UNCERTAINTY AND RISK IN THE ECOSYSTEMS APPROACH TO FISHERIES MANAGEMENT: SOME INSIGHTS FROM AN ECOSYSTEM COMPUTER SIMULATION MODEL

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ABSTRACT

Understanding the complexities of ecosystems is difficult enough, but when the human dimension is added to the inherent uncertainty and risk in fisheries management, the actual versus expected results move from the counter-intuitive to the paradoxical. Without an adequate understanding of the interrelationships between ecosystem components, including the human dimension, scientific management becomes intuition-based management, which is often counterproductive to achieving desired goals and objectives. A computer simulation model is developed for multiple species, resource areas, stocks, and cohorts. To explicitly incorporate ecosystem effects predator-prey and competitor relationships are constructed to interpret interactions between different species of fish. Fishing fleet dynamics are captured by modeling multiple vessel classes based on specifications for catchability and concentration profiles. Additional uncertainty is included through the effects of market supply and demand on price for different discount rates. Economic impacts are also estimated for each point in time as biological and market conditions change. This simulation model results are then compared to determine if the management objective of maximization of net benefits subject to the fish stock conservation goal are achievable in an ecosystem context while also considering impacts on jobs, income, and sales. Insights from this simulation of an ecosystem should provide information on the needed research required for the ecosystem approach to fisheries management to be successful in achieving its multiple objectives.

Keywords: Ecosystem, Computer Simulation Model, Human Dimensions, Uncertainty and Risk, Bioeconomic Model

INTRODUCTION

Without a penalty, there is no risk and a risk neutral bet is one in which the inherent uncertainty about future events is incorporated into the decision making process to ensure that an outcome does not incur too great an impact on an economic entity. In fisheries management, whether wild capture commercial fishermen, recreational anglers, or marine aquaculturists, risk and uncertainty are inherently complex and multifaceted. Obviously, the natural world generates substantial amounts of risk and uncertainty with its seemingly random oscillations of patterns in sea temperature, weather, geological and solar conditions, and biological activity.

Scientific research on these cycles and their effect on the physical world has made great progress in recent years in understanding ecosystems; e.g., CFC and the ozone layer and the causes of global warming. These two examples also highlight anthropogenic sources of risk and uncertainty. Human behavior is driven by incentives that are formed in a marketplace, for the exchange of goods and services, based on a regulatory or governance infrastructure. These incentives and the resulting human behavior are affected by market failures. The classic market failure associated with the lack of free mobility of inputs and outputs in fisheries results in the open access management problem. However, imperfect information about goods and services is another market failure that can lead to distorted market prices which creates an incentive for inefficient human behavior. For example, imperfect information about the effect of CFCs on ozone in the presence of ultraviolet light resulted in a life threatening environmental hazard from a product intentionally designed to be used as a benign refrigerant and pressurizer of aerosol cans. Uncertainty about future events caused by this imperfect information created a substantial risk whose costs extended far beyond the loss of revenue from the sales of CFCs in the marketplace.

Unfortunately, perfect information about a good or service is not an achievable goal. This is the reason why the proposed precautionary approach is an empty meaningless shell of an idea grasped by managers in their ivory towers who are at a loss when forced to deal with actual problems in a complex world. The principle that development cannot occur unless no adverse effect can be demonstrated is not viable nor will it be tolerated in the political arena when states are forced to address the needs of a growing global population expected to stabilize at nine billion by the end of this century. The only viable management approach is to understand the inherent uncertainties caused by imperfect information, its associated risks, and, then, address the incentives that result in abhorrent human behavior by adjusting the regulatory infrastructure.

Uncertainty can be scientifically addressed by determining the probability of a particular event based on past occurrences while risk is the expected level of net benefits that would result if that event occurred. As an example, the probability of an oil well exploding and dumping millions of gallons of petroleum into the Gulf of Mexico is extremely low, but the economic costs of this environmental disaster are allegedly astronomical. By calculating the expect value from the low probability of a disaster with its high economic cost to the marine environment, oil companies can be required through regulations to adopt safety equipment in their production technology equal to this expected cost to prevent such events from occurring to maximize economic net benefits. The technology to mitigate the damage of other events is less well developed or nonexistent, such as increased frequency and ferocity of hurricanes caused by global warming. The expected value of the damage function estimated from the probabilities for each class of hurricane and its associated level of damage can be used to determine how individuals will behave under different management infrastructures. How this infrastructure could be changed can then be estimated and compared in a computer simulation of the affected ecosystem that includes the human environment.

The incorporation of the human environment in an ecosystem model is described to explain the dynamic relationship between fishing effort and fishing mortality. This linkage provides the feedback between the physical and the human environments necessary to understand the effects of different management approaches and regulations on net benefits. Next, the incorporation of global warming on hurricane ferocity and frequency into the ecosystem model is presented with emphasis on the derivation of the probability of uncertain events using existing scientific information with the associated risk level based on a hurricane damage function. Finally, the outcomes from different regulatory modifications designed to reduce the risk of hurricanes on fishing operations are presented and discussed in terms of their affect on economic values.

