Impact Analysis of NASA Earth Science Applications Project

The Pelagic Habitat Analysis Module (PHAM)
&
Improving The National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) & International Commission for the conservation of Atlantic Tunas (ICCAT) Atlantic Bluefin Tuna Fisheries Management Decision Support System

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Table of Contents

List of Text Boxes

List of Figures

Executive Summary

The NASA Applied Sciences Program supports efforts to discover and demonstrate innovative and practical uses of NASA Earth Science data and knowledge. The program funds applied science research and applications projects across a range of themes to enable near-term uses of NASA Earth science by public and private organizations.

The loss and decline of fisheries can cause devastating economic and environmental impacts in countries and markets across the globe. In 2004 and 2007, the Applied Sciences Program initiated projects selected under open, competitive solicitations. Two projects, *The Pelagic Habitat Analysis Module (PHAM)* and *Improving the NOAA NMFS & ICCAT Atlantic Bluefin Tuna Fisheries Management Decision Support System*, focused on improving assessments of fisheries stocks using satellite observations of parameters including: sea surface temperature, salinity, thermocline depth, currents, chlorophyll concentration, and frontal boundaries. Better knowledge of fish spawning (reproduction) and recruitment (growth to adulthood) leads to more robust estimates of fish population sizes and growth rates. These improved estimates enable international fisheries management organizations to formulate more informed policies for managing stable and productive fisheries, thereby mitigating the risks of stock collapse, extirpation (localized population extinction), and species extinction.

To estimate the immediate and potential future socioeconomic impacts of the two projects, the Applied Sciences Program assembled an analytic team to develop an impact analysis based on both projects. The team conducted interviews with subject matter experts, soliciting estimates of the relative value that Earth observations contribute to accurate stock size assessments, both through improvements in targeting larvae sampling sites and through improvements in calculating population size. The experts provided consensus estimates of the reduction in uncertainty that might reasonably be attributable to the NASA projects. The analytic team also examined relevant literature pertaining to fisheries management when the actual stock size is uncertain. These studies provided a framework for determining the differences in management policy associated with varying levels of stock size confidence, measuring the resulting differences in allowable catches, and assessing the relative change in the likelihood of a stock collapse. Using data from the United Nations Food & Agricultural Organization (FAO), the analytic team estimated the relative value of improved stock size estimates resulting from use of the Earth observations. This value is the sum of marginally higher catch rates (valued at market prices) and the costs avoided by preventing a stock collapse.

Based upon modeling analysis and expert opinion on the reduction in uncertainty of fisheries stock size and recruitment estimates, the team estimated that the NASA projects reduced the probability of a collapse of Atlantic bluefin tuna fisheries over the next 10 years by approximately 17 percent based on the reduced stock size uncertainty (for optimal management). Applying this reduction in risk to a set of assumptions about the risk of collapse, the analysis yielded *net present values of risk mitigation* for the NASA projects of $21 million for Atlantic bluefin, $3.1 million for Pacific bluefin, and $0.3 million for yellowfin fisheries.

Introduction

A. NASA Applied Sciences Program

The NASA Applied Sciences Program supports the Earth Science Division within the NASA Science Mission Directorate. The overarching purpose of the Applied Sciences Program is to discover and demonstrate innovative uses and practical benefits of NASA Earth science data, scientific knowledge, and technology.

The program funds applied science research and applications projects to promote innovative use of NASA Earth science data for near-term societal benefits. Overall, the Applied Sciences Program serves as a bridge between the data and knowledge generated by the NASA Earth Science Division and the information and decision-making needs of public and private organizations. To this end, the program increases the benefits to society of the Nation's important investments in NASA Earth science.

The Applied Sciences Program primarily works through partnerships with public and private organizations to improve their internal decision-making activities and/or the products and services they provide their constituents and customers. Where NASA Earth observations and modeling capabilities are evaluated to have potential application, NASA and the partner organizations collaborate to test and integrate the data and modeling capabilities into the decision making and/or products and services. These collaborations involve appropriate academic, business, nonprofit, and other entities to accomplish the project and extend the results.

B. Challenges Addressed by the NASA Fisheries Projects

Tuna are a high-value commodity that generally live and are caught in international waters. As a result of the questionable property rights associated with international fisheries, competition is fierce and incentives for countries to overfish many species are strong—a classic "Tragedy of the Commons." Due to a lack of ownership rights over the fishery, no one entity is responsible for keeping the stock healthy and the catch rates sustainable in the long run, and individuals' actions can result in a less than optimal result for all. To address this problem, the international fisheries management agencies oversee the fisheries to ensure stable populations, while also balancing the economic well-being of the fishermen, the various countries affected by the active management of the species, and the overall sustainability of the market. A 2009 study by the World Bank and FAO[1] found that proper fisheries management could recoup $50 Billion in annual value worldwide, and that the state of many fisheries risk potential stock collapse.

Imperfect data concerning the overall size of a fishery stock poses a significant risk to the proper management of a fishery, threatening both the survival of the species, as well as the economic wellbeing of those that depend on the stock for their livelihood. If the stock size is uncertain, the "optimal" catch rate can be hard to determine, as the appropriate catch rate depends on the size of the breeding stock currently active. Armed with poor estimates of the stock size, a fishery manager could set the quota either too low or too high. Either of these possibilities is problematic. Overfishing can lead to significantly reduced quota in future years, downward spiraling stock sizes, stock collapse, or even species extinction. Conversely, under-fishing can harm the livelihood of the fishermen and unnecessarily drive up commodity prices, which could have severe

[1] *Sunken Billions – The Economic Justification for Fisheries Reform.* 2009.

economic impacts for some countries.[2] As a result, the operation of an international fishery has the potential to greatly impact the environment, and also has significant economic and political implications. Two articles in the February 25th, 2012 edition of *The Economist*[3] discuss these problems in depth, and the associated importance of proper stock assessments.

- ICCAT – The International Commission for the Conservation of Atlantic Tunas
- IATTC – Inter-American Tropical Tuna Commission
- IOTC – Indian Ocean Tuna Commission
- WCPCF – Western and Central Pacific Fisheries Commission
- CIAT – The International Center for Tropical Agriculture

Box 1 – International Tuna Regulatory Agencies

Currently, five international fishery regulatory bodies (see Box 1) oversee the sustainable management policies of most species of tuna in different parts of the world. While most species overseen by these agencies appear to be maintaining robust populations, Atlantic bluefin, Pacific bluefin, and bigeye tuna populations are declining.[4] Were there to be large-scale stock collapse, the monetary costs to these markets would be substantial. In 2009, the world tuna catch (all species) was over four million metric tonnes, representing well over $7B in gross sales. As this analysis shows, several of these species have experienced dwindling populations (and steadily increasing prices), threatening well over $1B worth of revenue over the next decade. The value of obtaining good estimates for population size and recruitment rates of the stock increases as populations decline and the threat of a stock collapse gets closer. Simultaneously, the difficulty and cost of assessing the stock increases as populations decline and proper sampling becomes both harder to carry out and more prone to error. While the pace of stock depletion varies across species, several multi-million dollar fishing industries face a significant chance of stock collapse over the coming decade, including a very high probability of collapse in the Atlantic bluefin tuna.[5] As this analysis shows, collapse of the Atlantic bluefin population could result in revenue losses well over $500 million over the next decade. Thus, tools that facilitate better estimates of the true stock size play an increasingly valuable role in designing proper management strategies and protecting the extremely valuable market. Proper management of these renewable resources requires finding an equilibrium whereby catch rates (and other factors that cause attrition) are not greater than the rate of recruitment and stock expansion (see Appendix C for an overview of fisheries stock dynamics and assessment).

