park, seen whales and glaciers, been warned by rangers in Kodiak that we were "too close to the bear," and ridden horses along natural beaches. Although there are many reasons to visit Alaska, there is one in particular that always dictates why and when we go: king salmon season. Each summer, the salmon fight upstream against strong river currents in order to return to where they were born so they can spawn before dying. Some of the king salmon come back home after spending a year out at sea, while others come back after as long as seven years, weighing eighty pounds of pure lean muscle.

No experience is as beautiful or rewarding as fishing for kings. My family and I wake up early in the morning with the Alaskan summer sun to meet our guide, Tad, and get the boat out onto the Kenai River. The 82-mile long Kenai River connects the mountainous Kenai Lake with the Pacific Ocean. Famous for its large fish, the Kenai River is where, in 1985, Alaskan native Les Anderson landed the largest king salmon ever caught by a sports fisherman. Our mornings on the Kenai begin slowly as we drive out to our first fishing hole and set up our rods. Once everything is ready, I cast out, put my rod in my holder, and calmly wait as the river's current methodically rocks the boat.

As soon as I have a bite, the atmosphere in the boat completely changes. The rod gives a *tug, tug, TUG*, and slams down flat as the line flies out faster than I can imagine reeling it in. I hop up and yell, "Fish on!" while everyone else furiously reels their lines up so they do not tangle with mine. Getting a king into the boat is no easy feat. I have to

dance with the fish, let him pull line when he wants, but reel him in when I can, all while

not letting the hook pop out.  As soon as the king nears the boat, someone grabs the net

and desperately helps me bring him in.  Once the king is finally in the boat, I am relieved

and proud of my efforts.  Now my limit is reached, and I sit back, enjoy that other half of

the sandwich I was too nervous to take a bite out of earlier in case a king bit, and wait to

see how everyone else fares.

*Figure 1: Chinook (King) Salmon*[1]



Sadly, others may not have the chance to experience the same joy of fishing for

kings on the Kenai.  Last summer was the first time that fishing for king salmon was

prohibited in the Kenai due to low numbers.  This decline will not only have

environmental repercussions, but financial ones as well.  With kings in low supply, the

commercial and sport fishing industries have taken losses and are worried about their

futures.[2]

## Consequences of Overfishing:

The Alaskan king salmon is not the only species in danger of overfishing.

Currently, the National Oceanic and Atmospheric Administration (NOAA) lists 41 stocks

---

[1] Chinook Salmon, photograph
[2] Mauer

as overfished in the United States.[3]  In 2006, research published in *Science* magazine by the research group of Canadian marine ecologist, Boris Worm, estimated that all fished taxa stocks will completely collapse by the year 2048.[4]  We are running out of time to save and protect the biodiversity on this planet.

The extinction of marine life would cause worldwide food shortages and financial ruin for all fishing communities.  Fish serve as the main source of protein for 1 billion people on Earth, while 2.6 billion consume 20% of their animal protein from fish.[5]  The fishing industry employs 200 million people worldwide[6] and catches around $84 billion worth of seafood a year.[7] Both marine and land ecosystems would be irreversibly impacted by such a tragic event.  In order to prevent this doomsday scenario, sustainable fishing practices must be implemented and enforced immediately.

## History of Law & Regulation:

In 1976, the United States Congress passed the Magnuson-Stevens Fishery Conservation and Management Act (MSA).  Part of its original purpose was to establish Regional Fishery Management Councils (RFMC), which were designed to create and execute fishery management plans (FMP) to restore depleted fish stocks.  These FMPs were supposed to be updated regularly and to explain how each regional council would combat overfishing in the years to come.

Despite the establishment of these councils, fish stocks continued to decline and in response, the United States amended the MSA to include the Sustainable Fisheries Act

---

[3] "Overfished Stocks (41)"
[4] Worm 790
[5] Oliver
[6] Ibid.
[7] "Marine Fisheries and the World Economy"

(SFA) of 1996. This act stated why management plans failed and identified many of the problems that needed to be addressed in order to fish sustainably:

> (2) Certain stocks of fish have declined to the point where their survival is threatened, and other stocks of fish have been so substantially reduced in number that they could become similarly threatened as a consequence of (A) increased fishing pressure, (B) the inadequacy of fishery resource conservation and management practices and controls, or (C) direct and indirect habitat losses which have resulted in a diminished capacity to support existing fishing levels.[8]

The recognition that it was the "inadequacy of […] conservation and management practices and control" marked a change in how fishery management and planning was approached. This act called for greater research to be done, more specifically in the development and testing of new gear technology, the study of fish behavior, and the creation of fishing techniques that harvest target species efficiently while minimizing bycatch and any adverse effects on the essential fish habitat (EFH).[9] According to the SFA, EFH are the "waters and substrate necessary for fish to achieve spawning, breeding, feeding or growth to maturity"[10] and bycatch are the fish caught by a fishery but "not sold or kept for personal use."[11] This focus on an ecosystem based fishery management (EBFM) was and continues to be a huge contribution to improving sustainable fishing. For the first time nationally more than just the target fish population was taken into account in determining how stocks should be fished.

The next historic change in fishing regulation was the 2006 reauthorization of the Magnuson-Stevens Act (MSRA). It mandated that every fishery council "develop annual catch limits (ACL) for each of its managed fisheries, as to not exceed the fishing level

---

[8] Magnuson-Stevens Act, 1
[9] Ibid. 156
[10] Ibid. 6
[11] Ibid. 4

recommendations by [the council's] scientific and statistical committee."[12]  Catch limits

are a necessity in guaranteeing that overfishing does not occur.  Without this restriction,

fisheries had been shutting down due to a "tragedy of the commons" scenario.  During

fishing seasons, there would be a "mad rush" for fish; fishers would travel out to sea, no

matter the weather conditions, and accumulate large amounts of bycatch by trying to

collect as many fish as possible in a short period of time.  This practice led to shorter and

shorter fishing seasons and eventually closures of fisheries in overfished areas.  To avoid

this fate and to comply with the changes in the MSRA, many fisheries enacted ACLs,

which limited the allowed total amount of fish caught instead of restricting the length of

the season.  Under this system, fishers have all year to catch their allocated share of fish,

thus allowing them time to fish in safe weather conditions and practice more selective

fishing.

---

[12] Ibid. 68

# Chapter Two: The Model

## Rights-Based Approach:

In order to fish sustainably by complying with the regulations imposed by the MSA and its changes, I have created a simulation that does not allow a target species to be overfished, while minimizing the amount of habitat destroyed and the quantity of bycatch caught. Each fishery is assigned the rights to a certain amount of habitat damage and a limited number of targeted and non-targeted fish per year. To enact this, my model revolves around three integral variables: total allowable catch (TAC), total allowable bycatch (TAB), and total habitat quota (THQ), which is measured in habitat impact units (HIU). For simplicity, my model assumes that a fishing season is one year long and starts at the beginning of each year.

TAC is the same as annual catch limits mentioned in the MSA. This means that each year, a fishery is restricted by the biomass (total weight) of the target fish population that it is allowed to harvest. As one can see from the past, limiting how much of a target fish population can be removed is crucial to the survival of a fishery. If a fishery uses up all of its TAC in a year, then the fishery is automatically closed until the next year.

TAB is similar to TAC, but instead of limiting how many target fish can be caught, it restricts the amount of bycatch that can be harvested each year. Similarly, when an industry runs out of TAB, it is closed for the remainder of the year. This type of closing is very costly since the fishery would have to forgo the profits from what was left of their TAC.

Finally, a region is only allotted a particular number of HIUs that it can use in a year. This regulates how much damage can be caused to the environment and dictates the

minimum percentage of healthy habitat that must be maintained.  If this THQ runs out, all

fisheries in that region must close for the rest of year, thus relinquishing the potential

economic gains from the leftover TAC.  The end goal for a fishery is to harvest all of the

TAC without depleting either its TAB or the regional HIUs.  While each fishery is

allocated its own TAC and TAB limits, the THQ is allocated to a given region, and thus

all the fisheries in that area must share the THQ.

Fusing these three principals together, I have created a system that sustains fish

populations and also protects their habitats.  The following sections will detail how the

model works.

## Model Background:

My model expands on multiple research papers by Daniel S. Holland from the

Gulf of Maine Research Institute and Kurt E. Schnier from the Department of

Environmental & Natural Resource Economics at the University of Rhode Island in

which they propose "individual habitat quota (IHQ) systems for habitat conservation that

[…] utilize economic incentives to achieve habitat conservation goals effectively."[13]  As

explained, an IHQ system refers to the distribution of HIUs among fisheries in a

particular region to limit the amount of habitat damage done in a given year.  Although

the grid and many of the processes used in my model are adapted from their research, my

scenario is different.  While their reports are designed to analyze the effects of fishing a

single species while preserving the essential fish habitat, my thesis concentrates on

minimizing bycatch and habitat damage when there are multiple target species.

---

[13] Holland, "Modeling a Rights-Based Approach…" 405

There are two target fish stocks in my model, each with their own yearly catch limit.  The first species, let us call it Ben, lives on the seafloor and is fished on by benthic (seafloor) trawlers, which cause immense habitat damage and capture another type of fish, let us call this one Pel, as bycatch.  Pel is a pelagic (mid-water) species that is targeted by a different set of vessels that use pelagic trawls responsibly.  In my simulation, these pelagic trawls cause very minimal habitat damage and do not harvest any bycatch.

*Figure 2: Benthic Trawl (left) and Pelagic Trawl (right)[14]*
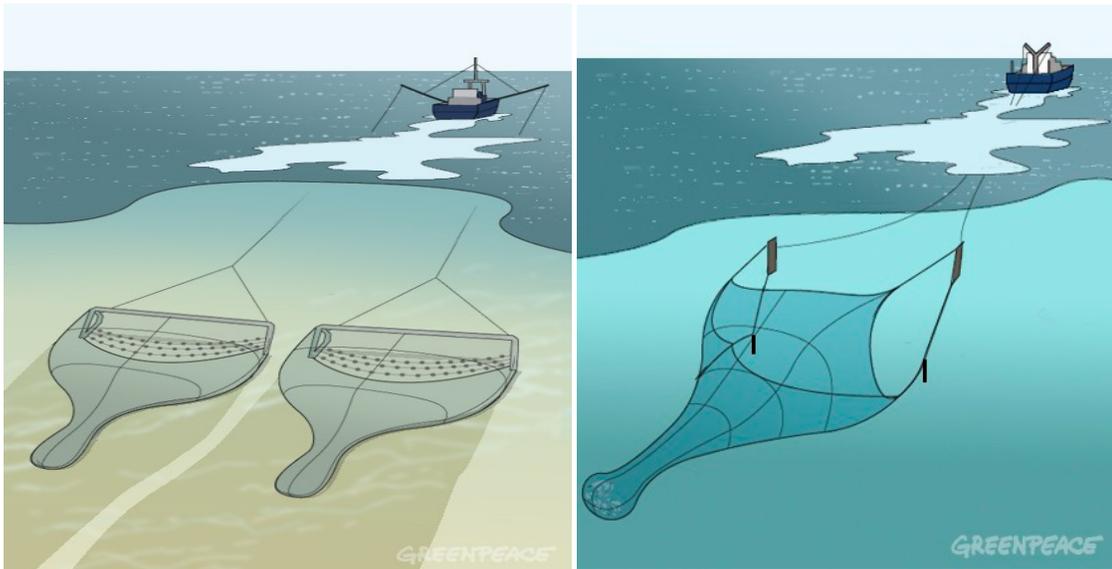


*As we can see from the image on the left, the nets from the benthic trawlers run along the sea floor, causing a significant amount of habitat damage.  The pelagic trawler, as seen on the right, uses nets in the mid-water column, avoiding most of the marine habitat.*

## The Grid:

Like Holland and Schnier, I use a spatial fishery simulation model,[15] which was originally created by James Sanchirico, a professor in the department of Environmental

---

[14] Beam Trawls, image; Pelagic Trawls, image
[15] Holland, "Modeling a Rights-Based Approach…" 410

Science and Policy at the University of California, Davis,[16] to represent a closed

ecosystem. The grid models the two target fish populations, their habitat, and the effects

of fishing the species and the area. The model follows a 25 cells x 40 cells, two-

dimensional, honeycomb structured grid, consisting of 1000 hexagonal cells as in

Holland and Schneir's later model.[17]

**Figure 3: Honeycomb Grid**
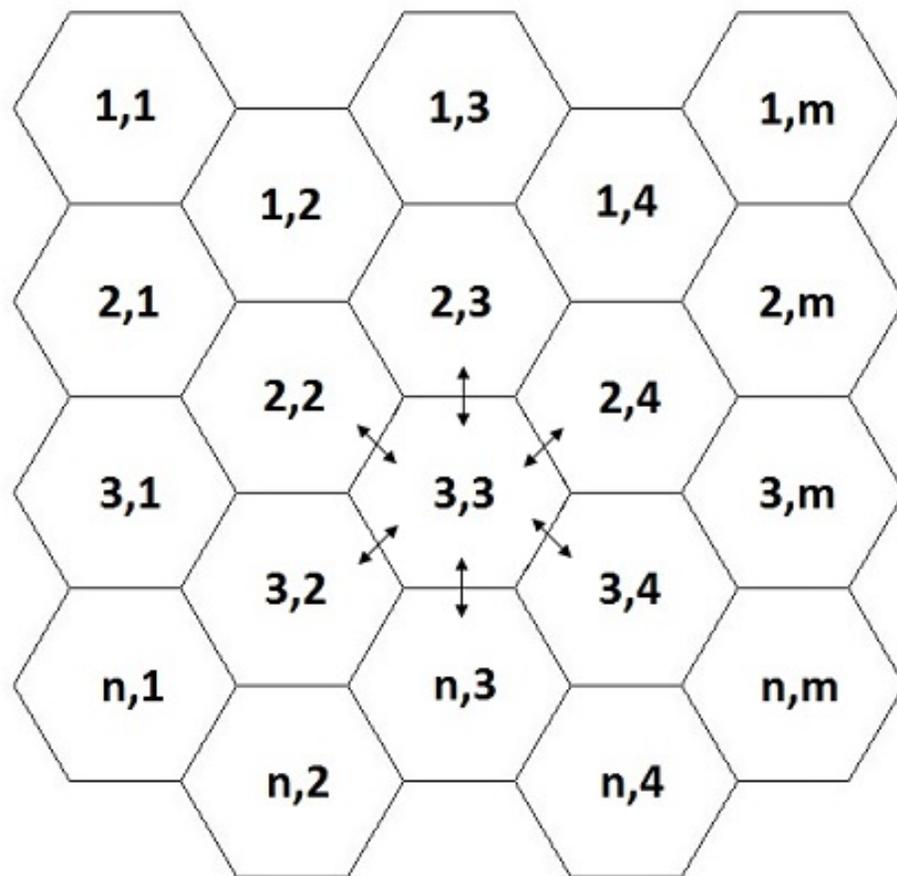


*Note: The cells in the middle of the grid are connected to surrounding cells. For example, (3,3) is connected to (2,2), (2,3), (2,4), (3,2), (n,3) and (3,4). Corner and side cells are also connected to six other cells. (1,1) is clearly linked to (2,1) and (1,2), but it also connects to (n,1), (n,2), (n,m), and (1,m).*

---

[16] Ibid. 410

[17] Holland, "Protecting Marine Biodiversity…" 1483

Each cell is six sided and allows for the fish populations to diffuse to surrounding cells at the end of every time period. In order to keep the connectivity consistent, all cells, even the edges are connected to six cells total. The right side is connected to the left and the top to the bottom. This means that corner cells are connected to the two or three cells surrounding them, and other corner or edge cells, as described in Figure 3. A vessel can only fish one cell at a time. Each deployment removes fish from the cell and destroys habitat determined empirically by the catchability coefficients of the fishing gears used.

## Habitat:

Habitat levels are monitored using an IHQ system similar to the one proposed by Holland and Schnier.[18] Initially, all cells start at a pristine, or maximum, habitat level equal to their area in m$^2$. For example, since each cell in my model is 20,000m$^2$, each cell has 20,000 Habitat Impact Units (HIU) before any fishing takes place. If a benthic trawler has a habitat impact coefficient, $q^H$, of 0.8, then one trawl will remove 80% of a cell's HIUs. In this example, a pristine habitat would cost 16,000 HIUs for a trawler to fish in and the cell will be left with 4,000 HIUs. If a trawler were to pass through this cell immediately after the first trawl, it would remove another 80% and the area would be reduced to 800 HIUs. Since cells with more depleted habitats are cheaper to fish in than healthier ones, fishers are incentivized to preserve areas with a high habitat level.