INTEGRATED ECOSYSTEM MODEL

Rarely are fully integrated ecosystem models of a fishery used in fisheries management. Even when attempted, the biological population dynamics are usually run independently of the economic subcomponent using a fixed fishing effort level. In these cases, the economics rarely consists of more than a rudimentary cost benefit analysis (CBA). In this analysis, a flexible, integrated, ecosystem model that allows feedback between the biological and economic components is developed for the ecosystem approach to fisheries (EAF) management. This basic framework can be expanded upon to incorporate additional ecosystem elements as they are developed; i.e., the uncertainty and risk associated with global climate change. First, the dimensions of the model and then, the framework components are summarized and presented. Following this model description, the linkages of this fishery management tool to global climate change are discussed.

Dimensions

Species, stock, resource area, cohorts, fleet, and vessel class make up the dimensions of this integrated ecosystem model. Keeping with the spirit of EAF management, the first dimension is the number of fish species to be considered in the management problem. The tuna fisheries include bluefin, bigeye, yellowtail, etc., and the shrimp fishery harvests between 3 and 8 species of shrimp in the Gulf of Mexico alone. Many fisheries, even those focused on a particular fish species, involve multiple fish species as bycatch, include predator-prey or competitor biological relationships, or are managed as part of an ensemble of similar fish species. Many commercial fishermen and recreational anglers also participate in multiple fisheries some of which may be ecologically independent. Biologists have emphasized understanding the population dynamics of different fish species. Under the EAF management, the interactions of these fish species will become of paramount importance in the future and have implications for both consumptive and non-consumptive users of these resources.

The second dimension of this framework is the number of stocks that exist for each fish species being considered. Multiple stocks of fish could exist even if only one species of fish is being considered for management. Fishermen and anglers may harvest from one, two, or many stocks of a fish species that are biologically independent. Stocks of two or more species may also be interrelated on the same fishing grounds. Identifying and confirming the existence of independent stocks of fish has been emphasized in the population dynamics literature. For example, genetic tests have been developed to separate a fish species into its different stocks for the purpose of improving fish stock conservation.

The definition of resource area, the third dimension of this framework, can take on different meanings depending on the nature of the fishery management problem being considered. It can represent a fishing area such as Georges Bank distinct from Brown’s Bank, a habitat attribute such as a reef or sunken vessel, or it could be used to represent a marine protected area separately from an area open to resource exploitation. Resource areas could also be used to represent a commercial fishing dependent community or a fishing marina for charterboats or headboats. This dimension increases the flexibility of the framework to incorporate geo-political, ecological, and environmental characteristics of a fishery.

Cohorts, as a dimension of the EAF management framework, are a representation of the different year classes or sizes of individual fish in a fishery. The number of cohorts can be set to reflect the maximum age or size of a fish or a group of fish species.

The fifth dimension, fleet, is set at the number of consumptive and non-consumptive user groups who will have access to or value the fish stock or stocks in this fishery. Fleet can be specified to represent commercial versus recreational fishing activities or to represent non-consumptive users who get negative satisfaction from knowing that fish are being harvested. For example, anglers may compete with other users of the fishery resources including commercial and artisanal fishermen who harvest these living marine resources to support their livelihoods. Anglers may also harvest prey species that are important to protected predator species such as marine mammals.

The final dimension, vessel class, is created to increase the heterogeneity of a fleet and is used to describe the fishing fleets or participants in a fishery. In a manner similar to the creation of species cohorts, different characteristics such as vessel length could be included for each fleet. Fishermen could be differentiated by gear classification or anglers by recreational fishing mode, such as privately owned fishing craft, charterboats, headboats, shore and peer fishing, etc.

Framework Components

To fully encapsulate the EAF management in this multi-disciplinary scientific fisheries management framework, at least five components need to be specified. First and foremost are the population dynamics of the fish stocks subject to management. This component captures growth, natural and fishing mortality, recruitment, and reproduction of each fish stock under management consideration. In addition, stock abundance acts as the constraint on yield from the fishery and subsequently revenue, profits, and fisherman and angler behavior.

A Shepherd spawners per recruit model (Quinn and Deriso, 1999) is used to develop an estimate of the number of recruits that enter into each fishery for a particular species.

$$R_{sp} = \frac{(\text{fecundity}_{sp,st,ra,ch} \cdot \exp(-as_{sp,st,ra,ch}\, RT_{sp,st,ra,ch}) \cdot \text{Spawners}_{sp,st,ra}}{\text{Gama}_{sp,st,ra,ch}\,(1+\text{fecundity}_{sp,st,ra,ch} \cdot cs_{sp,st,ra,ch})/[(as_{sp,st,ra,ch} ds_{sp,st,ra,ch})(1-\exp(-as_{sp,st,ra,ch} RT_{sp,st,ra,ch}))]} \quad (1)$$

Where fecundity represents the number of eggs produced by the spawners,

as = the density independent mortality parameter,

RT = the time of recruitment,
Spawners = the number of fish that reproduce,
cs/ds = the density dependent mortality parameters,
Gama = a shape parameter where Gama
< 1, recruitment has no asymptote;
= 1, corresponds to a Beverton-Holt recruitment model; and
> 1, represents a dome shaped recruitment model, and
R_{sp} = recruitment for each species.

