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Bioeconomic Implications of Modifying the Selectivity Properties of Fishing Gears

J. J. Agar Donald
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BIOECONOMIC IMPLICATIONS OF MODIFYING THE SELECTIVITY
PROPERTIES OF FISHING GEARS

BY

J. J. AGAR DONALD

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

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IN

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2000

DOCTOR OF PHILOSOPHY DISSERTATION

OF

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ABSTRACT

This study investigates the biological and economic consequences of modifying the species selectivity properties of fishing gears in a multispecies context. The objective is to examine whether modifying the species selectivity properties can contribute to rebuild overexploited stocks. To meet this objective, conceptual and empirical bioeconomic models were constructed. The conceptual model was used to investigate the qualitative impacts and the empirical model was used to derive the quantitative impacts of modifying the species selectivity properties of the gear.

In the conceptual part of this study, a stylized model was developed to analyze the long-run equilibrium bioeconomic properties of modifying the species selectivity properties of the gears. The study examined two polar cases, namely when the gears were perfectly non-selective and perfectly selective.

The analysis showed that there was a considerable amount of uncertainty regarding the impact of technological improvement. Policy prescriptions for rebuilding stocks varied dramatically depending on the type of technology employed and the presence of biological interrelationships. In the perfectly non-selective gear case, rebuilding strategies would benefit from decreasing the catchability of the overexploited species as long as the stocks were biologically independent. In the presence of biological interrelationships, decreasing the catchability yielded ambiguous results. Other policies, such as increasing the catchability of accompanying species, and simultaneously

decreasing the catchability of the target species and increasing the catchability of the accompanying species also generated ambiguous results.

In the empirical part of the study, a bioeconomic model of the Georges Bank multispecies fishery was constructed. The model had four species groups (roundfish, flatfish, elasmobranchs, and pelagics) and three gears types (otter trawl, gillnet and longline). The model evaluated the long-term biological and economic implications of changing the gear design or configuration (technology-based changes) and the creation of a tax-subsidy program (market-based changes).

Model results suggested that technological and market-based programs could aid in the rebuilding process; however, by themselves they are insufficient to recover the stocks. Rebuilding the overexploited roundfish and flatfish stocks requires significant reduction in fishing effort.

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Chapter 1: Introduction

1.1. Problem statement

The development of marine fishing technology has long been recognized to be a double-edged sword (Bell, 1978, Cunningham *et al*, 1985). Technological advancement, while allowing for factors of production to be used more efficiently, also tends to deplete open access resources.

The reasoning and dynamics are identical to the open access paradigm. The adoption of new technology by fishermen raises productivity and improves profitability but also acts as an incentive for newcomers to adopt new technology and enter the fishery. The absence of property rights breeds competition among fishermen to harvest the fish before others do. Fishermen have no incentive to conserve the resource for their own use nor to invest in the resource, for instance, by allowing it to grow larger since someone else can harvest any un-caught fish. This competition leads to a race to fish, which in aggregate, not only depletes the resource but also decreases each fisherman's economic performance. Decreasing economic returns, in turn, create an additional incentive for fishermen to continue to improve their gear's efficiency in pursuit of higher profits.

This cycle repeats itself until the fishery becomes overexploited and over-capitalized. In short, technological improvement sets forth two opposing forces. On one hand, it raises the productivity of factors of production, but on the other hand, by exhausting the fish

stocks, it lowers overall productivity. Not surprisingly, Whitmarsh (1990) points out that “Perhaps, the most fundamental issue as far as policy is concerned is the need to monitor the advance of fisheries technology and, where possible, to forecast its future time path.”

Clearly understanding the impact of the technological change on harvesting practices and on the environment is instrumental to improving fisheries management. The management of multispecies fisheries is notoriously complex because managers not only have to understand the impact technological change has on the selectivity properties of fishing gears but also on the biological characteristics of the fishery.

Changes in a multiproduct firm’s technology can modify the species selectivity properties affecting transformation and substitution possibilities. Many species occur in mixed-species aggregations, resulting in significant by-catch interactions among fisheries directed towards a particular target species or species group. Similarly, technological improvements can yield excessive fishing pressure that may disrupt predatory and competitive interactions. While these changes may not necessarily lead to loss of species diversity and ecosystem resilience, they may stress fishing communities (Gudmundsson and Sutinen, 1998). The Georges Bank ecosystem, for example, has undergone dramatic changes in species composition and abundance. Following the overexploitation of the valuable groundfish resources, low value elasmobranch resources flourished. Trawl survey indexes from Georges Bank show that dogfish and

skates abundance increased from roughly 25 percent in weight in 1963 to almost 75 percent in weight in recent years.

Despite the growing recognition of the need to understand the impacts of technological advancement, the fisheries economics literature has given little attention to this issue. Whitmarsh (1990) studied the factors influencing technological diffusion. Whitmarsh (1998) explained how the technological progress in the presence of free access conditions leads to the “fisheries treadmill”, where fishermen in spite of adopting new efficient technology, are unable to obtain a lasting increase in profits. Cunningham *et al* (1985) and Anderson (1986) examined the long-run effects of improving the catchability coefficient in an open access, single species fishery. Remarkably, little attention has been paid to the impact of technological change in a broader ecological context.

1.2. Goal, objective, approach and methods

The goal of this work is to understand the biological and economic consequences of modifying the species selectivity properties of fishing gears in a multispecies context. The objective is to investigate whether modifying the species selectivity properties can contribute to rebuilding overexploited stocks. To meet this objective, a conceptual and an applied bioeconomic model were constructed. The theoretical model was used to investigate the qualitative impacts whereas the empirical model was used to derive the quantitative impacts of changing the species selectivity properties of the gear.

Comparative statics method was used to describe the marginal impacts of three different policies. The first policy considers reducing the catchability of the overexploited target species while the second policy considers increasing the catchability of the underexploited accompanying species. The third policy considers a simultaneous combination of both. For expository purposes, the analysis focuses on perfectly selective and perfectly non-selective technologies in the presence and absence of biological interactions.

Later, a bioeconomic model that couples the salient ecological and economic features of the Georges Bank multispecies fishery is constructed. A numerical simulation model that incorporates multiproduct firm technology with a biomass dynamic model is used to evaluate the long-term biological and economic implications of selected policies. These policies include changes in the gear design or configuration (technology-based changes) and the creation of a tax-subsidy program (market-based changes). Under a tax-subsidy program, taxes would discourage fishermen from targeting overexploited species while subsidies would encourage fishermen to target underexploited species. After conducting a range of policy simulations, the main results are discussed. Finally, conclusions and policy implications of this research are presented.

1.3. Organization of dissertation

The remainder of this piece has six chapters. Chapter 2 presents a brief overview of the structure of the Georges Bank fishery. This chapter provides a background on the resource, industry structure and recent management history. Chapter 3 introduces the

conceptual model, which investigates the bioeconomic impacts of modifying the species selectivity properties of fishing gears in a multispecies fishery. The conceptual model evaluates rebuilding strategies in the presence of perfectly selective and perfectly non-selective technologies, including the cases where the stocks are biologically independent and interrelated. Chapter 4 describes the specification and estimation of the components needed to develop a bioeconomic model. Chapter 5 describes the bioeconomic model and discusses the main results. Chapter 6 presents the conclusions and policy implications of the research.

Chapter 2: Overview of the Fishery

2.1. Introduction

The development of management policies requires an understanding the relationships between the ecosystem and human activities. The status of the resource, structure of the industry, and management history are integral components of the fishery, which need to be accounted for in the formulation of policy. The objective of this chapter is to review the recent changes in the marine ecosystem and the experiences in regulating the New England groundfish fishery as the backdrop for our study. The following section describes the recent changes in the Northwest Atlantic ecosystem. Next, an account of the harvesting sector is provided. The last section reviews the management history.

2.2. Overview of Fishery Resources

The Northwest Atlantic shelf have supported many commercially important fisheries for centuries. Within this region, the Georges Bank area supports one of the highest fish production rates in the world. The high primary and secondary production rates are linked to the topographic and hydrographic features of the Bank. The water mass over the Georges Bank plateau is well mixed and isothermal throughout the year allowing continuous nutrient regeneration (Fogarty and Murawski, 1998). Scientists have observed that even though Georges Bank is an open system, production is tightly bound, with most of the fish production being consumed by other fish species (Sissenwine et al., 1984, Fogarty and Murawski, 1998). This feature has maintained overall biomass and production levels relatively constant, even though significant fluctuations on the species level. While fisheries management often requires

information at the species level, aggregating species into species groups provides a synoptic illustration of the dynamics of the marine ecosystem which otherwise may be overlooked (NMFS, 1998).

Since the 1960's, the Georges Bank ecosystem has undergone significant changes in species composition and yield (Figure 1). The increased distant water and domestic fishing pressure disrupted the existing trophic interactions (i.e., competition and predation) and changed the structure of the exploited marine assemblages.¹ The heavy exploitation of valuable groundfish resources (gadoids, and flatfish) in the 1960's and 1970's resulted in record high catches and record low abundance. The aggregate index for this group declined by almost 70% between 1963 and 1974. Sharp declines were observed in the haddock, silver and red hake, and most of the flatfish stocks. In the mid and late 1970's, the stocks appeared to increase following stricter management regime imposed by ICNAF and the Magnuson Act. Haddock and cod showed a sharp increase in biomass. The abundance and recruitment of flatfish also increased substantially. Consequently, the aggregate index showed an increasing trend peaking in 1978. In the early eighties, the aggregate index dropped again following a sharp increase in fishing effort and recruitment overfishing. In 1987 and 1988 the index reached the lowest values since 1963 (NMFS, 1998).

Meanwhile, the elasmobranch population (spiny dogfish and skates) rapidly grew. Standardized trawl surveys show that dogfish and skates catches increased from 25

¹ Assemblage refers to a group of species which are distributed in the same geographic areas and habitat type for most of the year, sharing common environmental regimes and feeding areas (Overholtz and Tyler, 1986)

percent (by weight) in 1963 to nearly 75 percent in the late 1980's (NMFS, 1996).² Since the early 1990's, the elasmobranch biomass index declined reflecting the increased fishing pressure on this resource. NMFS scientists have noted that while minimum biomass estimates for the spiny dogfish stocks are high, mature females may already be overexploited. This may threaten the stock in the future given the low birth rates and long gestation period of this specie. Herring and mackerel stocks were overexploited in the 1960's and 1970's but since have recovered to record levels. The pelagic index has markedly increased since 1983, peaking in 1994.

Collie and DeLong (1999) note that while these shifts are attributed to high harvest rates, predation is an important factor controlling the dynamics of the fish community. Several studies have studied the impact of species interactions in the dynamics of fish communities. Grosslein *et al* (1980) documented moderate to high dietary overlap between spiny dogfish and gadoids, and silver and white hakes, and between little skate and haddock, yellowtail flounder and winter flounders.

² Since 1963 the Northeast Fishery Science Center has conducted surveys to generate abundance indexes and monitor resource trends. Survey data is very valuable for monitoring trends in population size since unlike catch-per-unit-effort data from commercial or recreational fisheries, its catchability does not change markedly over time.

Figure 1: Trends in aggregate biomass indexes for major fish assemblages.

Overholtz and Tyler (1986) proposed a model where juvenile haddock competitive pressure on food resources kept the growth rate of other species at low levels. Following intense harvesting pressure on haddock and poor haddock recruitment, a competitive release mechanism allowed other species to increase in number and biomass. Initially, yellowtail flounder and longhorn sculpin populations dominated. Thereafter, skates and windowpane flounder dominated the system. Spencer and Collie (1996) proposed a stochastic predator-prey model, which incorporated an alternative prey. Their study examined how fishing mortality rates, predation rates and environmental variability affected the equilibrium and dynamics of the Georges Bank haddock and spiny dogfish system. More recently, Collie and DeLong (1999) constructed a dynamic production model to examine species interaction between four species groups, which included gadoids, flatfish, elasmobranch, and pelagics. They

found that the most important interactions were predation of gadoids and elasmobranchs on pelagics. They also found some evidence to support apparent competition between elasmobranchs and gadoids.

2.3. Overview of Fishing Industry

The Northeast region's commercial oceanic and estuarine fisheries generated US\$ 869 million (ex-vessel) worth of seafood in 1993. Of this total, finfish generated 35% the revenue for the region (NMFS, 1994). The New England groundfish fishery is characterized by the diversity of its fishing operations, gear types, vessel sizes and prosecuted species. The New England fleet employs several gears including otter trawls, gill nets, longlines, pots and traps, among others.³

In 1993, there were 1,347 vessels in the fishing fleet. Otter trawl is dominant gear in fleet. One thousand and forty otter trawls were in operation in 1993 landing 129.7 thousand tons of seafood valued at US\$ 187 million. Most of revenue was derived from cod (20%), *Loligo* squid (12%), winter flounder (8%), American plaice (8%), yellowtail flounder (7%) and monkfish (7%). During the same year, the gillnet and longline fleet had 244 and 229 vessels, respectively. The gillnet fleet landed 22.7 thousand tons of seafood valued at US\$ 24.8 million while longline fleet landed 7.66 thousand tons of seafood valued at US\$ 29.7 million. Most of gillnet revenue was derived from cod (33%), pollock (14%), and monkfish (10%) whereas most of the longline revenue was

³ The New England fleet consists of those vessels based in the states of Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut.

attributed to swordfish (31%), tilefish (16%), bigeye tuna (16%), and cod (13%) (NMFS, 1994).

The New England fleet is divided into inshore and offshore sectors. The inshore sector consists of small vessels (5-50 tons) and employ 2-3 crew. In 1993, their average revenue per day absent was US\$ 886. Due to their small size, these vessels usually fish close to shore and rarely go to offshore grounds. The effort of these boats is concentrated in summer months since they tend not to fish in rough weather. Their fishing trips usually last one day, but they can go on 2-3 day trips. Since the inshore vessels' trips are short, smaller vessels tend to be opportunistic, ready to profit from price changes and species availability (Doeringer and Terkla, 1995). Vessels correspond to some extent with port size; that is, smaller vessels tend to be housed in smaller ports spread throughout New England. For instance, Chatham's geography (narrow inlet and distance from major ports) discourages larger vessels from operating from this port.

The offshore sector consists of larger vessels (51-150+ tons) that employ between 3 and 15 crew. The number of crew has declined sharply following reductions of days at sea brought about by Amendments # 5 and 7. These larger boats tend to fish year around. The continuing poor condition of the groundfish stock forced captains to thin their crews and begin targeting other fisheries like dogfish, herring, mackerel, shrimp, and other species that do not fall under groundfish rules (Canfield,1997). The larger vessels tend to based in the ports of New Bedford, Gloucester, Boston, Pt. Judith, Portland, and Rockland. The species composition varies significantly with port. This situation not

only reflects species abundance in the different grounds but also the degree of fleet specialization among the different ports. For example, in New Bedford, scallops and the main groundfish (cod, haddock, and yellowtail flounder) account for most of the landings, whereas in Pt. Judith lobster, Loligo squid, silver hake, monkfish, scup and butterfish accounted for most of the landings.

2.4. History of the New England Groundfish Fishery

2.4.1. Early Times

The harvesting of groundfish has a long tradition in North America dating back to colonial times. The development of the cod fishery was a leading factor of the European settlement in North America. Cod fishing was not only a source of food for the locals, but was also an important commodity. Dried salted cod was an internationally traded commodity. Dried salted cod production peaked in the 1880's and then declined due to advent of steam-powered boats, competition among other food products, and the appearance of fresh fish outlets (Parsons, 1993, Murawski, 1996).⁴

Prior to the development of a formal system of collecting fishery statistics in the 1930's and 1940's, fluctuations in stock abundance were assessed from anecdotal reports and/or from trends in landings (Serchuk, and Wigley, 1992). In the early 1870's, the short supply of Gulf of Maine cod led to the first study of the impact of human activities on fishery resources (Baird, 1874 as reported by Serchuk and Wigley, 1992). In 1913, the first study on the impact of otter trawl fishing on the abundance of fish stocks of

⁴ Steam-powered trawlers were able to deliver a steady year-around supply of fresh fish.

Georges Banks was conducted. The analysis revealed that cod, haddock, and hake in Georges Bank were not being overfished (Alexander *et al.*, 1915 as reported by Serchuk, and Wigley, 1992). The study, however, did raise concerns about excessive discards if the otter trawl fleet expanded significantly. Scientific evidence indicated that the new gear was extremely destructive and discarding was prevalent.

During the turn of the century, new technologies rapidly changed the fishery. Schooners were soon replaced by steam-powered trawlers. By the 1930's, there were over 300 trawlers in the fishery (Murawski, 1996).⁵ The development of refrigeration, filleting and canning in 1920's contributed to the fast development of the groundfish resources and eventually led to the demise of the haddock stock in the 1930's (Hoagland, Kite-Powell and Schumacker, 1996).

Prior to the 1900's, haddock landings had been relatively low since it did not preserve well when salted. However, improved cold storage, marketing, and distribution made the industry switch from salt dried cod to haddock. Haddock landings continued to increase as the demand grew (Murawski, 1996). Unfortunately, the increased fishing pressure soon collapsed the haddock resource as landings dramatically fell from 120,000 tons in 1929 to 28,000 tons in 1934. During this time, cod landings decreased and haddock, redfish, and other species commanded higher prices in the domestic market.

⁵ Interestingly, the Canadian trawl fleet never exceed 4 vessels by the 1930's because of the opposition of the inshore sector, and Canadian policy to maintain the largest possible labor force employed in the fishery (Parsons, 1993).

The collapse of the haddock fishery prompted new research to investigate causes of the crises and recommend potential solutions. Scientists confirmed earlier work by Alexander, which showed the negative impact of discarding of juvenile haddock. One study estimated that for the 37 million pounds of haddock landed in Boston, 70-90 million juvenile haddock were discarded dead at sea. Although no estimates are available, large quantities of cod are believed to have been discarded (Serchuk and Wigley, 1992). Scientists recommended increasing trawl mesh size, but the industry rejected this proposal.