In particular, the market for Atlantic bluefin tuna is extremely contentious, due to the relative scarcity of the population. This scarcity, paired with robust demand growth, has driven significant price increases over the past decade.[6] The price for the Atlantic

[2] Note that under-fishing could also increase demand for substitute species, which might put pressure on other species or food chains
[3] Articles "Fisheries Lost" and "How to Stop Fishermen Fishing"
[4] Based on stock size data reported in the FAO Fishstat database (see section 2.A) and expert interviews
[5] Based on expert interviews, news and journal articles, as well as, two FAO reports listed in Appendix E - References and the FAO Fishstat J databases.
[6] For example, a 754-pound Atlantic bluefin sold for a record $396,000 on January 5, 2011. Note that the price was significantly higher than the market as a result of the rarity of this particular outsized catch. However, that these large above-market windfalls are possible further incentivizes fisherman to over-fish. See MSNBC article referenced in Appendix E.

bluefin tuna surged from under $200 per tonne in 1995 to $1400 in 2007[7], reflecting that increased demand. This increased demand resulted in more incentives to supply the resource to market which pushed that species to the brink of collapse. The Atlantic bluefin tuna spawning biomass steadily decreased over the last several decades, on both sides of the Atlantic.[8] Several other factors have also contributed to these problems and will likely contribute to these problems in the future, including over-fishing and population declines of the bluefin's food sources, as well as potentially lasting disruption of breeding grounds in the Gulf of Mexico caused by the Deepwater Horizon oil spill in 2010. The importance of fisheries management policies will therefore continue to play an essential role in the survival of this lucrative commodity market and the continued existence of the species.

There are currently several programs that incorporate Earth observations into their efforts to gauge the size of Tuna stocks. Satellite sensor data is proving to be helpful in determining stock size through several different mechanisms: data on temperature and currents can help determine effective geographic locations for surface-level sampling of stock counts, and data on temperature, currents, and salinity can provide inputs to models for estimating seasonal recruitment rates. This space-based sensing has the potential to influence management policy going forward[9]:

- Remote sensing data can identify areas with appropriate conditions for sampling the stock size. Figure 1 shows an example of such data used in the PHAM.

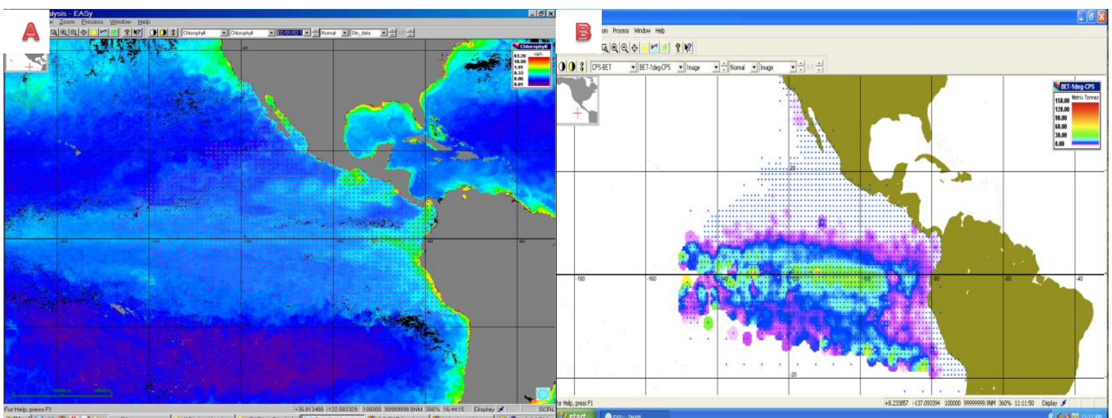

Figure 1

- Panel A shows an example of the PHAM screen of SeaWiFS image of surface chlorophyll, which can help identify where fish species are likely located, and IATTC's tuna fishery stations.
- Panel B shows PHAM screen of distribution of big eye tuna catch per set for IATTC's 34 year time series

- Remote sensing data can also be used to develop better stock position forecasts, resulting in reduced resource usage and fishing intensity required to locate and collect maximum fish catch. Figure 2 panel A shows an image

[7] Chart of the prices can be found in Appendix D, Figure D-1.
[8] Graphic of spawning biomass compared to catch rate can be found in Appendix D, Figure D-2, as well as catch tonnage in Figure D-4.
[9] Principal investigator interviews.

identifying currents and temperatures using remote sensing data. Figure 2 panel B is a screen shot from a NOAA product on predictive models of stock spawning locations that was developed in part using the circulation model depicted in Panel A.

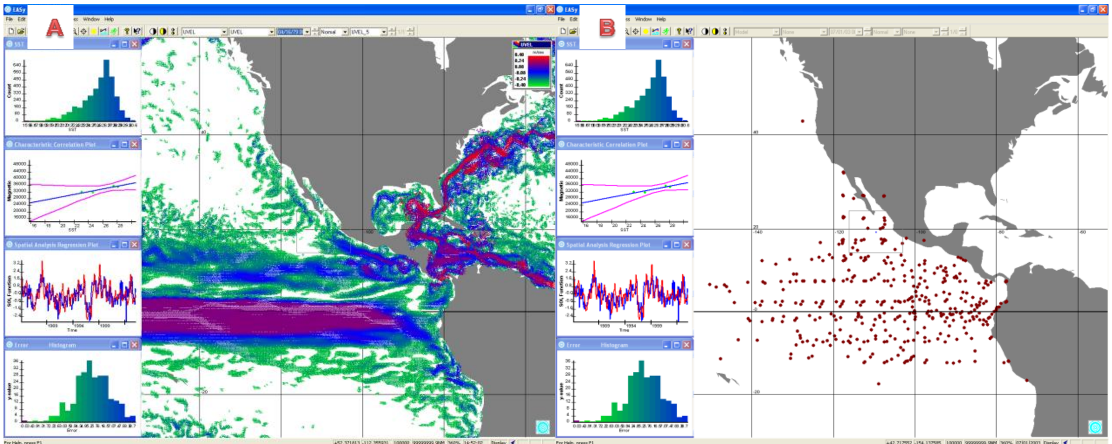

Figure 2

- Panel A shows an example of the PHAM screen of NASA's ECCO-2 global circulation model
- Panel B shows a map of skipjack spawning sites calculated from NASA's ECCO-2 global circulation model and fisheries age structure analysis of catch.

C. NASA Applied Sciences Fisheries Projects – 2 Case Studies

The Applied Sciences Program selected two projects as case studies for this analysis; 1) *Improving the NOAA NMFS & ICCAT Atlantic Bluefin Tuna Fisheries Management Decision Support System* and 2) *The Pelagic Habitat Analysis Module (PHAM).* The projects focused on systems with similar traits in trying to identify information and key factors concerning the environment that help predict the location of several species of marine wildlife; this information can contribute directly to the accuracy of stock assessments. As the analysis in this paper demonstrates, improved stock assessments in managed fisheries can lead directly to reductions in risk of stock collapse and to higher sustainable catch rates, and lower the at-sea cost of observing and collecting the data. By securing better stock assessments, fisheries managers can more accurately estimate how their annual decisions will influence the population dynamics and properly assess how close to collapse their annual catch rates will bring the population.[10] Thus, these two projects potentially contribute to optimal management of the fisheries, as they refine the inputs upon which the managers base their decisions.

1. Atlantic and Pacific Stock Estimates and Stock Tracking

A. Project Descriptions

The two projects, described below, rely on NASA Earth observations to estimate the size of several fish species. The data provided by NASA are instrumental in the production of stock size estimates of certain species in the Pacific, Atlantic, and Gulf of Mexico.

[10] A basic discussion of fisheries population dynamics can be found in the Appendix C.

Several regulatory bodies use these stock size estimates to perform their functions; thus, the data NASA has made available greatly aids worldwide fisheries management efforts.

i. The NOAA NMFS and ICCAT Atlantic Bluefin Tuna Fisheries Management Decision Support System Project

The *NOAA NMFS and ICCAT Atlantic Bluefin Tuna Fisheries Management Decision Support System* project focuses on extending Earth science research results to decision support systems in ecological forecasting—a National priority. The project seeks to improve the existing NOAA National Marine Fisheries Service decision-making system for population assessment and management of Atlantic bluefin tuna (*Thunnus thynnus*).

Roffer's Ocean Fishing Forecasting Service, Inc. (ROFFS) has undertaken an effort to create better estimates of the stock size of the Atlantic bluefin tuna, with the goal of providing NOAA and ICCAT better estimates of the declining size of the population spawning in the Gulf of Mexico. Data employed in the project includes virtual population analysis, as well as larvae surveys using aerial and remote sensing data. These data help measure the time and duration of the breeding season by identifying when conditions are conducive to successful breeding. Also, the remote sensing data provides measurements of the ocean temperature and currents, which help direct the ocean surface survey crews to optimize their sampling locations and the placement of their measurement buoys, further improving the estimates of stock size.