*Table 1: Habitat Variables*

| Habitat Variable | Value |
|---|---|
| Final target habitat level ($H^{Tar}$) | 30% - 50% |
| Maximum habitat regeneration rate per cell ($rT$) | 0.1 * $h_{max}$ |

---

[18] Holland, "Modeling a Rights-Based Approach…" 405

Each simulation has a final target habitat goal for the whole environment. For example, if the final target habitat is 30%, the grid will be sustained at 6,000,000 HIUs, since it would be worth 20,000,000 HIUs (1,000 cells worth 20,000 HIU each) when all cells are at the pristine level. To ensure that this goal is reached, the total habitat quota (THQ) will be set every year by subtracting the current target habitat from the projected habitat level if no fishing were to take place that year:

### Equation 1: Yearly THQ

$$THQ_y = -H^{Tar} + \sum_i \left[ h_{i,y-1,T,V} + min[(h_{max} - h_{i,y-1,T,V}), rT] \right]$$

When the total habitat level is below the final target habitat, the current target habitat level, $H^{Tar}$, is equal to this total habitat plus 2% of the total pristine habitat (400,000 HIUs). Once the total habitat level surpasses the target habitat level, the current target habitat is simply equal to the final target habitat for the remaining years.

## Effects of Fishing:

The fishing season in my model lasts $T$ periods, where each fishery sends a total of $V$ vessels per each period, adding to a total of $2V$ vessel deployments every period. Every time period, the fishery harvesting Ben sends the first vessel and all subsequent odd numbered vessels ($v = 1, 3, 5, \cdots, 2V - 1$), while the fishery that targets Pel sends every even numbered vessel ($v = 2, 4, 6 \cdots, 2V$). Every time a vessel harvests from a cell $i$, the fish populations, represented by $M$, and the habitat level must be updated for that location:

## Equation 2: Fish Harvest from Cell

$$x^M_{i,y,t,v+1} = x^M_{i,y,t,v} - q^M x^M_{i,y,t,v}$$

Above, $x^M_{i,y,t,v}$ is the biomass (in tons) of the fish $M$ in cell $i$, year $y$, time $t$, before

vessel $v$'s deployment. The fishing catchability coefficient, $q^M$, is the percent of fish $M$

that vessel $v$ removes from the fished cell $i$. Similarly, a habitat catchability coefficient

refers to the percent of a cell's habitat that vessel $v$ removes when it fishes cell $i$. Note

that there are two fisheries in my model and the benthic trawlers catch both the benthic

fish as a target species and the pelagic species as bycatch simultaneously. This means

both types of fish are removed according to the above equation after bottom trawling.

### Table 2: Trawl Catchability Coefficients on Fish and Habitat

| | | CATCHABILITY COEFFICIENT | | |
| --- | --- | --- | --- | --- |
| | | $q^{Ben}$ | $q^{Pel}$ | $q^H$ |
| **TRAWL** | **Benthic** | 0.4 | 0.05 | 0.8 |
| | **Pelagic** | 0.0 | 0.4 | 0.01 |

As we see in Table 2, the pelagic trawl has a benthic species catchability coefficient of

zero, so they are not captured as bycatch. Finally, a cell's level of habitat must be

updated after it is fished in:

### Equation 3: Cellular Habitat Reduction

$$h_{i,y,t,v+1} = h_{i,y,t,v} - q^H h_{i,y,t,v}$$

Like the above biomass equations, the cell's current habitat level, $h_{i,y,t,v}$ (in HIUs) is

reduced by the amount of damage the vessel caused during fishing.

# Growth:

At the end of a period, after all vessels have fished, growth occurs. The habitat regenerates by the following equation:

### Equation 4: Cellular Habitat Regeneration

$$h_{i,y,t+1,0} = h_{i,y,t,V} + min\big[(h_{max} - h_{i,y,t,V}), r\big]$$

The habitat grows by the period habitat growth rate, $r$. If this were to put the habitat level above its maximum habitat, the cell would simply return to its "pristine level", $h_{max}$. To calculate $r$, divide the habitat's yearly habitat growth rate, $rT$, by the number of periods, $T$. Since various environments respond differently to various fishing gear types (bottom trawl, pelagic trawl, etc.), empirical research is needed to find $rT$. There are even some compilations on how different destructive gear types harm various ecosystems, such as the Swept Area Seabed Impact (SASI)[19] database created by the New England Fishery Management Council for estimating the adverse effects of fishing on EFH.

### Table 3: Fish Growth Variables

| | | GROWTH VARIABLES | | |
|---|---|---|---|---|
| | | $\delta^M$ | $K^M$ | $\alpha^M$ |
| **FISH** | **Benthic** | 0.4 | 3,000,000 | 0.5 |
| | **Pelagic** | 0.4 | 3,000,000 | 0.5 |

Both fish populations, Ben and Pel, follow logistic growth. This is based off the size of its total population at the end of the year:

---

[19] New England Fishery Management Council

$$G_{y+1}^M = \delta^M \sum_{i=1}^{N} x_{i,y,T,V}^M \left[1 - \frac{\sum_{i=1}^{N} x_{i,y,T,V}^M}{K^M}\right]$$

where $\delta^M$ is the intrinsic growth rate of species $M$, and the summation of $x_{i,y,T,V}^M$ over $N$ cells is the total population of fish $M$ at the end of the year after the last period. Carrying capacity, $K^M$, refers to the grid's maximum population for a given species. When the total population of fish $M$ is low, its total growth for the following year, $G_{y+1}^M$, is a larger percentage of the total population of fish $M$, compared to when the total biomass is closer to $K^M$.

At the end of every period, the biomasses of both fish species in each cell increase due to adult fish growing in size and recruitment, which is population growth due to the birth of new fish:

***Equation 6: Fish Cellular Growth and Recruitment***

$$x_{i,y,t+1,0}^M = x_{i,y,t,V}^M + \alpha^M \left[\left(\frac{G_y^M}{T}\right)\frac{x_{i,y,t,V}^M}{\sum_{i=1}^{N} x_{i,y,t,V}^M}\right] + (1 + \alpha^M)\left[G_y^M \frac{z_{i,y,t}}{\sum_{i=1}^{N} \sum_{t=1}^{T} z_{i,y,t}}\right]$$

Adult growth, represented by the second term, is found by multiplying the adult share of total growth, $\alpha^M$, by the percent of the total population in cell $i$ and by the growth rate of the period. While physical growth in a cell depends on its internal population, recruitment is random. For each time period in a year, each cell in the grid is assigned its own random recruitment variable, $z_{i,y,t}$, which is a uniformly distributed random number between the values of zero and one. A cell's yearly growth due to recruitment is determined by the random percentage its $z$ is of the total sum of every $z$ for that year.

## Diffusion:

After the biomass increases from recruitment and adult size growth, diffusion occurs. It follows the equation:

### *Equation 7: Fish Diffusion between Cells*

$$x_{i,y,t+1,1}^{M} = x_{i,y,t,V}^{M} + d^{M}\left(\sum_{k=1}^{6} x_{k,y,t,V}^{M} - 6x_{i,y,t,V}^{M}\right)$$

where $x_{k,y,t,V}^{M}$ is the biomass in each of the cells connected to cell $i$ as described in Figure 3 and $d^{M}$ is the diffusion rate of each species. If a cell $i$ is connected to other cells that have a greater population on average, then fish will flow into cell $i$. Fish will diffuse out if the connected population is lower on average.

## Optimization:

When each vessel deploys to fish an area, it follows a very specific profit maximization equation:

### *Equation 8: Profit*

$$\pi_{i,y,t,v}^{M} = p^{Tar}q^{Tar}x_{i,y,t,v}^{Tar}exp\left(\sigma\varepsilon_{i,y,t,v}^{Tar}\right) - p^{H}q^{H}h_{i,y,t,v} - p^{By}q^{By}x_{i,y,t,v}^{By}exp\left(\sigma\varepsilon_{i,y,t,v}^{By}\right)$$

where the first term is the profit from capturing the target fish and the other two terms are the cost from habitat damage and bycatch, respectively, which is why they are subtracted. The target profit is calculated by multiplying the price of the target catch, $p^{Tar}$, by the estimated amount of fish to be caught. This estimation is the product of the target catchability coefficient, $q^{Tar}$, and the estimated biomass in the cell being fished in, $x_{i,y,t,v}^{Tar}exp\left(\sigma\varepsilon_{i,y,t,v}^{Tar}\right)$. The accuracy of this estimate relies on the fisher's uncertainty, $\sigma$, of the tons of fish in the cell and a normally distributed random variable, $\varepsilon_{i,y,t,v}^{Tar}$, which

has a mean of zero and a standard deviation of one. The same methodology is used to solve for the cost of bycatch. Finally, multiplying the amount of HIU removed by its price, $p^h$, gives the cost of habitat destruction. While the price of a targeted fish is constant throughout a simulation, each year my simulation calculates the price of both habitat and bycatch as described in the next section. It must be noted that each fishery has its own price for target catch and bycatch. In other words, the target price for Pel in the pelagic fishery is not the same as the bycatch price for Pel in the benthic fishery.

## Simulation:

Initially, the two target fish stocks are distributed evenly throughout the grid with their total population equal to half of their respective carrying capacities and all cellular habitats are at a pristine level. The first 20 years of the simulation are spent fishing without bycatch or habitat regulation, while still maintaining a TAC policy. This allows us to witness the effects of implementing sustainable fishing practices on an ecosystem in bad shape due to previous years of poor fishing habits.

| Simulation Variable | Value |
|---|---|
| Ben Diffusion Rate ($d^{Ben}$) | 0.1 - 0.3 |
| Pel Diffusion Rate ($d^{Pel}$) | 0.1 - 0.3 |
| Ben Price ($p^{Ben}$) | 1.00 |
| Pel Price ($p^{Pel}$) | 1.00 |
| Uncertainty ($\sigma$) | 0.0 - 0.2 |
| Number of Benthic Trawlers | 10 |
| Number of Pelagic Trawlers | 10 |
| Number of Unregulated Years | 20 |
| Number of Regulated Years | 50 |
| Number of Periods per Year | 50 |

This unregulated 20-year period is followed by 50 years of fishing with bycatch and habitat regulation. At the start of every year, TAC and TAB are set for each fishery. In order to have a consistent population size every year, the amount of catch allowed is equal to the species' annual growth rate. Since the benthic trawlers capture some Pel as bycatch, 10% of Pel's allowable catch is given to the bottom trawlers as their TAB of Pel. This means the pelagic trawl fishery is assigned 90% of the Pel's annual growth rate for its TAC. In this model, Ben is only caught by its fishery and is not bycatch of the pelagic trawlers, so the benthic fishery has a TAC equal to the growth rate of Ben for that year.

The yearly THQ, or habitat quota, is also set at the beginning of each year using the method described earlier. Both fisheries detract from the same quota when they fish a region. Benthic trawlers tear up the seafloor and in this model destroy 80% of a cell's habitat when it decides to fish there. The pelagic fishery however makes no contact with the sea bottom and contributes very little to habitat damage. It thus has a habitat catchability coefficient of 1%.

Each year is split into 50 periods; within each period, all 20 vessels (10 from each fishery) are deployed one at a time to the cell that maximizes their profit equation. At the end of each period, growth occurs in each cell followed by diffusion. The target prices, $p^{Tar}$, for each fishery are constant at 1.00, while the price of bycatch, $p^{By}$, and the cost of habitat damage, $p^H$, are dynamic. These two prices are set at zero for the first run of each year. If a simulation runs out of TAB before the benthic TAC is exhausted, then $p^{By}$ is raised by 0.1 and the year starts over with the updated profit maximization equation. Similarly, if THQ is used up before both TACs, then the price of habitat destruction increases by 0.001. Once the prices are calibrated correctly and the total allowable catch for each fishery is reached, or the fisheries run out of time before their bycatch and environmental quotas are depleted, the simulation updates and moves on to the next year. Since the unregulated years do not have TAB or THQ policies, the bycatch and habitat price is always zero for these years.

# Chapter Three: Results

## Bycatch & Habitat Prices:

Running my simulation given different input variables demonstrates the effect these variables have on fishing. The diffusion rates of both species, the uncertainty multiplier, and the final target habitat level are input variables functioning as described in chapter two. Each of the four input variable has three possible values, giving 81 unique possible simulations.

*Table 5: Input Variables*

| Input Variable | Possible Values | | |
|---|---|---|---|
| Pel diffusion rate $(d^{Pel})$ | 0.01 | 0.02 | 0.03 |
| Ben diffusion rate $(d^{Ben})$ | 0.01 | 0.02 | 0.03 |
| Final target habitat level $(H^{Tar})$ | 30% | 40% | 50% |
| Uncertainty $(\sigma)$ | 0.0 | 0.1 | 0.2 |

Different settings altered the efficiency of fishing sustainably. We can witness how each variable affected the bycatch and habitat prices by comparing the average habitat or bycatch prices resulting from a two variable combination, where one variable was kept constant while the other fluctuated. For example, if the average habitat price was higher when $d^{Ben}$ equaled 0.01 and $d^{Pel}$ equaled 0.02 than when they both equaled 0.01, it would have suggested that the habitat price would increase as $d^{Pel}$ increased. As there were nine different simulations where both diffusion rates were 0.01, the average habitat price of all nine simulations was compared to the average habitat price of the nine simulations where $d^{Ben}$ equaled 0.01 and $d^{Pel}$ equaled 0.02 and vice versa. All of the following graphs plot the resulting average bycatch or habitat price given a two variable combination.

**Figure 4: The Effect of the Pelagic Diffusion Rate on the Bycatch Price**
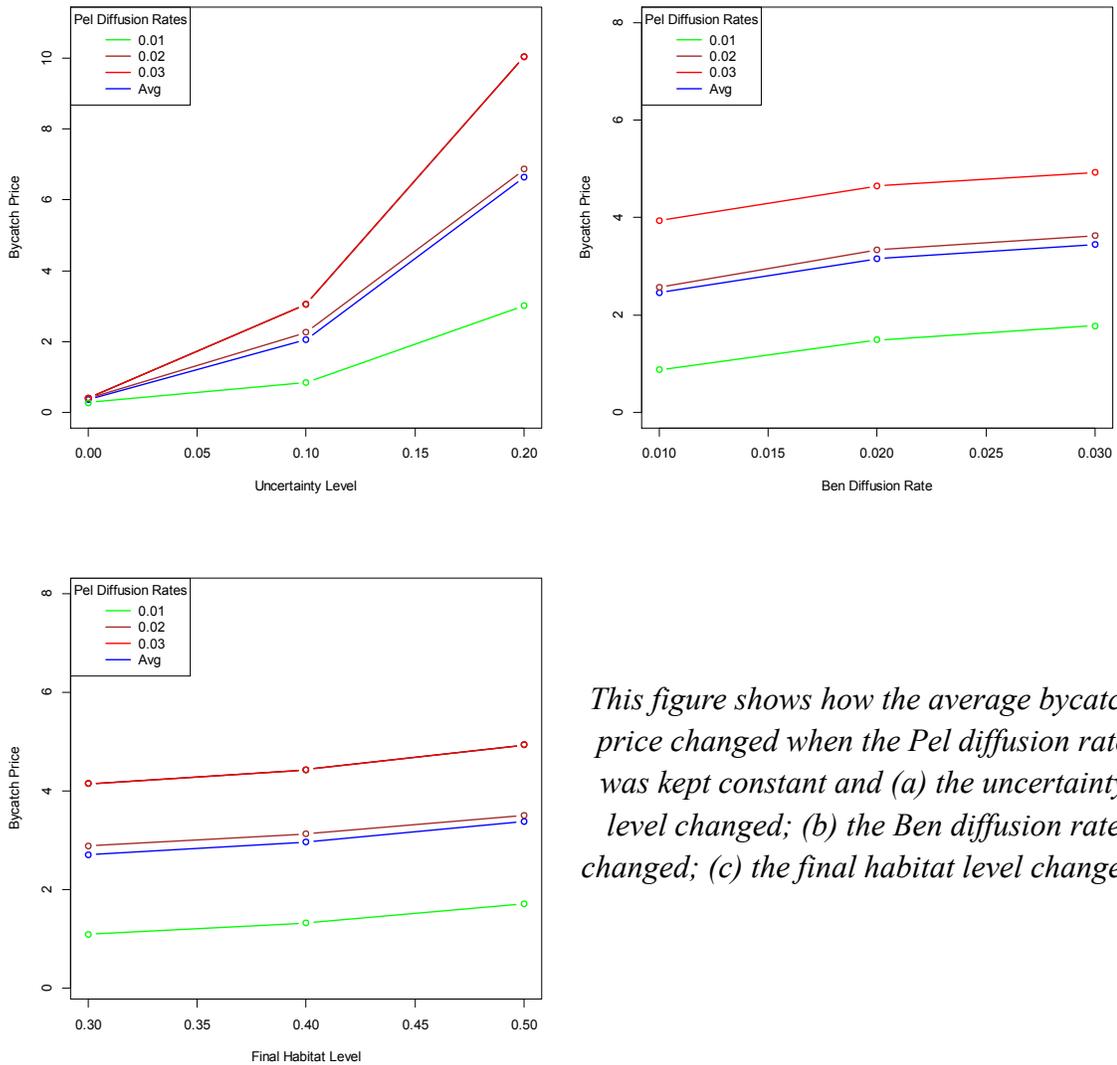


*This figure shows how the average bycatch price changed when the Pel diffusion rate was kept constant and (a) the uncertainty level changed; (b) the Ben diffusion rate changed; (c) the final habitat level changed.*

The graphs in Figure 4 demonstrate the relationship between the pelagic diffusion rate and the other variables and the resulting effect on the price of bycatch. All three graphs show that average bycatch price increased as the pelagic diffusion rate increased. This trend makes sense because as the pelagic diffusion rate increased, the pelagic species was more spread out, making it difficult for benthic trawlers to avoid them.