In the 1930's, the redfish fishery was initiated. The U.S. landings peaked in the 1942 at 60,000 metric tons, and then declined as the fishery expanded to the Scotian Shelf, peaking at 120,000 metric tons in the 1950's. Murawski (1996) notes that the fishery was fished down to moderate levels in the Gulf of Maine during the 1930's and 1940's, and the stock collapsed in the mid-1970's following the return of the fleet from Canada. U.S. redfish catches oscillated between 14,000 to 15,000 metric tons in 1978-79, and dropped to 530 metric tons in 1991.

Until the 1940's, flatfish landings were dominated by winter flounder, witch founder and American plaice. Subsequently, yellowtail flounder became the most important flatfish. Yellowtail landings and abundance however decreased substantially during the 1940's and 1950's. Although, the reasons for the decline are not known, warm water temperatures are believed to have affected recruitment. In the 1960's, when the water

temperatures were cooler and increased in yellowtail abundance and landings was observed (Muraswki, 1996).

Prior to the Second World War, the New England fleet was large and not very profitable. Thereafter, it became very prosperous as the war effort required the supply of large amounts of protein, and rationing increased the consumption of fish. The fleet became more active as many large fishing vessels were used in the military activities such as mine-sweeping.

2.4.2. ICNAF Era

During the 1940's, the United States and Canada began expressing concern about the conservation of marine fisheries in the Northeast Atlantic and the potential impact of foreign fleets on domestic fishermen. This concern led to the establishment of the International Commission for the Northwest Atlantic Fisheries (ICNAF) in 1949, and effectively came into force in 1951 (Table 1). ICNAF's objective was to investigate, protect, and conserve fisheries of the NW Atlantic in order to maintain maximum sustainable catch from each species. Originally Canada, the United States, and a few European nations were its only members. Fishing effort initially was moderate and ICNAF managed the fishery by controlling the size of first capture. Mesh size regulations were first imposed in 1953.

In late 1950's, Northwest Atlantic fisheries underwent a dramatic and uncontrolled expansion. The arrival of new distant water fleets led to a precipitous increase in

landings. The USSR factory fleet engaged in "pulse fishing", a practice where a large amount of fishing effort is directed to a particular species in a given area until its abundance is reduced to a low level. USSR catches increased from 17,000 metric tons in 1956 to 370,000 metric tons in 1962, to 853,000 metric tons in 1965, finally peaking at 1,357,000 metric tons in 1973. During the same period, the tonnage of fishing vessels increased from 400,000 metric tons to a peak of 1,500,000 tons in 1974 (Parsons, 1993).⁶

In the early 1960s, ICNAF recognized that mesh size regulations were not sufficient to control fishing mortality as long as fishing effort continued to increase (Anthony and Garrod, 1986). Attempts to discuss effort regulation failed in 1965, 1966, and 1967. In 1968, it was reported that cod in subarea one and haddock in subarea five were 'demonstrably overexploited', and by-catch problems were recognized from the very beginning in some fisheries.

Rapid changes in technology continued to improve the fishing efficiency resulting in a tremendous increase in fishing effort and capacity. The total tonnage of vessels fishing in the NW Atlantic (excluding boats less than 50 feet) went from 400,000 tons in 1959s to a peak of 1,500,000 tons in 1974. Despite the increased effort level, total landings continued to decline from 4,600,000 metric tons in 1968 to 4,200,000 metric tons in the early 1970's. The pulse fishing strategy of the distant water fleets resulted in the collapse of many stocks such as the haddock, silver and red hakes, Atlantic mackerel, and Georges Bank herring (NEFSC, 1995).

⁶ Excludes boats under 50 metric tons.

Table 1: Management of New England groundfish fishery.

Year	Management measures implemented
1949	International Commission for the Northwest Atlantic Fisheries (ICNAF) is established.
1953	Establishment of minimum mesh size for otter trawl (4 1/2 inches).
1970	Haddock spawning area closures (March through May). Total Allowable Catch (TAC) for haddock implemented.
1971	Total Allowable Catch (TAC) for yellowtail flounder implemented.
1972-1976	TACs for all regulated stocks established. TACs assigned by country. "Second tier" TACs where the sum of national species TACs had to be less than the sum of individual countries'. TACs to allow for species interactions and by-catch. Extension of haddock spawning area closures (February- May).
1976-1977	Declaration of Extended Jurisdiction by Canada and the United States. Fisheries on Georges Banks no longer regulated by ICNAF. Canadian and American fishermen continue to harvest in overlapping area of Georges Bank claimed by both countries.
1977-1982	U.S. Fishery Management Plan for cod, haddock, and yellowtail flounder based on quotas (annual, quarterly, by vessel classes, and lastly, trip limits). Minimum otter trawl mesh size (5 1/8 inches) Seasonal spawning closures for haddock Canadian TACs for cod, haddock, and yellowtail flounder
1982-1985	Interim U.S. Fishery Management Plan for cod, haddock, and yellowtail flounder. All direct controls (quotas) on fishing mortality eliminated by the United States and replaced by indirect controls (minimum mesh size of 5 1/2 inches, minimum landings sizes for cod, haddock, and yellowtail flounder, seasonal closed areas retained, etc.) Canada retains TAC system
1984	World Court establishes maritime boundary, "Hague line" across Georges Bank.
1986	U.S. Northeast Multispecies Management Fishery Management Plan extend management to a complex of groundfish species, including cod, haddock, flounders, hakes, and other species. Establishes acceptable levels of spawning potential for individual stocks. Also, imposes minimum fish sizes, mesh size restrictions, and closed haddock spawning areas.
1991-1994	Amendment No. 4 to the Northeast Fishery Management Plan establishes overfishing definitions, harvest rates above which recruitment overfishing would occur. Stock assessment of cod, haddock, and yellowtail flounder establish that recruitment overfishing is occurring and that stocks continue to decline.

Group of conservation organizations files suit based on continued over-exploitation of groundfish resource.

Canada develops and individual transferable quota (ITQ) system for some segment of the fleet.

1994 Amendment No. 5 implemented to address overfishing of groundfish resource. Regulations included days at sea reductions, moratorium on new vessels, eastern haddock closed area expanded and closed (January-June), 500 lb. trip limit for haddock, minimum trawl mesh size of 6 inches, and mandatory logbooks.

Canadian TACs for cod and haddock adjusted to achieve fishing rates below $F_{0.1}$.

Secretary of Department of Commerce takes emergency action in December permanently closing two areas on Georges Bank and one in southern New England to all fishing gears harvesting groundfish, including scallop dredges.

1996 Amendment No. 7 to the Northeast Multispecies Plan mandates further days at sea reductions, expands limited entry to include groundfish otter trawl and gillnet from 45 to 30 ft., raises haddock trip limits, and establishes "target" TAC quotas for cod, haddock, yellowtail flounder and other species

Sources: Fogarty and Murawski, 1998, Wang and Rosenberg, 1998, OECD, 1996.

In 1971, a global TAC for haddock in division 4X and subarea five (i.e. Scotian Shelf, Gulf of Maine, Georges Bank, and Southern New England) was first established together with a Scheme of Joint Enforcement to ensure catch compliance. Additionally, there was a provision that stated that the directed fishery should cease whenever the accumulated catch (directed catch plus by-catch) reached 80 percent of the quota, anticipating that the by-catch after the closure would be 20 percent. Mesh size limits, closed spawning areas, and a closed area-season for haddock division 4X were also in place. The TAC for haddock went from 18,000 tons in 1970 to 12,000 tons in 1972. Despite a continued increase in fishing effort from 1968 to 1974, the total catches in NW Atlantic declined to about 4.2 million tons (MMT) in the early 1970s (from 4.6 MMT in 1968).

In 1972, ICNAF's MSY objective was changed to the optimum utilization of stocks. In the same year, catch quotas were allocated between countries. The allocation of catch-quotas among countries was new and restrictive, so cheating and mis-reporting occurred (Anthony, 1990). Non-contracting parties fished in the area but their catches were not considered when allocating quotas. Each country was initially responsible for enforcement within its own fleet, but later enforcement among countries was limited to above the deck examination of catch only. North Americans inspectors were dissatisfied with the system since they felt that infractions by distant water nations went unpunished. ICNAF management work was also hampered by poor and limited information for assessments, inaccuracy of catch reporting and time lags obtaining data and use of MSY or $F_{\max}$ did not provide sufficient safeguard against errors in assessments due to these factors. Catches reflecting abundance continued to decline dramatically between 1970 and 1975.

In 1973, it became obvious that single-species quotas were not reducing fishing mortality.⁷ After a series of meetings, ICNAF decided to implement a 'second-tier scheme' to deal with excessive fishing and by-catch problems. The second-tier TAC procedure set a TAC for each country and was always to be less than the sum of the country's catch quotas for individual species. This forced each country to direct its fishing towards the species that was the most valuable to that country so that unwanted by-catch, which counted against the total second-tier quotas, was not taken (Anthony

⁷ The number of stocks under TACs grew from four in 1972, to 24 in 1973.

and Murawski, 1986). There were several indications that the second-tier quota scheme was effective in reducing the level of overall by-catch and helped to control landings on a species basis to be less than the TACs.⁸ The adoption of the second-tier scheme led some countries to redirect their fisheries to minimize or reduce by-catch. By reducing the by-catch of species with small allocations, countries were able to catch higher proportions of their second tier quotas than if fishing patterns used in previous years were employed. The second-tier quota scheme was abandoned in 1977 when the US extended its fisheries jurisdiction to 200 miles.

In 1976, ICNAF called for a 40 percent reduction in effort by non-coastal states (relative to 1972-73 levels) with specific stock quotas largely responding to the imminent implementation of extended jurisdiction. ICNAF also adopted $F_{0.1}$ for setting TACs and agreed to give coastal states a higher percentage of shares of the overall quotas. The quotas were often exceeded due to the multispecies nature of the fisheries and non-selective properties of gear; however, by 1975 and 1976, stocks were beginning to recover.⁹ Actual reduction in fishing effort was less than the 40 percent targeted; it appears that as much as 1/3 of the reduction occurred between 1973 and 1976 in subareas two, three, and four. ICNAF ceased to exist shortly after the United States and Canada extended jurisdiction. In addition to the difficulties of managing a multigear and multispecies fishery, ICNAF had a reputation for being slow, awkward

⁸ Parsons (1993) argues that it was not in place long enough to assess its effectiveness.

⁹ The major groundfish stocks on Georges Banks and Southern New England increased by 86 percent from 1974 to 1977. Groundfish abundance in all of subareas two, three and four decreased by more than ½ between 1967 and 1975, they remained stable in 1975-1976, and then more than doubled between 1976 and 1984.

and often incapable of implementing regulations contrary to the interests of any of its members (Eckert, 1979).

2.4.3. Magnuson Era

In 1976, Fisheries and Conservation and Management Act (FCMA) was enacted. The Act (subsequently renamed the Magnuson Act) gave the U.S. government authority to regulate and manage marine fisheries between 3 to 200 miles from the coastline. Under this Act, the New England groundfish fishery became under the United States jurisdiction and the New England Fishery Management Council (NEFMC) was given the responsibility of its management.

On March 15 1977, the Council implemented its first Groundfish Fishery Management Plan (FMP), which was developed to protect and enhance the severely overexploited stocks of cod, haddock and yellowtail flounder. The plan called for annual catch quotas, closed spawning areas, mesh-size restrictions, minimum fish sizes, and trip limits for yellowtail flounder. The groundfish plan was essentially the resumption of the management scheme in effect under ICNAF.¹⁰

At the beginning, the Council set annual quotas, or Optimal Yields (OYs), at levels which would promptly recover the stocks. Fishermen resisted them since they felt that with the departure of the foreign fleets there was little need for management

¹⁰ ICNAF largely regulated its fisheries by allocating catch quotas by species and geographic area, closed spawning areas, and minimum-mesh size.

(Hennemuth and Rockwall, 1987). Furthermore, some stocks like haddock appeared to be recovering and making a strong comeback.

Soon after of the implementation of the FMP, it became clear that the annual cod and haddock quotas would be met in the first five months of 1977. In June 1977, concerns over the possibility of market gluts, price declines, and having an idle fleet for half the year, led the Council to implement quarterly quotas, haddock trip limits, additional catch restrictions on yellowtail flounder west of 69° longitude, and new haddock by-catch regulations (Anthony, 1993). The Council's intention was to spread the catch over the year and minimize potential user conflicts (Appolonio, 1978). Quarterly quotas soon proved to have its limitations too. Since the fleet was so diverse in their fishing capacity and capability to operate under different weather conditions and or seasons, some segments of the fleets could not harvest their share of the quarterly allocation before they were met or exceeded (Appolonio, 1983). To counter this situation the Council allocated quotas to specific vessel classes. This was steered at increasing the change that each vessel would have an opportunity to harvest their fair share. In July 1977 the U.S.-Canadian Reciprocal Fishing Agreement was signed. The arrangement allocated Canada 17 percent of cod quota, 20 percent of the haddock quota, and 1 percent of the flounder quota. As result the cod quota was met in August of 1977 and the directed fishery was closed (Anthony, 1990).

Between 1979 and 1982, the abundance of principal groundfish species had declined by 53 percent, while fishing trips increased by 47 percent. Fishing mortalities for cod and

haddock increased dramatically (nearly doubled between 1977 and 1986). The seasons became shorter as the number of vessels (and vessel size) and trip rose. The lack of control on the number of participants proved to be disastrous. Between 1977 and 1980, the fishing fleet increased from 836 vessels to 1,316 vessels (57% increase). This surge in capacity was fueled by a sense of optimism, which reigned in the fishery. Fishermen believed that since the foreign fleet was gone, large amounts of fish would be available to them. Easy financing and government subsidies only aggravated matters. The failure to control catches required an increasing number of regulations. Discarding, under-reporting and mislabeling catches became rampant during this time. Halliday and Pinhorn (1997) observe that between a quarter and half of all the fishermen operating on Georges Bank frequently violated fishing regulations. Disagreement and poor communication between scientists, managers, and fishermen resulted in a loss in confidence in the program and mistrust. The plan was finally replaced in March of 1982.

In 1982, the Council implemented the Interim Fishery Management Plan for Atlantic Groundfish. The Council believed that quota management program was not necessary for rebuilding the resources; instead it relied indirect methods of controlling fishing mortality such as minimum fish sizes, mesh-size regulations, spawning area closures, and seasonal closures for protection of resources (Anthony, 1990). The plan was a stopgap measure until a more encompassing plan could be established (Halliday and Pinhorn, 1997). The focus of the plan was to maintain stock sizes and enhance the prospects of spawning of cod, haddock and yellowtail flounder while reliable data could be collected on the fish stocks and harvesting practices (Halliday and Pinhorn, 1997).

The main groundfish stocks, however, continued to decline. Effort declined on Georges Bank, but continued to rise in Gulf of Maine and Southern New England. Despite decreasing effort on Georges Bank, CPUE and landings declined.

The interim plan was replaced by the Fishery Management Plan for the Northeast Multispecies fishery in 1986. The goal of this plan was allow the fishery to operate with minimum intervention while safeguarding reproductive potential of the stocks. The main goal was to control fishing mortality, primarily of juvenile fish as to maintain adequate spawning potential (Halliday and Pinhorn, 1997). The plan contained a series of regulations that included minimum mesh sizes, enlarged closed areas, and greater restrictions on small mesh fishing. In the following years, fisheries regulation was strengthen by a series of amendments.

In 1987, Amendment # 1 increased minimum fish sizes and enlarged the areas where large mesh size regulations were in effect. This amendment also scheduled a mesh size increase from 5.5 to 6 inches. The groundfish resources continued to decline in this period. In 1989, Amendment # 2 dropped the scheduled mesh size increase in favor of by-catch limits. The plan also increased minimum fish sizes and expanded large mesh areas to cover identified spawning grounds and seasons. In the same year, Amendment # 3 was introduced which created a flexible area action system to protect juvenile fish. In 1991, Amendment # 4 established more stringent minimum fish sizes, mesh size restrictions, and closed haddock spawning areas. Amendment # 4 also recognized the need to develop and implement rebuilding strategies for the principal groundfish stocks.

The failure of indirect control to prevent overfishing resulted in environmental groups suing the Department of Commerce in 1991. The suit eventually led to Amendment # 5.

In 1994, Amendment # 5 was introduced. The goal of the Amendment was to reduce fishing mortality to a level, which will increase the percentage of maximum spawning potential for cod and yellowtail flounder to 20% in 5 years and to 30% for haddock in 10 years. The plan called for a moratorium on new entry and a reduction in fishing effort by 50 percent over 5-7 years. The Council also required fishermen to keep and submit log records, to accept sea-observers, and banned certain gears.

The groundfish resource continued to decline. In 1994, 17 percent of Georges Bank was closed. On June 1994, Amendment # 6 established 500-lb. haddock possession limit. In 1996, Amendment # 7 was implemented. The amendment instituted additional restraints on fishing effort as the number of days at sea were further reduced. The amendment also established target quotas, stringent days at sea controls, minimum fish sizes, closed haddock spawning areas, mesh size restrictions, and permanently closed areas for fish habitat. These measures have resulted in marked reductions in fishing mortality for four main New England groundfish stocks (Georges Bank cod, haddock, and yellowtail flounder, and Southern New England yellowtail flounder). The latter of the three stocks has recently changed from overexploited to fully exploited.

Chapter 3: Conceptual Model

3.1. Introduction

Traditionally reducing the species selectivity properties of the gears has been advocated for rebuilding overexploited stocks. On the surface, such policies are expected to recover dwindling stocks by reducing fishing effort and thus allowing the stocks to recuperate. While these policies may be sensible in a single species fisheries, it is unclear their impact in a multispecies context. Well-intentioned policies may generate un-intended consequences given the complex biological, economic and technological interrelationship present in multispecies fisheries.

The goal of this chapter is to qualitatively derive the biological and economic consequences of modifying the species-selectivity properties of fishing gears. To achieve this goal we draw on the method of comparative statics. Comparative statics allows us to investigate how a system changes from one equilibrium position to another in response to changes in one variable. For the purposes of this chapter, we only examine selected rebuilding scenarios. However, the results are sufficiently general to contemplate other management scenarios.