Furthermore, the authors of the study found that the sampling properties of the fish population are not normally distributed, and thus the need for precision placements and measurements is significantly higher than one would traditionally expect for an optimal stock assessment; this situation means that sampling in areas without larvae is even more costly, as their absence cannot be predicted as well as would be the case with a normalized distribution. As the cruises used to measure the stock cost more than $20,000 per day, and since the market for bluefin tuna is so lucrative, the opportunity cost of poor sampling, and the resulting poor stock estimate, are quite high.

The information provided by the NASA remote sensing data and models helped to identify areas with high probabilities of containing bluefin larvae. Also, the NASA-enabled data are extremely effective at identifying areas where the environment suggests there will be no bluefin larvae (93% success rate), implying no need for sampling in those areas. These results can minimize the costly time that measurement cruises spend on the water, while also maximizing the results desired from the analysis.

The NASA project team estimated that using remote sensing as a tool for determining stock estimates to aid in targeted adaptive sampling efforts ultimately reduced the estimated variance by 50% of mean.[11] This reduction suggests that remote sensing data can potentially play a large role in the proper identification of the bluefin stock size in the Gulf of Mexico, as well as that of other species elsewhere in the world. Similar results are also seen in other analyses of comparable topics.[12]

The project investigators also note that the NASA remote sensing data is helpful in other ways. The recent oil spill in the Gulf of Mexico caused by the Deepwater Horizon had the potential to significantly disrupt the bluefin larvae population. Some initial estimates

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[11] Estimates derived from interviews with project investigators, as well as other references and interviewees suggested by the research.

[12] The study cites similar results from ABT Med, NOAA, Univ. of Miami, Fish & Wildlife Service, and Univ. Southern Mississippi.

suggested so much damage to the juvenile stock that bluefin would need to be placed on the Endangered Species List. This situation would have severely impacted the worldwide market for bluefin tuna, and further devastated the fishing and tourism industries in the Gulf and along the Eastern Seaboard. NASA remote sensing data helped determine that the spill would influence only 5-15% of the fish stock based on traditional breeding grounds, as compared to some initial estimates of as high as 90%.[13]

ii. Pelagic Habitat Analysis Module Project: Enhanced Decision Support for Pelagic Fisheries and Marine Sanctuaries

The objective of the Pelagic Habitat Analysis Module project is to provide an advanced information system that will enhance decision support systems at agencies managing pelagic fisheries and marine protected areas. PHAM leverages streams of NASA research products and integrates them with multivariate datasets in support of marine-resource management applications. Managers of marine fisheries at the Inter-American Tropical Tuna Commission (IATTC) and the NOAA Southwest Fisheries Science Center (SWFSC) incorporate the information on habitat provided by PHAM into stock recruitment and stock assessment models.

NASA remote sensing data was critical to the development of the PHAM. PHAM is a geographic information system that offers custom integration and analytical tools to help marine sanctuary managers better identify the stock size of several species of fish and shark in the Pacific, and gauge factors that will better predict the recruitment rate of the species of interest. The PHAM project's goal is to develop a decision support system that merges NASA remote sensing data and models with fishery data to define the habitat of commercial and threatened pelagic species. The Eastern Pacific Ocean (EPO) Tuna application helps improve stock assessment of tropical tuna species of the eastern Pacific, and the Cal Pelagics application improves stock assessment of albacore (*Thunnus alalunga*) and sharks of the California Current.

PHAM, and the information it provides, can help authorities better manage fisheries. One of the model's major contributions is mapping the spawning sites of several species based on the presence of chlorophyll in the water, juvenile drift, currents, and temperature shifts from El Niño. Without NASA remote sensing data, these factors would be much harder to assess, and the estimates of future stock size changes much less robust. PHAM will greatly aid in producing new and improved stock assessment models, allowing for better fisheries management and reducing potential costs from stock size uncertainty.

B. Potential Benefits

The contributions from NASA remote sensing data can greatly increase the precision of fish stock estimates, which in turn can lead to better management of fisheries. Improved management of fisheries has several positive benefits:

- Protection of several valuable commodities markets
- Sustainment of profitable sport-fishing and tourism markets that depend on open fisheries and reasonably efficient methods of catching the fish
- Assurance that the species remain a valuable and renewable product year-in and year-out

[13] Principal investigator interviews.

To properly maintain a fishery, managers must identify both the current size of the stock and the factors that influence stock growth rate. The NASA data aid in measuring stock size and forecasting future growth, and help reduce the effort and resources required to reach the annual catch quotas. Without accurate stock information or proper management, stocks are likely to collapse or species could become extinct.

While gathering the information necessary to properly manage a fishery can be costly, not doing so could be catastrophic. Fisheries in general, but especially fisheries with international ranges, are classic examples of failed economic markets.

- Since the fish are a finite resource, and the ability to catch the fish is reduced as the population dwindles, there is a clear advantage to fishermen that arrive first: the effort expended on catching the fish is lower and the likelihood of not earning as much profit due to a smaller catch is lower
    - Thus, it is in a fisherman's best interest to expend a portion of the resources gained from being early to arrive first and capture as many fish as possible, rather than catch a sustainable amount
- Since ownership stakes in the fishery do not exist, there is an incentive to run down the entire fishery stock rather than fish a sustainable amount
- Holding back on the catch size to ensure that the resource regenerates sustainably only works if every fisherman agrees to do so
    - If other fishermen deviate and fish as much as possible, the act of accepting a sustainable (smaller) catch merely enriches the other fishermen who pick up the leftover catches, rather than ensuring a robust stock in the next season

Because individuals' incentives are not aligned with the general welfare of the world commodity market and the sustainability of the species, fisheries are prime candidates for regulation and management.

However, sustainable management of a fishery requires that the stock size be gauged accurately to maximize both the profits of the fishermen and the likelihood of a sustainable stock. Setting quotas too low can needlessly limit the earnings of the fishermen; setting quotas too high can imperil the stock just as much as not regulating it. Since the regeneration rate of the species is directly tied to the stock size, the appropriate sustainable catch size is also tied to the stock size. Therefore, formulating optimal policy requires a robust estimate of the stock size. As such, anything that reduces the uncertainty of a stock size can create better policy regimes, potentially creating significant value through avoided losses and increased fishing revenues.

2. Socioeconomic Impact - Methods

The methodology for estimating the potential impact of NASA remote sensing data relies on finding the change to the present discounted value of the fisheries that result from the use of NASA remote sensing data. This evaluation is done in a series of steps. The first step is to assess the "value" of the market for the Atlantic bluefin tuna and other fish managed by the relevant bodies, and thus the effective cost associated with the collapse of the fishery stock. The second step involves estimating the reduction in uncertainty surrounding the stock size estimates associated with the NASA remote sensing data; these estimates are based on interviews conducted in the course of the analysis and on expert estimates as to the reduction in uncertainty in stock size. These estimates were combined into a consensus estimate. The third step is to calculate the net change in optimal fisheries management associated with this more accurate stock-size assessment.[14] This calculated change influences the present discounted value of the market, which is the difference between the initial value of the markets under uncertainty and the value after reducing the uncertainty in the estimate. This value represents the change attributable to better information. A discussion of how these estimates are derived is provided in the following sections.

A. Valuation of Fisheries Using Fishstat (FOASTAT J)

The market values of the fish markets are constructed using the Food and Agricultural Organization's tool FishStat J.[15] The tool includes time-series data on previous years' catches, including tonnage and value. Additionally, the tool includes a database documenting international trade flows associated with the species- and commodities-specific flows. These data are used to construct the rough market value of annual sales of the species of interest; from this value, a rough calculation of the present discounted value of the fisheries is calculated. This calculation serves as the baseline for the value of avoiding a stock collapse.

B. Managing Under Uncertainty: The Da-Rocha and Gutierrez Framework

Da-Rocha and Gutierrez (2010) created an extended framework whereby they examined the role of uncertainty in stock size and the minimum reproduction rate in determining the optimal fishery management strategy, as well as the within-season choices made by fishermen. Using a much-simplified version of this framework that focuses on the fishery manager only, a method for determining the value of uncertainty associated with the stock size is created. This method reflects that the optimal sustainable management policy of a fishery is a function of both the size of the stock and the recruitment rate. Following from the literature, and backed by their estimation, Da-Rocha and Gutierrez find that the optimal management policy and the likelihood of stock collapse are both directly impacted by the uncertainty surrounding the stock size. Under stock certainty, Da-Rocha and Gutierrez (and other sources from the academic literature) report that a constant recruitment policy is optimal, whereby only a drop in stock size below a certain threshold requires closing the fishery.