In the first graph, it is interesting to note that with zero uncertainty, the average bycatch price was close to zero, no matter the pelagic diffusion rate. The uncertainty level had more of an effect on the bycatch price when the pelagic rate was high compared to when it was low, as shown by the increasing distance between the lines. This makes sense because uncertainty refers to a fisher's knowledge of where both the targeted species and the bycatch species are located. A lower uncertainty enabled fishers to catch more of the targeted species and avoid more bycatch. When uncertainty was zero, the average bycatch price had a small range of 0.13 units. This range went up to 1.35 units at a 0.1 uncertainty level and 4.01 at a 0.2 uncertainty level.

The other two graphs suggest that the pelagic diffusion rate had a much larger influence on the bycatch price than both the diffusion rate of the benthic species and the final habitat level. As the second graph shows, increasing the benthic diffusion rate from 0.01 to 0.02 raised the bycatch price by only 0.61-0.76 units, while an increase from 0.02 to 0.03 raised the price by almost exactly 0.29 units no matter the pelagic diffusion rate. On the other hand, changing the pelagic diffusion rate from 0.01 to 0.02 increased the bycatch price by 1.74-1.85 units, and 2.23-3.08 units when the rate changed from 0.02 to 0.03. This clearly shows that increasing the pelagic diffusion rate raised the bycatch price much more than increasing the benthic rate did. This makes sense since Pel is the only bycatch species in this model.

The third graph, which compares the final habitat level to the pelagic diffusion rate is very similar to the second graph shown above, therefore we can conclude that the pelagic diffusion rate had a much larger influence on the bycatch price than the final habitat level. The final habitat level did not have much of an effect on the bycatch price

because changes in the final habitat level were directly reflected in the habitat price, as will be discussed later on.

**Figure 5: The Effect of the Benthic Diffusion Rate on the Bycatch Price**
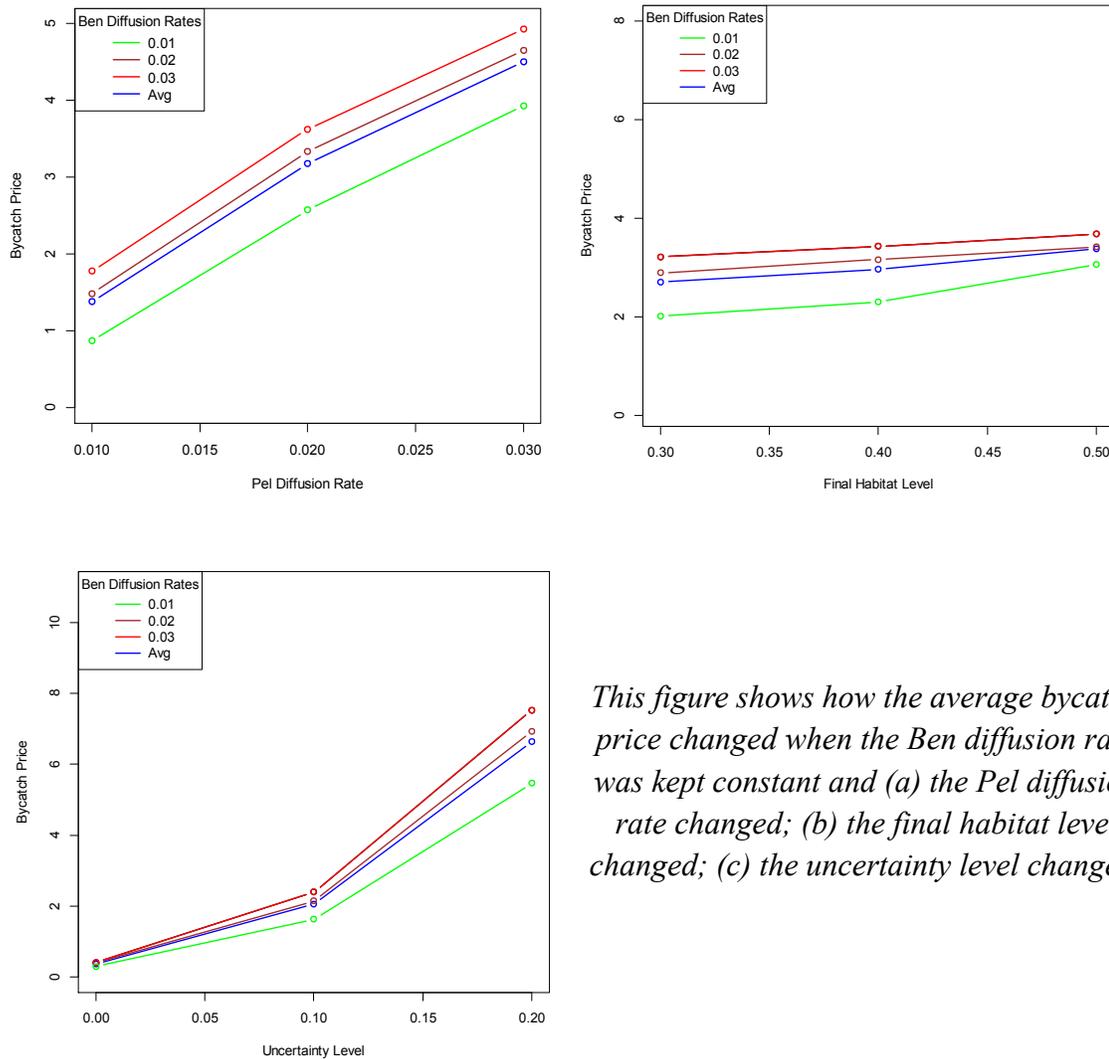


*This figure shows how the average bycatch price changed when the Ben diffusion rate was kept constant and (a) the Pel diffusion rate changed; (b) the final habitat level changed; (c) the uncertainty level changed.*

The graphs in Figure 5 demonstrate the relationship between the benthic diffusion rate and the other variables and the resulting effect on the price of bycatch. All three graphs show that average bycatch price increased as the benthic diffusion rate increased, however to a lesser degree than when the pelagic diffusion rate increased.  As the Ben

species diffused, they were less concentrated in one particular cell, and thus it was more difficult for fishers to target cells with only the benthic species. The benthic trawlers ended up fishing in cells that had a mix of both Ben and Pel fish; the more benthic diffusion that took place, the greater the mixing between the two species.

The first graph above again shows that the Pel diffusion rate had a much greater effect on the bycatch price than the benthic diffusion rate. For example, when the benthic diffusion rate was held constant at 0.01 as shown by the green line, and the pelagic diffusion rate increased to 0.03 from 0.01, the bycatch price increased by 3 units. However, when the pelagic diffusion rate was held constant at 0.01 and the benthic diffusion rate increased from 0.01 to 0.03, the bycatch price only rose by 0.9 units.

The horizontal nature of the lines in the second graph again illustrates the minimal effect that the habitat level had on the bycatch price compared to the benthic diffusion rate. When the benthic diffusion rate was held constant at 0.02 and the final habitat level increased from 30% to 50%, as shown by the brown line, the bycatch price only increased by 0.5 units. On the other hand, when the final habitat level was held constant at 40% and the benthic diffusion rate changed from 0.01 to 0.03, the bycatch price increased 1.1 units. It is interesting to note that increasing the final habitat level from 40% to 50% while the benthic diffusion rate remained constant at 0.01 had the greatest influence on the bycatch price, as shown by the green line.

The third graph shows that the uncertainty level had a much greater effect on the bycatch price than the benthic diffusion rate did. For example, when the uncertainty level increased from 0.0 to 0.2 and the benthic diffusion rate remained constant at 0.03, as shown by the line in red, the bycatch price increased by 7.1. However, when the

uncertainty level was held constant at 0.2 and the benthic diffusion rate increased from

0.01 to 0.03, the bycatch price only increased by 1.0. In fact, the effect of the benthic

diffusion rate on the bycatch price was only noteworthy when the uncertainty was 0.2;

the effect was negligible when the uncertainty was 0.0 or 0.1. This was because as

uncertainty increased, it caused the other variables to have a greater influence on the

bycatch price, as well. The uncertainty level is in an exponent in the profit maximizing

equation, so as it increases linearly, the bycatch prices increases exponentially.

**_Figure 6: The Effect of the Final Habitat Level on the Bycatch Price_**
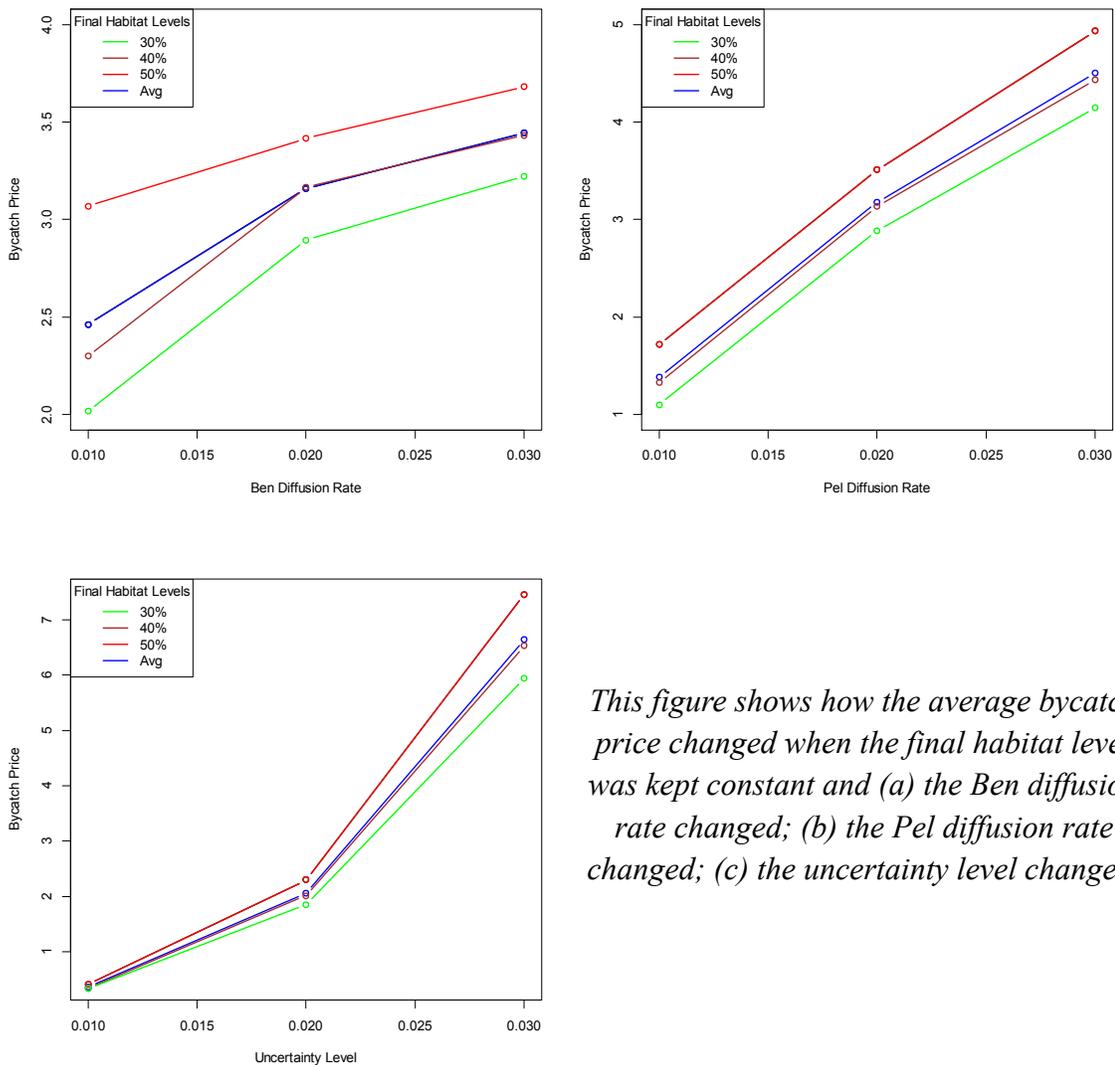


*This figure shows how the average bycatch price changed when the final habitat level was kept constant and (a) the Ben diffusion rate changed; (b) the Pel diffusion rate changed; (c) the uncertainty level changed.*

The graphs in Figure 6 demonstrate the relationship between the final habitat level and the other variables and the resulting effect on the price of bycatch. For the most part all the lines in each of the graphs above remain close together illustrating that the final habitat level had only a minimal effect on the bycatch price. However, the bycatch price did increase slightly as the final habitat level increased. This is because, as shown in Equation 1, as the final habitat level increases, the THQ for the region decreases. This

caused each vessel to target cells that had fewer HIUs, but a greater amount of bycatch. These cells would have had more bycatch, since they would have been targeted originally if not. In order to balance out this increase in bycatch, the bycatch price had to increase as well.

*Figure 7: The Effect of the Uncertainty Level on the Bycatch Price*
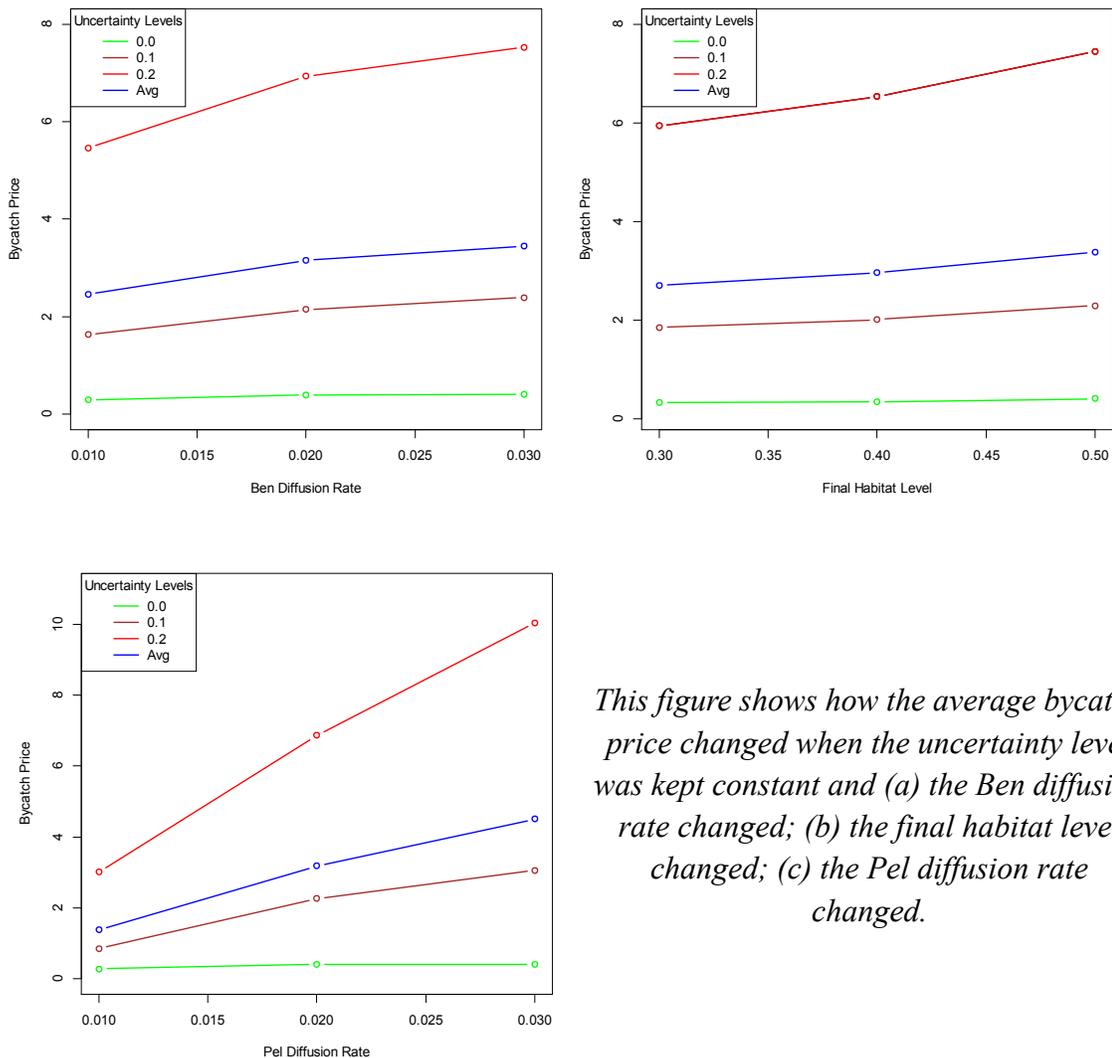


*This figure shows how the average bycatch price changed when the uncertainty level was kept constant and (a) the Ben diffusion rate changed; (b) the final habitat level changed; (c) the Pel diffusion rate changed.*

Figure 7 shows that the uncertainty level had a major effect on the bycatch price, which is reflected in the large distance between the lines in the three graphs above. In each of the graphs when the uncertainty level was 0.0, the bycatch price was very close to

0. When there was no uncertainty, fishers knew exactly where the target fish and bycatch species were and thus could avoid the bycatch.  As the uncertainty increased, the fishers were more likely to fish in areas where there was a greater amount of bycatch.  The exponential nature of the uncertainty level's effect on bycatch price can be seen in the position of the blue average line.  Since this line is above the 0.1 uncertainty level line in each graph, it implies that each incremental increase of uncertainty had a greater effect on the bycatch price than the previous increment. This means that the increase in uncertainty from 0.1 to 0.2 caused the bycatch price to increase by a greater amount than the increase of uncertainty from 0.0 to 0.1.