The organization of this chapter is as follows. The next section reviews the implications of modifying the species selectivity properties drawing on production theory. The third section introduces the bioeconomic framework. The fourth and fifth sections analyze bioeconomic impacts of modifying the species-selectivity properties of fishing gears in

a single and multispecies fishery context. The last section summarizes the main results and discusses policy implications.

3.2. Production Possibility (Transformation) Frontier

Fishing, like most economic activities, turns inputs into outputs. During the production process, fishermen are faced with a set of alternative output combinations for a fixed amount of inputs given the existing technology. The set of maximum feasible output combinations is often referred as the production possibility (transformation) frontier. Figure 2 shows the production possibility frontier for a fishing vessel that harvests two species.

Mathematically, we can express it as

$$e = \varphi(h_1, h_2, x_1, x_2) \quad (3.1)$$

where e is fishing effort (an aggregate input), x_i is the stock size of species i , and h_i is the harvest of species i . The stock sizes are assumed to be constant.

The slope of the tangent line to a point of the frontier is the rate at which one output is substituted by another at a given input level. Thus, moving along the frontier reflects the rate of technical substitution (RTS). The rate of product transformation (RPT) is defined as the negative of the slope of the product transformation curve.

Figure 2: Production Possibility Frontier

To derive the RPT, the production function needs to be totally differentiated

$$de = \frac{\partial \varphi}{\partial h_1} dh_1 + \frac{\partial \varphi}{\partial h_2} dh_2 \quad (3.2)$$

Since a small change in de is zero when the factor level is fixed (i.e., moving along the frontier). Then the above relationship reduces to

$$RTS_{12} = -\frac{dh_2}{dh_1} \quad (3.2')$$

where the RTS_{12} is equal to the ratio of marginal physical productivity of x in the production of h_2 to the marginal productivity of h_1 . Economic theory tells us that the

profit maximizing output level (h_1^0 and h_2^0) is found where the marginal rate of technical substitution equals the outputs price ratio. Conceptually, modifying the species selectivity properties of the gears involves changing the shape of the production frontier (figure 2). For instance, if we were interested in reducing the catchability of species 1 we would modify the technology as to shift inward the lower part of the production possibility frontier. Conversely, if we were interested in increasing the catchability of species 2 we would modify the technology as to shift outward the upper part of the production possibility frontier.

3.3. The Model

To investigate the impact of improving the species-selectivity properties of the gear, we assume a stylized open access fishery where fishermen are allowed to choose the most efficient gear configuration and effort levels as to maximize profits. The fishing fleet's profit function is given by

$$\pi = \sum_{i=1}^n p_i h_i - c(e) = \sum_{i=1}^n p_i q_i e^{\gamma} x_i^{\beta} - c(e) \quad (3.3)$$

where p_i is the price of species i , h_i is the harvest rate of species i , e is the rate of fishing effort (i.e., labor and capital devoted to harvesting), q_i is the constant catchability coefficient of species i , x_i is the stock size of species i , $c(e)$ is the harvest cost function, and β and γ are constants.

Clark (1985) uses the coefficient on the stock size to capture the relationship between fish density and population size.¹¹ The β represents the output-stock elasticity, that is, the percentage change in the output due a to percentage change in the stock size. The output-stock elasticity embodies the impact the stock size and fish density relationship has on harvesting costs. The low values imply that harvesting costs are less dependent on stock size. A stock-output elasticity of zero indicates that harvesting costs are independent of the stock size. Although we recognize that fishermen's ability to select the harvest mix (i.e., target) is a function of the technology and relative prices, for present purposes, we assume that relative prices are constant.¹² Furthermore, we assume that the effort and population dynamics are given by

$$\dot{e} = k \left(\sum_{i=1}^n p_i q_i x_i - c_e \right) \quad (3.4)$$

$$\dot{x}_i = G(x_i) - \sum_{i=1}^n h_i = G(x_i) - \sum_{i=1}^n q_i e x_i^\beta \quad \forall i \quad (3.5)$$

where $\dot{x}_i$ and $\dot{e}$ are the rate of change of the fleet's effort and population size of species i , and $G(x_i)$ is the growth rate of species i , c_e is the marginal cost of effort, and k is a constant. The friction parameter, k , captures the system's inability to adjust effort instantaneously both at the individual vessel level and at the fleet level through entry and exit. We also assume that the growth function has the following curvature properties

¹¹ In Clark's formulation, β 's greater than one were found to correspond to demersal fisheries whereas $0 \leq \beta \leq 1$ were found to correspond to pelagic schooling fisheries. This formulation, however, is not necessarily fishery-specific. Hanneson (1983), Flaaten (1987), and Eide et al., 1998 use this Cobb-Douglass formulation as gear specific instead. Eide et al., (1998) indicate that active gears such bottom trawls and gears which attract fish such as longlines and hand lines tend to have low β values. Gill nets, on the other hand, were found to possess β 's closer to one.

¹² For a discussion on this issue see Campbell and Nicholl (1994).

$$\begin{aligned}
G(x_i) &> 0 \quad \forall \quad 0 < x_i < K, \\
G(0) = G(K) &= 0, \quad \wedge \\
G_{x_i x_i}(x_i) &< 0 \quad \forall \quad x_i > 0
\end{aligned}$$

In the following sections, we present the long-run impact of modifying the species selectivity properties of the gear both in a single and multispecies context. Although we do not discuss the effects of improving the catchability in the short-run, we introduce both short-run and long-run results in appendix A.¹³

3.4. Technical change in a single species fishery

To investigate the long-run implications of modifying the catchability coefficient it is useful to start our analysis examining a single species fishery. For this case we assume that the bionomic conditions are specified by

$$\dot{e} = k(pqx^\beta - c_e) \quad (3.6)$$

$$\dot{x} = G(x) - qex^\beta \quad (3.7)$$

To solve for the long-run impacts of modifying the species selectivity properties of this system, we set equations 3.6 and 3.7 equal to zero (i.e., equilibrium) and differentiate with respect to q , the catchability coefficient. To ensure that a stable equilibrium exists, we restrict the sign of specific terms based on dynamic stability considerations.¹⁴ The use of these stability conditions is important since it allows us to make determinate qualitative inferences about comparative statics results. In our case, these conditions determine that the sign of the denominator be positive in the comparative statics results (Appendix B).

¹³ For the purposes of this chapter, the difference between short-run and long-run is that in the long-run the stock size adjusts to a new equilibrium whereas in the short-run there is no change in the stock size.

¹⁴ This method is also known as the “correspondence principle” (Samuelson, 1947).

Solving for the long-run impact on effort of modifying the species-selectivity properties of the gear, we find that

$$\frac{de}{dq} = \frac{-px^\beta G_x}{\underbrace{\beta pq^2 x^\beta x^{(\beta-1)} - (G_x - \beta qex^{(\beta-1)}) c_{ee}}_{(+)}} \quad (3.8)$$

The long-run impact on the stock size is given by

$$\frac{dx}{dq} = \frac{-x^\beta \overbrace{(pqx^\beta + c_{ee}e)}^{(+)}}{\underbrace{\beta pq^2 x^\beta x^{(\beta-1)} - (G_x - \beta qex^{(\beta-1)}) c_{ee}}_{(+)}} \quad (3.9)$$

The long-run impact on the harvest rate is given by

$$\frac{dh}{dq} = \frac{-x^\beta G_x \overbrace{(pqx^\beta + c_{ee}e)}^{(+)}}{\underbrace{\beta pq^2 x^\beta x^{(\beta-1)} - (G_x - \beta qex^{(\beta-1)}) c_{ee}}_{(+)}} \quad (3.10)$$

A summary of the long-run impacts of improving the catchability coefficient in a single species fishery is presented in table 2.

Table 1: Long-run impacts of improving the catchability in a single species fishery.

Exploitation level	de/dq	dx/dq	dh/dq
Underexploited($G_x < 0$)	(+)	(-)	(+)
Maximum sustainable yield ($G_x = 0$)	No change	(-)	No change
Overexploited ($G_x > 0$)	(-)	(-)	(-)

Until now the exposition has focused on the mathematical derivation of the long-run impacts on effort, stock size, and harvest rates of modifying the species selectivity

properties of the gear. The attainment of these new equilibria, however, has been assumed to have occurred instantaneously. While the technique employed provides valuable insight into the long-run effects, it neglects the dynamic adjustments between equilibria. The understanding of this transition is useful since many of the variables do not adjust instantaneously. The population size, for example, will not adjust immediately to increased levels of effort. In fact it will take several time periods to equilibrate to new effort levels. Similarly, the presence (absence) of rents will not necessarily result in rapid entry (exit) of vessels into the fishery as there are significant start-up costs and capital is not malleable.

For expository purposes, we assume that the fleet is initially in long-run bionomic equilibrium (point A in figure 3). At this equilibrium the fleet's long-run average revenue of effort, $AR_E^{LR}(X_0)$, intersects the short-run average revenue curve, $AR_E^{SR}(X_0)$, and the marginal cost of effort, MC_E . The long-run average revenue curve, $AR_E^{LR}(X_0)$, describes how the fleet's total revenue varies per unit of effort produced when both effort and stock size have fully adjusted. The short-run average revenue curve, $AR_E^{SR}(X_0)$, also known as the stock-constant average revenue curve, captures the fleet's average revenue over a shorter period of time, where effort is allowed to vary but stock size is held fixed. In other words, the period of time is too short for the stock size to adjust to new effort levels. Lastly, the marginal cost of effort, MC_E , shows how costs increase by employing an additional (marginal) unit of effort. In the panel below, the curve labeled PEC, the population equilibrium curve, describes the relationship between long-run population size and effort.

Now let us assume that there is a reduction in the catchability coefficient, which makes harvesting less efficient. In the short-run, we expect that revenue will decrease as the fleet's short-run average revenue of effort shifts downwards, decreasing effort to point B. At this effort level, the marginal cost of effort, MC_E , is equal to the new short-run (stock-constant) average revenue of effort curve, $AR_E^{SR'}(X_0)$. Although the AR_E^{LR} and PEC shift when the catchability coefficient is changed, the fishery is not in equilibrium in the short-run. The PEC shifts outwards because more effort is needed to maintain the stock at any given size. Similarly, the lower portion of the AR_E^{LR} rotates outwards, as more effort is needed to produce the same amount of revenue formerly generated. As the stock size declines, the short-run average revenue of effort increases. The fleet reaches a new effort equilibrium where the short and long-run average revenue curve intersect with the marginal cost of effort yielding a new equilibrium effort (E_1) and stock size (X_1) levels (see, point C in figure 3). In short, reducing the catchability coefficient results in a long-run increase in effort and stock size.

Figure 3: Reduction in the catchability coefficient

3.5. Technical change in a multispecies fishery

When considering the impact of modifying the selectivity properties of the gear, it is useful to distinguish between two polar cases: perfectly selective and perfectly non-selective fishing technologies. Perfectly selective technologies grant fishermen perfect

control of the harvest mix. In other words, fishermen can catch (target) specific species or species group. Conversely, perfectly non-selective technologies do not allow fishermen control over the catch composition. In reality, the selectivity properties of most gears fall between these categories. Squires and Kirkley (1991), for instance, have shown that non-selective technologies such as trawls have a modicum of flexibility depending on the species harvested. Nevertheless, this categorization provides us with clearer understanding of how improving the selectivity impacts different types of harvesting technologies.

The adoption of improved technology has been instrumental to the rise and demise of many fisheries. Excessive fishing pressure has been linked to changes in the food web structure and species composition. In our model, we consider how technology impacts the fish community structure. In particular we investigate multispecies fisheries that are biologically independent and interdependent. We focus on these scenarios because we want to derive qualitative insights for developing rebuilding strategies and establish benchmarks to investigate to what extent shifts in the community structure are dependent on fishing activities and biological interactions.

While the derived theoretical results are sufficiently general to investigate a wide range of cases, our exposition will focus on three specific rebuilding strategies.

- a) Reducing the target species catchability. Gear restrictions, such as, limitations on mesh size, number of hooks per line, and dredge size are often adopted for

rebuilding overexploited fisheries. These policies contribute to the rebuilding process by decreasing the fishing pressure on the target species, allowing the stocks to recover.

b) Increasing the non-targeted species, or accompanying species, catchability. It has been argued that these policies increase the economic returns from the accompanying species by making their harvest less expensive. These policies are expected to divert some effort away from the target overexploited species.

c) Simultaneously decreasing the target species catchability and increasing the accompanying species catchability. This policy, when feasible, is preferred because any losses in profitability caused by reductions in the catchability in the target species can be at least partially offset by increasing economic returns from the accompanying species.

3.5.1. Perfectly Selective Technology

3.5.1.a. Biologically Independent Two-Species Fishery Case

We assume that either one fleet harvests two species simultaneously or that two independent fleets individually harvest one species. Additionally we assume that the fleet(s) is (are) operating under open access conditions and that the long-run equilibrium the following conditions hold

$$\dot{e}_i = k_i(p_i q_i x_i^p - c_{e_i}(e_i, e_j)) = 0 \quad (3.11)$$

$$\dot{e}_j = k_j(p_j q_j x_j^\alpha - c_{e_j}(e_i, e_j)) = 0 \quad (3.12)$$

$$\dot{x}_i = G(x_i) - q_i e_i x_i^\beta = 0 \quad (3.13)$$

$$\dot{x}_j = H(x_j) - q_j e_j x_j^\alpha = 0 \quad (3.14)$$

where e_i and e_j are the effort levels devoted to harvesting the target species i and the accompanying species j , respectively. Also, we assume that the fleet(s) are economically interrelated. The fleet(s) marginal cost of effort is dependent on the amount of effort devoted to each species. For instance, if we attenuate fleet i 's catchability coefficient, we also reduce the opportunity cost of effort devoted to harvesting species i . The opportunity cost of effort is the forgone benefits for employing the effort in the next best alternative. Since fishery j has now a higher opportunity cost of effort, some effort is transferred from species i to species j as to maximize the economic returns per unit of effort. This transfer of effort increases the marginal cost of effort of harvesting species i ($c_{e,i}$) and decreases the marginal cost of effort of harvesting species j ($c_{e,j}$). The new equilibria is reached when each fleet's long-run average revenue curve equals their respective marginal cost of effort at the new equilibrium stock sizes and effort levels. Lastly, throughout the analysis, we assume that the target species i is overexploited, and the accompanying species j is underexploited.

To investigate the long-run consequences of improving the catchability coefficient in biologically independent two-species fishery, we set equations (3.11)-(3.14) equal to zero and differentiate them with respect to q_i . Since we are only interested in stable equilibrium results we draw on stability conditions to determine unambiguous

qualitative results. The effects of modifying the catchability of species i are shown in appendix C.

Initially, we consider the case where we reduce the catchability of the overexploited species i . Comparative statics results show that the long-run effort on the overexploited species i increases while the long-run effort on the underexploited species j decreases (Figure 4). In the long-run both stock sizes increase. The intuition of this case is as follows. We begin by assuming that the fleets are in long-run bioeconomic equilibrium at point A and A', respectively. Decreasing the species i 's catchability causes fleet i 's short-run (stock-constant) average revenue to fall reaching point B, decreasing fleet i 's short-run effort level. In contrast, fleet j 's short-run average revenue curve remains in the original position; however, fleet j 's $MC(e_{j,0} | e_{i,0})$ shifts to B' as if receives some effort from fishery i .

As more effort is transferred from fishery i to fishery j , the costs of fishery i increase, shifting the $MC(E_{i,0} | E_{j,0})$ to the left. This marginal cost curve shift further reduces fishery i effort level to point C. Similarly fishery j 's costs decrease, and fishery j effort level increases to C' (respect to A). As mentioned above, the marginal cost curves shift because of economical interdependencies. Changing species i 's catchability coefficient shifts the population equilibrium curve, PEC, outward.

As the harvesting rate of species i decreases, its size stock begins to recuperate raising fleet's i short-run average revenue curve. The increase in species i stock size, causes

fleet i 's profitability to increase drawing effort back from the accompanying species j fishery and also rotates outward the lower portion of species i 's long-run average revenue curve. This shift in effort releases some of the fishing pressure from species j , which then starts to increase as well. The effort transfer shift target species, shifts species i and j marginal cost of effort curve to right and left, respectively. Once both populations stabilize both fleets' short and long-run average revenue curves intersect the new marginal cost of effort curve reaching a new long-run effort and stock size equilibria at D and D' . In the long-run, effort devoted to the harvest of species i increases to $E_{i,l}$ while the effort devoted to the species j decreases to $E_{j,l}$. The long-run both stock sizes increase to $x_{i,l}$ and $x_{j,l}$.

Next we consider the case where we improve the catchability of the underexploited species j . In the long-run, the effort level on overexploited species i decreases and its stock size increases. On the other hand, the long-run effort level on species j decreases and its stock size decreases (figure 5).

The economic reasoning is as follows. Increasing species j 's catchability raises fleet j 's short-run average revenue curve from A' to point B' and increases short-run effort. As the opportunity cost of effort increases some is transferred from fishery i to fishery j . Fleet i 's short-run average revenue curve remains in its original position but the effort level diminishes as its marginal cost of effort shifts to the left (point B). As more effort is transferred, fleet j 's marginal cost curve shifts to the right to point C' . As before, changing the catchability of species j shifts the PEC_j outwards.

Figure 4: Decreasing the catchability coefficient of the target species.

The increased harvesting pressure on species j , decreases species j 's stock size and increases species i 's stock size. The increase in species i 's population, increases fleet i 's profitability and draws effort away from fleet j . This raises (drops) fleet i 's (j 's) short-run average revenue curve and shifts the marginal cost of effort curve to the right (left). Eventually, both fleets' stock size and effort level settle into a new long-run equilibrium at D and D'. In the long-run, species i 's population size increases and its effort level decreases. In contrast, in the long-run, species j 's stock size decreases and its effort level increases.