Under uncertainty, a constant recruitment policy is no longer possible, as the level of recruitment is no longer certain at the end of the season. Since the optimal policy requires that a year's catch be exactly replaced by new fish, and the level of replacement is directly tied to the spawning population within the stock, not knowing the stock size implies that catch rates can be higher or lower than replacement rates. As such, the regulators either need to lower catch rates in proportion to the uncertainty of their estimates to avoid reducing the stock to an unrecoverable level, or allow higher current catch rates at the expense of increased future risk of fishery closures, stock

[14] This calculation relies on the theoretical framework laid out by Da-Roche and Gutierrez (2010).
[15] FishStat J is the newly released next generation of their previously available program FishStat Plus.

collapse, or even species extinction.[16] Thus, the more uncertain (or volatile) the stock estimate is, the higher the probability of an incorrect catch quota being set.

Thus, in terms of NASA remote sensing data, more accurate tracking of spawning, larval drift, stock movements, and water conditions that are conducive to better breeding can enable more robust dynamic stock estimates. A stronger understanding of the current stock and future stock allows for more sustainable (and less volatile) quotas, reducing the waste associated with overly restrictive limits and the catastrophic costs associated with a stock collapse.

C. Optimal Stock Management Under Uncertainty

According to the literature, optimal management of the stock requires that the marginal benefit of further fishing is equal to the marginal cost. In the model used in estimation, the stock size is required to be such that the catch rate matches the recruitment rate at an equilibrium level of stock that maximizes profits across all seasons. The population follows the following growth dynamics:

(1) $X_t = (1 + z_t) * F(S_{t-1}, \delta)$

(2) $S_t = X_t - H_t$

(3) $Q_t = f(E[S_t], \delta)$

Here, X_t is the size of the stock in period t, z_t is the amount of uncertainty[17] associated with the size of the stock's breeding population carried forward from the previous season, S_{t-1}. The term δ is the regeneration rate of the breeding stock and is a constant percentage of the stock size in each period. H_t is the size of the harvest, and Q_t is the quota on catches set by the fisheries' manager, and is solely a function of the fisheries expectations of the likely carry forward of the breeding stock.

In the model, we are assuming there is some minimum level of recruitment, $\bar{S}$, for a stock collapse to be prevented. If the stock collapses, all future seasons are considered cancelled, making the income from future seasons nil. Thus, for simplicity, it is assumed that:

(4) $S^* \geq \bar{S}$

(5) $Q_t \geq H_t$

Where the equilibrium value of the annual recruitment, S^*, is large enough to prevent a stock collapse, and there is no "cheating" by the fishermen (so that the quota is never exceeded). Thus, the fisheries manager will want to optimize the following:

$$\max_{\{Q_t, S_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t Q_t$$

Subject to:

$$S_t = F(S_{t-1}, \delta) - Q_t,$$

And:

[16] Note that, while the multi-year dynamics of Tuna growth to adulthood makes the likelihood of species extinction lower (as several years of low catch can allow regulators time to close the fishery without exhausting future breeding stock), the slow replacement rate and long lags can also make over-fishing more costly, as costs of longer duration closures may be increasing in a non-linear way due to liquidity issues or bankruptcies.

[17] Note that $z_t \sim N(0, \sigma)$

$$g(z_t, \delta, X_t) * S^* \geq \bar{S}$$

This constrained optimization implies that the regulator wants to maximize the sum of the present value of quotas over time, subject to the stock *S* being reduced by the quota *Q*, and with the requirement that the current (uncertain) stock *S* must be greater than the level at which fishery will collapse, $\bar{S}$, in all periods. The uncertainty factor *g* is a safety term that the regulator applies to his current stock estimate *S** to ensure that the actual stock does not fall below the collapse level $\bar{S}$. Future years' quotas are discounted by a factor β, meaning that high quotas next year do not "count" as much as high quotas this year in the regulator's sum of value.

In the deterministic case, where z_t = 0 (that is, where there is no uncertainty), the second constraint does not matter, as we have assumed that $S^* \geq \bar{S}$. Under this scenario, the optimal solution is to set Q_t to carry forward a stock of size S^*, which is equal to the point where the slope of the growth function is equal to the inverse of the discount factor, β.

However, in the case where $z_t \neq 0$, the regulator must guard against the possibility of a stock collapse, because any large disturbance that reduces the stock size below replacement level would permanently reduce future catches to zero. Thus, the equilibrium value of the stock occurs at the level where the cost from the collapse of all future years of income is balanced by the foregone income from slightly lower quota values. The regulator thus choses S^* to maintain a sufficiently large cushion above $\bar{S}$ as a way to avoid stock collapse.[18] Based on the Euler equation, this situation occurs at the point where the slope of the growth function, g', is equal to the inverse of the discount factor. As such, decreases in the variance of z_t will decrease the cushion used to prevent stock collapse while also increasing the net present value of the market.

Thus, anything that decreases the uncertainty surrounding the size or behavior of the breeding stock that is carried forward into the next season will allow for an equilibrium with larger catches and a lower probability of stock collapse (or extinction).

3. Findings and Conclusions

A. Summary of Findings

i. Market Size

According to the Fishstat database, the 10-year average value of the Atlantic bluefin tuna market alone is $28.5 million per year (averaging 32,000 tonnes per year). Atlantic bluefin tuna is considered an extremely overfished species. The catch rates have been declining over the past few years, and the species could potentially be poised for a stock collapse in the next few decades, if not the next few years.[19] There are several indicators suggesting that the Atlantic bluefin stock is in danger:[20]

- 1996-2001: The annual catch plummeted 60%, from >52,000 to ~21,000 tonnes

[18] Formally, $S^* - \bar{S} = g'(\sigma^2) * \frac{d(S^*-\bar{S})}{d\sigma^2}$, where $\frac{d(S^*-\bar{S})}{d\sigma^2} < 0$

[19] Note that there are a wide variety of estimates of when a stock collapse could occur that range from no probability to imminent collapse. For example, the World Wildlife Fund estimates as early as 2012, as discussed here: http://wwf.panda.org/?162001/Mediterranean-bluefin-tuna-stocks-collapsing-now-as-fishing-season-opens. Most estimates are for a stock collapse much later.

[20] All data cited are from FishStatJ. See Figures D-3 and D-4.

- 2007: Total sales approached $50 million in 2007, suggesting a supply shock amid healthy demand, as prices rose and quantity fell, despite the reduction in catches
- 2009: Although reduced, the price per pound remained high in 2009 despite the world recession, suggesting continued supply pressures despite less robust demand
- 2010 & 2011: Prices rebounded, signaling the potential for increasing demand.

Using these data and a discount rate of 5% per year[21] on the 10-year moving average of sales volume, the present discounted value of the Atlantic bluefin revenues is potentially $570 million over the next decade (in 2011 dollars). Thus, a collapse or complete shut-down of the fishery[22] could have first-order economic costs exceeding half a billion dollars. Additionally, this economic shock could have multiplier effects, as the reduction in income in the fishing and distribution industries would reduce demand in the home communities of these fishery-dependent workers. Further, the absence of bluefin tuna would likely put pressure on "substitute" species, potentially threatening other fisheries.

While other fish species are not considered as in danger of a stock collapse as the Atlantic bluefin, there are other species that are considered to be significantly over-fished and potentially facing a stock collapse as well. One of these species is the Pacific bluefin:

- The Pacific bluefin has annual sales averaging $20.3 million (9-year average based on data availability)
- Using the same valuation methodology as with the Atlantic bluefin, the Pacific bluefin projects to have revenue of over $400 million over the next decade

Thus, the markets for these two threatened species of bluefin represent fairly substantial revenues, reaching roughly $50 million per year and with a discounted revenue worth over $1 billion. In all, when also including relatively well-managed species, the market for the threatened species have estimated revenues of nearly $1.2 billion per year, which represents current discounted cash flows in excess of $24 billion.