## Figure 8: The Effect of the Pelagic Diffusion Rate on the Habitat Price
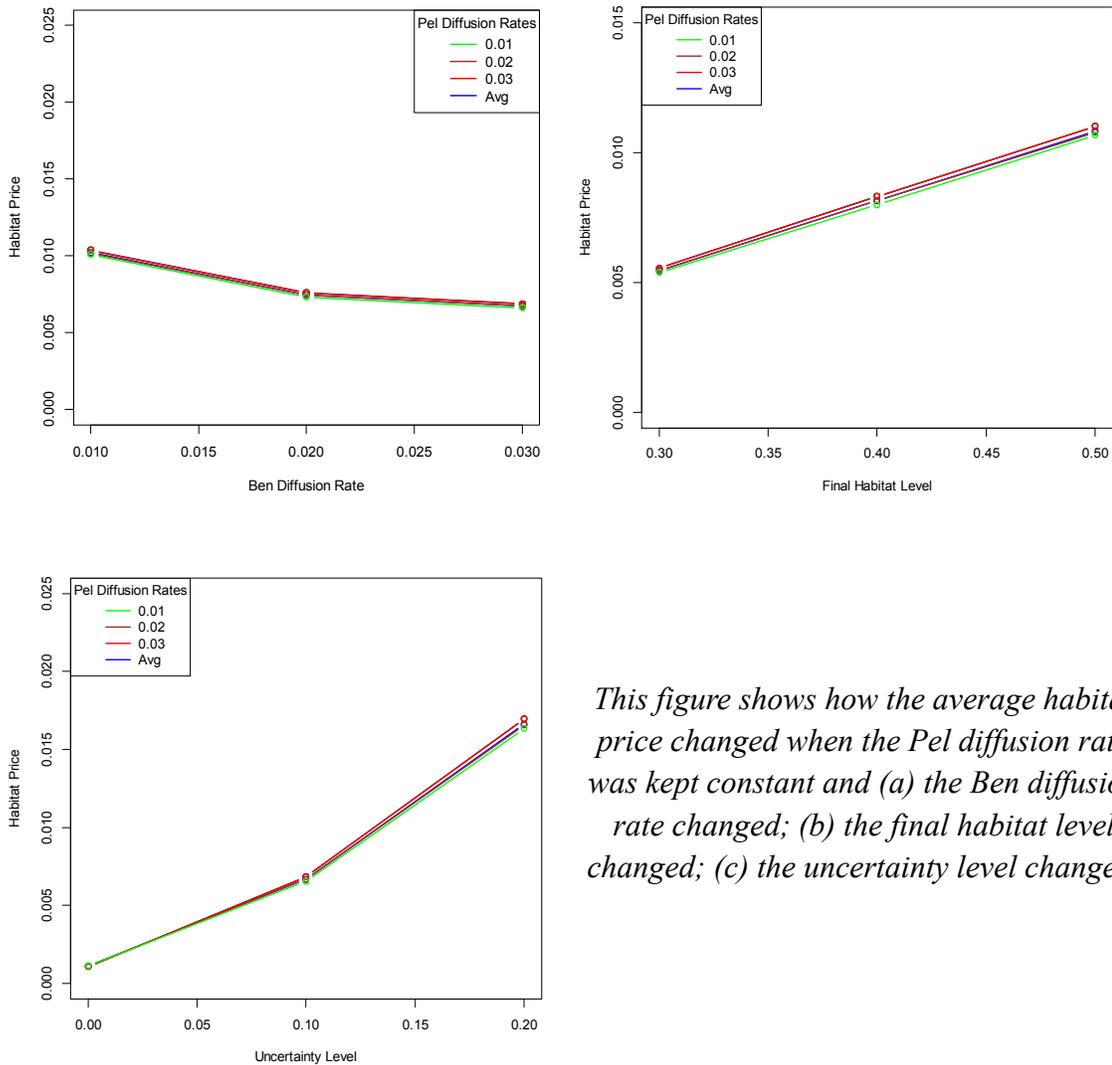


*This figure shows how the average habitat price changed when the Pel diffusion rate was kept constant and (a) the Ben diffusion rate changed; (b) the final habitat level changed; (c) the uncertainty level changed.*

I assessed the effects of different variables on the habitat price the same way I evaluated their effects on the bycatch price. The graphs in Figure 8 demonstrate the relationship between the pelagic diffusion rate and the other variables and the resulting effect on the habitat price. All three graphs clearly show that the pelagic diffusion rate had essentially no effect on the habitat price. Since pelagic trawls caused only very minimal habitat damage, it makes sense that the diffusion rate of the pelagic species did

not affect the habitat price. This means the graphs show how the other variables affected the price of habitat.  The habitat price increased as the uncertainty level and the final habitat level increased, but decreased as the benthic diffusion rate increased.

***Figure 9: The Effect of the Benthic Diffusion Rate on the Habitat Price***
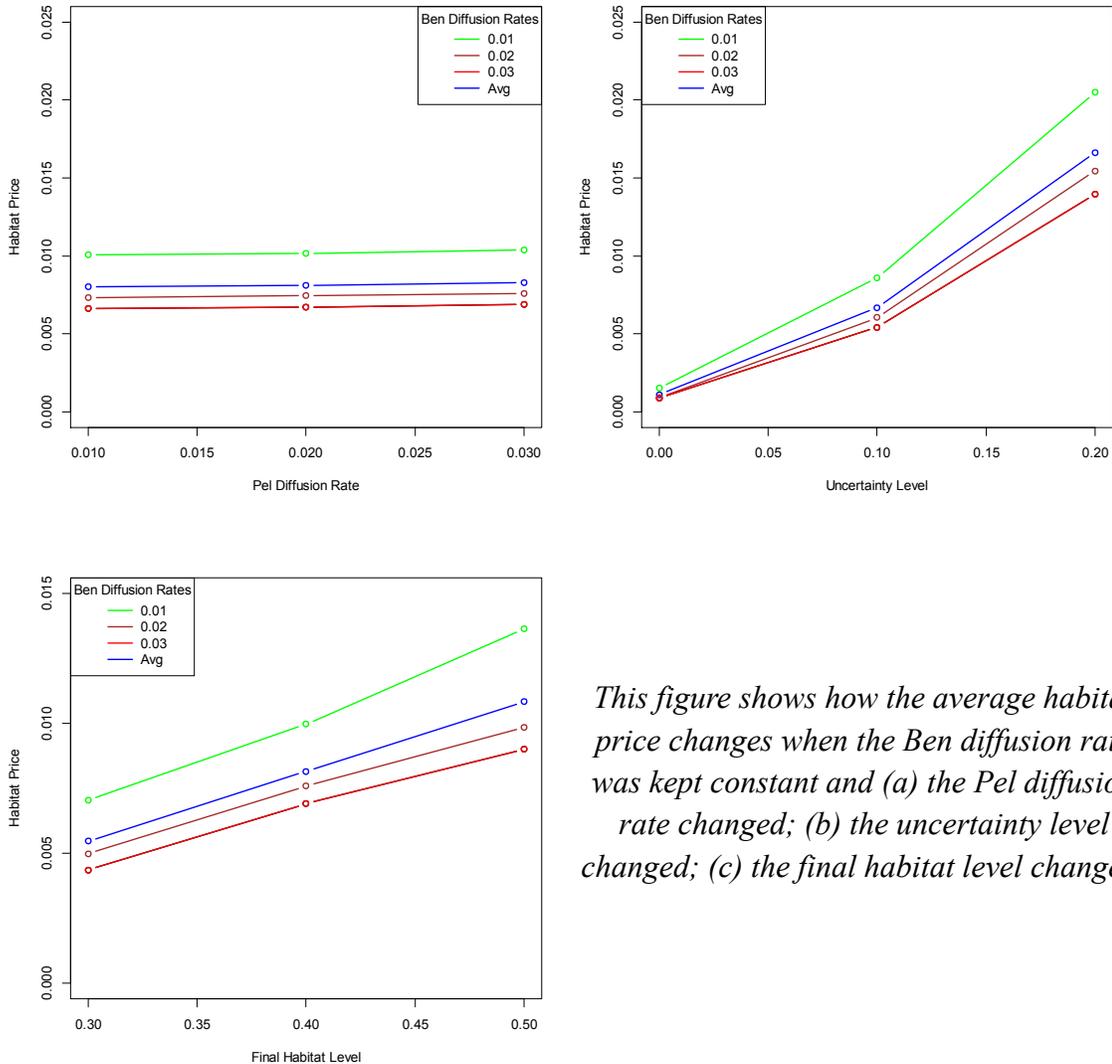


*This figure shows how the average habitat price changes when the Ben diffusion rate was kept constant and (a) the Pel diffusion rate changed; (b) the uncertainty level changed; (c) the final habitat level changed.*

The graphs in Figure 9 demonstrate the relationship between the benthic diffusion rate and the other variables and the resulting effect on the habitat price.  Because in all three graphs, the green line, which represents a 0.01 benthic diffusion rate, is above the

brown line, which represents a 0.02 benthic diffusion rate, which in turn is above the red

line, which represents a 0.03 diffusion rate, the average habitat price decreased as the

benthic diffusion rate increased.  A low benthic rate meant that after a cell was fished,

only a small amount of Ben diffused into that cell.  Thus in subsequent deployments

fishers had to target cells that had not been fished in order to fulfill their TAC.  Since

these cells cost more HIUs to fish, it makes sense that lower benthic diffusion rates

correlated to a higher habitat price.

### Figure 10: The Effect of the Final Habitat Level on the Habitat Price
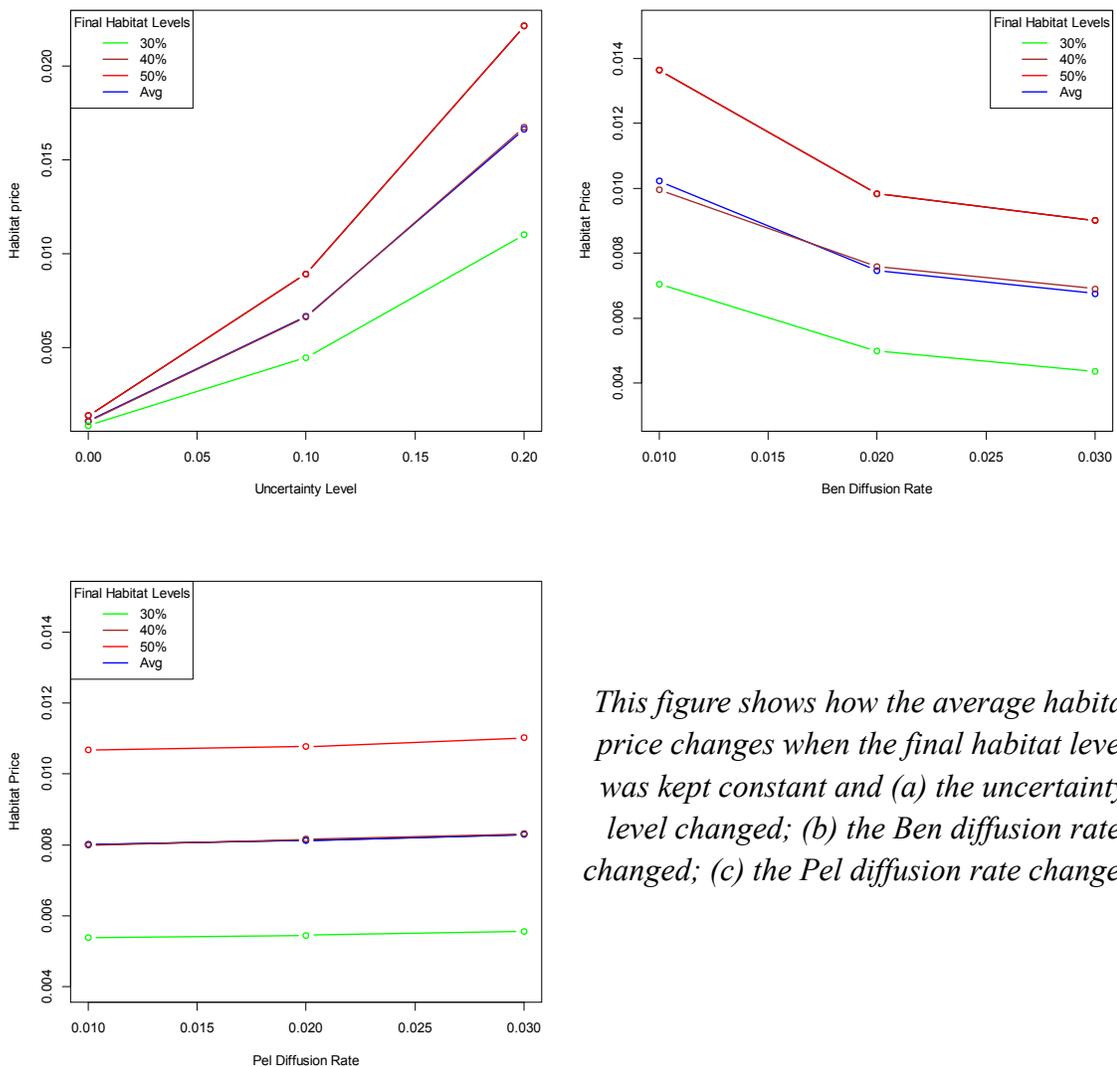


*This figure shows how the average habitat price changes when the final habitat level was kept constant and (a) the uncertainty level changed; (b) the Ben diffusion rate changed; (c) the Pel diffusion rate changed.*

It can be deduced from Figure 10 that the habitat price increased as the final

habitat level rose.  This makes sense because, according to Equation 1, raising the final

habitat level results in a smaller THQ.  A smaller THQ means that a fishery is more likely

to deplete its THQ before its TAC.  A higher habitat price prevents this from occurring.

It should also be noted that the plots of the average final habitat levels overlap the 40%

habitat level for the most part. This means the marginal effect on habitat price from

increasing the final target habitat level from 30% to 40% was the same as when this level

increased from 40% to 50%.