Figure 5: Increase in the catchability of the accompanying species in the selective case.

Lastly, we consider the impact of regulations that simultaneously increase the underexploited species j 's catchability and decrease overexploited species i 's catchability. Comparative statics results show ambiguous results for both effort levels and species j 's stock size. However, species i 's stock size increases. As in the previous case, the fleet i 's effort is initially drawn into the accompanying species j causing the species j 's (i 's) short-run average revenue curve to fall (rise). As the profitability of fleet j 's declines because of diminishing stocks, fleet i 's profitability increases due to increasing stocks. As result, fleet i draws back some effort initially taken by fleet j . Ultimately both fleets adjust to a new stock and effort equilibria. As before, altering the

catchability coefficient causes the lower portion of the long-run average revenue curve of species i (j) to rotate outward (inward). The extent of shift determines the magnitude and sign of the species i and j effort level, and species j stock size. Species i stock size increases ambiguously.

3.5.1.b. Biologically Interdependent Two-Species Fishery Case

In the preceding analysis, we assumed there were no biological interactions between the harvested species. An open question is how do the results change when biological interdependencies are present, in particular predator-prey relationships. To explore this case we introduce a vector of interdependent stocks as arguments in the growth functions such that

$$\dot{e}_i = k_i(p_i q_i x_i^\beta - c_{e_i}(e_i, e_j)) = 0 \quad (3.15)$$

$$\dot{e}_j = k_j(p_j q_j x_j^\alpha - c_{e_j}(e_i, e_j)) = 0 \quad (3.16)$$

$$\dot{x}_i = G(\mathbf{x}) - q_i e_i x_i^\beta = 0 \quad (3.17)$$

$$\dot{x}_j = H(\mathbf{x}) - q_j e_j x_j^\alpha = 0 \quad (3.18)$$

where $\mathbf{x}$ is a vector of biologically interdependent stock sizes, $G(\mathbf{x})$ and $H(\mathbf{x})$ are the growth function of species i and j , respectively. Applying the comparative statics technique, we obtain the long-run equilibrium effects on effort and stock size (see, Appendix D). Throughout we assume that species i is the prey while the species j is the predator.

The first case is where we reduce the catchability of the overexploited prey species i . Comparative statics results show that in the long-run both stock sizes increase and that the impact on both effort levels is ambiguous. The reasoning for this result is as follows. Reducing the catchability of the prey species i reduces fleet i 's profitability. Therefore, some of the prey effort is drawn to predator fleet j . The prey stock size increases in response to reduced harvesting and predatory pressure. As the prey becomes more abundant, the prey fleet i 's profitability increases and some of the effort is drawn back from the predator fleet j . This effort transfer relieves some of the harvesting pressure from predator stocks, which now have a more abundant food source. This increased food availability allows the predator stock size to increase. Eventually, both stocks settle to new higher stock size equilibrium. The long-run impact on effort levels is ambiguous because it depends on the relative magnitudes of predatory response and the economic value of the two species. Flaaten (1991), for instance, has shown that when the prey is inexpensive to harvest compared to the predator there is the possibility that the predator may not be harvested under open access conditions.

We next examined the case in which the selectivity of the underexploited predator species j is increased. In this case, comparative statics results show that in the long-run the impact on both effort levels and predator stock size is ambiguous. The prey population size, however, increases. The third case examined was where the selectivity of the predator species j is increased and the selectivity of the prey species i is decreased. Comparative statics analysis showed inconclusive long-run results for both effort levels and for the predator stock size. The prey stock size increased. The

economic reasoning for these two cases follows the logic of the first case. As mentioned earlier, the ambiguity of some results is due to the relative magnitudes of economic and biological interactions, which determine the sign and extent of long-run impacts.

3.5.2. Non-Selective Technology

3.5.2.a. Biologically Independent Two-Species Fishery Case

So far, we have considered the impact of modifying the catchability coefficient when the technology is selective. Remarkably, all three policies in the biologically independent, perfectly selective gear case contribute to rebuilding the stocks. The issue we examine in this section is whether the effectiveness of these policies will hold in the biologically independent, perfectly non-selective case.

To examine this case we assume that the fishery is in the long-run equilibrium where the following conditions hold

$$\dot{e} = k(p_i q_i x_i^\beta + p_j q_j x_j^\alpha - c_e) = 0 \quad (3.19)$$

$$\dot{x}_i = G(x_i) - q_i e x_i^\beta = 0 \quad (3.20)$$

$$\dot{x}_j = H(x_j) - q_j e x_j^\alpha = 0 \quad (3.21)$$

To explore the long-run consequences of modifying the catchability coefficient in a biologically independent two-species fishery, we set equations (3.20)-(3.22) equal to zero and differentiate them with respect to q_i . The derivation of the effects of changing the catchability of species i is shown in appendix C. Throughout the analysis we assume

that species i is the overexploited targeted species while the species j is the underexploited accompanying (non-targeted) species.

First, we investigate the impact of reducing the catchability of the overexploited target species i 's. Comparative statics results indicate that reducing the target species i 's catchability increases long-run effort and the target species stock size. The accompanying species stock size, on the other hand, decreases. The economic reasoning is straightforward.

Starting where the fishery initially is in long-run equilibrium, the fleet's short-run and long-run average revenue of effort curve intersect the marginal cost of effort curve (point A in figure 6). Note that the long-run average revenue curve is kinked. Reducing the catchability coefficient of species i , lowers the fleet's short-run average revenue curve, and, thus, decreases short-run effort to point B. The change in catchability coefficient shifts outward species i 's population equilibrium curve, PEC_i' , as more effort is needed maintain any stock size.

The increased harvesting pressure lowers accompanying species j 's stock size. Species j 's population equilibrium curve is not altered since there is no change in its catchability coefficient. As the target species i stock size increases, the fleet's short-run average revenue curve rises reaching a new higher equilibrium at $AR_E(x_{i,l}, x_{j,l})^{SR}$. The top portion of the long-run average revenue curve rotates inwards and the lower portion outwards. The new long-run and short-run average revenue curve of effort intersects

marginal cost of effort curve at point C. This new long-run equilibrium results in a higher long-run effort level (E_1) and target stock size ($x_{i,1}$), and lower accompanying stock size ($x_{j,1}$).

Figure 6: Reduction in the catchability coefficient of the target species.

Second, we analyze the case where we improve the catchability of the underexploited accompanying species j . In this case, comparative statics results show that long-run effort increases and both stock sizes decrease. The economic reasoning for this case is as follows. Increasing the catchability of the accompanying species, raises the fleet's short-run average revenue curve, and thus, short-run effort.

Figure 7 shows how the short-run average curve increases from $AR_E(x_{i,0}, x_{j,0})^{SR}$ to $AR_E(x_{i,0}, x_{j,0})^{SR'}$. This increased short-run effort results in lower short-run stock sizes. After the initial increase in effort, harvest rates become unsustainable. This lowers the fleet's short-run average revenue curve as both stocks begin to decline. Simultaneously to change the catchability coefficient the population equilibrium curve, PEC_j , shifts inward and the lower part of the fleet's long-run average revenue curve rotates inward. Eventually, the system settles into new bioeconomic equilibrium where the short and long-run average curve intersect the marginal cost of effort curve. This new equilibrium yields lower long-run effort levels, and population sizes. In this case, policies that increase the catchability of accompanying species will not aid the rebuilding process.

Figure 7: Increase in the catchability of the accompanying species in the non-selective case.

Third, we consider the case where we simultaneously increase the catchability of the accompanying species and reduce the catchability of the target species. Comparative statics results show that in the long-run, effort increases while the accompanying species stock size decreases. The long-run impact on the target stock size is ambiguous.

The intuition of this case is similar to that presented in the previous cases. The ambiguity, however, arises from the magnitude of the impact each species has on the fleet's average revenue curve. The long-run impact on the target stock depends on the

magnitude of the shift in the population equilibrium curve. If there was a significant change in the catchability of the target species i , this would cause a notable outward shift in the population equilibrium curve, which in turn would result in a larger population size. Conversely, if the reduction of the catchability of the species i was minimal then its stock size could either increase or show no change, depending on the extent of the shift in the population equilibrium curve. The population size of the accompanying species j , however, will always decrease since the population equilibrium curve shifts inward.

3.5.2.b. Biologically Interdependent Two-Species Fishery Case

Now we incorporate biological interactions into the perfectly non-selective technology case. To explore this instance we introduce a vector of interdependent stocks as arguments in the growth functions such that

$$\dot{e} = k(p_i q_i x_i^\beta + p_j q_j x_j^\alpha - c_e) = 0 \quad (3.22)$$

$$\dot{x}_i = G(x) - q_i e x_i^\beta = 0 \quad (3.23)$$

$$\dot{x}_j = H(x) - q_j e x_j^\alpha = 0 \quad (3.24)$$

where $\mathbf{x}$ is a vector of biologically interdependent stock sizes, $G(\mathbf{x})$ and $H(\mathbf{x})$ are the growth function of species i and j , respectively. Applying the comparative statics technique, we obtain the long-run equilibrium effects on effort and stock size (Appendix D).

Here we revisit the same extensions discussed in the earlier sections, however, we incorporate predator-prey relationships to examine how these new results differ from the biologically interdependent, perfectly selective case. In the latter case, it was found that in the long-run the prey stocks increased unambiguously, however, the long-run impact on the predator stock size varied depending on the case considered.

First, we consider the case where we reduce the catchability of the overexploited target prey species i . Comparative statics analysis yields ambiguous results on long-run effort and long-run prey and predator stock sizes. To understand these results, we need to know how the predator stocks vary with changes in prey abundance.

Setting equations (3.23) and (3.24) equal to zero, we obtain

$$\frac{G(\mathbf{x})}{q_i x_i} = \frac{H(\mathbf{x})}{q_j x_j}$$

Differentiating the above equation with respect to the stock sizes, we obtain

$$\frac{dx_j}{dx_i} = \frac{\frac{H_{x_i}}{q_i x_i} + \frac{G(\mathbf{x})}{q_i x_i^2} - \frac{G_{x_i}}{q_j x_j}}{\frac{G_{x_j}}{q_j x_j} + \frac{H(\mathbf{x})}{q_j x_j^2} - \frac{H_{x_j}}{q_i x_i}} \quad (3.25)$$

By inspection it is clear that the sign of the marginal increase in the prey abundance (species i) is ambiguous given the assumptions of this case. In the numerator, for instance, the first and second terms are positive while the last term is negative. Therefore, the increases (decreases) in prey abundance do not necessarily translate into higher (lower) predator abundance.

We observe that by decreasing the catchability of the target prey stock, the short-run profitability and effort decrease. As the prey abundance begins to increase, several scenarios are possible. Larger prey stocks could provide additional food to the predator, thus, increasing the abundance of the latter. The increased stock will result in greater profits, leading to larger effort levels. The increased effort could, depending on the magnitude of the reduction in the prey's catchability, decrease the predator's abundance to a greater extent. Thus, in the long-run, effort levels and prey stock size could increase while the predator stock size could decrease. Alternatively, if predation rates were sufficiently large as to consume any gains from stock rehabilitation, increased predator stock levels could further depress prey stocks and the profitability of the fleet. Lower profits could result in further lower effort levels. Eventually, the fleet could achieve a new long-run equilibrium with lower effort and prey stock size and a higher predator stock size.

The second case is where the catchability of the predator is increased. Comparative statics results show that in the long-run effort increases and the predator stock decreases. The impact on the prey stock, however, is unclear. The reason for this result is that by increasing the catchability of the predator, the prey stock size increases. This increase in prey abundance increases the fleet's profitability and effort level. This effort increase further diminishes the predator stocks. The impact on the prey stock, however, depends on the relative strength of the offsetting effects of predation and harvesting pressure.

The third case examined is where there is a simultaneous increase in the catchability coefficient of the predator species and reduce the catchability of the prey species. In this case, the long-run effects on effort and stock size are ambiguous. As in the previous cases, the ambiguity results from the relative magnitude of decreasing predation rates and increased harvesting pressure.

3.6. Discussion and Concluding Remarks

In this paper we have discussed, in qualitative terms, the bionomic impacts of modifying the species selectivity properties of the selective and non-selective gears in a multispecies fishery. We consider the cases where the fishery is biologically independent and biologically interdependent. Our analysis shows that there is a considerable degree of uncertainty regarding the qualitative impact of technological improvement. Not surprisingly, the level of uncertainty increases when biological interrelationships are introduced. In the perfectly non-selective gear case, the number of effects with ambiguous signs increased from one to seven in the presence of predator-prey relationships. Similarly, in the perfectly selective gear case, the number of effects with ambiguous signs increased from three to eight.

The major thrust of this piece, however, is to consider policies that can contribute to rebuilding overexploited stocks. Our analysis shows that policy prescriptions vary considerably with the type of technology employed. When regulating non-selective gears, managers interested in rebuilding stocks should focus on reducing the catchability of the target species (table 3). Policies intended to divert effort towards

accompanying species can wind up further decreasing the stock of the overexploited species. Policies that simultaneously decrease the catchability of the target species and increase the catchability of the accompanying species yield ambiguous results. In the presence of predator-prey relationships, none of the policies yield unambiguous results.

Managers have greater leeway when regulating perfectly selective gears. Restricting the catchability of the target species, or increasing the selectivity of the accompanying species, or a combination of these policies, can contribute favorably to the rebuilding efforts. The presence of a biological interaction does not add ambiguity to the rebuilding process. However, it does not yield clear-cut results on the impact on the accompanying species (Table 4). Although no general results could be obtained for some of the cases, uncertainty could be reduced on a case by case basis by the use of numerical simulations. Bioeconomic outcomes could be significantly different depending on the relative strength of the biological and economic terms.

These results have useful implications for rebuilding New England groundfish stocks. If managers were interested in recovering the overexploited stocks policies should be not only species specific but also gear specific. When regulating non-selective gears, such as trawlers and gillnets, managers should focus on policies that reduce the catchability of target species. Decreasing the selectivity of target species will contribute to rebuilding the stocks while increasing long-run effort.

Another consideration in regulating non-selective gears is the notion that fishermen, in some cases, can choose the catch composition in response to relative prices (Kirkley and Strand, 1988; Squires and Kirkley, 1991; Campbell and Nichols, 1994). We, however, assumed that prices were fixed in this study. Nevertheless, if fishermen can select to some extent the catch mix, then it is possible to create a system of incentives that would allow fishermen to manage stocks on an individual basis (Sissenwine and Kirkley, 1991, Campbell and Nicholl, 1994). This implies that market-based mechanisms may have a role in rebuilding the stocks. For instance, to expedite the groundfish rebuilding process a program could be instituted where groundfish catches (prey) are taxed and pelagic and /or elasmobranch catches (predators) are subsidized. If fishermen cannot select their output mix then the catch is technologically determined and such methods would not be effective. Taxes and subsidies would provide no protection to overexploited species and, under certain conditions, could lead to extinction (Costa Duarte, 1992).

Table 3: Main results from the perfectly non-selective multispecies technology case.

[illegible]

Table 4: Main results from the perfectly selective multispecies technology case.

[illegible]

Another implication for managing New England groundfish stocks is that perfectly selective gears provide greater flexibility. Fishermen's ability to allocate effort between species until the marginal revenue per unit of effort is equal among species expands the suite of options available to the manager. In fact, all three gear modification policies considered under both biologically dependent and biologically interdependent conditions contributed to the rebuilding of the groundfish stocks. Analogous to the non-selective case, managers can also make use of market-based mechanisms. Costa Duarte (1992) notes that when fishermen can perfectly select their catch, a tax (subsidy) policy would be appropriate since it would lower (increase) the marginal revenue from the overexploited species and transfer effort to the accompanying species.

Chapter 4: Econometric Estimation

4.1 Introduction

Most multispecies models assume that the output (species) mix of multiproduct firms is fixed in proportions. This specification is extremely restrictive since fails to recognize that the harvest mix may be a function of relative prices as well as technology. Depending on the type of technology, fluctuations in market prices may induce firms to modify the harvest mix. Failing to recognize that fishermen may be able to respond to relative prices has important implications for management.

In this chapter, we examine the technology of the New England fishing fleet, which operates in Georges Bank. The model serves as a basis for empirically testing to what extent, if any, fishermen can select the composition of their catch. The estimates are then used in chapter five to develop an empirical bioeconomic model.

The organization of this chapter is as follows. In the second section, we describe alternative approaches to modeling multiproduct firm's technology. The third section presents the profit maximizing duality-based approach to examine the underlying characteristics of the technology. Section four describes the estimation procedure and section five describes the statistical results. The last section summarizes the main results and limitations.

4.2 Approaches to modeling firm's technology

The firm's technology can be derived from two distinct but equivalent approaches. The primal approach explicitly solves the firm's production optimization problem. Under this approach, the usual behavioral objective is profit maximization. After solving for the first order conditions, output supply and input demand curves can be derived. This approach has been prevalent in fisheries economics literature for decades (see, for instance Clark, 1990). Most of the work under this approach has focused on comparing the different forms of exploitation such as open access and optimal management.

A limitation of the primal approach is that fails to introduce profit-maximizing behavior on the part of the fishermen into the estimation of production functions. In other words, production functions simply describe relationships between outputs and inputs (Dupont, 1988). Prices do not play a significant role in the description of the technology. Furthermore, input-output relationships are usually in fixed proportions.

An alternative to the primal approach is the dual approach. Under a dual approach, we assume that fishermen have solved the optimization problem and that the solution yields an indirect objective function. Since the indirect profit function represents the maximum profit associated with given output and factor prices, the fishing vessel's technology can be derived by applying the envelope theorem.¹⁵ The optimal levels of output and factors are a function of output and factor prices. The dual approach yields output supply and

¹⁵ The envelope theorem states that a change in the maximum value of a function brought about by a change in the parameter of the function can be found by partially differentiating the function with respect to the parameter (when all other variables are taken at their optimal values).

factor demand equations by partially differentiating the indirect objective function with respect to output and input prices, respectively.