Further, while generally considered less threatened, the yellowfin Tuna (*Thunnus albacares*) is another species that is considered at risk of future stock collapse:

- The 10-year catch volume for the yellowfin is over 800,000 tonnes per year.
- This catch volume is roughly 25 times that of Atlantic bluefin and 40 times that of the Pacific bluefin,

Thus, including the less threatened species of tuna greatly increases the annual revenues at risk, with recent catch values of $6-$8 billion in the Pacific Ocean alone. Even if the prices of yellowfin tuna are substantially less than the other two species, the sheer size of sales makes the yellowfin another large market with potentially large annual revenues. Even slight improvements in the management of these species have

[21] This number is selected from Sethi et al (2005).
[22] Note that on March 18th, 2010 the US suggested just such a ban, fearing that a moratorium on Atlantic bluefin was already required due to mismanagement of the stock.

the potential to generate significant additional wealth and avoid substantial costs associated with a possible stock collapse.[23]

ii. Reduction in uncertainty estimate and changes to optimal policy

This analysis yielded several key findings concerning the role of NASA remote sensing in properly measuring the size of the fish stock. Based on discussions with the project investigators, as well as several scientists, experts, and academics, and estimates from publically available resources, the consensus is that NASA satellite observations substantially improved the variance of stock estimates.

- The experts suggest that the variance of the stock estimates (and the uncertainty associated with those estimates) was largely mitigated, with the average estimate implying that the coefficient of variance decreased by 50% of the mean value
- This reduction in the variance leads to significantly more accurate estimates of the stocks—information which can filter into the policy decisions of the fishery manager by altering the uncertainty that the manager must consider when setting quotas

Estimation of the stock uncertainty comes from the Da-Rocha and Gutierrez paper, wherein they estimated the uncertainty variance as 0.4050.[24] A reduction of 50% of the variance in this case would lower the uncertainty to 0.2025. This analysis uses the 0.4050 and 0.2025 values as the measures of uncertainty, as well as other parameters calibrated elsewhere in the literature on Atlantic bluefin tuna[25] and other species. Inserting these values into the Da-Rocha and Gutierrez framework, the model yields changes in the probability of complete fisheries closure (or extinction) as:

$$\left(1-\frac{\beta}{\Delta\sigma}\right) * P[closure]$$

When entering the calibrated values from the literature into the relevant regulator's equation, the likelihood of fishery closure or extinction of the species is reduced by 17.3% of the initial value. Unfortunately, only the relative change in closure probability can be identified; finding the level change would require significant assumptions regarding the data.

While the actual values of the likelihood of fishery closures (or extinction) are not known for any species, using *a priori* assumptions is a reasonable test to simulate the relative effect of reducing uncertainty. As an example, using probabilities of collapse for Atlantic

[23] Though not included in this report, the bigeye tuna (*Thunnus obesus*) is another large species that is moderately threatened, with annual average sales of 436,000 tonnes, 14 times as large as the Atlantic bluefin and 22 times that of the Pacific bluefin.

[24] Note that the authors obtain this number from an estimate of Iberian Sardine; there is some evidence that the uncertainty associated with the Sardine stock size is likely substantially lower than the uncertainty surrounding the larger, relatively elusive, and extremely itinerant Tuna species. This suggests that the estimated effects used in this section probably represent the lower bound of possible values.

[25] Stock estimates from The Report of the 2010 Atlantic bluefin tuna Stock Assessment Session, found here: http://www.iccat.es/Documents/Meetings/Docs/2010_BFT_ASSESS_REP_ENG.pdf, and from this study: http://www.iccat.int/Documents/Meetings/Docs/SCRS/SCRS-08-084_Secor_et_al.pdf and Turner & Restrepo Model (1994)

bluefin tuna at 50%, Pacific bluefin tuna (*Thunnus orientalis*) at 10%, and yellowfin tuna (*Thunnus albacares*) at 1%, produces the following estimates.

- For Atlantic bluefin tuna, the model finds that a closure within the next 10 years could disrupt $125 million of present discount cash flow
  - By reducing the likelihood of stock collapse from 50% to 41.35%[26], the potential risk-adjusted disruption costs drops from $125 million to $104 million, representing $21 million in potentially protected revenue
- For Pacific bluefin, the model finds that the 10% risk of closure over the next 10 years costs $17.8 million,
  - The reduction in uncertainty brings the likely cost of collapse down to $14.7 million, generating a net optimized savings of $3.1 million
- Even a relatively safe species, such as the yellowfin tuna, with a 1% risk of a fishery closure over the next ten years, has significant costs of failure at $1.78 million in present discounted cash flow
  - The better stock estimate could generate a potential $309,000 savings from optimized policy under reduced uncertainty

Thus, fisheries managers can achieve a potentially beneficial first-order effect by using NASA data to reduce the uncertainty of the stock size, thereby greatly reducing the risk of fishery collapse.

B. Conclusions

Currently, researchers are using NASA remote sensing data to construct better estimates of tuna stock size. Through direct observation, indirect tracking of environmental conditions, and targeted adaptive sampling methodologies, analysts have developed more robust stock estimates of fish species, and have significantly reduced the uncertainty that complicates the formulation of optimal fisheries policy. The improved estimates are now being incorporated into fisheries management programs. The reduction in uncertainty enables managers to set quotas more reliably, reducing the risk of fisheries collapse without placing unnecessary limitations on the fishing industry.

This analysis derived a first-order estimate of the potential value of the NASA data in devising fisheries policy. Employing a framework that values uncertainty by the downside risks of imprecise estimates, this analysis shows that the optimal policy changes with the level of uncertainty; the results suggest that use of NASA data may result in significant savings. Furthermore, these savings increase in magnitude as the stock drops closer to the terminal (closure) size, where the species is more likely to suffer a collapse or near collapse. Because these threatened and dwindling species are more difficult to sample due to their low numbers, the level of stock uncertainty using traditional (on-sea observation) techniques increases, further enhancing the value of the NASA data.

The NASA remote sensing data provide useful information that can be used to protect and enhance several multi-million dollar industries. Looking forward, the importance of

[26] The NASA data reduced the variance by 17.3 percent (0.173) of its original value. If the original value for variance was 50 percent (0.50), then the reduction is (0.173) x (0.50) = 0.0865, and the reduced variance is (0.50) – (0.0865) = 0.4135, or 41.35 percent. Similar calculations were used for the other fisheries, using 10 percent and 1 percent in place of 50 percent.

the NASA remote sensing data in tracking fish stocks and improving sampling techniques will continue to grow as stocks dwindle and accurate assessments become more important. NASA remote sensing data is becoming integral in the estimation of stock size, and these estimates will help guide policy concerning regulation of the lucrative fish commodities markets.

Appendix A: Glossary of Terms

Discount Rate – The discount rate is the reduction in value associated with the passage of time. As money realized today is more valuable than money realized in the future, comparing the discounted value versus the nominal value requires a rate at which time reduces value. Several values can be used for the discount rate based on risk and opportunity associated with the span of time examined. In this report, a 5% discount rate is used to match the rate in the literature upon which the analysis is based

Discounted Revenue or Discounted Value – A discounted value is the price or worth of some amount of money in present dollars. As the value of money today is worth more than money in the future, a discounted value will adjust for the amount of time before the value is realized. Note that the discounted value of an asset that is on hand today is equivalent to the actual value, whereas the present value of a future asset is lower than its nominal value in the future (e.g. $100 payment due in a year is only worth $95 today in discounted value).

Net present value – The net present value of an asset is the current price of all future income from that asset, with each income value discounted based on when the payment is due. For example, take a $1,000 bond that matures in 5 years and pays a $100 coupon annually. This bond will thus pay a total of 5x$100 interest payments, plus return the $1,000 for total payments of $1,500. However, using a discount rate of 5% means that the net present value of the payment next year is worth only $95 dollars today, while the payment after year two is worth only $90.25, etc. Thus, the net present value of the bond, including all interest payments and principle, is only $1,203.60 compared to the nominal (non-discounted) value of $1,500.

Opportunity cost – Opportunity cost is the cost of any activity relative to the foregone best alternative for that activity. For example, if an ocean survey costs $10,000 to conduct but directly leads to $500,000 in additional revenue that would not have been realized without the information, then the opportunity cost of not conducting the survey is $490,000 ($500,000 in additional revenue less $10,000 required to conduct the survey).