**Figure 11: The Effect of the Uncertainty Level on the Habitat Price**
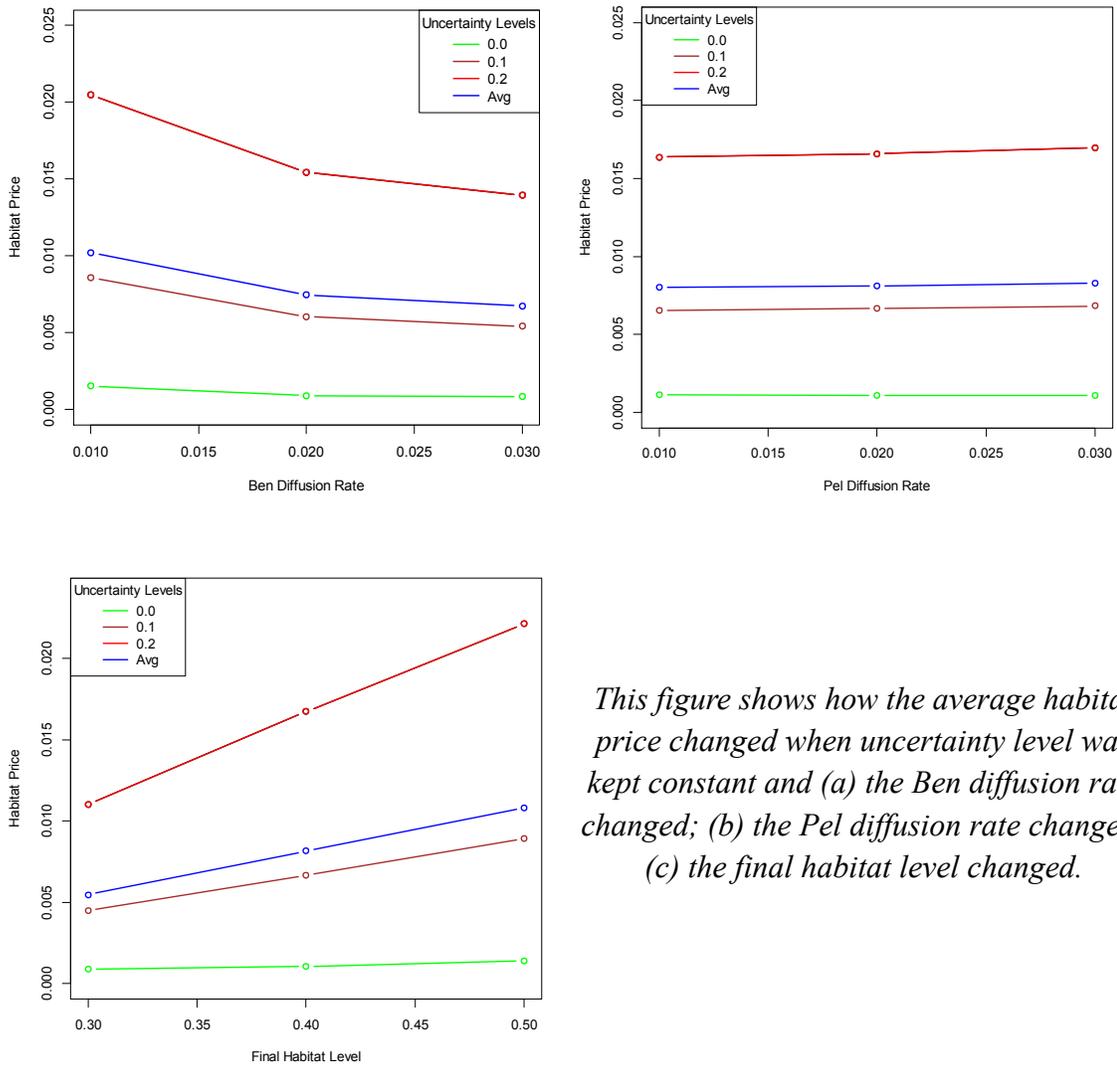


*This figure shows how the average habitat price changed when uncertainty level was kept constant and (a) the Ben diffusion rate changed; (b) the Pel diffusion rate changed; (c) the final habitat level changed.*

Figure 11 shows that the uncertainty level had a major effect on the habitat price, which is reflected in the large distances between the lines in the three graphs above. In each of the graphs when the uncertainty level was 0.0, the habitat price remained very close to 0. When there was uncertainty, it took more effort for the fishers to harvest their TAC. This increased the habitat price because more trawls were needed to fulfill the TAC, causing greater total habitat damage. In order to avoid depleting the THQ before the TAC, the habitat price had to be higher for greater uncertainty.

As with the bycatch price, uncertainty had the most influence on how high the habitat price was. Again, the Pel diffusion rate shown had almost no effect on the habitat price. Comparing these graphs with the graphs showing the uncertainty level's effect on the bycatch price, it can be seen that the final habitat level had an influence on the habitat price that was similar to the influence the pelagic diffusion rate had on the bycatch price.

## Final Habitat Distribution:

Different inputs resulted in various distributions of cellular habitat levels in the grid. In order to reach the targeted habitat levels, some cells were either not fished in or fished in so little by the bottom trawlers that they had rebounded to maximum habitat by the end of the simulation.

*Figure 12: 30% Final Habitat Grids: (a) most pristine (b) least pristine*
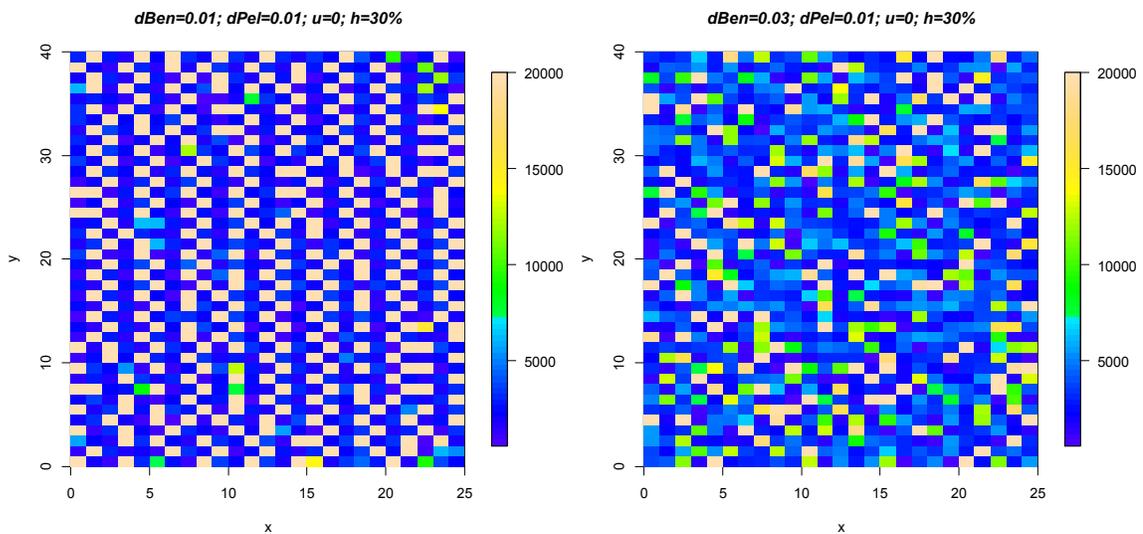


When the final target habitat level was at 30%, the highest number of cells at the pristine level (represented in tan above) occurred when both the pelagic and benthic species' diffusion rates were 0.01 and there was zero uncertainty. With these inputs,

31.8% of the grid's cells were at maximum habitat levels. Most of the other cells had a very low habitat level of under 5000 HIUs (represented in blue).

When the final target habitat level was 30%, two simulations produced a grid with the fewest number of pristine habitats. This occurred when the benthic diffusion rate equaled 0.03, the pelagic diffusion rate was 0.01, and the uncertainty was either 0.2 or zero. Only 8% of the cells were at their maximum habitat level, but the other cells had a more even distribution of final habitat levels than the situation where more habitats were pristine.

*Figure 13: 40% Final Habitat Grids: (a) most pristine (b) least pristine*
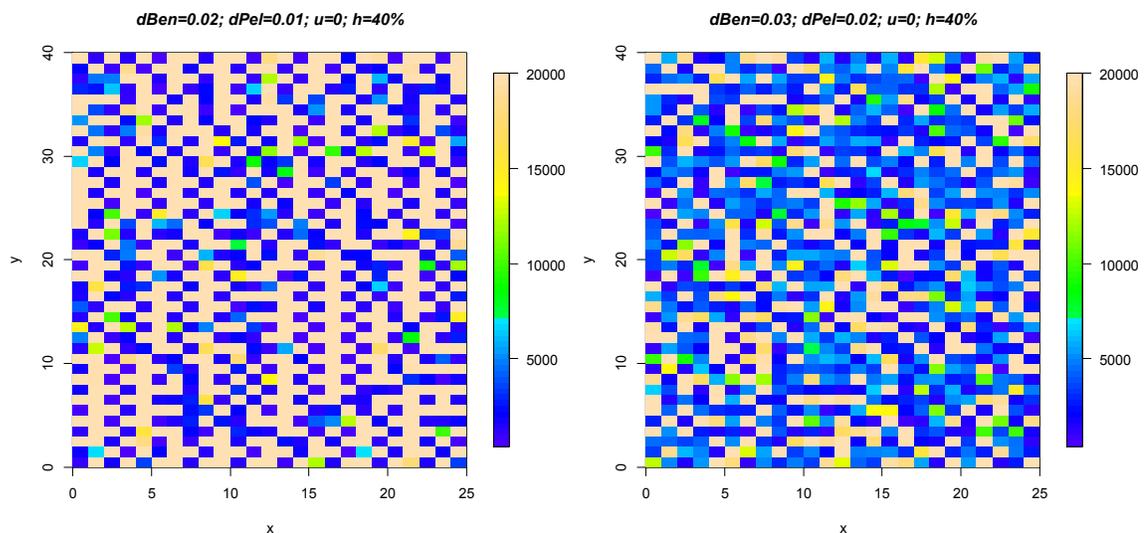


With a 40% final habitat target level, there were many more cells at maximum habitat level than in the 30% case. 48.4% of the grid's cells had a pristine habitat when the diffusion rate of the benthic species was 0.02, the diffusion rate of the pelagic species was 0.01 and the uncertainty was zero. The cells with pristine habitats surrounded the cells that were most fished in. Many more of the fished in cells were purple instead of dark blue as in the scenario where the target habitat level is 30%, suggesting that they

were even more depleted. When a cell was not fished in it allowed the population in that cell to surpass those of other cells. Most purple cells were surrounded by multiple untouched cells, thus allowing many fish to be caught from this repeatedly fished in cell through the diffusion of fish from the pristine cells.

The grid that had the fewest number of cells at the maximum habitat level had 20.3% that were pristine. This happened when the benthic diffusion rate was 0.03, the diffusion rate of the pelagic fish was 0.02 and the uncertainty was again 0. There was some clumping of these untouched cells, but again the cells around them were repetitively fished in and had low habitat levels due to their proximity to the pristine cells.

*Figure 14: 50% Final Habitat Grids: (a) most pristine (b) least pristine*
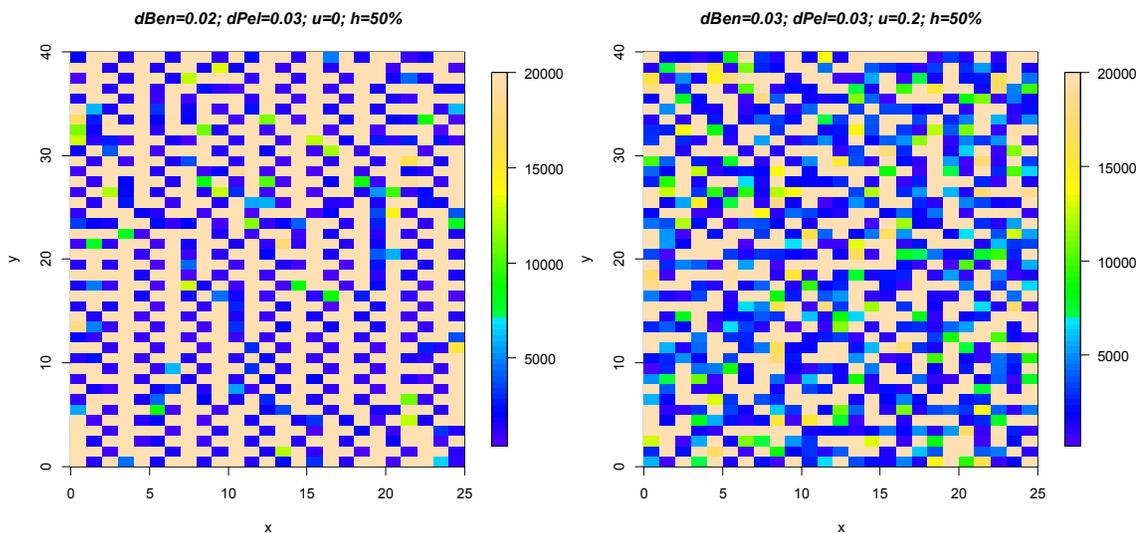


Finally, it makes sense that the grid with the highest number of cells with a pristine habitat resulted from running the simulation with a 50% final target habitat level. When the diffusion of the benthic species was 0.02 and that of the pelagic fish was 0.03 and the uncertainty was zero, 56% of the cells in the resulting grid after the simulation

had pristine habitats. This was less than an 8% increase in the total number of cells with pristine habitats from the 40% target habitat level scenario, which was smaller than the change between the greatest number of pristine cells within a 30% target habitat level and the greatest number of pristine cells within a 40% level.

Again, the grid with the lowest number of pristine cells for the given habitat level had these maximum habitat cells clumping together and was surrounded by cells with very low habitat levels. 35.4% of the grid's cells were pristine in this scenario, and occurred when the diffusion rates of both species equaled 0.03 and the uncertainty multiplier was 0.2.

## Comparison to Unregulated Bycatch and Habitat Impact:

While the previous results show the difference between simulations running my rights-based model that limits bycatch and habitat destruction, the following compares this approach to one where only total allowable catch was taken into account.

When there was no regulation to preserve the habitat, the final habitat level ranged from 17.6% to 22.5%. Since a fishery could still capture all of its TAC under an IHQ system while maintaining at least a 50% habitat level, the environment was obviously worse off without regulations. In order to see if enacting an IHQ system was as profitable for a fishery as no regulation, I compared the catch per unit effort (CPUE) of the benthic and pelagic fisheries under no regulation to the CPUE of these fisheries under regulation. CPUE refers to the average amount of a target species a vessel can catch in one cell during a given deployment.

Since habitat level is not an input in the simulation where there is no bycatch or environmental regulation, I looked at the average CPUE of regulated and unregulated

simulations with different combinations of diffusion rates and uncertainty.  Regulation

only occurred in the last fifty years of fishing in the models with TAB and THQs, so I

compared the average CPUE from the last fifty years of each simulation.  The ratio of the

average CPUE for regulated fishing to the average CPUE for unregulated fishing

illustrated which was more profitable.  When the ratio was greater than 1.00, the fisheries

obeying the habitat and bycatch regulations were more profitable than those that were

unregulated.

*Table 6: Average Ben CPUE Ratio between Unregulated and Regulated Simulations*

| Ben Diffusion | Pel Diffusion | Uncertainty | | |
|---|---|---|---|---|
| | | 0.0 | 0.1 | 0.2 |
| 0.01 | 0.01 | 1.00 | 0.99 | 0.99 |
| 0.01 | 0.02 | 1.00 | 0.99 | 0.99 |
| 0.01 | 0.03 | 1.00 | 0.99 | 0.99 |
| 0.02 | 0.01 | 1.00 | 1.00 | 0.99 |
| 0.02 | 0.02 | 1.00 | 1.00 | 1.00 |
| 0.02 | 0.03 | 1.00 | 1.00 | 0.99 |
| 0.03 | 0.01 | 0.99 | 1.00 | 1.00 |
| 0.03 | 0.02 | 0.99 | 1.00 | 0.99 |
| 0.03 | 0.03 | 1.00 | 1.00 | 1.00 |

*This table shows the CPUE ratio for the benthic fishery.  It is a ratio between the CPUE of the benthic species from the regulated simulations and the CPUE of the benthic species during unregulated simulations resulting from different combinations of benthic diffusion rates, pelagic diffusion rates and uncertainty.*

The benthic fishery's CPUE was barely affected by regulation.  Although a lot of

uncertainty could have lowered the CPUE, rates were within 99% of what they would

have been without regulation.  With these types of returns, there is very little reason for

the benthic fishery to oppose bycatch and habitat protection.