Mathematically,

$$\tilde{\pi} = \sum^m P_i Q_i^*(P, W) - \sum^n W_i E_i^*(P, W) \quad (4.1)$$

where P is a vector of m output prices, Q is a vector of m outputs, W is the vector of n input prices, and E is a vector of inputs.

More compactly,

$$\tilde{\pi} = \tilde{\pi}(P, W) \quad (4.2)$$

Applying Hotelling's lemma (i.e., differentiating the profit function with respect to price P_i), we obtain

$$\frac{\partial \tilde{\pi}}{\partial P_i} = Q_i^*(P, W) \quad (4.3)$$

where Q_i is the i^{th} output supply equation.

Similarly, partially differentiating by the input price we obtain

$$\frac{\partial \tilde{\pi}}{\partial W_i} = -E_i^*(P, W) \quad (4.4)$$

where E_i is the i^{th} factor demand equation.

While the dual approach does not offer more insight than the primal approach, it is often a more convenient way to estimate technological relationships. The primal approach uses quantities as arguments while the dual approach uses prices as arguments. The dual approach has the advantage that when we statistically estimate technological relationships, the potential of simultaneity bias is avoided since input and output prices are assumed to be exogenous; however, this is not usually the case with quantities. Also, the dual approach is useful in generating a functional specification for a consistent set of output supply and factor demand equations for econometric estimation (Beattie and Taylor, 1993). To recover all the relevant economic information about the technology from the indirect profit function a series of regularity conditions must be met. Regularity conditions require that the profit function be continuous, twice differentiable, bounded, linearly homogenous and convex in input and output prices, and increasing and concave in the fixed factors.

4.3 The Model

To estimate the multiproduct fishing vessel's technology we drew on the duality framework. We assumed that fishermen maximize profits (revenue) in two stages as

hypothesized by Squires and Kirkley (1991). In the first stage (short-run), fishermen maximize revenue, while at sea, by selecting the most valuable output mix for a given level fixed inputs, and relative output prices. During the fishing trip, vessel inputs are largely fixed and cannot be readily modified (Kirkley and Squires, 1991). Therefore, profit (revenue) maximizing is an appropriate behavioral objective for a fishing trip once the fishing grounds have been decided (Kirkley and Strand, 1988). In the second stage (long-run), we assume that fishermen choose the effort level that minimizes costs (and thus maximizes profits) by selecting the optimal capital stock.

We modeled the short-run, revenue maximizing stage where fishermen decide on its output mix given a fixed level of inputs, weather and stock constraints, and relative output prices. McFadden (1978) has shown that revenue maximization is equivalent to profit maximization when inputs are fixed. Chambers (1988) observes that revenue maximizing is a true economic problem since firms for a fixed input bundle can choose to produce an array of outputs.

To examine fishing vessel technology a specific functional form must be selected. The selection of the functional form was governed by a number of issues. An initial consideration may be the number of parameters to be estimated since insufficient data may prevent the adoption of richer and more complex specifications. Second, the researcher must be careful in choosing a specification that imposes restrictions on the hypothesis to be tested. For instance, the use of the normalized quadratic imposes homothetic input-output separability (Dupont 1990). Third, the investigator may want to

select a specification that yields direct estimates of output quantities as opposed to shares. For instance, the Leontief specification uses quantities as dependent variables whereas the translog specification uses shares as the dependent variable. Lastly, the investigator may desire analytical solutions rather than numerical approximations, which can be very unstable.

An important consideration in selecting a specification is the ability to test a certain hypothesis, in our case fishermen's ability to target or select their harvest mix. A commonly tested hypothesis is the presence of non-jointness-in-inputs. A production process that is non-joint-in-inputs does not require all inputs to produce all outputs.

Under the revenue-maximizing framework, fishermen maximize benefits by selecting a point on the product transformation frontier where the marginal rate of transformation equals the relative price of the outputs. If the technology is non-joint-in-inputs then a separate production function exists for each output (or set of outputs) since there are no technological or cost tradeoffs between the different production processes. This suggests that producers maximize the production of outputs and that the supply of the individual outputs is inelastic. Since the supply of outputs is inelastic the output mix is technologically determined.

Graphically, the proportion of each species harvested depends upon the effort level but not on relative prices (Figure 8). Since fishermen harvest in fixed proportions the product transformation curve traces the output expansion path. From an economic

perspective, this case is trivial since it can be easily converted to a single product case by defining a new composite input and a new composite price.

More interesting is the joint-in-inputs case. A technology that is joint-in-inputs requires all inputs to produce all outputs. Jointness-in-inputs suggests the presence of technological and cost interrelationships in the production process. Since joint-in-inputs technologies are not necessarily inelastic, fishermen may have some control over the harvest mix. In other words, technologies that are joint-in-inputs allow fishermen to select (target) their output composition (species mix) in response to market conditions.

Types of non-jointness-in-inputs

Non-joint-in-inputs

Joint-in-inputs

Figure 8: Types of technology

Estimation

The estimation of the multiproduct firms technology requires the fulfillment of regularity conditions. Unfortunately, a significant share of the applied economic production work frequently violates these conditions, particularly the theoretically expected curvature conditions.¹⁶ Our empirical results were no different. Our estimates failed to conform to economic theory. Violations in the curvature conditions were manifested in the wrong signs on the own-price elasticities of supply.

In this section, we review the different specifications that we tried in our search for theoretically sound estimates. We estimated a non-homothetic generalized Leontief profit function and two forms of the normalized quadratic profits functions (i.e., non-constant and constant returns to scale) on an annual level. Finally, we estimated the non-homothetic generalized Leontief profit function on a trip level.

Initially, we selected a non-homothetic generalized Leontief profit (revenue) function to characterize the economic and technological interactions of the multiproduct firms.¹⁷ Kirkley and Strand (1988) originally used this specification to describe the harvesting technology of the New England fishing fleet. The Leontief functional form is a flexible functional form. Flexible functional forms are second order numerical or differential approximations to an unknown function. Chambers (1988) observes that the advantage

¹⁶ For instance, if the profit function is not convex this suggests that output supply and factor demand functions are not well-behaved since they could have the wrong slopes or show discontinuities or kinks.

¹⁷ The non-homothetic nature of the function arises from the effort-squared term which allows for a non-linear relationship between effort, outputs, and revenue.

of a flexible functional form is the ability to place few restrictions on the estimates. This allows the researcher to derive relationships directly from the data rather than from the chosen functional form. In other words, flexible functional forms allow the data to “speak”. In the case of the Leontief functional form, the flexibility of the form permits the investigator to derive non-constant substitutions relationships between outputs. However, the Leontief functional form imposes linear homogeneity in prices. This restriction does not preclude us from examining important characteristics of the technology such as separability and non-jointness (Kirkley and Strand, 1988).

Mathematically, the non-homothetic Leontief profit (revenue) function can be expressed as

$$\pi = \sum_i \alpha_i E^2 + \sum_i \sum_j \beta_{ij} (P_i P_j)^{1/2} E + \sum_i \sum_k \chi_{ik} D_k P_i E + \sum_i \delta_i X_i P_i E + \sum_i \sum_s \varepsilon_{is} F_s P_i E \quad (4.5)$$

Applying Hotelling’s Lemma, we obtain the input-compensated supply functions¹⁸

$$\frac{\partial \pi}{\partial P_i} = Q_i(P_i, E) = \alpha_i E^2 + \beta_{ii} E + \sum_j \beta_{ij} \left(\frac{P_j}{P_i} \right)^{1/2} E + \sum_k \chi_{ik} D_k E + \delta_i X_i E + \sum_s \varepsilon_{is} F_s P_i E \quad (4.6)$$

where R_i is the revenue function, Q_i are landings of species i , P_i is the price of species i , E is effort measured as days absent, and X_i is the stock size of species i , D_k is the port

¹⁸ The input-compensated supply functions only consider substitution and complementarity effects among output pairs since the input endowment is fixed.

dummy which captures the regional effects relative to the port of New Bedford, Massachusetts. F_s are the quarterly dummies for winter, spring, and fall. Symmetry was imposed by the restriction $\beta_{ij} = \beta_{ji}$ for $i \neq j$.

Firm level input-compensated supply functions were estimated for the gillnet, longline, and otter trawl gears that operate in the Georges Bank multispecies fishery. Landing, revenue and vessel characteristics data was obtained from the National Marine Fisheries Service Weightout File. Species landed were aggregated into five categories: roundfish (cod, haddock, and silver hake), flatfish (yellowtail and winter flounders), elasmobranchs (spiny dogfish and skates), pelagics (mackerel and herring), and 'other species' or miscellaneous group. This last group was set equal to total landings minus the sum of the other groups. In cases where the landings for the species' groups were zero, they were assigned an arbitrarily low value of 0.01 kg. Implicit ex-vessel prices for the species groups were estimated by dividing the total revenue by the quantity landed.

The data used ranged from 1989 to 1993. The fleet was subdivided by tonnage classes to reflect different operational strategies, capital stock and location of fishing grounds. Smaller fishing vessels tend to harvest inshore, whereas larger fishing vessels tend to harvest offshore. The otter trawl fleet was divided into four tonnage classes: 5-50 GRT, 51-100 GRT, 101-150 GRT, and 151+ GRT. The gillnet and longline fleets were not subdivided by tonnage classes because of the small number of observations present in the larger tonnage classes.

The input-compensated supply equations were estimated using Zellner's seemingly unrelated regression technique and iterated to convergence (Squires and Kirkley, 1991). Each individual input-compensated supply equation was tested for autocorrelation and heteroscedasticity. To correct for heteroscedasticity we assumed that error variance was proportional to the effort-squared. Therefore, we normalized all the input supply equations by effort. While this approach did not remove all the heteroscedasticity present, it reduced the number of equations with this problem. The effort normalization also reduced the level of multicollinearity present. We tried to reduce the heteroscedasticity by normalizing by different vessel characteristics, but our attempts proved unproductive.

Following Kirkley and Strand (1988) we estimated an annual model where the species i total annual landings by vessel were the dependent variable. Theoretically, we expected that the sign on the effort term to be positive. The effort-squared term could be negative, zero, or positive depending whether the technology exhibited decreasing, constant, or increasing returns to scale. Similarly, we expected positive own-price elasticities. Our initial estimates consistently violated the theoretically expected curvature conditions since all the own-price elasticities were negative.

As an alternative to the non-homothetic Leontief functional form, the non-constant returns to scale normalized quadratic form was tested. The advantage of this form is that convexity can be imposed without losing the flexibility of the functional form. While the proper curvature conditions can be imposed globally on the Leontief functional

form, the restrictions are too stringent for applied work.¹⁹ Dupont (1988) first used this normalized quadratic form in a fisheries context to study rent dissipation in the British Columbia salmon fishery.

The normalized quadratic profit functional form is given by

$$\begin{aligned} \pi(P, Z) = & \frac{1}{2} \sum_j \alpha_j Z_j \sum_i \sum_k a_{ik} (P_i P_k) / P_1 + \frac{1}{2} \sum_i \beta_i P_i \sum_j \sum_h b_{jh} (P_j P_h) / Z_1 \\ & + \sum_i \sum_j c_{ij} P_i Z_j + \sum_i \beta_i P_i \sum_j b_j Z_j / Z_1 + \frac{1}{2} \sum b_o \beta_i P_i / Z_1 + \sum_i c_i P_i \end{aligned} \quad (4.7)$$

Applying Hotelling's lemma we obtained the associated supply equations. For $i=1$ the output supply is given by

$$\begin{aligned} \frac{\partial \pi}{\partial P_1} = Q_1 = & -\frac{1}{2} (\sum_j \alpha_j Z_j \sum_i \sum_k a_{ik} P_i P_k) / P_1^2 + \frac{1}{2} (\beta_1 \sum_j \sum_h b_{jh} Z_j Z_h) / Z_1 \\ & + \sum_j c_{1j} Z_j + \beta_1 (\sum_j b_j Z_j) / Z_1 + \frac{1}{2} b_o \beta_1 / Z_1 + c_1 \end{aligned} \quad (4.8)$$

For $i \neq 1$ the supply equations are given by

$$\begin{aligned} \frac{\partial \pi}{\partial P_i} = Q_i = & \sum_j \alpha_j Z_j \sum_k a_{ik} P_k / P_1 + \frac{1}{2} \beta_i \sum_j \sum_h b_{jh} Z_j Z_h / Z_1 + \sum_j c_{ij} Z_j \\ & + \beta_i \sum_j b_j Z_j / Z_1 + \frac{1}{2} b_o \beta_i / Z_1 + c_i \end{aligned} \quad (4.9)$$

¹⁹ For instance, the imposition of concavity in the cost function rules out complementarity between input pairs

where P_i are prices, Z_j are the fixed factors (effort and stock size), and α and β are predetermined parameters. The price of roundfish, P_1 , and Z_1 , effort, where the arbitrarily chosen as numeraires.

Attempts to use this specification with five outputs (i.e., species groups) and five inputs (i.e., four stock sizes and effort) were thwarted by the presence of perfect multicollinearity. The multicollinearity arose from the terms where annual estimates of stock abundance were multiplied together.

Contingent on these results, a variant of the normalized quadratic was utilized. This flexible functional form imposes constant returns to scale and requires one less free parameter than a flexible functional form. Grafton (1992) first used this specification in fisheries context to study rent capture in the British Columbia sablefish fishery.

The normalized constant returns to scale quadratic profit (revenue) function was defined as

$$\pi(P, E) = \frac{1}{2} \alpha E \sum_{i=2}^N \sum_{j=2}^N a_{ij} (P_i P_j) / P_1 + \sum_{i=1}^N c_{ix} P_i E + \sum_{i=1}^N c_i P_i + \sum_{i=1}^N d_i P_i D \quad (4.10)$$

where α is a predetermined parameter. Symmetry was imposed by setting the coefficients $a_{ij} = a_{ji}$. Diewert and Wales (1987) observe that α can be a priori preset by the observer without losing flexibility. Following Grafton (1992), we arbitrarily set the

(Diewert and Wales, 1987).

predetermined parameter, α , equal to $1/E_1$, where E_1 is the first observation of the input (i.e., effort).

Applying Hotelling's lemma the associated supply equations can be derived. For $i=1$ the output supply for the normalized price is given by

$$X_1 = -\frac{1}{2}\alpha E \sum_{i=2}^N \sum_{j=2}^N a_{ij} \frac{(P_i P_j)}{P_1^2} + c_{1z}E + c_1 + d_1 D \quad (4.11)$$

For $i=2,3,..N$ the supply equations are given by

$$X_i = \alpha E \sum_{j=2}^N a_{ij} \frac{P_j}{P_1} + c_{1z}E + c_i + d_i D \quad (4.12)$$

For the normalized quadratic revenue function to describe the underlying technology, several conditions must be met (Diewert and Ostensoe, 1988). First, the profit function must be linearly homogenous. The price of roundfish (P_1) is used as the normalizing price which guarantees homogeneity of degree zero in the outputs. Second, the profit function must be convex in prices. Convexity in prices can be established when the matrix of all a_{ij} is positive semidefinite. A sufficient condition for a positive definite matrix is that all the eigenvalues be non-negative.

Following the estimation, properties of the technology were examined. The resulting parameters were checked for convexity in prices. Because the eigenvalues of the

different fleets were not all non-negative, the function was not found to be globally convex. There are several reasons why convexity may be violated including data aggregation, inadequate data variation and multicollinearity (Dupont, 1990).

Since all output supply equations were non-convex, all equations were reparameterized to impose convexity. Wiley, Schmidt and Bramble (1973) developed a method where convexity is imposed by replacing the a_{ij} matrix by a lower triangular matrix D and its transpose such that $A = DD^T$.²⁰ The a_{ij} parameters can be retrieved from the coefficients of the D matrix. The correspondence was $a_{ff} = d_1^2$, $a_{fe} = d_1d_2$, $a_{fp} = d_1d_4$, $a_{fo} = d_1d_7$, $a_{ee} = (d_2^2 + d_3^2)$, $a_{ep} = (d_2d_4 + d_3d_5)$, $a_{eo} = (d_2d_7 + d_3d_8)$, $a_{pp} = (d_4^2 + d_5^2 + d_6^2)$, $a_{po} = (d_4d_7 + d_5d_8 + d_6d_9)$, and $a_{oo} = (d_7^2 + d_8^2 + d_9^2 + d_{10}^2)$.

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & a_{ff} & a_{fe} & a_{fp} & a_{fo} \\ 0 & a_{fe} & a_{ee} & a_{ep} & a_{eo} \\ 0 & a_{fp} & a_{ep} & a_{pp} & a_{po} \\ 0 & a_{fo} & a_{eo} & a_{po} & a_{oo} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ d_1 & 0 & 0 & 0 & 0 \\ d_2 & d_3 & 0 & 0 & 0 \\ d_4 & d_5 & d_6 & 0 & 0 \\ d_7 & d_8 & d_9 & d_{10} & 0 \end{bmatrix} \begin{bmatrix} 0 & d_1 & d_2 & d_4 & d_7 \\ 0 & 0 & d_3 & d_5 & d_8 \\ 0 & 0 & 0 & d_6 & d_9 \\ 0 & 0 & 0 & 0 & d_{10} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The reparameterization of the A matrix requires a non-linear estimation technique since the profit function becomes non-linear in the parameters. These samples were estimated using maximum likelihood. Initially, the parameters were estimated using the Newton and Marquadt methods in SAS. Since the parameters failed to converge, the Davidson-Fletcher-Powell algorithm in SHAZAM was used instead. When using a numerical optimizer, caution must be exercised because the method may converge to a local

optimum other than the global maximum. For this reason, the model was re-estimated at different starting values (i.e., one and five). Maximum likelihood estimates for most of the cases were close in magnitudes but not identical suggesting that the surface of the function was flat.

Reparameterization had two main effects. First, it imposed the theoretically proper curvature conditions in some but not all of the supply equations. The small magnitude of some of the a_{ij} parameters may have contributed to approximation errors. Second, many of the estimated elasticities (and, thus curvature conditions) were highly inelastic (very close to zero).