Recruitment – The time at which a juveniles turns into a spawning adult. The recruitment rate is the rate at which a stock is able to replace one generation with the next. Thus, a shock to a fish stock with a low recruitment rate will persist for much longer than one with a higher recruitment rate, leaving the stock in danger of collapse for a longer period of time.

Stock – Fish stocks are subpopulations of a particular species fish that is moderately self-contained. For example, the Atlantic bluefin tuna have very little or no contact with the Mediterranean bluefin tuna; this separation and separate breeding grounds implies that each group is influenced by different geographic factors and is fished by different groups of fishermen (and regulated by different bodies, in some cases).

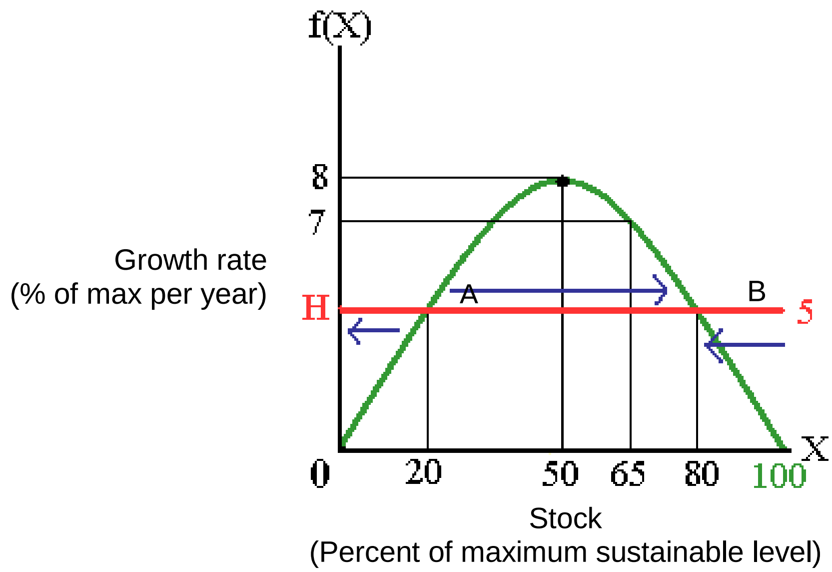
Stock assessment – The information describing a fish stock. This information will include population figures, age breakdowns, health, spawning age, male-to-female ratio, food preferences and supply, mortality rate, and all other pertinent information needed to successfully regulate the stock.

Appendix B: Acronyms

CIAT	International Center for Tropical Agriculture (Centro Internacional de Agricultura Tropical)
EPO	Eastern Pacific Ocean
GIS	Geographic Information System
IATTC	Inter-American Tropical Tuna Commission
ICCAT	International Commission for the Conservation of Atlantic Tunas
IOTC	Indian Ocean Tuna Commission
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PHAM	Pelagic Habitat Analysis Module
WCPCF	Western and Central Pacific Fisheries Commission

Appendix C: Stock Dynamics and Optimal Catch Rate

The following is an example of stock dynamics associated with a constant catch rate. The numbers used and the graphical depiction are theoretical and simplified in order to illustrate the general intuition behind the growth rate and evolution of a particular population; these relationships are at the basis of the model analysis. Figure C-1 shows the expected recruitment of a stock based on the size of that stock (green line) as well as a constant catch rate.



Here, the horizontal axis indicates fish population as a percentage of maximum sustainable population. The vertical axis represents the annual growth rate, f(X), also as a fraction of the maximum sustainable population. The green line has a bell shape: With no fish, there is no spawning, and hence no growth. As more fish are added, the probability of their meeting and spawning increases, so the growth rate increases. As the population, grows, however, food and other resources become limiting, so the growth rate eventually peaks and starts to decline. When the population reaches 100%, resources become completely limiting, so the population will stop growing and remain constant. The red line indicates a fishing harvest (H) of 5 percent of the maximum population per year.

Thus, there are two potential equilibria in this example: a stable equilibrium at point B (80% stock, 5% growth) and an unstable equilibrium (20%, 5%). When not at equilibrium, the stock size will either grow or shrink until it arrives at equilibrium. There are three different regions:

1) When the population is less than 20% of the maximum, the stock cannot breed fast enough to overcome the harvest rate of 5%, and the population dwindles until the entire stock collapses.
2) When the population is between 20% and 80%, the stock is breeding faster than 5% rate. Population will continue to grow until the recruitment rate falls to the 5% harvest rate. This occurs at point B.
3) When the population is greater than 80% of the maximum sustainable level, the replacement rate is below 5%, and thus the population will dwindle until the growth rate is equal to the replacement. This occurs at point B.

This framework can lead to several key insights with regards to fisheries management. Since the fisheries management organization can set the harvest rate (the red line), the level at which they choose can lead to very different results.

i) Any negative shock to the unstable equilibrium (point A) can lead to stock collapse, whereas a negative shock to the stable equilibrium (point B) does not pose that threat. Thus, if the stock is at the point A (20%, 5%), anything that nudges the population down would require quick action to restrict the harvest rate to ensure survival of the stock, whereas the stable equilibrium does not require any action to return.

ii) The stable equilibrium (point B) occurs at the point where resource constraints are slowing the growth of the population. Thus, raising the harvest rate H can actually *increase* the amount of sustainable capture that the stock can provide. In the example above, if the stock starts at point B (80% of maximum sustainable level, 5% harvest rate), increasing the harvest rate to 7% would be sustainable. This would push the stock down to 65% of the sustainable level, but allow for more fishing and higher revenue as the market grows.

iii) Thus, optimal management for sustainably high profits would have the fishery managers put the harvest rate as high as possible. In the illustration, that would be at a rate of 8%, with a stock size of 50% of the sustainable level.

iv) *However*, putting the harvest rate at the apex of the curve is problematic if there are shocks to population size or uncertainty about the actual size of this stock. This is because placing the harvest rate tangent to the apex then puts the two equilibrium points on top of one another, effectively eliminating the stable equilibrium. At this point, any negative shock to the population, or any uncertainty about the actual size of the stock, threatens to push the stock towards collapse.

Taking these factors into account suggests that optimal fisheries management could follow one of two paths.

In cases where negative shocks are usually small, stock size is easily identified and measured, and harvest rates are regulated relatively well, the manager should put the harvest rate as high as possible (8% in the example) and then lower the harvest rate whenever a negative shock is perceived. This regime would work well in these cases because the benefit from higher annual output outweighs the risk of stock collapse, as the regulator can quickly respond to a shock and enforce lower harvest rates to ensure the stocks survival.

In cases where negative shocks are potentially large, stock size is hard to measure, and harvest rates are poorly regulated, then the manager should set harvest rates well below the apex of the curve. The rationale in this method is to set the stable equilibrium (point B) sufficiently far from the unstable equilibrium (point A) so that no shock, uncertainty about stock size, or poor harvest enforcement can push the population into the region where the stock is likely to collapse. Thus, the annual foregone profits from a lower harvest rate are outweighed by ensuring the long-run health of the fishery. Note that better estimates of the stock size, such as those determined by the projects discussed in this report, can nudge a regulatory regime from the first method towards the second method, increasing annual catches without sacrificing any sustainability of the stock.