***Table 7: Average Pel CPUE Ratio between Unregulated and Regulated Simulations***

| Ben Diffusion | Pel Diffusion | Uncertainty | | |
|:---:|:---:|:---:|:---:|:---:|
| | | 0.0 | 0.1 | 0.2 |
| 0.01 | 0.01 | 1.01 | 1.00 | 1.00 |
| 0.01 | 0.02 | 1.02 | 1.01 | 1.00 |
| 0.01 | 0.03 | 1.02 | 1.00 | 1.01 |
| 0.02 | 0.01 | 1.01 | 1.00 | 1.00 |
| 0.02 | 0.02 | 1.02 | 1.00 | 1.01 |
| 0.02 | 0.03 | 1.02 | 1.01 | 1.01 |
| 0.03 | 0.01 | 1.03 | 1.01 | 1.00 |
| 0.03 | 0.02 | 1.02 | 1.01 | 1.00 |
| 0.03 | 0.03 | 1.02 | 1.01 | 1.01 |

*This table shows the CPUE ratio for the pelagic fishery. It is a ratio between the CPUE of the pelagic species from the regulated simulations and the CPUE of the pelagic species during unregulated simulations resulting from different combinations of benthic diffusion rates, pelagic diffusion rates and uncertainty.*

Even better, the pelagic fishery was slightly more profitable when bycatch regulation was imposed since all of the CPUE ratios were equal to or greater than 1.00. Limiting the amount of the pelagic species caught as bycatch kept the population from decreasing as rapidly as the case in which there was no regulation. This allowed the pelagic fishery to capture more fish per every vessel deployment. Even though the pelagic fishery's TAC is ninety percent of the Pel's yearly growth rate under bycatch regulation, instead of 100% without, it still captured more fish per year due to the increased population size.

# Chapter Four: Discussion & Conclusion

## Discussion:

There are many advantages to putting yearly limits on total allowable bycatch and habitat damage. Habitat levels and bycatch can be controlled with very little downside, keeping ecosystems healthy and fish populations in good numbers.

The results show that uncertainty had the greatest influence on the price of bycatch out of all the input variables. In fact, uncertainty seems to have dictated the price given how little the price fluctuated for a given level of uncertainty. This makes sense as, in this model, uncertainty refers to the degree to which fishers know the population in each cell.

The diffusion rate of the pelagic species had the second greatest effect on the price of bycatch. This price barely fluctuated when the pelagic diffusion rate was held constant, except of course when uncertainty was varied. As the diffusion rate rose, the pelagic species were more dispersed throughout the grid, making it more difficult for the bottom trawlers to avoid them.

As the benthic diffusion rate rose, it too increased the bycatch price, although not as much as the uncertainty and the pelagic diffusion rate did. Low diffusion rates meant more cells had a high concentration of benthic fish, which made them easier to target while avoiding bycatch. Finally, the target habitat level had very little to do with the bycatch price, mainly because the habitat price rose from not reaching target habitat levels.

Habitat prices were also primarily affected by uncertainty. With zero uncertainty, the habitat price remained fairly low, since knowing where all the fish were enabled the fishers to reach their TAC earlier, thus destroying less habitat.

The final target habitat had the second greatest influence in determining the habitat price. Since this metric measured how much habitat must be preserved, it is intuitive that the greater the final value required for the final target habitat, the more difficult it was for fishers to catch all of their TAC without exhausting the THQ.

The benthic diffusion had minimal influence on the habitat price, but it is interesting to note that the price increased as the diffusion rate decreased. This was the only variable that was inversely related to either the bycatch or the habitat price. As benthic diffusion increased, more bottom fish diffused into a recently bottom-trawled cell, which was more likely to have been trawled a second time without regeneration than in a scenario with low diffusion.

Finally, pelagic diffusion rates were seen to have no effect on the habitat price. In this model, the pelagic trawlers caused negligible habitat damage, so the habitat price remained unassociated with the pelagic diffusion rate.

Obviously, as we raised the final habitat level, individual cells had a greater habitat level throughout the grid. However, it is interesting to look at the spatial patterns of cellular habitat levels given different inputs. The pristine habitats tended to connect to cells with very low habitat levels and other pristine cells. This grouping of pristine cells is similar to the idea of Marine Protected Areas (MPA), where some areas are off-limits to fishing. Theoretically, this allows many fish to reproduce safely in the MPA while still travelling out to areas where fishing is permitted, thus increasing catch and protecting

species from overfishing.  Holland and Schnier executed a thorough analysis on the differences between rotating MPAs, fixed MPAs, and their IHQ system with different final target habitat.[20]  In their research they concluded that "an individual habitat quota management regime is a more cost-effective means of achieving a given level of average habitat quality than either a fixed or rotating MPA policy."[21] It seems that when fishers left many cells untouched and connected to heavily fished areas, as in my model, it enabled fish populations to grow without reducing the targeted catch.

The greatest benefit of my model is that it is cost-effective.  Although the CPUE for the benthic species dropped slightly when TAB and THQ were implemented, the CPUE for the pelagic species increased when regulation was imposed.  With enough knowledge of a fishing zone and the biodiversity of the life inside it, fishers can practice sustainable fishing methods that preserve habitat and keep fish stocks from collapsing.

## Implementation:

Although my model illustrates how different factors affect essential fish habitat and fish population dynamics, a slightly different approach is necessary to apply it to a real fishery.  First off, all target and bycatch fish stocks in a region must be assessed.  In real life, a region will have many more targeted and bycatch species than were illustrated in this model.  Once it is known which fish need to be accounted for, sufficient research should be done in the area, such as observing the ecosystem in order to set up a proxy that simulates the entire fishing region.  Some of these variables include the catchability coefficients for all the types of gear used as in Table 2, the growth variables as in Table 3,

---

[20] Holland, "Protecting Marine Biodiversity…" 1483
[21] Ibid. 1493

the size and distribution of all target and bycatch populations, and the recovery rate(s) of the habitat. Some fisheries already have a vessel monitoring system (VMS) that keeps approximate track of bycatch. While this system would work well as a way to monitor bycatch, a similar system should also be used to record cellular habitat levels.

After these metrics are solved for, my simulation should run with every fishery limited by a TAC for their target fish, a TAB for each bycatch species, and an IHQ. Allocating these variables can be done in numerous ways, but my implementation only takes into account the sum of the total allowable catch and the bycatch of a species, which are limited by the ecological sustainable yield (ESY). This is the yield an ecosystem can sustain without shifting to an undesirable state.[22]

All the fish accounted for in the model have their own growth, population, and diffusion variables, determining their own growth and diffusion according to Equations 6 and 7. The implemented profit equation would have to take into account the multiple species of bycatch in the grid so that vessels could target cells that maximize their target catch while minimizing bycatch and habitat damage. Here is an example of a profit equation where there are *b* types of bycatch species considered:

*Equation 9: Profit Given Multiple Bycatch*

$$\pi_{i,y,t,v}^{M} = p^{Tar}q^{Tar}x_{i,y,t,v}^{Tar}exp\left(\sigma\varepsilon_{i,y,t,v}^{Tar}\right) - p^{H}q^{H}h_{i,y,t,v} - p^{By1}q^{By1}x_{i,y,t,v}^{By1}exp\left(\sigma\varepsilon_{i,y,t,v}^{By1}\right)$$

$$- p^{By2}q^{By2}x_{i,y,t,v}^{By2}exp\left(\sigma\varepsilon_{i,y,t,v}^{By2}\right) - \cdots - p^{Byb}q^{Byb}x_{i,y,t,v}^{Byb}exp\left(\sigma\varepsilon_{i,y,t,v}^{Byb}\right)$$

Once the simulation runs and all the variables are set, real-life fishing can begin. Instead of maximizing profits based off of blind uncertainty as in the above equation, the profit equation would be based on the expected profit:

---

[22] Harvey 156

*Equation 10: Real World Expected Profit*

$$\pi_{i,y,t,v}^{M} = p^{Tar}q^{Tar}\bar{x}_{i,y,t,v}^{Tar} - p^{H}q^{H}h_{i,y,t,v} - p^{By1}q^{By1}\bar{x}_{i,y,t,v}^{By1} - p^{By2}q^{By2}\bar{x}_{i,y,t,v}^{By2}$$

$$- \cdots - p^{Byb}q^{Byb}\bar{x}_{i,y,t,v}^{Byb}$$

where $\bar{x}_{i,y,t,v}^{M}$ is the expected value of the biomass of fish $M$ in cell $i$, at time $t$, in year $y$, vessel departure $v$. This value would be based off of real life data produced by the monitoring system.

Since this is an online problem, if it were determined that any of the variables were inaccurate during a fishing season, they could be updated to better fit the real world. For example, if too many of one type of fish were being caught as bycatch and as a result, the fishery was expected to close early, the price of that bycatch would increase, ensuring that fishers target areas with a smaller amount of that species. Additionally, diffusion rates and growth do not follow one equation as suggested in my model, but fluctuate throughout times and regions. These estimates could also be updated spatially and between periods to more accurately represent the real world.

## Further Research:

Although my model has some promising results, further research must be done to test its true efficiency before it can be implemented in the real world. A fishery with multiple target and bycatch species should be analyzed to see if similar successful results could be produced.

Also, as my model is based on limits, adding a bartering factor would make it a true cap-and-trade system. This way, if say one fishery has depleted its TAB for a particular species, it could purchase more catch from either the fishery targeting that fish

or another fishery who has been allocated that fish as bycatch.  This would allow inefficient fisheries to come closer to fulfilling their total allowable catch if it is financially viable for both parties, while still sustaining all fish populations involved.