A major difficulty with these estimates was the lack of stock abundance term necessary for the bioeconomic model. The presence of perfect multicollinearity in non-constant returns to scale normalized quadratic formulation prevented us from adopting stocks sizes as explanatory variables. Rather than incorporating stock sizes in the cost function, which would have been ad hoc, we resorted to re-estimating the non-homothetic generalized Leontief functional form on a trip rather than an annual basis. In the following section, we describe the results from the trip level non-homothetic generalized Leontief functional form.

4.4 Results

Trip level input-compensated supply equations were estimated using Zellner's seemingly unrelated method. As before, we corrected for autocorrelation and

²⁰ The first column and row of the A matrix are zeros because of linear homogeneity.

heteroscedasticity by normalizing all the equations by effort. This partially mitigated the heteroscedasticity problem.

The generalized R^2 for the system of equations prior to the correction for heteroscedasticity varied between 0.97 and 0.16. Table 5 shows a high R^2 for the gillnet fleet and a medium to low R^2 for the otter trawl and longline fleets (Table 5). The generalized R^2 was computed

$$R^2 = 1 - \exp\left[\frac{2(L_0 - L_1)}{N}\right] \quad (4.13)$$

where $L_0(L_1)$ is the sample maximum log-likelihood when all the slope coefficient are constrained to zero (unconstrained) and N is the sample size.

Table 5: Goodness of fit for selected fleets and tonnage classes

Fleet	Tonnage class	R^2
Otter trawl	5-50 GRT	0.59
	51-100 GRT	0.23
	101-150 GRT	0.16
	151+ GRT	0.66
Gillnet	All	0.97
Longline	All	0.49

To assess the ability of fishermen to target, we examined whether the technology was non-joint-in-inputs. The econometric restriction for overall non-jointness-in-inputs requires all cross-price coefficients $\beta_{ij}=0$ for all j not equal to i . Non-jointness-in-inputs for individual outputs, Q_i , requires that $\beta_{ij}=0$ for all j not equal to i . We also tested whether ports, seasons, and abundance as individual groups were statistically significant.

4.5.1. Results from the Otter trawl fleet

4.5.1.1 Estimation of the 5-50 tonnage otter trawl fleet

We first analyzed the technology of the smaller vessels of the otter trawl fleet. The Wald, Likelihood ratio and Lagrange multiplier test failed to reject overall non-jointness-in-inputs as well as individual species group's non-jointness-in-inputs (table 6). Both port and season dummies as individual groups were found to be statistically significant whereas stock sizes as a group were not. These results were surprising because of all tonnage classes, we expected 5-50 GRT to be the most responsive to price changes. Kirkley and Strand (1988) rejected overall non-jointness-in-inputs for this segment of the fleet but observed that some species such as cod and mixed flounders were non-joint-in-inputs.

As Kirkley and Strand (1988) observe, the operational strategy of this fleet is not well known and likely to vary significantly across ports. For instance, New Bedford has traditionally harvested mostly scallops and groundfish species, whereas Pt. Judith has always fished a wider range of species. The level of species aggregation may be also response for these counter-intuitive results. The high level of species aggregation can confound harvesting strategies by obscuring fleet's price responsiveness. The presence of low-value silver hake in the high-value roundfish group (which includes cod and haddock) likely biases some of the results. Furthermore, not all species are harvested together since they are necessarily present in the same fishing grounds.

Table 6: Statistical tests for the harvesting technology of the otter trawl fleet (5-50 GRT)

Test	No. of independent restrictions	Wald	Reject?	L.R.	Reject?	L.M.	Reject?
Overall	10	14.50	N	14.49	N	14.49	N
non-jointness Roundfish	4	6.11	N	6.11	N	6.11	N
non-jointness Flatfish	4	8.86	N	8.84	N	8.84	N
non-jointness Elasmobranch	4	1.81	N	1.81	N	1.81	N
non-jointness Pelagic	4	7.64	N	7.63	N	7.63	N
non-jointness Miscellaneous	4	4.81	N	4.81	N	4.81	N
Port dummies	30	581.10	Y	581.11	Y	581.11	Y
Season dummies	15	56.55	Y	56.55	Y	56.55	Y
Stock size	4	0.86	N	0.86	N	0.86	N

Contingent on these results we re-estimated the input-compensated supply equations. However, we left stock size as an explanatory variable in spite of its statistical insignificance because we needed them for the simulation. Also, since some of the stock sizes showed negative signs, meaning that as stocks increased the fishing vessels would harvest less of them, we restricted them to be positive.

The re-estimated individual supply equations for roundfish, flatfish, elasmobranch, pelagic and miscellaneous species had an R^2 of 0.176, 0.316, 0.06, 0.266, and 0.228, respectively. Table 7 reports the estimated parameter values for input-compensated supply equations. All of the effort terms (β_i 's) and effort-squared terms (α_i 's) showed positive and negative signs, respectively. The effort or own-price estimates (β_i 's) were statistically significant for roundfish, flatfish and elasmobranch

groups, whereas the effort-squared estimates were only statistically significant for the miscellaneous species group. Since the technology was non-joint the cross-price terms were omitted in the re-estimation.

About fifty percent of the port dummies were statistically significant. Most these statistically significant estimates corresponded to the roundfish, flatfish, and miscellaneous supply equations. Notably, fishing vessels operating from the ports of Rhode Island, Gloucester, and Boston were shown to land more roundfish than those vessels from New Bedford. The higher landings rates were statistically significant at the 10% significance level for Rhode Island ports, and at the 5% significance level for Gloucester and Boston. This phenomenon is explained by the presence of high concentrations of silver hake in the roundfish group. In 1993, Pt. Judith and Gloucester were ranked the number one and two, respectively in whiting revenues. In contrast, New Bedford boats had the highest flatfish landing levels from New Bedford. This situation reinforces the distorting impact of silver hake when interpreting roundfish supply estimates. The fleet operating from the port of Chatham harvested less elasmobranchs than the New Bedford fleet. The statistically significant negative relationship was not surprising because it was not until late 1993 that this fleet started targeting spiny dogfish (MAFMC, 1993). Fishing vessels from Rhode Island ports landed more pelagics than their New Bedford counterparts. This relationship was expected given the multispecies nature of this fleet. The Rhode Island port dummy was statistically significant at the 5% level. Only two of the season dummies were statistically significant.

None of the stock abundance estimates were statistically significant. Restricting these parameters to be positive decreased the magnitude of flatfish, elasmobranch, and pelagic abundance estimates as these become essentially zero.

Table 7: Parameter estimates of the supply functions of the otter trawl fleet (5-50 GRT).

	Quantities supplied of				
	Roundfish	Flatfish	Elasmobranchs	Pelagics	Other Species
Effort	26921.27* (3638.6)	40380.04* (2553.0)	7379.488* (2769.4)	28.40943 (778.8)	30550.69* (3102.9)
Effort-squared	-659.93 (356.1)	-546.779 (293.1)	-274.925 (332.0)	-54.7771 (80.6597)	- 824.601** (360.2)
Stock size	11.56475 (25.0920)	1.01E-6 (.)	1.01E-6 (.)	1.01E-6 (.)	-
Rhode Island	21911.55** (8782.5)	-21471.2** (8650.7)	1371.342 (8013.6)	31950.25* (2780.5)	39377.56* (9053.4)
Gloucester	25713.97* (7568.5)	-38339.4* (5884.4)	-8978.88 (6937.3)	2026.795 (1729.8)	4686.713 (7779.7)
Boston	8200.672 (7621.7)	-38353.7* (6411.1)	-10299.8 (6955.2)	251.8448 (2014.3)	1737.626 (7861.0)
Ptown	-18699.6* (2984.6)	-39095.5* (2503.9)	260.6731 (2712.7)	130.0317 (775.7)	-24967.3* (3054.8)
Chatham	-22369.5* (2686.3)	-39216.9* (2230.2)	-6632.91* (2453.8)	174.6506 (689.3)	-29039.9* (2764.7)
Other MA	-24313.3* (9350.5)	-39297.4* (7957.1)	6152.152 (8524.6)	156.981 (2515.5)	-29219.2* (9632.2)
Quarter I	-3775.79 (2448.5)	1361.836 (1958.4)	-1932.66 (2232.1)	292.3569 (593.0)	1234.596 (2512.1)
Quarter II	-1931.54 (2283.9)	1924.967 (1805.5)	-1573.72 (2088.8)	41.45193 (538.7)	4668.148* * (2349.4)
Quarter III	-4870.19 (2587.6)	2425.395 (2044.9)	8197.782* (2369.1)	-261.264 (607.7)	1294.316 (2662.4)

* significant at 1% ** significant at 5%.

4.5.1.2 Estimation of the 51-100 tonnage otter trawl fleet

The statistical tests show that this segment of the fleet has the ability to respond to relative prices (Table 8). However, the harvesting of flatfish, elasmobranch, and miscellaneous species appears to be non-joint-in-inputs. These results unexpected given that pelagic landings only accounted for 1.6% of the total landings whereas roundfish

accounted for 45.8% of the total landings. This result speaks to one of the limitation of the dual approach where some species may be incidentally harvested with the target species but their low price discourages fishermen from allocating resources for their harvest (Kirkely and Strand, 1988). Port and season dummies as a group were statistically significantly different from zero while stock abundance estimates as group were not.

Table 8: Statistical tests for the harvesting technology of the otter trawl fleet (51-100 GRT)

Test	No. of independent restrictions	Wald	Reject?	L.R.	Reject?	L.M.	Reject?
Overall	10	21.36	Y	21.36	Y	21.36	Y
non-jointness Roundfish	4	10.17	Y	10.17	Y	10.17	Y
non-jointness Flatfish	4	2.93	N	2.93	N	2.93	N
non-jointness Elasmobranch	4	1.15	N	1.15	N	1.15	N
non-jointness Pelagic	4	10.42	Y	10.42	Y	10.42	Y
non-jointness Miscellaneous	4	9.17	N	9.17	N	9.17	N
Port dummies	40	523.24	N	523.24	N	523.24	N
Season dummies	15	52.21	N	52.21	N	52.21	N
Stock size	4	7.38	Y	7.37	Y	7.37	Y

Based on these results we re-estimated the output supply functions imposing restriction on stock size variables and on the cross-price coefficients (β_{ij}) between roundfish and pelagic stocks. We restricted the roundfish-pelagic cross-price coefficient because its sign was positive, which generated a downward sloping supply curve. To remedy this situation be restricted this parameter to be negative.

The re-estimated supply curves of roundfish, flatfish, elasmobranch, pelagic and other species had R^2 of 0.10, 0.128, 0.0024, 0.06, and 0.145, respectively. Parameter estimates are presented in table 9. Effort and effort-squared terms exhibited the all positive and negative signs, respectively with the exception of the effort-squared term on pelagics. A positive sign suggests increasing returns to scale for the pelagic group.

Ten of the forty port dummies were found to be statistically significant different from zero. The fishing vessels operating from Gloucester and Pt. Judith were found to be land more roundfish than fishing vessels from New Bedford. The Gloucester and Pt. Judith port dummies were statistically significant at the 5% level. This again captures the distorting effect on silver hake in the roundfish landings. Between 1989 and 1993, Pt. Judith's and Gloucester's silver hake contribution to roundfish landings was of 96.06% and 44.76%, respectively. In contrast, New Bedford's silver hake contribution to roundfish landings was less than 0.2%. The flatfish supply equation had only Pt. Judith as a statistically significant port dummy. The positive sign was unexpected given the New Bedford's heavy reliance on groundfish, particularly cod, haddock, and yellowtail flounder. One explanation for this is that while New Bedford caught more flounder, especially yellowtail flounder, Pt. Judith caught more winter flounder. Thus, the estimate may be capturing the relative higher efficiency of Pt. Judith vessels respect to New Bedford vessels. Recall that since heteroscedasticity was present, the dependent variable was landings per day absent. The pelagic supply equation had two statistically significant ports (Gloucester and other Rhode Island) while the elasmobranch supply

equation had none. Five of the fifteen season dummies were statistically significant while none of the abundance estimates were.

Table 9: Parameter estimates of the supply functions of the otter trawl fleet (51-100 GRT).

	Quantity supplied of				
	Roundfish	Flatfish	Elasmobranchs	Pelagics	All others
Effort	8952.302 (5318.7)	1496.814* (394.5)	1886.48** (811.1)	53.55962 (281.6)	10343.87* (2611.8)
Effort-squared	-1729.61* (520.7)	-63.9323 (49.0634)	-247.058** (100.9)	10343.87 (2611.8)	-795.385** (324.8)
Pelagics	-1E-8 (0)				
Maine	26464.14** (13312.2)	-339.202 (1253.0)	-1020.93 (2575.9)	205.3809 (667.2)	40697.95* (8294.6)
Gloucester	35096.26* (5153.6)	-96.8927 (485.7)	-772.462 (998.5)	963.1371* (259.1)	20681.01* (3215.4)
Boston	10847.09 (6149.9)	195.9616 (579.2)	-912.496 (1190.7)	45.38551 (308.4)	11251.17* (3834.3)
Provincetown	-6645.04 (3836.9)	-337.673 (361.7)	333.6045 (743.6)	-28.038 (192.9)	-1664.65 (2394.4)
Dukes	-4399.6 (15433.8)	615.788 (1453.5)	-1082.12 (2988.1)	119.6609 (773.2)	1922.778 (9621.8)
Newport	941.309 (7181.9)	369.314 (676.8)	206.7435 (1391.4)	45.31248 (360.0)	3969.381 (4480.3)
Pt. Judith	63407.32* (5498.0)	8376.546* (517.4)	1881.722 (1063.7)	2930.358 (276.7)	56209.89* (3425.3)
Other RI	-2784.6 (21770.8)	-538.854 (2049.6)	-653.107 (4213.7)	-134.8* (1093.3)	-4185.23 (13568.4)
Stock size	51.53025 (37.9628)	1.01E-6 (0)	1.01E-6 (0)	0.36138 (0.4709)	
Quarter I	-7380.46 (3965.1)	-622.643 (373.5)	-533.294 (767.8)	-1.3904 198.6	-5721.34** (2472.5)
Quarter II	-3957.21 (3613.9)	-935.603* (340.7)	-509.005 (700.4)	-88.0273 181.2	-7925.34* (2255.2)
Quarter III	2563.43 (3634.2)	-740.094** (342.5)	1273.239 (704.2)	-269.77 182.1	-6119.54* (2267.4)

*significant at 1% ** significant at 5%.

4.5.1.3 Estimation of the 101-150 tonnage otter trawl fleet

Statistical tests indicate that 101-150 tonnage class is joint-in-inputs. The presence of jointness-in-inputs indicates the presence of technological and cost tradeoffs. Table 10 shows that port, season, and stock dummies as a group are not statistically significantly different than zero.

Table 10: Statistical tests for the harvesting technology of the otter trawl fleet (101-150 GRT)

Test	No. of independent restrictions	Wald	Reject?	L.R.	Reject?	L.M.	Reject?
Overall	10	142.06	Y	142.06	Y	142.06	Y
non-jointness							
Roundfish	4	68.87	Y	68.87	Y	68.87	Y
non-jointness							
Flatfish	4	110.10	Y	110.11	Y	110.11	Y
non-jointness							
Elasmobranch	4	31.59	Y	31.59	Y	31.59	Y
non-jointness							
Pelagic	4	41.18	Y	41.18	Y	41.18	Y
non-jointness							
Miscellaneous	4	16.98	Y	16.98	Y	16.98	Y
non-jointness							
Port dummies	45	763.08	Y	763.09	Y	763.09	Y
Season dummies	15	79.46	Y	79.46	Y	79.46	Y
Stock size	4	65.38	Y	65.41	Y	65.41	Y

A close examination of the parameters showed that some of stock size variables were negative and that all of the own-price elasticities (not shown) were negative as well. To ensure theoretically consistent results for our simulation we restricted the abundance and own-price elasticity estimates to be positive. Rather than adopting Diewert and Wales (1988) approach, which is too restrictive for empirical work, we imposed a milder restriction to ensure positive own-price elasticities. For each own-price elasticity, we weighted the sum of cross-price coefficients by the sample mean of output prices.

While this condition did not ensure global convexity, it did not preclude obtaining substitution and complementarity relationships.

The parameters of the re-estimated supply equations are presented in table 11. The individual R^2 for the output supply equations of roundfish, flatfish, elasmobranch, pelagic, and miscellaneous species were 0.024, 0.027, 0.0032, 0.015, and 0.04 suggesting a poor fit of the model. Recall that the generalized R^2 for the system, prior to correcting for heteroscedasticity, was only 0.16.

All effort and effort-squared terms conformed to theory. Statistically significant cross-price coefficients indicate jointness particularly in the flatfish and elasmobranch groups. Cross-price coefficients suggest that flatfish is a substitute for elasmobranch and miscellaneous species while it is a complement to pelagics. The substitutability with elasmobranchs was intriguing given the both spiny dogfish and skates are often caught as by-catch in groundfish operations. NMFS documents indicate that during this time elasmobranch species were often discarded. The substitutability between flatfish and elasmobranchs may be explained by the fact that fishermen initially target flounders, and when they return they target skates. An increase in the price of flounder may encourage fishermen to devote more resources and time to the catch of flounders; thus, decreasing the harvest rate of elasmobranchs, which are mainly skates.²¹ It is noteworthy that both pelagic and elasmobranch groups only constitute 2.1% and 1.9% of this fleet's landings.

²¹ A Provincetown fisherman offered this explanation.

Thirteen of the forty-five port dummies were statistically significant. Vessels from the ports of Pt. Judith and Gloucester exhibited statistically higher roundfish landing rates than the New Bedford fishing vessels for the same reasons explained earlier. Similarly, fishing vessels from Gloucester, Boston, and Newport exhibited statistically lower flatfish landing rates than fishing vessels from New Bedford. In the elasmobranch supply equation, the ports of Pt Judith and Provincetown were statistically significant at the 5 and 10%, respectively; whereas in the pelagic supply equation, the port of Pt. Judith was statistically significant at the 5% level.