Appendix D: Charts & Figures on Bluefin Decline and Overall Harvest

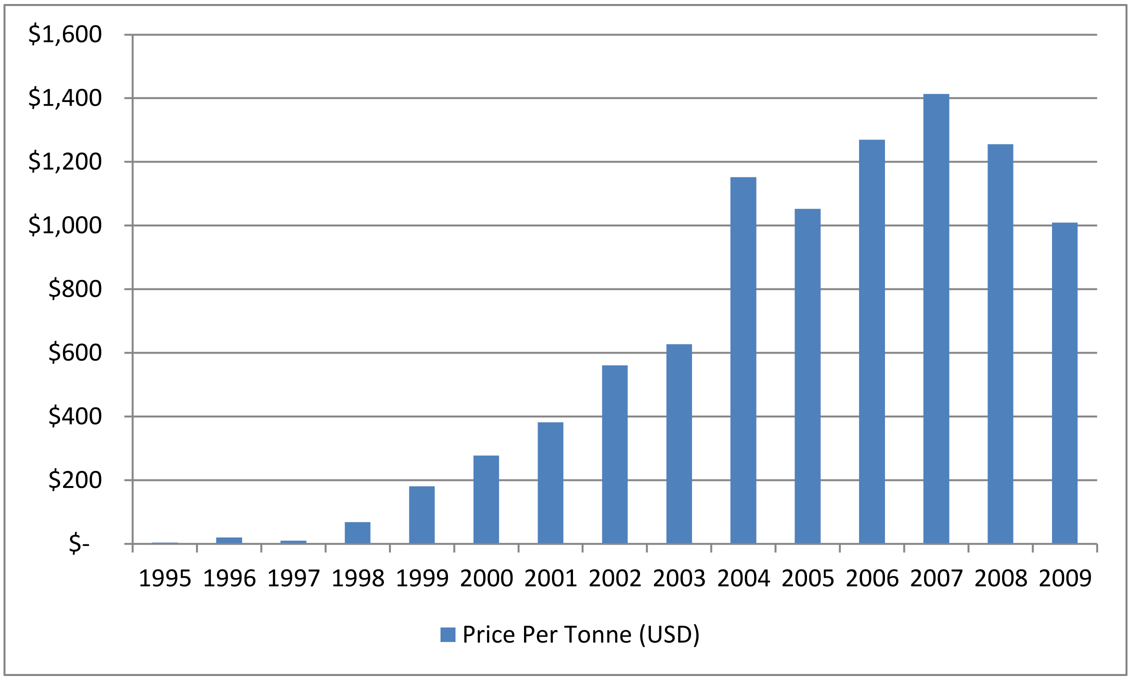


Figure D-1. Annual average Atlantic bluefin tuna prices have increased substantially in the past decade. The large increase in price is attributable mostly to a large decrease in supply (see Figure D-2), as well as increases in demand associated with increasing wealth in many areas of the world (with the tapering of prices in 2008 & 2009 attributed to a reversal of this effect because of the global downturn).

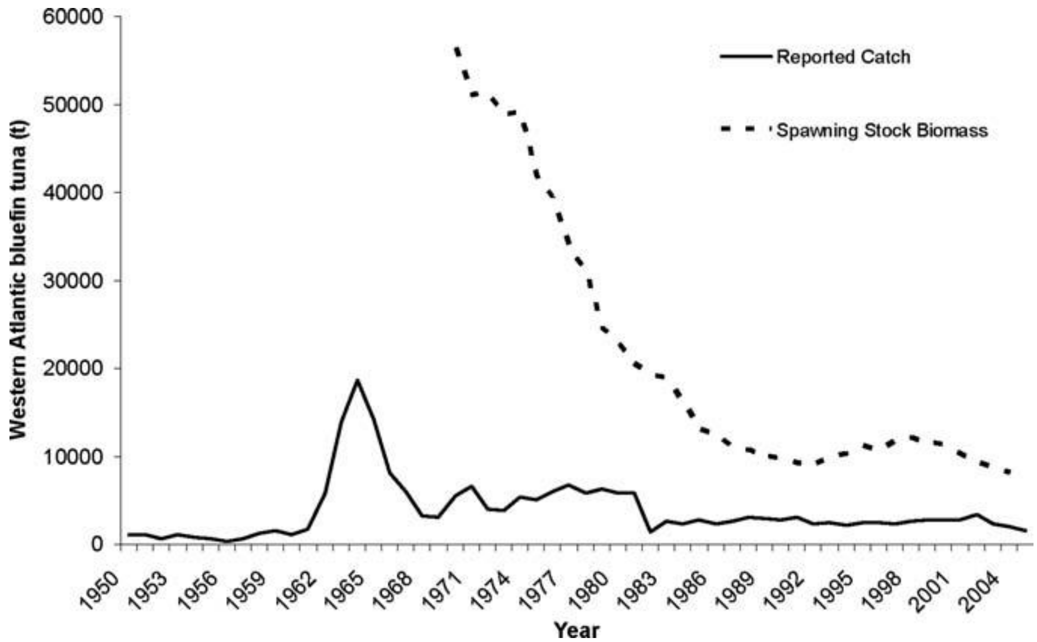


Figure D-2. *Western Atlantic bluefin tuna statistics, 1950-2004.* Dashed line shows decline in estimated spawning stock biomass over time. Solid line depicts the reported catch. Units of y-axis = metric tonnes. The intense pressure on the breading stock manifested itself in a substantial catch reduction in the early 1980s, as well as further downward population pressure during the 2000s.

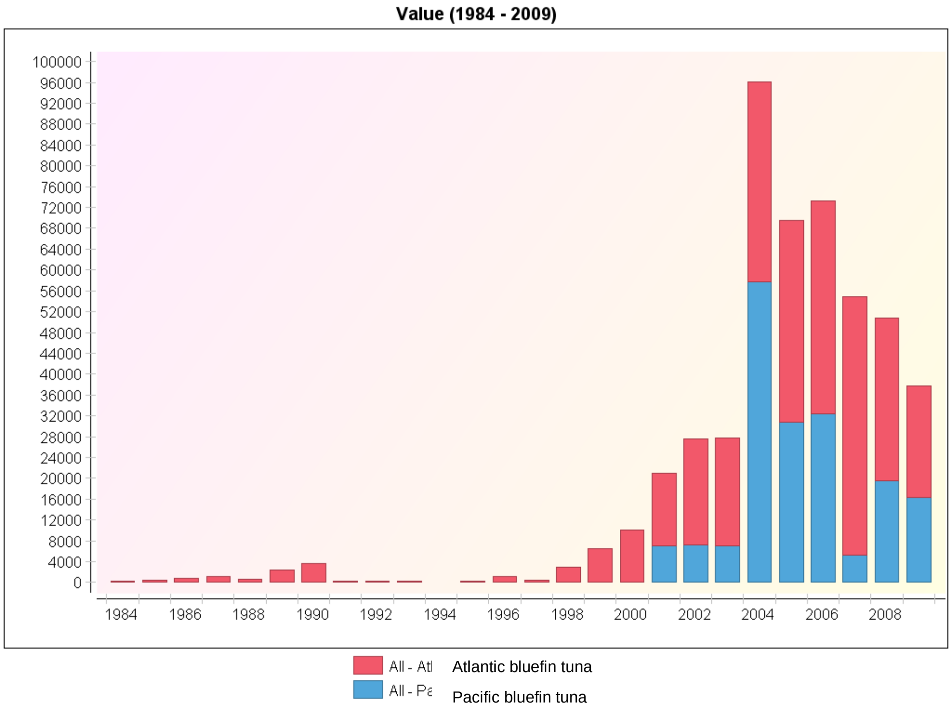


Figure D-3. Total Value of bluefin tuna catches in ‘000 of USD for both Atlantic and Pacific species. As prices have increased substantially in the past decade (see Figure D-1), the total value of the catch has increased substantially. The explosion of the market value of the tuna catches creates further incentive to over-harvest, and amplifies the potential costs of a stock collapse. Strong fisheries management could preserve these valuable markets by reducing the likelihood of a collapse.