A von Bertalanffy weight function is used to calculate the individual weight for the number of fish in each cohort:

$$w_{sp,st,ra,ch} = a_{sp,st,ra,ch}[1 - b_{sp,st,ra,ch} * \exp(-c_{sp,st,ra,ch}t)]^{bta_{sp,st,ra,ch}} \quad (2)$$

where $w_{sp,st,ra,ch}$ = weight for each species in a cohort,
$a_{sp,st,ra,ch}$ = the asymptotic weight
$b_{sp,st,ra,ch}$ = the growth rate
$c_{sp,st,ra,ch}$ = the growth rate decline factor,
t = cohort age, and
$bta_{sp,st,ra,ch}$ = the steepness coefficient.

The Beverton-Holt multi-cohort model (Beverton and Holt, 1957) of a fishery determines the number of fish in each cohort:

$$N_{sp,st,ra,ch} = N_{sp,st,ra,ch-1} \exp(-Z) \quad (3)$$

where $Z = M_{sp,st,ra,ch} + F_{sp,st,ra,ch}$
$M_{sp,st,ra,ch}$ = natural mortality,
$F_{sp,st,ra,ch}$ = total fishing mortality,
$N_{sp,st,ra,ch}$ = number of fish in a cohort, and
$N_{sp,st,ra,ch-1}$ = number of fish in the previous cohort.

Competitor and predator-prey relationships are built into the ecosystem model by modifying the natural mortality parameter (Yodzia, 1994). Competitors, predators, and prey species can be identified and their stock size at a point in time can be used to determine how the natural mortality rates are adjusted.

$$M_{sp,st,ra,ch} = M_{sp,st,ra,ch} - pry_{sp,st,ra,ch} * Biomass_{prey,st,ra,ch} \quad (4)$$

where $pry_{sp,st,ra,ch}$ = a parameter that reduces the natural mortality for the predator species, and
$Biomass_{prey,st,ra,ch}$ = the abundance of the prey species.

The effect on prey species and if prey species compete can be represented by

$$M_{sp,st,ra,ch} = M_{sp,st,ra,ch} + mrt_{sp,st,ra,ch} * Biomass_{predator,st,ra,ch} \quad (5)$$

where $mrt_{sp,st,ra,ch}$ = a parameter that increases the natural mortality of the prey species, and
$Biomass_{predator,st,ra,ch}$ = the abundance of the predator or competitor species.

The second component of the EAFM framework is an examination of the change in revenues and operating costs in response to changes in market, biological conditions, and fishery management regulations. Total Revenue is calculated in equation (6).

$$TR_{sp,st,ra,ch,flt,vcl} = FltYield_{sp,st,ra,ch,flt,vcl} * P_{sp,st,ra,ch,flt,vcl} \tag{6}$$

where $P_{sp,st,ra,ch,flt,vcl}$ = the exvessel price for each species, stock, resource area, cohort, fleet, and vessel class and

FltYield = the yield from the vessel class for a cohort.

Variable cost of operation is calculated based on equation (7).

$$OCost_{sp,st,ra,ch,flt,vcl} = e_{sp,st,ra,ch,flt,vcl} * Phi_{sp,st,ra,ch,flt,vcl} \tag{7}$$

where e = individual fishing effort level and

$Phi_{sp,st,ra,ch,flt,vcl}$ = a constant harvesting cost per unit of fish effort.

Total costs of operation should decline as stock abundance improves and can be calculated as

$$TotCost_{sp,st,ra,ch,flt,vcl} = FC_{sp,st,ra,ch,flt,vcl} + OCost_{sp,st,ra,ch,flt,vcl} * SSBR_{sp,st,ral}^{SSBRPhi_{sp,st,ra}} \tag{8}$$

where $FC_{sp,st,ra,ch,flt,vcl}$ = fixed operating costs,

$OCost_{sp,st,ra,ch,flt,vcl}$ = variable operating costs,

$SSBR_{sp,st,ral}$ = spawning stock biomass per recruit as a measure of stock abundance, and

$SSBRPhi_{sp,st,ra}$ = a negative constant.

Profit can be calculated from equations (6) and (8)

$$Profit_{sp,st,ra,ch,flt,vcl} = TR_{sp,st,ra,ch,flt,vcl} - [FltYield_{sp,st,ra,ch,flt,vcl} * CPLB_{sp,st,ra,ch,flt,vcl}] \tag{9}$$

where

$$CPLB_{sp,st,ra,ch,flt,vcl} = \frac{TotCost_{sp,st,ra,ch,flt,vcl}}{FltYield_{sp,st,ra,ch,flt,vcl}} = \text{cost per pound harvested.}$$

The third component of the EAFM framework is a market assessment of the potential changes in prices, quantities produced or consumed, fishing or observational trips taken, etc., as a result of changing supply and demand conditions in the marketplace. The calculation of the change in fishing effort with respect to time in equation (12) is dependent on the cost of harvesting fish and the demand for fish, which are both important components of profits as described by Smith (1969). This price information is also necessary in the calculation of producer and consumer surplus for various fishery products or activities and provides a measure of net benefits derived from the fishery. Expected price changes may be characterized by accounting for the levels of imports, exports, domestic landings of substitute and complementary fishery products and other consumer goods, disposable income, and other effects. In this case, a simple demand function is given by:

$$P_{sp,st,ra,ch,flt,vcl} = B^0_{\ sp,st,ra,ch,flt,vcl} * \text{Yield}_{\ sp,st,ra,ch}^{\ B^1_{\ sp,st,ra,ch,flt,vcl}} \tag{10}$$

where $B^0_{\ sp,st,ra,ch,flt,vcl}$ = the maximum price for a species, stock, resource area, cohort, fishing fleet, vessel class,
Yield $_{sp,st,ra,ch}$ = is the level of harvest of a species, stock, resource area, and cohort by all fishing fleets and vessel classes, and
$B^1_{\ sp,st,ra,ch,flt,vcl}$ = the demand coefficient; ≤ 0.