Three of the four stock abundance coefficients were statistically insignificant. Only the pelagic stock's abundance was statistically significant at the 5% level. Five of the fifteen season dummies were statistically different from zero.

Table 11: Parameter estimates of the supply functions of the otter trawl fleet (101-150 GRT).

	Quantity supplied of				
	Roundfish	Flatfish	Elasmobranchs	Pelagics	Misc. Species
Effort	1551.076* (569.8)	594.1454* (58.5882)	164.076* (41.6531)	-173.267 (128.0)	1793.49* (494.6)
Effort-squared	-150.617** (63.1506)	-12.5852 (6.4888)	-11.0942* (2.7057)	-2.8268 (10.5648)	-108.411** (53.7672)
Roundfish		36.33482 (47.5232)	18.26466 (11.3206)	-222.818* (53.2825)	42.17843 (56.3957)
Flatfish			-20.6377** (9.7116)	214.923* (41.3853)	-105.15* (37.0775)
Elasmobranch				-56.8824* (11.9488)	14.97303* (5.8147)
Pelagic					-17.4571 (33.6465)
Misc. Species					
Maine	9264.756* (1245.1)	-40.6156 (127.9)	72.48458 (53.3011)	376.5949 (207.4)	13715.49* (1060.0)
Gloucester	3276.413* (739.8)	-234.302* (76.1017)	-49.3124 (32.0392)	15.30252 (123.8)	1441.897** (629.9)
Boston	568.2496 (591.5)	-304.044* (60.7637)	-42.4398 (25.3293)	35.31837 (98.4802)	740.4387 (503.6)
Provincetown	30.25201 (995.0)	-121.602 (102.5)	106.966** (42.8964)	35.26444 (166.0)	37.86365 (847.2)
Dukes	-165.465 (5865.4)	815.9928 (602.4)	-85.2506 (250.4)	73.82621 (974.1)	683.1054 (4993.6)
Newport	4.779799 (568.5)	-130.159** (58.7166)	11.75669 (24.5143)	-12.6042 (95.3785)	220.2205 (484.2)
Pt. Judith	8477.559* (728.4)	520.8881* (75.3889)	236.0714* (32.2588)	885.6881* (123.3)	7199.631* (619.9)
Other State I	-233.803 (10154.7)	-231.88 (1043.0)	-8.335 (433.5)	-79.0295 (1686.5)	10156.92 (8645.3)
Other State II	415.5655 (10157.4)	-296.462 (1043.4)	15.52872 (433.6)	-53.0907 (1687.1)	267.8108 (8647.7)
Stock size	1.01E-6 (0)	1.01E-6 (0)	1.01E-6 (0)	0.569556** (0.2363)	
Quarter I	-497.485 (510.1)	-122.004** (52.4087)	-22.9753 (21.9964)	-54.0362 (85.4387)	-547.66 (434.3)
Quarter II	-160.796 (500.7)	-152.171* (51.5316)	-13.0393 (21.6293)	72.01692 (83.9663)	893.579** (426.3)
Quarter III	-393.287 (498.7)	-215.427* (51.2167)	23.56345 (21.3796)	-162.66 (83.1782)	-1504.45* (424.5)

4.5.1.4 Estimation of the 151+ tonnage otter trawl fleet

As in the previous case, the larger tonnage classes showed that the technology was joint-in-inputs (table 12). Both port and season dummies were statistically significant as a group. Abundance and own-price elasticities (not shown) were negative. For the purposes of the simulation, we restricted the stock abundance and own-price elasticity estimates to be positive.

Table 12: Statistical tests for the harvesting technology of the otter trawl fleet (151+ GRT)

Test	No. of independent restrictions	Wald	Reject	L.R.	Reject	L.M.	Reject
Overall	10	284.87	Y	283.65	Y	282.37	Y
non-jointness							
Roundfish	4	238.72	Y	237.05	Y	235.17	Y
non-jointness							
Flatfish	4	72.45	Y	72.30	Y	72.31	Y
non-jointness							
Elasmobranch	4	18.64	Y	17.62	Y	17.07	Y
non-jointness							
Pelagic	4	84.15	Y	83.77	Y	83.45	Y
non-jointness							
Miscellaneous	4	145.57	Y	144.87	Y	143.74	Y
non-jointness							
Port dummies	35	2238.9	Y	2122.3	Y	2082.1	Y
Season dummies	15	72.88	Y	72.67	Y	72.49	Y
Stock size	4	8.76	N	8.39	N	8.17	N

The re-estimated output supply equations for roundfish, flatfish, elasmobranch, pelagic and miscellaneous species yielded an individual R^2 of 0.17, 0.07, -0.01, 0.27, and 0.01, respectively. The re-estimated model, showed the theoretically expected signs on all effort terms. Significant cross-price variables in the roundfish supply curve indicated that flatfish, elasmobranchs and pelagics were complements whereas miscellaneous

species were substitutes. This complementarity was not surprising since flatfish and elasmobranchs are often harvested together. Kirkley and Strand (1988) also found that for vessels of this tonnage class, cod and yellowtail flounder were complements. In the production of flatfish, elasmobranch, pelagics and miscellaneous species were found to be substitutes. Flatfish was found to be substitute for elasmobranchs (mostly skates), pelagics and miscellaneous species. Lastly, elasmobranchs and pelagics were found to be complements of miscellaneous species.

Twenty of the thirty-five dummy ports were statistically significant. Both roundfish and flatfish port dummies exhibited the same trends present in smaller tonnage classes. Estimates from the elasmobranch supply equation indicate that vessels from Pt. Judith landed more elasmobranchs than vessels from New Bedford, while the vessels from Maine, Gloucester, Boston, and Newport landed less elasmobranch than vessels from New Bedford. In the pelagic group, only the other Rhode Island port was statistically significant. The Rhode Island dummy reflects the activity of the fleet operating in Quonset Point, which targets pelagics (mainly mackerel) and *Loligo* squid. None of the abundance estimates were statistically significant while four of the season dummies were statistically significant.

Table 13: Parameter estimates of the supply functions of the otter trawl fleet (151+ GRT)

	Quantity supplied of				
	Roundfish	Flatfish	Elasmobranchs	Pelagics	Misc. species
Effort	1026.124*	336.8175*	115.0486	54.05242	885.4309
	(343.9)	(59.0625)	(86.5968)	(374.4)	(497.6)
Effort-squared	-213.25*	-1.21341	-5.69854*	-22.5351	-126.73*
	(24.2797)	(3.1227)	(2.1972)	(23.8834)	(46.3863)
Roundfish		87.31942**	58.96083*	333.404*	-237.842*
		(38.8866)	(12.3216)	(108.3)	(52.1611)
Flatfish			-76.322*	-110.215**	-6.29598
			(11.3199)	(47.6461)	(23.3481)
Elasmobranch				-19.9323	29.50682**
				(14.9285)	(7.2681)
Pelagic					-155.197*
					(75.8691)
Misc. Species					
Maine	2363.51*	-284.436*	-56.0717**	32.46466	3864.671*
	(278.4)	(35.7950)	(25.0722)	(271.3)	(534.5)
Gloucester	1330.166*	-307.38*	-69.563*	9.759805	798.8908**
	(208.8)	(26.7385)	(19.0606)	(203.2)	(400.3)
Boston	612.0636*	-316.57*	-72.1222*	-24.1633	876.8434**
	(195.9)	(25.1333)	(17.6394)	(190.9)	(376.2)
Newport	736.3775	-109.969**	-45.3105	72.96831	387.4356
	(417.6)	(53.5522)	(37.4836)	(407.5)	(801.7)
Pt. Judith	6625.9*	-170.433*	65.85736**	376.976	1125.521**
	(265.6)	(35.7131)	(26.7549)	(272.1)	(498.6)
Other RI	1073.427	-302.223**	-39.1166	30002.83*	8280.735*
	(831.6)	(106.7)	(74.6536)	(812.1)	(1595.7)
Other State	-1114.42	-293.547	108.9576	207.8199	2652.55
	(4311.7)	(552.1)	(385.6)	(4194.6)	(8278.0)
Stock	3.572765	8.643869	0.139085	1E-8	
size	(2.5084)	(6.2434)	(0.4477)	(0.6048)	
Quarter I	473.7387**	-4.07991	-12.1515	27.35761	1059.278*
	(212.4)	(27.3280)	(19.4040)	(208.4)	(407.7)
Quarter II	302.4815	-36.2135	-5.99297	316.5499	-156.693
	(205.3)	(26.4380)	(18.6667)	(205.0)	(393.8)
Quarter III	876.1154*	-61.1493**	-17.0164	-14.0539	-401.777
	(206.3)	(26.4514)	(18.5842)	(200.7)	(395.8)

4.5.2. Estimation of the gillnet fleet

The Wald, L.R., and L. M. test suggested that the gillnet production process is non-joint. However, the production of flatfish appeared to respond to relative prices (table 14). Port, season, and abundance estimates as a group were statistically not different from zero.

Table 14: Statistical tests for the harvesting technology of the gillnet fleet

Test	No. of independent restrictions	Wald	Reject	L.R.	Reject	L.M.	Reject
Overall	10	14.60	N	14.59	N	14.59	N
non-jointness							
Roundfish	4	6.42	N	6.40	N	6.40	N
non-jointness							
Flatfish	4	9.71	Y	9.71	Y	9.71	Y
non-jointness							
Elasmobranch	4	2.45	N	2.45	N	2.45	N
non-jointness							
Pelagic	4	5.43	N	5.43	N	5.43	N
non-jointness							
Miscellaneous	4	8.67	N	8.67	N	8.67	N
non-jointness							
Port	30	82.78	Y	82.77	Y	82.77	Y
dummies							
Season	15	201.96	Y	201.96	Y	201.96	Y
dummies							
Stock	4	7.36	Y	7.36	Y	7.36	Y

The R^2 re-estimated supply output curve for roundfish, flatfish, elasmobranch, pelagic and miscellaneous species were estimated at 0.1015, 0.0748, 0.1023, 0.0396 and 0.2057, respectively. Effort terms in general followed theoretical expectations. However, only one effort term on elasmobranchs was statistically significant while two effort-squared terms on roundfish and miscellaneous species were statistically significant. Their negative sign on the effort-squared terms indicates decreasing returns to scale.

Only three of thirty-six port dummies were statistically significant. Statistically, only fishing vessels from Chatham and Barnstable landed less elasmobranchs than their New Bedford counterparts. This reflects New Bedford increased interest in this fishery. Since the early 1990's, New Bedford's fixed gear fleet began targeting elasmobranchs,

primarily spiny dogfish. The larger tonnage vessels (51+ GRT) more found to land less elasmobranchs, pelagics, and miscellaneous species than the smaller tonnage vessels. None of the abundance estimates were statistically significant while six of the fifteen season dummies were statistically significant.

Table 15: Parameter estimates of the supply functions of the gillnet fleet

	Quantity supplied of				
	Roundfish	Flatfish	Elasmobranch	Pelagic	Misc. Species
Effort	1322.798 (2703.2)	-144.553 (451.0)	22184.87* (7483.1)	35.67559 (64.2565)	3946.528 (4353.9)
Effort-squared	-103.265** (46.7833)	1.732504 (7.8685)	-195.958 (130.6)	-1.09329 (1.0864)	-202.296* (75.9669)
Maine	3490.731 (2684.1)	97.61999 (451.3)	-10445 (7489.0)	43.93175 (62.3413)	9232.385** (4357.3)
Gloucester	2942.576 (2677.0)	614.7927 (449.8)	-13822.9 (7463.3)	8.127567 (62.3997)	4441.841 (4342.4)
Barnstable	-8.15234 (3101.6)	49.34266 (521.7)	-21450.1** (8657.1)	-10.1377 (72.0468)	-1236.13 (5037.0)
Chatham	-245.772 (2666.4)	137.0019 (448.4)	-21579** (7441.0)	-21.6092 (61.9085)	-2072.63 (4329.4)
Other MA	-79.7915 (3494.2)	-41.4263 (587.4)	-20353.6 (9746.4)	51.84492 (81.4545)	-1243 (5670.8)
Other State	-937.362 (5282.3)	145.0877 (888.6)	-21988.9 (14745.0)	-53.6602 (122.7)	-3739.7 (8579.2)
Large vessel dummy	-1296.92 (817.4)	-96.9041 (137.5)	-6981.9* (2280.8)	-37.4023** (19.0014)	-3044.59** (1327.1)
Stock size	1.885822 (5.4255)	1E-8 (0)	1E-8 (0)	0.049063 (0.0304)	
Quarter I	-869.171 (529.4)	-53.8486 (89.0620)	-2317.36 (1477.8)	-25.5854** (12.3130)	128.5754 (859.9)
Quarter II	-941.022 (526.1)	267.6565* (88.5047)	-1146.69 (1468.6)	-48.2157* (12.2184)	-2481.87* (854.5)
Quarter III	302.2671 (400.1)	-14.2891 (67.3183)	3291.115* (1117.0)	-40.3738* (9.2886)	-1089.11 (649.9)

4.5.3. Estimation of the longline fleet

Lastly we estimated the technology of the longline fleet. Statistical test suggested that production was non-joint-in-inputs(i.e., there is a separate production function for each

species group). Port dummies as a group were statistically significant while season and abundance estimates as a group were not statistically different from zero (table 16).

Table 16: Statistical tests for the harvesting technology of the longline fleet

Test	No. of independent restrictions	Wald	Reject	L.R.	Reject	L.M.	Reject
Overall	10	16.13	N	16.11	N	16.11	N
non-jointness							
Roundfish	4	14.71	N	14.68	N	14.68	N
non-jointness							
Flatfish	4	9.32	N	9.30	N	9.30	N
non-jointness							
Elasmobranch	4	2.68	N	2.67	N	2.67	N
non-jointness							
Pelagic	4	0.62	N	0.61	N	0.61	N
non-jointness							
Miscellaneous	4	6.18	N	6.18	N	6.18	N
non-jointness							
Port dummies	30	145.15	Y	145.14	Y	145.14	Y
Season dummies	15	13.63	N	13.63	N	13.63	N
Stock size	4	3.50	N	3.48	N	3.48	N

Table 17 shows parameter estimates of the re-estimated input-compensated supply equations. Two of the five effort terms were negative while two of the five effort-squared terms were positive. Only the effort term on miscellaneous species was statistically significant.

Four of thirty port dummies were statistically significant. For the roundfish equation, the port of Gloucester was statistically significant while for the miscellaneous species equation the ports of Gloucester, Chatham, and other Massachusetts were statistically significant. Larger vessels (51+ GRT) were found to statistically land more roundfish

and miscellaneous species than the smaller vessels. None of the abundance estimates were statistically significant while only one season dummy was statistically significant.

Table 17: Parameter estimates of the supply functions of the longline fleet

	Quantity supplied of				
	Roundfish	Flatfish	Elasmobranch	Pelagic	Misc. Species
Effort	749.6613 (606.9)	1.88109 (3.0679)	-64.7747 (229.5)	-0.6927 (0.6779)	3917.334* (1017.0)
Effort-squared	-34.9293 (20.7614)	-0.0879 (0.0986)	2.116814 (8.6577)	0.023613 (0.0215)	-40.0317 (38.3677)
Maine	136.4355 (515.0)	0.083945 (2.4383)	50.68681 (214.5)	-0.21353 (0.5324)	714.8744 (950.7)
Gloucester	1346.681* (502.1)	0.247839 (2.3806)	371.0619 (208.0)	0.04008 (0.5192)	2645.186* (921.8)
Ptown	-319.43 (1057.2)	-0.93487 (4.9864)	68.13725 (438.8)	0.149255 (1.0891)	-2658.44 (1944.6)
Chatham	-20.0979 (538.0)	0.207043 (2.5458)	38.57052 (224.0)	0.219146 (0.5565)	-3477.52* (992.8)
Other MA	-216.241 (646.3)	-0.37719 (3.0415)	27.3486 (267.6)	0.167524 (0.6688)	-3636.59* (1186.1)
Boston	188.2733 (869.6)	0.099133 (4.1214)	55.62657 (362.6)	-0.03112 (0.8986)	963.258 (1606.9)
Large vessel dummy	-631.917** (272.4)	-0.22718 (1.2876)	8.658852 (113.3)	-0.07961 (0.2815)	-2561.15* (502.1)
Stock size	2.324345 (3.8828)	0.054482 0.4065	1E-8 (0)	0.00101 (0.000723)	
Quarter I	-15.1093 (180.7)	-1.52695 (0.8515)	-25.7652 (74.9004)	0.068626 (0.1860)	-264.197 (331.9)
Quarter II	26.63872 (192.5)	-1.09072 (0.9124)	10.66658 (80.2701)	0.318993 (0.1989)	-527.815 (355.7)
Quarter III	18.91855 (244.6)	-1.5428 (1.1699)	220.8819** (101.7)	-0.03712 (0.2540)	183.4074 (450.9)

4.6 Summary

The econometric analysis suggests the technological and economic interactions vary significantly across firms. For instance, the otter trawl fleet showed a wide range of technologies. The smaller tonnage classes exhibited non-joint-in-inputs technologies while the larger tonnage classes exhibited joint-in-input technologies. The presence of jointness-in-inputs in the larger otter trawls evidences the presence of technological and cost interrelationships. It also suggests that fishermen can select the catch composition

to some extent. Gillnet and longline vessels, on the other hand, exhibited non-jointness-in-inputs, suggesting that there are no technological and cost tradeoffs during their production process. It also evidences that these fleets have a separate production process for each species harvested.

The absence of price responsiveness especially in the smaller otter trawl tonnage class, which is known for its opportunistic behavior, is troublesome. This situation underscores potential problems with our estimates. One of the most vexing problems during the estimation was the consistent presence of downward sloping supply curves and negative abundance terms. The empirical literature suggested several reasons for theoretically inconsistent results. The first and probably most important reason is aggregation. Gates (1974) reports that aggregation bias may yield negative and statistically insignificant own-price elasticities. Kirkley and Strand (1988), who examined the otter trawl fleet operating on Georges Bank, showed consistent positive own-price elasticities of supply. However, their estimates rejected the imposition of symmetry, which casts doubts on the robustness of their results. Squires (1987), who also examined the New England otter trawl fleet, reports negative own-price elasticities of supplies for some of its aggregated species groups.