# Appendix

## <u>Acknowledgements:</u>

# Code:

I used the statistical program R to create my simulation and some of the graphs in
my thesis.  R is free to download, so if anyone wishes to use my code in their own
research, they are not restricted by access to software.  Here is the code for running one
of my simulations:

```
#####################################################################
## Fishing Within the Limits: A Sustainable Fishing Model
## Author: Brett Leibowitz
## 4/15/12
#####################################################################

#####################################################################
## Target Variables
#####################################################################
# Target1 growth rate
grTar1 <- 0.40
# Initial target1 growth rate
GTar1 <- 300000
# Target1 carrying capacity
KTar1 <- 3000000
# Target1 adult growth share of total growth
aTar1 <- 0.50
# Target1 on Tar1 fish catchability coefficient
qTar1 <- 0.40
# Target1 on Tar2 fish catchability coefficient
qTar12 <- 0.05
# Target1 price of fish
pF1 <- 1.00
# Target1 diffusion rate
dTar1 <- 0.03
# Target1 Habitat destruction rate
qH1 <- 0.80

#####################################################################
## Bycatch Variables
#####################################################################
# Target2 growth rate
grTar2 <- .40
# Initial Target2 growth rate
GTar2 <- 300000
# Target2 carrying capacity
KTar2 <- 3000000
# Target2 adult growth share of total growth
aTar2 <- 0.5
# Target2 on Tar2 catchability coefficient
qTar2 <- 0.4
# Target2 on Tar1 catchability coefficient
qTar21 <- 0.0
# Target2  price of fish
pF2 <- 1.00
# Target2  diffusion rate
dTar2 <- 0.03
# Target2 Habitat destruction rate
qH2 <- 0.01
# Cost of fishing other species
pTar21 <- 0.0

#####################################################################
```

```
## Habitat Variables
####################################################################
# maximum habitat level
hMax <- 20000
#Maximum annual habitat regeneration rate per cell
rT <- 0.1*hMax

####################################################################
## Index/Other Variables
####################################################################
# Unceratinty multiplier
sig <- 0.20
# Target1 fleet size
fs <- 10
#Time steps modeled each year
T <- 50
#area per cell
area <- 20000
#Max i
iMax <- 25
#Max j
jMax <- 40
#Number of locations within simulation grid
N <- iMax * jMax
# target habitat
tarH <- .5*N*area
#Initializing mi1, mj1, mi2, mj2
mi1 <- 0
mj1 <- 0
mi2 <- 0
mj2 <- 0
#Initializing yearly TAC for Tar1
TAC1Y <- GTar1
#Initializing yearly TAC for Tar2
TAC2Y <- GTar2

####################################################################
##Initialize state of fishery when habitat policy implemented
####################################################################
# target1 fish biomass matrix
xTar1 <- array(1500,dim=c(iMax,jMax))
# starting xTar1
xTar1Start <- xTar1
# target2 fish biomass matrix
xTar2 <- array(1500,dim=c(iMax,jMax))
# starting xTar2
xTar2Start <- xTar2
# profit1 matrix
prof1 <- array(0,dim=c(iMax,jMax))
# profit2 matrix
prof2 <- array(0,dim=c(iMax,jMax))
# Tar1 uncertainty matrix
uncerTar1 <- array(0,dim=c(iMax,jMax))
# Tar2 uncertainty matrix
uncerTar2 <- array(0,dim=c(iMax,jMax))
# random numbers between 0-1 for each i,y,t
zTar1 <- array(0,dim=c(iMax,jMax,T))
# random numbers between 0-1 for each i,y,t
zTar2 <- array(0,dim=c(iMax,jMax,T))
# habitat level matrix
h <- array(hMax, dim=c(iMax,jMax))
# habitat start
hStart <- h
####################################################################
##Unregulated years variables
####################################################################
# years unfished simulation
unYears <- 20
```

```
# Sum of xTar1 at end of year
unXTar1Sum<-array(0,dim=c(unYears,1))
# Sum of xTar2 at end of year
unXTar2Sum<-array(0,dim=c(unYears,1))
# habitat sum
unHSum <-array(0,dim=c(unYears,1))
# habitat percent
unHPer <-array(0,dim=c(unYears,1))
# catch1 over time
unCatch1 <-array(0,dim=c(unYears,1))
# catch2 over time
unCatch2 <-array(0,dim=c(unYears,1))
# Effort1 over time
unEffort1 <-array(0,dim=c(unYears,1))
# Effort1 over time
unEffort2 <-array(0,dim=c(unYears,1))


##################################################################
##Regulated years variables
##################################################################
# years fished simulation
fYears <- 50
# sum of xTar1 at end of year
fXTar1Sum <-array(0,dim=c(fYears,1))
# sum of xTar2 at end of year
fXTar2Sum <-array(0,dim=c(fYears,1))
# h sum
fHSum <-array(0,dim=c(fYears,1))
# habitat percent
fHPer<-array(0,dim=c(fYears,1))
# CPUE over time
# catch1 over time
fCatch1 <-array(0,dim=c(fYears,1))
# catch2 over time
fCatch2 <-array(0,dim=c(fYears,1))
# Effort1 over time
fEffort1 <-array(0,dim=c(fYears,1))
# Effort2 over time
fEffort2 <-array(0,dim=c(fYears,1))
# initializes pH array
pHTime <-array(0, dim=c(fYears,1))
# initializes pBy array
pByTime <-array(0, dim=c(fYears,1))


##################################################################
#20 year simulation without habitat controls
##################################################################
for (y in 1:unYears) {
        print(y)
        # random numbers 0-1 for each fish,i,j,t
        zTar1Sum <- 0
        zTar2Sum <- 0
        for (t in 1:T) {
                for (i in 1:iMax) {
                        for (j in 1:jMax) {
                                zTar1[i,j,t] <- runif(1)
                                zTar2[i,j,t] <- runif(1)
                                zTar1Sum <- zTar1Sum + zTar1[i,j,t]
                                zTar2Sum <- zTar2Sum + zTar2[i,j,t]
                        }
                }
        }
        # T periods
        t <- 1
        while (t <= T && (TAC1Y > 0 || TAC2Y > 0)) {

                # k-th fishing vessels
                k <- 1
```

```
while (k <= fs && (TAC1Y > 0 || TAC2Y > 0)) {
        #initializes the maximum profit
        maxProf1 <- 0
        maxProf2 <- 0
        for (i in 1:iMax) {
                for (j in 1:jMax) {
                        uncerTar1[i,j] <- rnorm(1)
                        uncerTar2[i,j] <- rnorm(1)
                }
        }
        if (TAC2Y > 0) {
                for (i in 1:iMax){
                        for (j in 1:jMax) {
                                prof2[i,j] <- pF2*qTar2*xTar2[i,j]*exp(sig*uncerTar2[i,j])
                                if (prof2[i,j] > maxProf2) {
                                        maxProf2 <- prof2[i,j]
                                        mi2 <- i
                                        mj2 <- j
                                }
                        }
                }
                unCatch2[y] <- unCatch2[y] + xTar2[mi2,mj2]*(qTar2)
                unEffort2[y] <- unEffort2[y] + 1
                TAC2Y <- TAC2Y - xTar2[mi2,mj2]*(qTar2)
                xTar2[mi2,mj2] <- xTar2[mi2,mj2]*(1-qTar2)
                h[mi2,mj2] <- h[mi2,mj2]*(1-qH2)
        }
        if (TAC1Y > 0) {
                for (i in 1:iMax){
                        for (j in 1:jMax) {
                                prof1[i,j] <- pF1*qTar1*xTar1[i,j]*exp(sig*uncerTar1[i,j])
                                if (prof1[i,j] > maxProf1) {
                                        maxProf1 <- prof1[i,j]
                                        mi1 <- i
                                        mj1 <- j
                                }
                        }
                }

                unCatch1[y] <- unCatch1[y] + xTar1[mi1,mj1]*(qTar1)
                unEffort1[y] <- unEffort1[y] + 1
                TAC1Y <- TAC1Y - xTar1[mi1,mj1]*(qTar1)
                xTar1[mi1,mj1] <- xTar1[mi1,mj1]*(1-qTar1)
                xTar2[mi1,mj1] <- xTar2[mi1,mj1]*(1-qTar12)
                h[mi1,mj1] <- h[mi1,mj1]*(1-qH1)
        }
        k <- k+1
}

#habiat repair
for (i in 1:iMax) {
        for (j in 1:jMax) {
                h[i,j] <- h[i,j] + min((hMax - h[i,j]), (rT/T))
        }
}

unXTar1SumOld <- 0
unXTar2SumOld <- 0
for (i in 1:iMax) {
        for (j in 1:jMax) {
                unXTar1SumOld <- unXTar1SumOld + xTar1[i,j]
                unXTar2SumOld <- unXTar2SumOld + xTar2[i,j]
        }
}

#recruitment
unXTar1Sum[y] <- 0
unXTar2Sum[y] <- 0
```

```
unHSum[y] <- 0
for (i in 1:iMax) {
            for (j in 1:jMax) {
                        xTar1[i,j] <- xTar1[i,j] + aTar1*((GTar1/T)*xTar1[i,j]/unXTar1SumOld) +
                                    (1-aTar1)*(GTar1*zTar1[i,j,t])/(zTar1Sum)
                        unXTar1Sum[y] <- unXTar1Sum[y] + xTar1[i,j]
                        xTar2[i,j] <- xTar2[i,j] + aTar2*((GTar2/T)*xTar2[i,j]/unXTar2SumOld) +
                                    (1-aTar2)*(GTar2*zTar2[i,j,t])/(zTar2Sum)
                        unXTar2Sum[y] <- unXTar2Sum[y] + xTar2[i,j]
                        unHSum[y] <- unHSum[y] + h[i,j]

            }
}
unHPer[y] <- unHSum[y]/(area*N)

# diffusion for corners, edges and middle
xTar1Old <- xTar1
xTar2Old <- xTar2
for (i in 1:iMax) {
            for (j in 1:jMax) {
                        # top left (1,1)
                        if (i == 1 && j == 1) {
                                    dSum <- xTar1Old[iMax,jMax] + xTar1Old[iMax,1] + xTar1Old[iMax,2] +
                                                xTar1Old[1,2] + xTar1Old[2,1] + xTar1Old[1,jMax]
                                    dBSum <- xTar2Old[iMax,jMax] + xTar2Old[iMax,1] + xTar2Old[iMax,2] +
                                                xTar2Old[1,2] + xTar2Old[2,1] + xTar2Old[1,jMax]
                        }
                        # top right (1, jMax)
                        else if (i == 1 && j == jMax) {
                                    dSum <- xTar1Old[1,jMax-1] + xTar1Old[iMax,jMax] + xTar1Old[1,1] +
                                                xTar1Old[2,1] + xTar1Old[2,jMax] + xTar1Old[2,jMax-1]
                                    dBSum <- xTar2Old[1,jMax-1] + xTar2Old[iMax,jMax] + xTar2Old[1,1] +
                                                xTar2Old[2,1] + xTar2Old[2,jMax] + xTar2Old[2,jMax-1]
                        }
                        # bottom left (iMax, 1)
                        else if (i == iMax && j == 1) {
                                    dSum <- xTar1Old[iMax-1,jMax] + xTar1Old[iMax-1,1] +
                                                xTar1Old[iMax-1,2] + xTar1Old[iMax,2] +
                                                xTar1Old[1,1] + xTar1Old[iMax,jMax]
                                    dBSum <- xTar2Old[iMax-1,jMax] + xTar2Old[iMax-1,1] +
                                                xTar2Old[iMax-1,2] + xTar2Old[iMax,2] +
                                                xTar2Old[1,1] + xTar2Old[iMax,jMax]
                        }
                        # bottom right (iMax, jMax)
                        else if (i == iMax && j == jMax) {
                                    dSum <- xTar1Old[iMax,jMax-1] + xTar1Old[iMax-1,jMax] +
                                                xTar1Old[iMax,1] + xTar1Old[1,1] + xTar1Old[1,jMax] +
                                                xTar1Old[1,jMax-1]
                                    dBSum <- xTar2Old[iMax,jMax-1] + xTar2Old[iMax-1,jMax] +
                                                xTar2Old[iMax,1] + xTar2Old[1,1] + xTar2Old[1,jMax] +
                                                xTar2Old[1,jMax-1]
                        }
                        # top even (1, even)
                        else if (i == 1 && ((j%%2) ==0) ) {
                                    dSum <- xTar1Old[1,j-1] + xTar1Old[iMax,j] + xTar1Old[1,j+1] +
                                                xTar1Old[2,j+1] + xTar1Old[2,j] + xTar1Old[2,j-1]
                                    dBSum <- xTar2Old[1,j-1] + xTar2Old[iMax,j] + xTar2Old[1,j+1] +
                                                xTar2Old[2,j+1] + xTar2Old[2,j] + xTar2Old[2,j-1]
                        }
                        # top odd (1, odd)
                        else if (i == 1 && ((j%%2) != 0) ) {
                                    dSum <- xTar1Old[iMax,j-1] + xTar1Old[iMax,j] + xTar1Old[iMax,j+1] +
                                                xTar1Old[1,j+1] + xTar1Old[2,j] + xTar1Old[1,j-1]
                                    dBSum <- xTar2Old[iMax,j-1] + xTar2Old[iMax,j] + xTar2Old[iMax,j+1] +
                                                xTar2Old[1,j+1] + xTar2Old[2,j] + xTar2Old[1,j-1]
                        }
                        # bottom even (iMax, even)
                        else if (i == iMax && ((j%%2) == 0) ) {
```

```
                                            dSum <- xTar1Old[iMax,j-1] + xTar1Old[iMax-1,j] + xTar1Old[iMax,j+1] +
                                                    xTar1Old[1,j+1] + xTar1Old[1,j] + xTar1Old[1,j-1]
                                            dBSum <- xTar2Old[iMax,j-1] + xTar2Old[iMax-1,j] +
                                                    xTar2Old[iMax,j+1]+ xTar2Old[1,j+1] + xTar2Old[1,j] +
                                                    xTar2Old[1,j-1]
                                }
                                # bottom odd (iMax, odd)
                                else if (i == iMax  && ((j%%2) != 0) ) {
                                            dSum <- xTar1Old[iMax-1,j-1] + xTar1Old[iMax-1,j] +
                                                    xTar1Old[iMax-1,j+1] + xTar1Old[iMax,j+1] + xTar1Old[1,j] +
                                                    xTar1Old[iMax,j-1]
                                            dBSum <- xTar2Old[iMax-1,j-1] + xTar2Old[iMax-1,j] +
                                                    xTar2Old[iMax-1,j+1] + xTar2Old[iMax,j+1] +
                                                    xTar2Old[1,j] + xTar2Old[iMax,j-1]
                                }
                                # left {odd} (:,1)
                                else if (j == 1) {
                                            dSum <- xTar1Old[i-1,jMax] + xTar1Old[i-1,1] + xTar1Old[i-1,2] +
                                                    xTar1Old[i,2] + xTar1Old[i+1,1] + xTar1Old[i,jMax]
                                            dBSum <- xTar2Old[i-1,jMax] + xTar2Old[i-1,1] + xTar2Old[i-1,2] +
                                                    xTar2Old[i,2] + xTar2Old[i+1,1] + xTar2Old[i,jMax]
                                }
                                # right {even} (:,m)
                                else if (j == jMax) {
                                            dSum <- xTar1Old[i,jMax-1] + xTar1Old[i-1,jMax] + xTar1Old[i,1] +
                                                    xTar1Old[i+1,1] + xTar1Old[i+1,jMax] + xTar1Old[i+1,jMax-1]
                                            dBSum <- xTar2Old[i,jMax-1] + xTar2Old[i-1,jMax] + xTar2Old[i,1] +
                                                    xTar2Old[i+1,1] + xTar2Old[i+1,jMax] + xTar2Old[i+1,jMax-1]
                                }
                                # middle even (:,even)
                                else if ((j%%2) == 0) {
                                            dSum <- xTar1Old[i,j-1] + xTar1Old[i-1,j] + xTar1Old[i,j+1] +
                                                    xTar1Old[i+1,j+1] + xTar1Old[i+1,j] + xTar1Old[i+1,j-1]
                                            dBSum <- xTar2Old[i,j-1] + xTar2Old[i-1,j] + xTar2Old[i,j+1] +
                                                    xTar2Old[i+1,j+1] + xTar2Old[i+1,j] + xTar2Old[i+1,j-1]
                                }
                                # middle odd (:,odd)
                                else if ((j%%2) != 0) {
                                            dSum <- xTar1Old[i-1,j-1] + xTar1Old[i-1,j] + xTar1Old[i-1,j+1] +
                                                    xTar1Old[i,j+1] + xTar1Old[i+1,j] + xTar1Old[i,j-1]
                                            dBSum <- xTar2Old[i-1,j-1] + xTar2Old[i-1,j] + xTar2Old[i-1,j+1] +
                                                    xTar2Old[i,j+1] + xTar2Old[i+1,j] + xTar2Old[i,j-1]
                                }
                                xTar1[i,j] <- xTar1Old[i,j] + dTar1*(dSum - 6*xTar1Old[i,j])
                                xTar2[i,j] <- xTar2Old[i,j] + dTar2*(dBSum - 6*xTar2Old[i,j])
                        }
                }
                t <- t + 1
        }
        # update growth and TAC
        GTar1 <- grTar1*unXTar1Sum[y]*(1-(unXTar1Sum[y]/KTar1))
        GTar2 <- grTar2*unXTar2Sum[y]*(1-(unXTar2Sum[y]/KTar2))
        print(TAC1Y)
        TAC1Y <- GTar1
        print(TAC2Y)
        TAC2Y <- (GTar2)
        print(TAC2Y)
        print(TAC1Y)
        unCPUE1 <- unCatch1 / unEffort1
        unCPUE2 <- unCatch2 / unEffort2

}

###################################################################
# Unregulated Plots
###################################################################
par(mfrow=c(3,2))
plot(unXTar1Sum)
```

```
plot(unXTar2Sum)
plot(unHSum)
plot(unHPer)
plot(unCPUE1)
plot(unCPUE2)

#####################################################################
# Variables after unregulation
#####################################################################
GTar120 <- GTar1
GTar220 <- GTar2
TAC1Y20 <- TAC1Y
TAC2Y20 <- TAC2Y
xTar120 <- xTar1
xTar220 <- xTar2
h20 <- h


#####################################################################
# Set variables for next part of sim
#####################################################################
xTar1Start <- xTar1
xTar2Start <- xTar2
hStart <- h
hSum <- unHSum[20]
TAC1Ystart <- TAC1Y
TABstart <- TAC2Y*.1
TAC2Ystart <- TAC2Y*.9
#####################################################################
#50 year simulation with habitat controls
#####################################################################
for (y in 1:fYears) {
          print("year")
          print(y)

          # initializes price of habitat and bycatch
          pH <- 0
          pBy <- 0

          # Becomes true when prices work
          works <- FALSE

          #solving for price of habitat and bycatch
          while (works == FALSE) {
                    xTar1 <- xTar1Start
                    xTar2 <- xTar2Start
                    h <- hStart
                    print("not yet")
                    TAC1Y <- TAC1Ystart
                    TAC2Y <- TAC2Ystart
                    TABY <- TABstart
                    fCatch1[y]<-0
                    fCatch2[y]<-0
                    fEffort1[y]<-0
                    fEffort2[y]<-0

                    # Total Habitat Quota
                    projH <- 0
                    for (i in 1:iMax) {
                              for (j in 1:jMax) {
                                        projH <- projH + h[i,j] + min((hMax - h[i,j]), rT)
                              }
                    }
                    if (hSum > tarH) {
                              THQ <- projH -tarH
                    }
                    else {
                              THQ <- projH - hSum - (.02*N*area)
                    }
```

```
zTar1Sum <- 0
zTar2Sum <- 0
for (t in 1:T) {
            for (i in 1:iMax) {
                        for (j in 1:jMax) {
                                    zTar1[i,j,t] <- runif(1)
                                    zTar2[i,,t] <- runif(1)
                                    zTar1Sum <- zTar1Sum + zTar1[i,j,t]
                                    zTar2Sum <- zTar2Sum + zTar2[i,j,t]
                        }
            }
}

# T periods
t <- 1
while (t <= T && THQ > 0  && ((TAC1Y > 0 && TABY > 0) || TAC2Y > 0)) {

            # k-th fishing vessels
            k <- 1
            while (k <= fs && THQ > 0  && ((TAC1Y > 0 && TABY > 0) || TAC2Y > 0)) {
                        maxProf1 <- 0
                        maxProf2 <- 0
                        for (i in 1:iMax) {
                                    for (j in 1:jMax) {
                                                uncerTar1[i,j] <- rnorm(1)
                                                uncerTar2[i,j] <- rnorm(1)
                                    }
                        }
                        if (TAC2Y > 0) {
                                    for (i in 1:iMax){
                                                for (j in 1:jMax) {
                                                            prof2[i,j] <- (pF2*qTar2*xTar2[i,j]*
                                                                        exp(sig*uncerTar2[i,j])) -
                                                                        (pH*qH2*h[i,j]) -
                                                                        (pTar21*qTar21*xTar1[i,j]*
                                                                        exp(sig*uncerTar1[i,j]))
                                                            if (prof2[i,j] > maxProf2) {
                                                                        maxProf2 <- prof2[i,j]
                                                                        mi2 <- i
                                                                        mj2 <- j
                                                            }
                                                }
                                    }
                                    fCatch2[y] <- fCatch2[y] + xTar2[mi2,mj2]*(qTar2)
                                    fEffort2[y] <- fEffort2[y] + 1
                                    TAC2Y <- TAC2Y - xTar2[mi2,mj2]*(qTar2)
                                    xTar2[mi2,mj2] <- xTar2[mi2,mj2]*(1-qTar2)
                                    THQ <- THQ - qH2*h[mi2,mj2]
                                    h[mi2,mj2] <- h[mi2,mj2] - qH2*h[mi2,mj2]
                        }
                        if (TAC1Y > 0 && TABY > 0) {
                                    for (i in 1:iMax){
                                                for (j in 1:jMax) {
                                                            prof1[i,j] <- (pF1*qTar1*xTar1[i,j]*
                                                                        exp(sig*uncerTar1[i,j])) -
                                                                        (pH*qH1*h[i,j]) -
                                                                        (pBy*qTar12*xTar2[i,j]*
                                                                        exp(sig*uncerTar2[i,j]))
                                                            if (prof1[i,j] > maxProf1) {
                                                                        maxProf1 <- prof1[i,j]
                                                                        mi1 <- i
                                                                        mj1 <- j
                                                            }
                                                }
                                    }
                                    fCatch1[y] <- fCatch1[y] + xTar1[mi1,mj1]*(qTar1)
                                    fEffort1[y] <- fEffort1[y] + 1
```

```
                                TAC1Y <- TAC1Y - xTar1[mi1,mj1]*(qTar1)
                                TABY <- TABY - xTar2[mi1,mj1]*(qTar12)
                                xTar1[mi1,mj1] <- xTar1[mi1,mj1]*(1-qTar1)
                                xTar2[mi1,mj1] <- xTar2[mi1,mj1]*(1-qTar12)
                                THQ <- THQ - qH1*h[mi1,mj1]
                                h[mi1,mj1] <- h[mi1,mj1] - qH1*h[mi1,mj1]
                }
                k <- k+1
        }

        # case if THQ and TAB run out at same time before TAC
        if (TAC1Y > 0 && TABY <= 0 && THQ <=0) {
                pH <- pH + .001
                pBy <- pBy + .1
                print("pH and pBy to low, TAC left:")
                print(TAC1Y)
                print(TAC2Y)
                print(TABY)
        }

        # case only THQ run out before TAC
        else if ((TAC1Y > 0 || TAC2Y >0) && THQ <= 0) {
                pH <- pH + .001
                print("pH too low, TAC left:")
                print(TAC1Y)
                print(TAC2Y)
                print(TABY)
        }

        else if (TAC1Y > 0 && TABY <= 0) {
                pBy <- pBy + .1
                print("pBy too low, TAC left:")
                print(TAC1Y)
                print(TAC2Y)
                print(TABY)
        }

        # case THQ and TAB not run out
        else {
                for (i in 1:iMax) {
                        for (j in 1:jMax) {
                                h[i,j] <- h[i,j] + min((hMax - h[i,j]), (rT/T))
                        }
                }

                xTar1SumOld <- 0
                xTar2SumOld <- 0
                for (i in 1:iMax) {
                        for (j in 1:jMax) {
                                xTar1SumOld <- xTar1SumOld + xTar1[i,j]
                                xTar2SumOld <- xTar2SumOld + xTar2[i,j]
                        }
                }
                #growth
                fXTar1Sum[y] <- 0
                fXTar2Sum[y] <- 0
                fHSum[y] <- 0
                for (i in 1:iMax) {
                        for (j in 1:jMax) {
                                xTar1[i,j] <- xTar1[i,j] +
                                        aTar1*((GTar1/T)*xTar1[i,j]/xTar1SumOld) +
                                        (1-aTar1)*(GTar1*zTar1[i,j,t])/(zTar1Sum)
                                fXTar1Sum[y] <- fXTar1Sum[y] + xTar1[i,j]
                                xTar2[i,j] <- xTar2[i,j] +
                                        aTar2*((GTar2/T)*xTar2[i,j]/xTar2SumOld) +
                                        (1-aTar2)*(GTar2*zTar2[i,j,t])/(zTar2Sum)
                                fXTar2Sum[y] <- fXTar2Sum[y] + xTar2[i,j]
                                fHSum[y] <- fHSum[y] + h[i,j]
```

```
                    }
        }
        fHPer[y] <- fHSum[y]/(area*N)
        xTar1Old <- xTar1
        xTar2Old <- xTar2
        # diffusion for corners, edges and middle
        for (i in 1:iMax) {
                for (j in 1:jMax) {
                        # top left (1,1)
                        if (i == 1 && j == 1) {
                                dSum <- xTar1Old[iMax,jMax] + xTar1Old[iMax,1] +
                                        xTar1Old[iMax,2] + xTar1Old[1,2] +
                                        xTar1Old[2,1] + xTar1Old[1,jMax]
                                dBSum <- xTar2Old[iMax,jMax] +
                                        xTar2Old[iMax,1] + xTar2Old[iMax,2] +
                                        xTar2Old[1,2] + xTar2Old[2,1] +
                                        xTar2Old[1,jMax]
                        }
                        # top right (1, jMax)
                        else if (i == 1 && j == jMax) {
                                dSum <- xTar1Old[1,jMax-1] +
                                        xTar1Old[iMax,jMax] + xTar1Old[1,1] +
                                        xTar1Old[2,1] + xTar1Old[2,jMax] +
                                        xTar1Old[2,jMax-1]
                                dBSum <- xTar2Old[1,jMax-1] +
                                        xTar2Old[iMax,jMax] + xTar2Old[1,1] +
                                        xTar2Old[2,1] + xTar2Old[2,jMax] +
                                        xTar2Old[2,jMax-1]
                        }
                        # bottom left (iMax, 1)
                        else if (i == iMax && j == 1) {
                                dSum <- xTar1Old[iMax-1,jMax] +
                                        xTar1Old[iMax-1,1] +
                                        xTar1Old[iMax-1,2] + xTar1Old[iMax,2] +
                                        xTar1Old[1,1] + xTar1Old[iMax,jMax]
                                dBSum <- xTar2Old[iMax-1,jMax] +
                                        xTar2Old[iMax-1,1] +
                                        xTar2Old[iMax-1,2] + xTar2Old[iMax,2] +
                                        xTar2Old[1,1] + xTar2Old[iMax,jMax]
                        }
                        # bottom right (iMax, jMax)
                        else if (i == iMax && j == jMax) {
                                dSum <- xTar1Old[iMax,jMax-1] +
                                        xTar1Old[iMax-1,jMax] +
                                        xTar1Old[iMax,1] + xTar1Old[1,1] +
                                        xTar1Old[1,jMax] + xTar1Old[1,jMax-1]
                                dBSum <- xTar2Old[iMax,jMax-1] +
                                        xTar2Old[iMax-1,jMax] +
                                        xTar2Old[iMax,1] + xTar2Old[1,1] +
                                        xTar2Old[1,jMax] + xTar2Old[1,jMax-1]
                        }
                        # top even (1, even)
                        else if (i == 1 && ((j%%2) ==0) ) {
                                dSum <- xTar1Old[1,j-1] + xTar1Old[iMax,j] +
                                        xTar1Old[1,j+1] + xTar1Old[2,j+1] +
                                        xTar1Old[2,j] + xTar1Old[2,j-1]
                                dBSum <- xTar2Old[1,j-1] + xTar2Old[iMax,j] +
                                        xTar2Old[1,j+1] + xTar2Old[2,j+1] +
                                        xTar2Old[2,j] + xTar2Old[2,j-1]
                        }
                        # top odd (1, odd)
                        else if (i == 1 && ((j%%2) != 0) ) {
                                dSum <- xTar1Old[iMax,j-1] + xTar1Old[iMax,j] +
                                        xTar1Old[iMax,j+1] + xTar1Old[1,j+1] +
                                        xTar1Old[2,j] + xTar1Old[1,j-1]
                                dBSum <- xTar2Old[iMax,j-1] + xTar2Old[iMax,j] +
                                        xTar2Old[iMax,j+1] + xTar2Old[1,j+1] +
                                        xTar2Old[2,j] + xTar2Old[1,j-1]
```

```
                                                }
                                                # bottom even (iMax, even)
                                                else if (i == iMax && ((j%%2) == 0) ) {
                                                        dSum <- xTar1Old[iMax,j-1] + xTar1Old[iMax-1,j] +
                                                                xTar1Old[iMax,j+1] + xTar1Old[1,j+1] +
                                                                xTar1Old[1,j] + xTar1Old[1,j-1]
                                                        dBSum <- xTar2Old[iMax,j-1] + xTar2Old[iMax-1,j] +
                                                                xTar2Old[iMax,j+1] + xTar2Old[1,j+1] +
                                                                xTar2Old[1,j] + xTar2Old[1,j-1]
                                                }
                                                # bottom odd (iMax, odd)
                                                else if (i == iMax  && ((j%%2) != 0) ) {
                                                        dSum <- xTar1Old[iMax-1,j-1] +
                                                                xTar1Old[iMax-1,j] +
                                                                xTar1Old[iMax-1,j+1] +
                                                                xTar1Old[iMax,j+1] + xTar1Old[1,j] +
                                                                xTar1Old[iMax,j-1]
                                                        dBSum <- xTar2Old[iMax-1,j-1] +
                                                                xTar2Old[iMax-1,j] +
                                                                xTar2Old[iMax-1,j+1] +
                                                                xTar2Old[iMax,j+1] + xTar2Old[1,j] +
                                                                xTar2Old[iMax,j-1]
                                                }
                                                # left {odd} (:,1)
                                                else if (j == 1) {
                                                        dSum <- xTar1Old[i-1,jMax] + xTar1Old[i-1,1] +
                                                                xTar1Old[i-1,2] + xTar1Old[i,2] +
                                                                xTar1Old[i+1,1] + xTar1Old[i,jMax]
                                                        dBSum <- xTar2Old[i-1,jMax] + xTar2Old[i-1,1] +
                                                                xTar2Old[i-1,2] + xTar2Old[i,2] +
                                                                xTar2Old[i+1,1] + xTar2Old[i,jMax]
                                                }
                                                # right {even} (:,m)
                                                else if (j == jMax) {
                                                        dSum <- xTar1Old[i,jMax-1] + xTar1Old[i-1,jMax] +
                                                                xTar1Old[i,1] + xTar1Old[i+1,1] +
                                                                xTar1Old[i+1,jMax] +
                                                                xTar1Old[i+1,jMax-1]
                                                        dBSum <- xTar2Old[i,jMax-1] + xTar2Old[i-1,jMax] +
                                                                xTar2Old[i,1] + xTar2Old[i+1,1] +
                                                                xTar2Old[i+1,jMax] +
                                                                xTar2Old[i+1,jMax-1]
                                                }
                                                # middle even (:,even)
                                                else if ((j%%2) == 0) {
                                                        dSum <- xTar1Old[i,j-1] + xTar1Old[i-1,j] +
                                                                xTar1Old[i,j+1] + xTar1Old[i+1,j+1] +
                                                                xTar1Old[i+1,j] + xTar1Old[i+1,j-1]
                                                        dBSum <- xTar2Old[i,j-1] + xTar2Old[i-1,j] +
                                                                xTar2Old[i,j+1] + xTar2Old[i+1,j+1] +
                                                                xTar2Old[i+1,j] + xTar2Old[i+1,j-1]
                                                }
                                                # middle odd (:,odd)
                                                else if ((j%%2) != 0) {
                                                        dSum <- xTar1Old[i-1,j-1] + xTar1Old[i-1,j] +
                                                                xTar1Old[i-1,j+1] + xTar1Old[i,j+1] +
                                                                xTar1Old[i+1,j] + xTar1Old[i,j-1]
                                                        dBSum <- xTar2Old[i-1,j-1] + xTar2Old[i-1,j] +
                                                                xTar2Old[i-1,j+1] + xTar2Old[i,j+1] +
                                                                xTar2Old[i+1,j] + xTar2Old[i,j-1]
                                                }
                                                xTar1[i,j] <- xTar1Old[i,j] + dTar1*(dSum - 6*xTar1Old[i,j])
                                                xTar2[i,j] <- xTar2Old[i,j] + dTar2*(dBSum - 6*xTar2Old[i,j])
                                        }
                                }

                        # if end of sim from out of time or out of TAC
                        if ((TAC1Y <= 0 && TAC2Y <= 0) || (t==T && k==(fs+1))) {
```

```
                                                              works <- TRUE
                                                              pHTime[y] <- pH
                                                              pByTime[y] <- pBy

                                                              if (THQ <= 0 &&  TABY <= 0 && TAC1Y <= 0 && TAC2Y <= 0) {
                                                                      print("all under")
                                                              }
                                                              if (TAC1Y <= 0 && TAC2Y <= 0) {
                                                                      print("Used TAC")
                                                              }
                                                              if (t==T && k==(fs+1)) {
                                                                      print("out of time")
                                                                      print(TAC1Y)
                                                                      print(TAC2Y)
                                                                      print(TABY)
                                                              }
                                                              fCPUE1 <- fCatch1 / fEffort1
                                                              fCPUE2 <- fCatch2 / fEffort2
                                                              GTar1 <- grTar1*fXTar1Sum[y]*(1-(fXTar1Sum[y]/KTar1))
                                                              GTar2 <- grTar2*fXTar2Sum[y]*(1-(fXTar2Sum[y]/KTar2))
                                                              TAC1Ystart <- GTar1
                                                              TAC2Ystart <- (GTar2*.9)
                                                              TABstart <- (GTar2*.1)
                                                              xTar1Start <- xTar1
                                                              xTar2Start <- xTar2
                                                              hStart <- h
                                                              hSum <- fHSum[y]
                                              }
                                      }
                                      t <- t + 1
                              }
                      }
}
print(xTar1)
print(xTar2)
print(h)
par(mfrow=c(4,2))
plot(pHTime)
plot(pByTime)
plot(fXTar1Sum)
plot(fXTar2Sum)
plot(fHSum)
plot(fHPer)
plot(fCPUE1)
plot(fCPUE2)
write.csv(unXTar1Sum ,"100unXTar1Sum.csv")
write.csv(unXTar2Sum ,"100unXTar2Sum.csv")
write.csv(unHPer ,"100unHPer.csv")
write.csv(unCPUE1 ,"100unCPUE1.csv")
write.csv(unCPUE2 ,"100unCPUE2.csv")
write.csv(unEffort1 ,"100unEffort1.csv")
write.csv(unEffort2 ,"100unEffort2.csv")
write.csv(unCatch1 ,"100unCatch1.csv")
write.csv(unCatch2 ,"100unCatch2.csv")
write.csv(fXTar1Sum ,"100fXTar1Sum.csv")
write.csv(fXTar2Sum ,"100fXTar2Sum.csv")
write.csv(fHPer ,"100fHPer.csv")
write.csv(fCPUE1 ,"100fCPUE1.csv")
write.csv(fCPUE2 ,"100fCPUE2.csv")
write.csv(fEffort1 ,"100fEffort1.csv")
write.csv(fEffort2 ,"100fEffort2.csv")
write.csv(fCatch1 ,"100fCatch1.csv")
write.csv(fCatch2 ,"100fCatch2.csv")
write.csv(pHTime ,"100pHTime.csv")
write.csv(pByTime ,"100pByTime.csv")
write.csv(h, "100h.csv")
```