This simple nonlinear demand model allows the estimation of first and second order derivatives needed to estimate the change in fishing effort over time in equation (12).

The fourth component of the EAF management framework translates individual commercial fisher and recreational angler fishing effort levels into fishing mortality as a function of harvest revenues and individual satisfaction levels, firm operating and recreational travel costs, and fish stock abundance. Aggregating individual fishing effort levels into total fishing mortality estimates that comply with models of fish stock population dynamics requires that fish harvest be from homogenous fishing areas (Clark, 1990). This requires that the summation of fishing mortality be conducted at the most disaggregated levels in the fishery, and hence the EAF management model, to minimize over or underestimating fishing mortality levels.

$F = \sum f_i = \sum q_i \, e_i \quad i = 1, \ldots, n$ fishing areas

where F = total fishing effort,
f = individual fisher or angler fishing mortality, and
q = catchability.

The catchability coefficient (q) can be set as a constant or it can take on a more devious nature whose value is inversely related to the level of abundance (Clark, 1985):

$$q_{sp,st,ra,ch,flt,vcl} = a_{sp,st,ra,ch,flt,vcl} \, \varepsilon_{sp,st,ra,ch,flt,vcl} \, \text{Biomass}_{sp,st,ra,ch}^{-b} \tag{11}$$

where
a = the volume of seawater screened by the fishing gear,
ε = the proportion of fish in a volume of seawater captured by the fishing gear,
b < 0 for sedentary; slowly diffusing fish stocks (Convex to the origin); Type 1,
b = 0 equally distributed fish stocks (linear); Type II,
0 < b < 1 transitional between a Type II and Type IV fishery (Concave); Type III, and
b = 1 schooling populations (constant); Type IV.

Equation (11) allows catchability to increase or decline inversely with changes in biomass levels as is preferred by stock assessment biologists. This is an ad hoc approach to account for changes in the technical efficiency of fishing technology. As stocks abundance declines, ceteris paribus, the cost per fish harvested for a given level of effort increases and profits decline. Fishermen increase their investment in more productive harvesting capital to offset the decline in profits in regulated open access or open access fisheries. As a result, it appears that catchability increases as stocks decline. A more realistic assumption would be to treat catchability as a function of investment and depreciation in harvesting capacity that changes over time. Catchability would then function as a component of a production function that produced fish as a result of changes in the efficiency of the fishing gear over time.

Efficient markets allocate the fish stock, labor, and capital efficiently and determine the optimal amount of time necessary to maximize net benefits generated by a fishery for society. Managers when faced with regulating a complex fishery or group of fisheries need to understand the population dynamics of the fish stock, the habitat and ecosystem in which the stock exists, the behaviors of the fishermen and anglers, and the dynamics of the fishing fleets. The anthropogenic factors depend on the market structures and management regime fishermen operate in, how they value the future use of the resources they exploit in the harvesting of fish, and their goals and objectives for the fishery. The incentives these market and biological forces create for fishermen and anglers must comply with the goals and objectives of fishery managers to ensure the successful operation of the fishery. The alternative is a series of management crises that never seem to be resolved.

Four elements of fishing effort (time, price, unit cost, and stock abundance) need to be captured in equation (12), which can be derived from a Hamiltonian for a profit maximizing firm or a satisfaction maximizing angler subject to a stock constraint.

$$\partial e / \partial t_{sp,st,ra,ch,flt,vcl} = \frac{[\delta_{sp,st,ra,ch,flt,vcl} - F'(B)_{sp,st,ra,ch}]\,[P'(h)_{sp,st,ra,ch,flt,vcl} + P(h)_{sp,st,ra,ch,flt,vcl} - c_{sp,st,ra,ch,flt,vcl}]}{q_{sp,st,ra,ch,flt,vcl}\,[hP''(h)_{sp,st,ra,ch,flt,vcl} + 2P'(h)_{sp,st,ra,ch,flt,vcl}]\,Biomass_{sp,st,ra,ch}} \qquad (12)$$

where δ = the discount rate; = 0 for maximum stock conservation, = ∞ for open access management,

P'(h) = the marginal revenue or value derived from fishing; first derivative of equation (8),

P"(h) = the slope of the marginal revenue function; second derivative of equation (10),

h = the fish yield from fishing,

C = the unit harvest or trip cost of fishing, and

F'(B) = the fish stock growth rate.