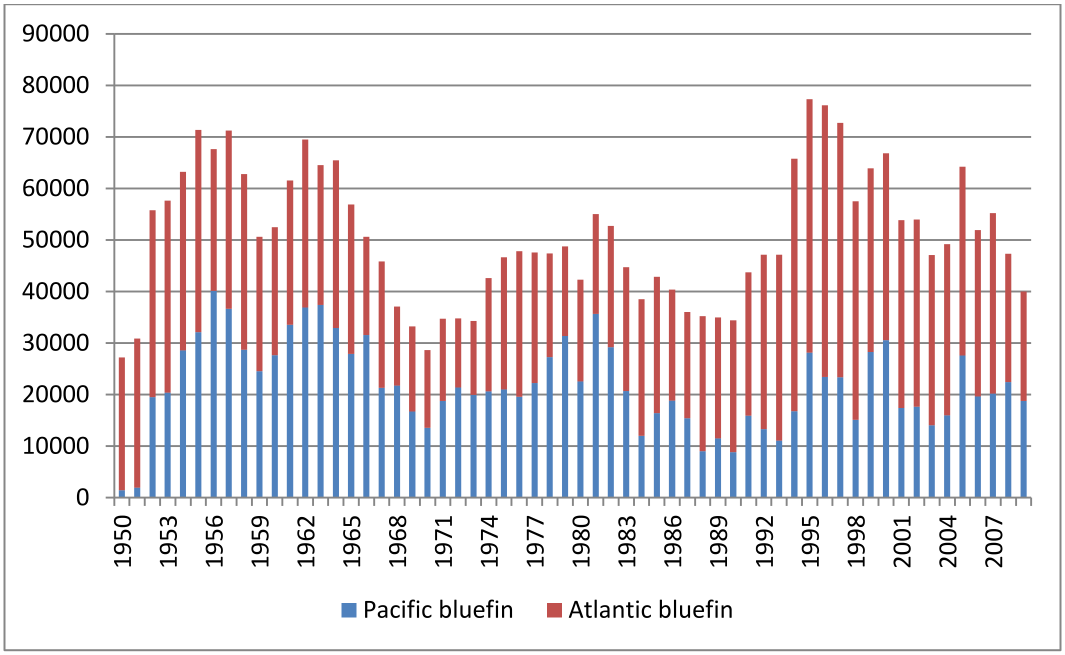


Figure D-4. Total Tonnage of bluefin tuna catches, in metric tonnes over 6 decades. The relative increase in bluefin tuna catches in the later third of the dataset matches and exceeds the highs achieved earlier on in the dataset, despite the large reduction in spawning biomass to replenish the stock, suggesting that further strain is occurring on the Atlantic bluefin in particular.

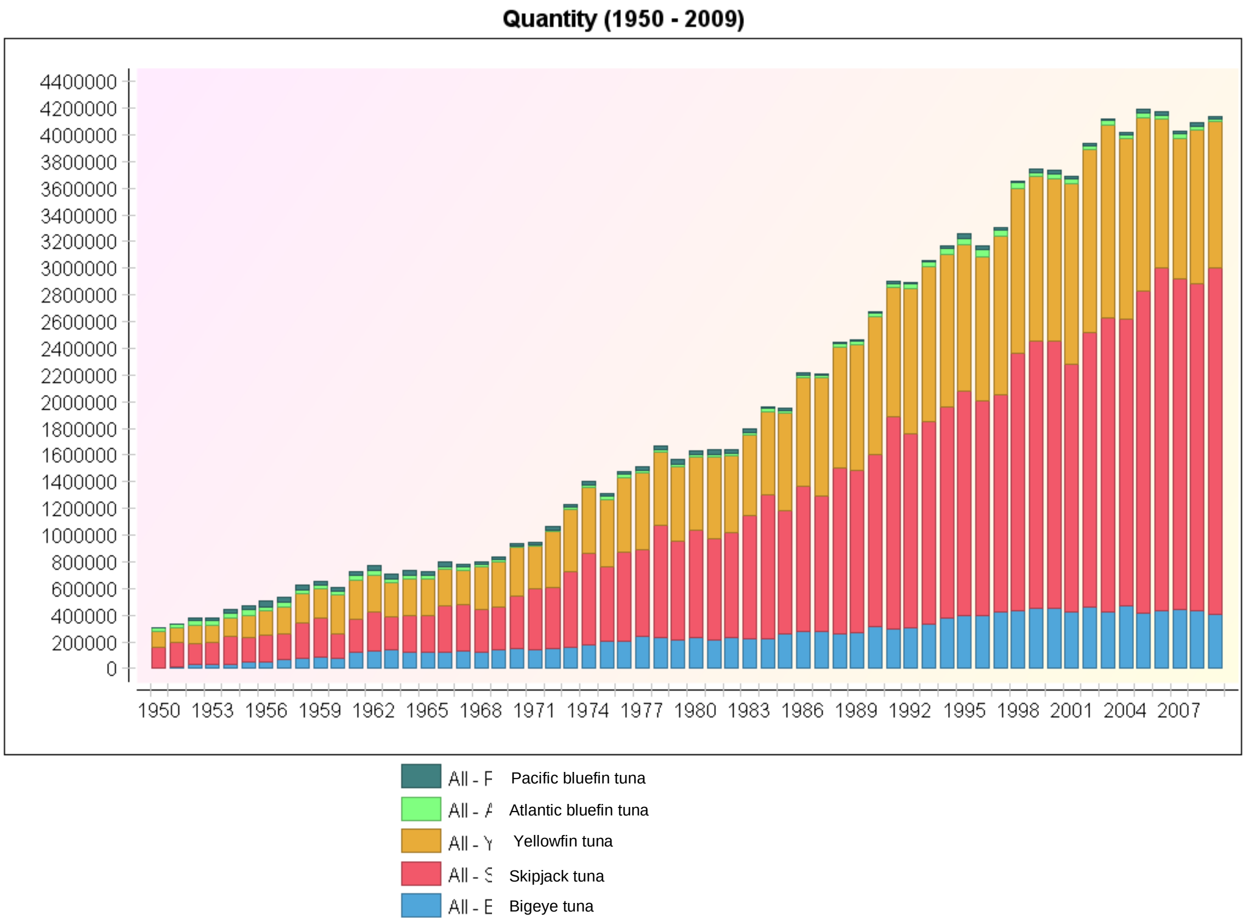


Figure D-5. Total World Capture, All Pelagic Species Data Available from 1950-2009. This chart shows the relative size of the bluefin tuna markets relative to other tuna species that are caught. While the Atlantic bluefin is the most threatened of the group, the sheer size of the other tuna markets suggest threats to their populations could impose similar economic costs were they to suffer a collapse.

Appendix E: References

Da-Rocha, José-María & María-José Gutiérrez, 2010. "Endogenous fisheries management in a stochastic model: Why do fishery agencies use TAC," DFAEII Working Papers 201013, University of the Basque Country - Department of Foundations of Economic Analysis II.

"Lost Property." The Economist. 25 February, 2012. <http://www.economist.com/node/21548212>

"How to Stop Fishermen Fishing." The Economist. 25 February, 2012. <http://www.economist.com/node/21548240>

Food & Agricultural Organization – Fisheries and Aquaculture Department. *The State Of World Fisheries And Aquaculture 2008.* ftp://ftp.fao.org/docrep/fao/011/i0250e/i0250e.pdf.

Food & Agricultural Organization – Fisheries and Aquaculture Department. *The State Of World Fisheries And Aquaculture 2010.* ftp://ftp.fao.org/FI/brochure/SOFIA/2010/english_flyer.pdf.

Food & Agricultural Organization – *FishStatJ Software for Fisheries Statistical Time Series*, http://www.fao.org/fishery/statistics/software/fishstatj/en#3. Downloaded May, 2011.

International Commission for the Conservation of Atlantic Tunas - Report of the 2010 Atlantic Bluefin Tuna Stock Assessment Session. http://www.iccat.es/Documents/Meetings/Docs/2010_BFT_ASSESS_REP_ENG.pdf.

Jolly, David And John M. Broder. "U.N. Rejects Export Ban on Atlantic Bluefin Tuna" New York Times on the Web 18 Mar.2010. June 1, 2011: http://www.nytimes.com/2010/03/19/science/earth/19species.html?src=sch&pagewanted=all.

MSNBC News Service. "Fish story: Big tuna sells for record $396,000", January 5, 2011. Retrieved June 23, 2011. http://www.msnbc.msn.com/id/40921151/ns/world_news-asia_pacific/t/fish-story-big-tuna-sells-record/.

NASA Research Team. Interview with PI at Roffer's Ocean Fishing Forecasting Service, Inc. April 14, 2011.

NASA Research Team. Interview with System Science Applications, Inc. staff, April 25, 2011.

NASA Research Team. Interview with Professor DG Webster (Dartmouth), April 29, 2011.

NASA Research Team. Email Exchanges with Several NOAA Researchers during May, 2011.

NOAA,: National Marine Fisheries Service – *FishWatch US Seafood Facts, Atlantic Bluefin Tuna*. http://www.nmfs.noaa.gov/fishwatch/species/atl_bluefin_tuna.htm. Accessed May, 2011.

Secretariat of the Pacific. *Update on Tuna Fisheries 2008.* http://www.imcsnet.org/imcs/docs/update_on_tuna_fisheries.pdf

World Bank – *Sunken Billions – The Economic Justification for Fisheries Reform.* http://siteresources.worldbank.org/EXTARD/Resources/336681-1224775570533/SunkenBillionsFinal.pdf