# Bibliography:

*Beam Trawls*. Digital image. *Greenpeace.org*. Greenpeace, 17 June 2008. Web. 13 Apr.
    2013.<www.greenpeace.org/international/en/campaigns/oceans/seafood/understan
    ding-the-problem/fisheries-problems-today/beam-trawls/>.

*Chinook Salmon*. N.d. Photograph. Alaska Department of Fish and Game, Juneau, AK.
    Alaska Dept. of Fish and Game. Web. 13 Apr. 2013.
    <http://www.adfg.alaska.gov/index.cfm?adfg=chinook.photogallery&number=3>.

Harvey, Chris, Phillip Levin, Richard Zabel, Steven Katz, and Thomas Good.
    "Ecologically Sustainable Yield." *American Scientist* 91.2 (2003): 150-57. Web.
    13 Apr. 2013. <http://www.americanscientist.org/issues/feature/ecologically-
    sustainable-yield/7>.

Holland, Daniel S., and Kurt E. Schneir. "Modeling a Rights-Based Approach for
    Managing Habitat Impacts of Fisheries." *Natural Resource Modeling* 19.3 (2006):
    405-35. Print.

Holland, Daniel S., and Kurt E. Schnier. "Protecting Marine Biodiversity: A
    Comparison of Individual Habitat Quotas and Marine Protected Areas." *Canadian
    Journal of Fisheries and Aquatic Sciences* 63.7 (2006): 1481-495. Print.

"Marine Fisheries and the World Economy." *Ocean Science Series* (2010): n. pag. *Pew
    Charitable Trusts*. The PEW Environmental Group, Sept. 2010. Web. 14 Apr.
    2013.
    <http://www.pewtrusts.org/uploadedFiles/wwwpewtrustsorg/News/Press_Release
    s/Protecting_ocean_life/Pew%20OSS%20World%20Economy%20FINAL.pdf>.

Mauer, Richard. "Kenai River Now Closed to All King Salmon Fishing." *Anchorage
    Daily News* 17 July 2012: n. pag. Web. 13 Apr. 2013.
    <http://www.adn.com/2012/07/17/2545689/kenai-river-to-close-to-all-
    king.html>.

New England Fishery Management Council, "The Swept Area Seabed Impact (SASI)
    Model: A Tool For Analyzing The Effects of Fishing On Essential Fish Habitat",
    Essential Fish Habitat (EFH) Omnibus Amendment, January 21, 2011. Web. 13
    Apr. 2013. <www.nefmc.org/habitat/sasi_info/110121_SASI_Document.pdf>

"Magnuson-Stevens Act." *NOAA Fisheries Feature – Magnuson-Stevens Act*. National

Oceanic and Atmospheric Administration, n.d. Web. 13 Apr. 2013.
    <http://www.nmfs.noaa.gov/msa2005/docs/MSA_amended_msa%20_20070112_
    FINAL.pdf>.

Oliver, Rachel. "All About: Global Fishing." *CNN.com*. Cable News Network, 29 Mar.
    2008. Web. 13 Apr. 2013.
    <http://edition.cnn.com/2008/WORLD/asiapcf/03/24/eco.aboutfishing/>.

"Overfished Stocks (41) - as of December 31, 2012." Map. *NOAA Fisheries*. Office of
    Sustainable Fisheries, n.d. Web. 13 Apr. 2013.
    <http://www.nmfs.noaa.gov/sfa/statusoffisheries/2012/fourth/MapOverfishedStoc
    ksCY_Q4_2012.pdf>.

*Pelagic Trawls*. Digital image. *Greenpeace.org*. Greenpeace, 17 June 2008. Web. 13
    Apr. 2013.
    <www.greenpeace.org/international/en/campaigns/oceans/seafood/understanding-
    the-problem/fisheries-problems-today/beam-trawls/>.

Worm, B., E. B. Barbier, N. Beaumont, J. E. Duffy, C. Folke, B. S. Halpern, J. B. C.
    Jackson, H. K. Lotze, F. Micheli, S. R. Palumbi, E. Sala, K. A. Selkoe, J. J.
    Stachowicz, and R. Watson. "Impacts of Biodiversity Loss on Ocean
    Ecosystem Services." *Science* 314.5800 (2006): 787-90. Web. 13 Apr. 2013.
    <http://www.sciencemag.org/citmgr?gca=sci;314/5800/787>.