The final framework component consists of the input-out multipliers. These multipliers are used to account for regional impacts that would result from proposed fishery management regulatory changes in the fishery. Once the proposed regulatory effects are estimated, the multipliers are used to determine how direct, indirect, and induced impacts in terms of jobs, income, and sales in the rest of the economy are affected. Economic impacts could decline as costs or expenditures decline which usually results in increases in benefits net of costs. However, there are some cases where both net benefits and economic impacts can increase or decline together. Only estimating the effects of a proposed fishery management regulation on net benefits can determine how economic impacts will change in the rest of the economy.

By melding these five components into an overall EAF management framework, a reasoned assessment of the expected direction of change in net benefits to the nation, as well as the specific effects on individual small entities for a proposed regulatory action, can be evaluated. Alternative metrics exist to determine if biological stock conservation goals are being achieved, for example spawning stock biomass per recruit, which proponents argue implicitly represent improvements in net benefits for the fishery, communities dependent on fisheries, regions, and the nation. Unfortunately, these biological based measures of stock abundance do not take into account the time dimension of how individuals value the future in fisheries. Stock conservation objectives can be achieved by very costly or alternatively very beneficial methods. Only explicit measures of net benefits over time accurately indicate if improvements in stock abundance are occurring for participants in various aspects of the fisheries. The present value of net benefits can be calculated based on the formula:

$$PV = \int_{t=0}^{t=T} NRe^{-\delta}dt \qquad (13)$$

where PV = present value, and

NR = the value of the natural resource at a point in time (t),

The present value of net benefits metric represented by equation (13) captures both the biological, economic, and other effects of changes to the fishery system so that different EAF management regulations can be compared. In the approach used in this EAF management model, the discount rate (δ) reflects the future value of the consumptive or nonconsumptive user group. That is, it is not a fixed δ established by an outside authority, such as the U.S. Office of Management and Budget which requires the use of a seven percent discount rate in all U.S. federal cost benefit analyses. Instead, the discount rate reflects the future value of the resource held by each user group represented in the model, and is used to estimate that value to aid decision makers in achieving management goals and objectives.

Linking Climate Change to Ecosystems

The ecosystem model described up to this point is capable of providing estimated changes in economic values and impacts with statistically valid confidence intervals with respect to time. However, a modification is necessary to incorporate climate change into the ecosystem model. Incorporating the uncertainty and risk associated with future hurricane events that result from geophysical cycles or anthropogenic causes of global warming is based on a risk assessment derived from synthetic hurricane tracks (Hallegatte, 2007). With global warming, hurricanes are predicted to increase in both number and ferocity. However, as the numbers of hurricanes increase their ferocity tends to subside as the previous storms extract the warmth from the oceans that acts as their fuel. The more hurricanes, the less fuel, and the less likely the storm is to build into a category five storm. Assuming that the damage function for a fishing firm is related to the ferocity of the storm, the lower will be the damage as storm ferocity subsides, but the higher as the number of storms in the lower categories increase.

A rewrite of the results from Hallegatte (2007) results in the probability of landfall for a hurricane in a particular category that accounts for the uncertainty associated with future events:

$$Pn = 1 - e^{(NQn)}$$

where Pn = probability of hurricane of category n,

Qn = the probability of a hurricane of category n making landfall, and

N = the average number of storms per year.

and the losses that would result:

$$L = a(s)W^3$$

where L = the economic losses in millions of dollars,

a(s) = the local vulnerability at location (s), and

W = the wind speed in meters per second.

These two algorithms for Pn and L are used in a risk assessment to determine the expected damages from hurricanes of different category strengths (1 to 5) for a particular year;[1] i.e.,

$$Q(t) = \log(\mathbf{1}-P(t))/(-N);$$

[1] This could be based on NOAA Weather Service hurricane predictions issued at the beginning of each hurricane season in the U.S.

$d(t) = ((\mathbf{1}\text{-}Q(t))^{Z})\pi;$

where Q(t) = the probability of landfall,
P(t) = the probability of a hurricane occurring in any season,
Damage d(t) = determined by the number of storms that do reach land,
T = the hurricane category (1 – 5) denoting ferocity,
π = the average damage that a hurricane can cause.

These two relationships [Q(t) and d(t)] provide information on the probabilities and expected damages in Tables 1 and 2, respectively. Note that the probabilities of a hurricane of a particular category (P1 – P5) increase over time while the actual probability of landfall (Q1-Q5) initially rises and then begins to decline over time as the number of storms (N) randomly increase over time due to global warming. The expected value of damage (d1 – d5) increases causing the total expected value of damage to increase which is then added to total cost of the fishing operation to account for the risk.

However, the economic effect of climate change is a valuation problem that is determined by analyzing changes in behavior that result from changes in costs and benefits. Based on this integrated, multi-disciplinary, scientific, ecosystem model that includes the human dimension, a multi-cohort fishery would be expected to have yields for various prices at a point in time. Figure 1 represents what those yields and prices per cohort would be if hurricanes did not affect the fishery. In Figure 2, the expected value of hurricane damage to fishing firms is incorporated into the fisherman's investment decision. That is, his fixed costs increase because he bought a very large fishing vessel capable of harvesting fish in the middle of a severe hurricane. Consider the "Deadliest Catch" Discovery Channel show where crabbers have a short fishing season and need a very large fishing vessel to enable them to fish regardless of the weather to remain financially viable. However, this does change fishing behavior resulting in a lower and distorted yield distribution and a higher price for the catch relative to the no hurricane base case. Unfortunately, in this case, profits decline because of the bigger capital investment even though fishing effort levels change very little relative to the base case.

As an alternative, consider the alternative extreme case, represented in Figure 3, where the fisher need not invest in a larger fishing vessel because his season is not limited, but instead adjusts the fishing effort level reflecting the same expected damages of a hurricane season. This is done by adding the expected damages to the variable costs of operating the fishing vessel. In a sense, this is like a shrimper who moves this vessel into a backwater when a hurricane is coming because he knows that the storm will be over in less than 72 hours and he can fish again. This change in behavior, results in a larger distortion in the yield distribution across cohorts with the same price effect as in the fixed cost scenario. Fishing effort levels are reduced and profits are higher than the previous fixed cost scenario, but still less than the no hurricane base case.

Table 1: Occurrence (P_i) and Landfall (Q_i) Probability of a Category 1 to 5 Hurricane

P1	P2	P3	P4	P5	Q1	Q2	Q3	Q4	Q5
0.15	0.125	0.10	0.075	0.05	0.027086	0.022255	0.017560	0.012994	0.008549
0.16	0.135	0.11	0.085	0.06	0.058118	0.048342	0.038845	0.029610	0.020625
0.17	0.145	0.12	0.095	0.07	0.016939	0.014241	0.011621	0.009075	0.006597
0.18	0.155	0.13	0.105	0.08	0.022050	0.018713	0.015474	0.012326	0.009265
0.19	0.165	0.14	0.115	0.09	0.021072	0.018032	0.015082	0.012217	0.009431
0.20	0.175	0.15	0.125	0.10	0.024794	0.021375	0.018058	0.014837	0.011707
0.21	0.185	0.16	0.135	0.11	0.019644	0.017047	0.014529	0.012085	0.009711
0.22	0.195	0.17	0.145	0.12	0.019112	0.016686	0.014333	0.012050	0.009833
0.23	0.205	0.18	0.155	0.13	0.023760	0.020856	0.018041	0.015311	0.012660
0.24	0.215	0.19	0.165	0.14	0.017152	0.015129	0.013170	0.011270	0.009426

Table 2: Expected value of Damage due to a Categories 1 to 5 Hurricane (d_i)

d1	d2	d3	d4	d5	Total Damages	Total Operating Costs	Predicted Number of Hurricanes
32.306	60.005	109.207	194.983	341.911	738.41	758.41	6
0.562	2.042	7.066	23.349	73.896	106.92	126.92	3
118.183	166.468	231.967	319.979	437.185	1273.78	1293.78	11
61.599	94.296	142.371	212.186	312.398	822.85	842.85	9
69.797	102.836	149.621	215.133	305.906	843.29	863.29	10
43.357	67.152	102.506	154.355	229.472	596.84	616.84	9
83.753	116.568	160.493	218.736	295.281	874.83	894.83	12
89.620	122.053	164.541	219.712	290.762	886.69	906.69	13
49.494	71.752	102.723	145.344	203.391	572.70	592.70	11
115.021	148.728	190.673	242.494	306.085	1003.00	1023.00	16

Summary

This EAF management model is flexible and incorporates multiple species, stocks, resource areas, cohorts, fleets, and vessel classes. It employs two feed-back loops for fishing effort and fish stock population dynamics using fishing mortality as the state variable. Spawning stock biomass per recruit, yield per recruit, exploitation rates, catch per unit effort, net benefits including existence values, and direct, indirect, and induced economic impacts are generated over the long-run for different governance regimes ranging from open access to sole owner management of the resource. Under different governance regimes, EAF management regulations would invoke different responses by fishermen resulting in different outcomes, some of which might be considered counterintuitive. Counterintuitive results are more likely as the number of fleets increase and become more heterogeneous as the number of vessel class dimensions increase.

The economic effect of climate change depends on how individual behavior changes as a result of the environmental change. Severe storms of long duration with short fishing seasons due to regulated open access management cause fishers to invest in capital that allows them to operate in the harshest conditions. Alternatively, storms of relatively short duration compared to the length of the fishing season cause fishers to stop their harvesting operations until the storms pass. Both strategies result in substantially different profit and yield per cohort levels than would result in the no storm scenario. The question that remains for managers is whether regulations could be postulated that result in a reduced risk from climate change on fishing operations. Economic values either increase or decline depending on how the industry responds to the affect and its governance infrastructure. If the costs of these regulations are less than the foregone consumer and producer net benefits, then an improvement in human welfare would result. Although not presented here, once the net benefits are estimated then the economic impacts on jobs, income, and sales can be determined for each potential climate change scenario. Most important, in determining how individual behavior as well as net benefits will change, is the need to work with other scientific expertise to incorporate the uncertainty and risk of climate change into the expected damage function for each industry sector.

While the quest to attain perfect information is akin to the search for the Holy Grail, the failure to effectively utilize existing information is a far more deadly sin for ecosystem managers. This simple model demonstrates that relatively minor changes in the human response to climate change can result in radically different outcomes in levels of yield, prices, value or net benefits, and economic impacts. A multi-disciplinary ecosystem model that incorporates the human dimension even if information is imperfect yields an integrated management framework that provides more useful information to managers than does its individual parts. Most importantly, rather than squandering scarce resources on repetitious analyses, attention can be focused on research to provide missing information necessary for management of our precious global marine resources.

Figure 1 Base Case: No Hurricane Effect

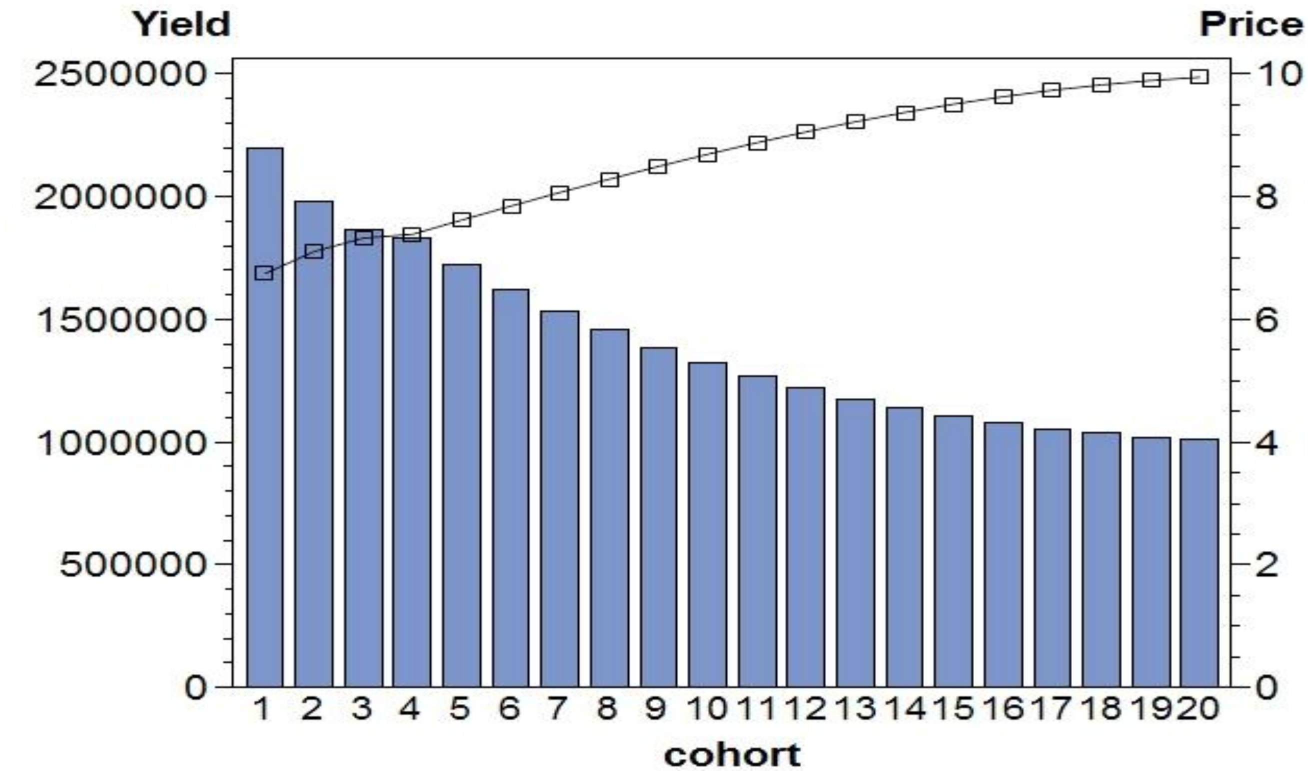


Figure 2: Variable Hurricane Effect on Yield and Prices for Changes in Fixed Costs

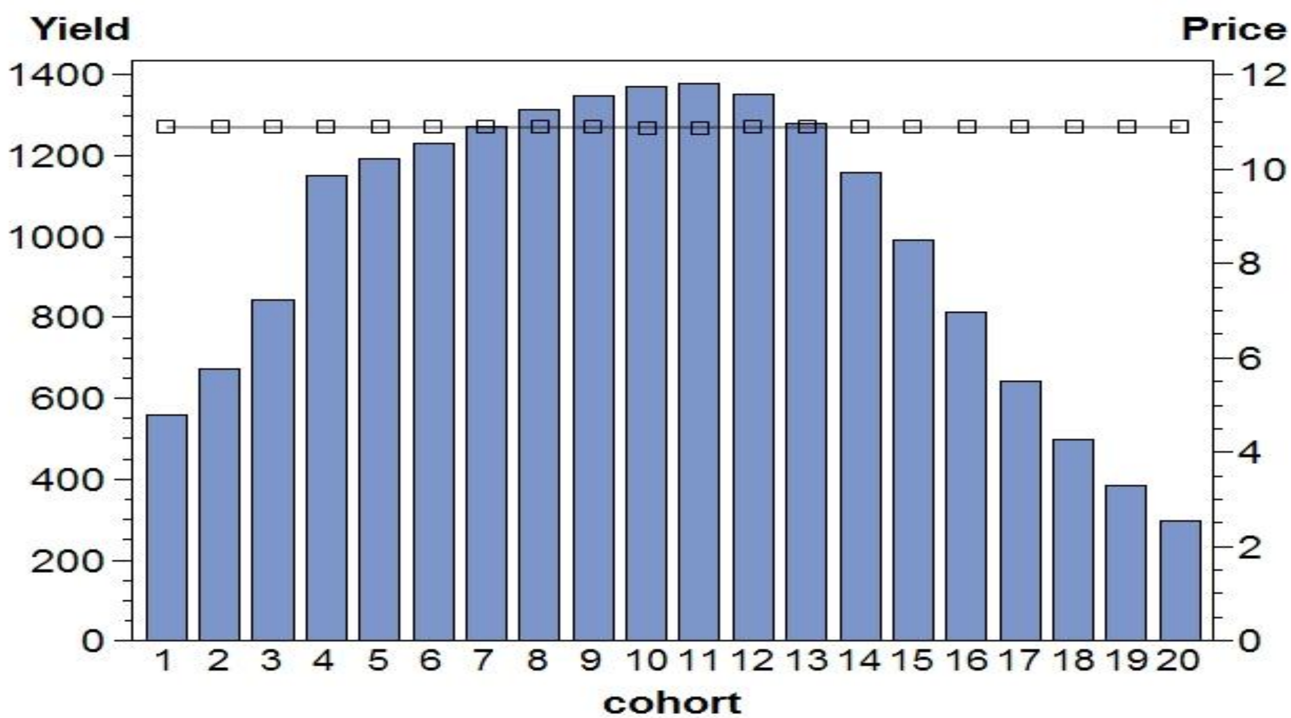
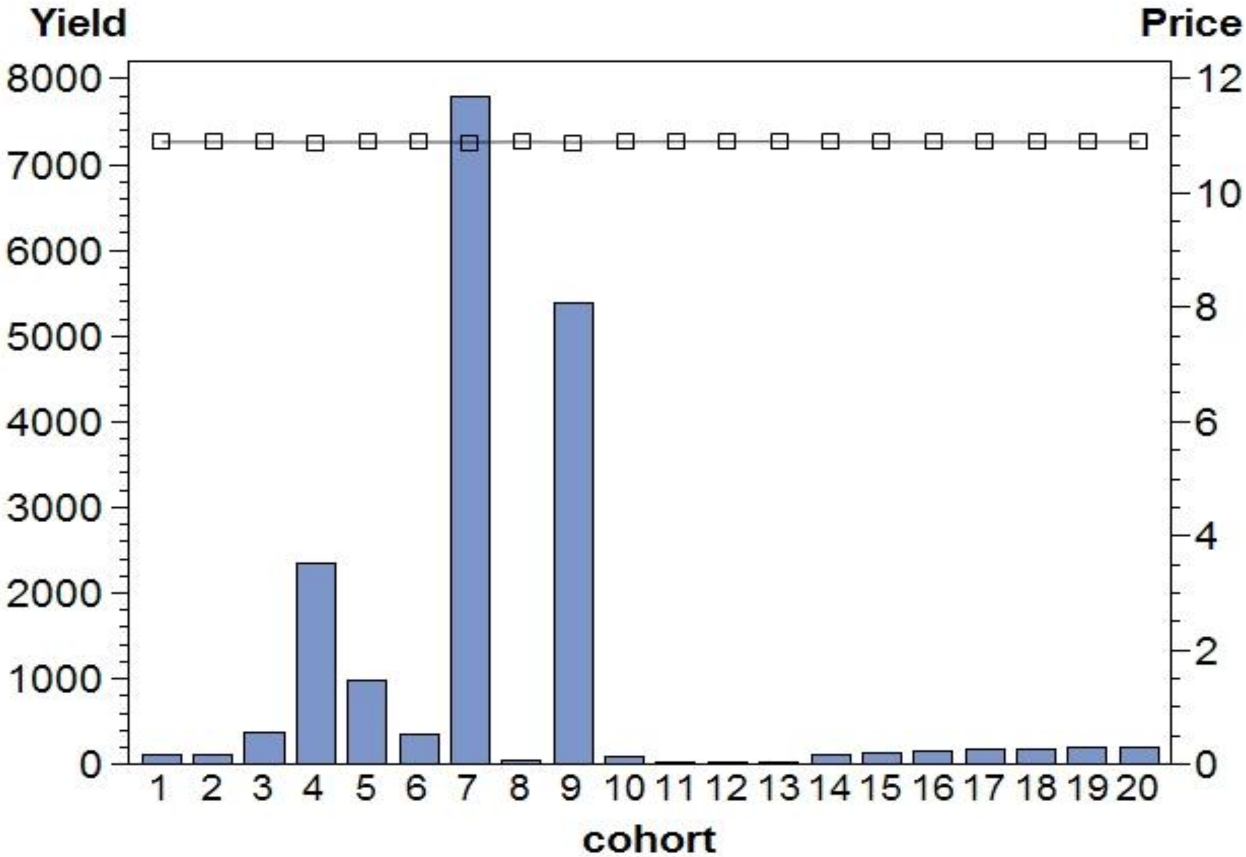


Figure 3: Variable Hurricane Effect on Yield and Prices for Changes in Variable Costs



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