Ideally to overcome this problem we could have had disaggregated our species groups. Unfortunately, given the scope of the study, which required coupling our estimates with an aggregated predator-prey model, we could not disaggregated our species group further. Kirkley and Stand (1988) observe that given the high number of species present

in the fishery, little can be done to resolve this problem. Moreover, aggregation bias may have been exacerbated since some of the individual species within the species groups had large price differentials masking the effect of prices. For instance, in 1993 the haddock ex-vessel price was approximately 1.38 dollars per pound while the silver hake ex-vessel price was approximately 0.37 dollars per pound. In hindsight, a better way to unravel the operational strategies of the different fleet segments would be to stratify the fleet not only by tonnage class but also by port.

Another limitation was the lack of variability both in prices and stock sizes, which may have contributed to multicollinearity. Given that many vessels did not land all species in all trips we resorted to placing monthly (or annual depending the case) prices. This may have caused coefficients to have the wrong sign or implausible magnitudes. This situation was particularly true for the pelagic group. Similarly, the use of annual abundance estimates may have further contributed to the poor econometric estimates.

Chapter 5: Empirical Model

5.1. Background

The objective of this chapter is to develop a bioeconomic model that explicitly accounts for multiproduct technological interrelationships. The model investigates the implications of modifying the species selectivity properties of the gears using the Georges Bank multispecies fishery as a case study. As mentioned earlier, Georges Bank has traditionally supported large pelagic and demersal resources. In the 1960's and 1970's, excessive harvesting by foreign fleets resulted in the over-exploitation of pelagic stocks. In the 1980's and early 1990's, intensive fishing by domestic fleets led to the decline of several demersal stocks. Simultaneously, the biomass of non-targeted species such as elasmobranchs, mainly spiny dogfish and skates, increased. More recently, previously overexploited pelagic resources recovered while the abundance of elasmobranchs began to decrease. This progression of over-exploitation to previously less desirable species has led to extensive changes in the structure of the Georges Bank ecosystem.

In recent years increased awareness of the negative environmental impacts of indiscriminate harvesting practices and increased research funding have encouraged the development of environmentally friendly gear technologies (FAO, 1997). A large share of gear technologists efforts, has been focused on the design of more selective trawl gear. In particular, designing new mesh configurations and incorporating selection

grids. Also significant amount of work has been devoted to the development of new gears.

Murawski (1990) observes that mesh size selectivity depends on cod-end dimensions and other operational factors such as towing speed, fish density, and net fullness. The impact of modifying the mesh size will not only depend on the size distribution and composition of the catch but also on fish behavior. DeAlteris and Morse (1997) observe that when otter trawls are dragged on the bottom, the doors will generate sand clouds that herd cod and haddock between the wing ends of the trawl. As the fish become tired, cod turn back into the trawl and dives down while haddock will attempt to rise above the headrope. Thus, fishermen trying to reduce the haddock bycatch in cod tows, will reduce the headrope height to facilitate the escape of haddock. The body shape is another consideration. Roundfish have a different body shape than flatfish; thus, different escapement rates are expected. Widening mesh sizes does not necessarily ensure that smaller sized fish will necessary escape due to clogging. Ueber (1990) observers that effectiveness of larger mesh sizes decreases with larger number of species. Not surprisingly, Hanna (1990) notes that in multispecies fisheries there is no optimum mesh size. An important consideration is that escapement does not guarantee survival since fish that successfully escaped through trawls may die shortly after due to injuries incurred while passing through the mesh.

In addition to changing mesh configurations, gear technologists have been developing a variety of devices that segregate the catch prior to entering the cod-end of nets (FAO,

1997). These devices use a separator grid and escape panels to allow the incidental catch to escape. The panel separates fish of different sizes by allowing the smaller fish to pass through the grid while deflecting larger fish. These grid systems are widely used in shrimp fisheries around the world.

Also gear technologists have been actively developing alternative technologies. Brewer *et al.* (1994) report that in Australia's northern fish trawl fishery, trials using semi-pelagic trawls have reduced the level of incidental catch without reducing the catch level of target species compared to the traditional bottom trawls. Similarly, the development of pots and traps has been shown to be an effective environmentally friendly alternative to traditional gears. Weyman (1995) reports that in the Bering Sea cod fishery, pots and lines significantly reduced the level of halibut bycatch. It is important to observe that in some cases modifying the species selectivity does not necessarily require changing the configuration of gear, but could include the management actions such as permitted fishing times and/or areas. Management can also modify the species selectivity of the gears by requiring additional devices such as pingers and bird scaring lines, which minimize the incidental catch of marine mammals and seabirds in gillnet and longlines, respectively.

While the adoption of a specific technology is an important issue in itself, the bioeconomic model focuses on the overall impact of modifying the species selectivity properties of the gear rather than addressing the specific technology to be used. The model is primarily concerned with understanding how improving the species selectivity

properties of the principal gears can contribute to the rebuilding the more commercially valuable Georges Bank groundfish stocks.

Despite the important biological and economic implications of rebuilding the groundfish stocks, scant economic work has been conducted in this area. Most of the empirical work focused on the bioeconomic implications of effort management. For instance, Edwards and Murawski (1993) estimated the dissipation of rent from the commercial harvest of groundfish resources of New England. They estimated that the net economic value of the fishery would be maximized by a 70% reduction in fishing effort.²² Overholtz *et al.* (1995) developed a multispecies model of the New England groundfish fishery to evaluate the impact of effort reduction policies. They found that significant reduction in short-term effort and catch would triple to quintuple catch per unit effort levels in the long-run, especially for haddock and flounder.

More recently, Thunberg, Helser, and Mayo (1998) examined the bioeconomic impacts of targeting different age groups of silver hake in the Northeast. They found that by shifting the harvesting pressure to younger age classes, the fleet experienced short-run gains at the expense of long-run declines in biomass, which lowered the fishery's value and yield. Conversely, they found that by targeting older individuals the value of the fishery might improve over present levels with modest reductions in short-run yield. Although Thunberg *et al.*'s work investigated the implication of modifying the

²² They estimated that the potential resource rent was approximately US\$ 130 million annually.

catchability properties of the gear, they did not examine this issue in a multispecies context nor did they investigate its impact on fish assemblage compositions.

5.2. Model Description

The model simulates the dynamics of a multispecies fishery under a suite of management measures. The primary focus of this work is to provide an improved understanding of species selectivity changes in a multispecies context. The model simulates the interaction between the main fish assemblages and fishing fleets operating on Georges Bank. Conceptually, the model is simple. There are two main components, one describing the population dynamics of the stocks and the other describing the economics of the fleets. The model is organized as a set of interrelated subroutines controlled by the main program.

The biological component is a multispecies aggregated surplus production model. Holling I type multispecies interactions are assumed.²³ The fish assemblages are selected because of their commercial and/or trophic importance. The main assemblages considered were roundfish, flatfish, elasmobranchs and pelagics. The roundfish assemblage is composed of Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and silver hake (*Merluccius bilinearis*). The flatfish assemblage consists of yellowtail flounder (*Limanda ferruginea*) and winter flounder (*Pleuronectes americanus*). The elasmobranch assemblage includes spiny dogfish (*Squalus acanthias*) and winter skates (*Raja ocellata*) and little skates (*Raja erinacea*), while the pelagics

²³ Functional response describes how the per capita growth rate is affected by predation and consumption. In our case, we assume that the functional response is a function of stock abundance (i.e., multiply both stock sizes together)

assemblage includes Atlantic mackerel (*Scomber scombrus*) and herring (*Clupea harengus*).

The stock dynamics are modeled as,

$$G_{t+1} = G_t + r_1 G_{t-1} - \frac{r_1}{K_1} G_{t-1}^2 - Y_{1,t} - \alpha G_{t-1} E_{t-1} + \beta G_{t-1} P_{t-1}$$

$$F_{t+1} = F_t + r_2 F_{t-1} - \frac{r_2}{K_2} F_{t-1}^2 - Y_{2,t} - \chi F_{t-1} E_{t-1}$$

$$E_{t+1} = E_t + r_3 E_{t-1} - \frac{r_3}{K_3} E_{t-1}^2 - Y_{3,t} - \chi E_{t-1} G_{t-1} - \delta F_{t-1} E_{t-1}$$

$$P_{t+1} = P_t + r_4 P_{t-1} - \frac{r_4}{K_4} P_{t-1}^2 - Y_{4,t} - \varepsilon P_{t-1} E_{t-1}$$

where r and K are the intrinsic growth rate and carrying capacity for species i , and Y is yield. $\alpha, \beta, \chi, \delta$, and ε are the interaction parameters of the Holling I functional response.

The economic component focuses on three fishing fleets, namely otter trawls, gillnets and longliners. Ideally, the fleet dynamics for the entire northeast region (i.e., Gulf of Maine, Georges Bank, and Southern New England), rather than partitioning the fleet's activity to Georges Bank only, would be modeled. Most of the fishing activity, especially of larger vessels, is not confined to one area. In fact, they straddle their harvesting operations across several areas.²⁴ Given that only a part of the system is modeled, this limits our understanding of the fleets' financial success or failure since many of these vessels participate in other areas. The fleets' participation in other areas

²⁴ This is particularly true, for Georges Bank where closures forced fishermen to operate in different waters and target different species. This model does not consider the impact of closures nor attempts to address fishing location issues.

and/or fisheries determines their overall profitability and thus investment and disinvestment decisions. Because of this, we did not model the fleets' entry-exit behavior but rather restricted ourselves to model total number of days absent. If we had modeled the entire northeast region, the fleets' financial viability could have been examined and their expected future participation could have been determined. When modeling a partitioned fishery, this feature cannot be fully captured.

In view of the above and the limited entry regime, we moved away from modeling fleet dynamics and switching behavior, and focused on developing a simpler model that captured days absent as a proxy of fishing effort. Fishing effort expended by the fleets was represented as the profit maximizing number of days absent per trip per season multiplied by the average number of trips per season taken by each fleet segment. For the purposes of this analysis, we used the average number of trips taken between 1989 and 1993.

The profit maximizing effort level is obtained by setting the value of marginal product of effort equal to the long-run marginal cost of effort and solving for the optimal level of effort. Mathematically, the value of the marginal product of effort is given by

$$\frac{\partial R}{\partial E} = 2 \sum_i \alpha_i P_i E + \sum_i \sum_j \beta_{ij} (P_i P_j)^{1/2} + \Omega \quad (5.1)$$

where Ω captures season and port dummies and stock abundance.

Since the NMFS Weightout database does not provide information on the cost structure, cost estimates were obtained from the Sea Sampling database. The variable costs included ice, fuel and labor costs. The return to labor was measured as its opportunity cost. We assumed that the crew would be employed in manufacturing sector. Estimated earnings were obtained from the Bureau of Labor Statistics. The captain's opportunity cost was set 30% higher than the average crewmen opportunity cost.

We assume that the long-run variable cost function was quadratic, such that

$$C = cE + dE^2 \quad (5.2)$$

where c and d are parameters on days absent and days absent square.

Combining the above equations, we solved for the profit maximizing effort level such that

$$E = \frac{1}{2 \sum_i \alpha_i P_i - d} (c - \sum_i \sum_j \beta_{ij} (P_i P_j)^{1/2} - \Omega) \quad (5.3)$$

In calibrating the model, the estimated cost parameters were adjusted until the value of effort was close to the 1989-1993 mean (Campbell, 1995). Then we mimicked 1989-93 mean landings by adjusting α_i 's and β_{ii} 's within one standard deviation. This allowed landings to be calibrated to within 10% 1989-93 mean.

5.3. Results

5.3.1. Introduction

Simulation runs indicated that without dramatic reductions in effort, roundfish and flatfish stocks would collapse soon. At the existing exploitation levels, roundfish and flatfish biomass collapsed in year 37 and 41, respectively. In contrast, elasmobranch and pelagic biomass continued to increase, stabilizing at 188.8 and 1,784.2 million tons respectively.

We also examined the impact of changing the species selectivity properties and taxing overexploited species. Model runs showed that this measures alone did not prevent the collapse of the roundfish and flatfish stocks. These measures simply delayed the collapse of the roundfish stocks. For example, reducing the roundfish catchability by 20% delayed the collapse of roundfish stocks by three years. Similarly, imposing a 20 % tax on roundfish landings pushed the collapse of the roundfish stocks by one year. Under both policies flatfish stock continued to collapse in year 41.

These results suggested that neither policy by itself would reverse the collapse of the roundfish and flatfish stocks. Thus, a different approach was needed to ensure the sustainability of these stocks. Ideally, we would have run the model until it reached some sustainable steady state. Then we would have re-run the model under some policy scenario until in reached again some sustainable steady state. Then both steady states

would be compared. Unfortunately, given the high exploitation rates, we were forced to reduce the overall effort level to generate new steady state stock size levels.

Simulations runs showed that overall effort had to be reduced by 58% in order to prevent the collapse of the roundfish and flatfish stocks. To meet this effort reduction, we reduced the number of trips taken by the fleet rather than reducing the fleet size.²⁵ At this effort reduction level, roundfish stock sizes stabilized at 840.1 million tons, whereas flatfish and pelagic stocks stabilized at 76.4 and 2,221.8 million tons, respectively. Elasmobranch stocks collapsed in year 66. Given that the reduction in effort recovered the roundfish and flatfish stocks, this work will focus on how effort reductions in conjunction with other policies can expedite the recovery of roundfish and flatfish stocks.

5.3.2. Bioeconomic performance of management alternatives

The behavior of the Georges Bank multispecies fishery was analyzed under two sets of policies. First, we considered a policy that would require the fishing industry to adopt new gear designs or configurations that modify the species selectivity properties of the gear. Second, we considered using market-based mechanisms to induce fishermen to change their harvest composition.

²⁵ We recognize that there are alternative approaches to reducing effort that may more accurately reflect the fleet dynamics. The chosen method may not accurately reflect the dynamics of large vessels since they may not be able to cover their fixed costs under days at sea limitation. Furthermore, Aguirre International (1996) observes that “while moving into alternative fisheries has been the most preferred response, most of the larger vessels of Gloucester and New Bedford have become too specialized and too dependent on family networks for staffing vessels to shift into other fisheries without substantial capital investments. Small and medium-sized (30-75’) vessels have had more

Changing the species selectivity properties of the gears has long been advocated. On the surface, the adoption of such policy should contribute to the rebuilding of the stocks. However, changing the catchability of one species may have adverse spillover effects into the other species depending on complementarity and substitution possibilities of the gear technology. The presence of biological interrelationships further complicates the issue.

To examine this issue, we followed Campbell and Nicholl's approach. In their 1995 paper, the authors modified the catchability of the gears by multiplying the parameters of supply equation species i by a scalar. Mathematically,

$$R = \sum_{j \neq i} \sum_{k \neq i} \beta_{jk} (P_j P_k)^{1/2} E + \sum_j \alpha_j P_j E^2 + \theta \left(\sum_j \beta_{ij} (P_i P_j)^{1/2} E + \alpha_i P_i E^2 \right) \quad (5.4)$$

Applying Hotelling lemma and assuming a two species system, we obtain

$$Q_i = \theta(\alpha_i E^2 + \beta_{ii} E + \beta_{ij} \left(\frac{P_j}{P_i}\right)^{1/2} E + \Omega E) \quad (5.5)$$

$$Q_j = \alpha_j E^2 + \beta_{jj} E + \theta \beta_{ij} \left(\frac{P_i}{P_j}\right)^{1/2} E + \Omega E \quad (5.6)$$

success moving into alternative fisheries, yet often have been met with hostility as they attempt to enter fisheries

where θ is the proportion by which the catchability of species i is modified. Note that since the β_{ij} 's have to be symmetric, θ has to appear in all the supply equations. Table 18 presents a summary of the technological change experiments conducted.

Next, we considered market-based mechanisms or incentive and disincentive programs as referred by Sissenwine and Kirkley (1982). The study of market-based mechanisms is motivated by two considerations. First, market-based mechanisms are prevalent in the resource economics literature. Taxes and subsidies are often advocated for correcting market inefficiencies. Taxes have been implemented to prevent the producer from exploiting resources too rapidly, whereas subsidies have implemented to encourage higher exploitation rates. Under market-based mechanisms, fishing pressure could be redirected by changing relative prices. By imposing a tax on the price of an overexploited species, fishermen would find harvesting the overexploited species less attractive. In contrast, by imposing a subsidy on an underutilized species, fishermen would find harvesting the underexploited species more attractive. This effort redirection implicitly assumes that markets for the underutilized species will develop. Several mechanisms for collecting and redistributing rents have been discussed including system of pooled landing fees, price controls, etc. Sissenwine and Kirkley (1982) discuss the benefits and shortcomings of each of these market-based approaches in a fishery context.

dominated by families and fleets that have been in those fisheries for generations".

A second motivation for market-based mechanisms is that they have been considered as a possible policy instrument for New England. The availability of overexploited species such as roundfish and flatfish stocks, and underexploited species such as pelagic stocks makes New England a good candidate. Moreover, several segments of the fishing industry had expressed support for this mechanism. However, this policy was never implemented.

Under our specification the impact of imposing a tax on species i , in a two species case would be modeled as

$$Q_i = \alpha_i E^2 + \beta_{ii} E + \beta_{ij} \left(\frac{P_j}{P_i - \tau} \right)^{1/2} E + \Omega E \quad (5.7)$$

$$Q_j = \alpha_j E^2 + \beta_{jj} E + \beta_{ji} \left(\frac{P_i - \tau}{P_j} \right)^{1/2} E + \Omega E \quad (5.8)$$

where τ is the tax. Table 19 summarizes the main experiments conducted.

To gauge the performance of the different scenarios we developed a baseline scenario. This benchmark scenario assumed that the current limited entry regime remains in place for the duration of the simulation. Throughout the analysis, we normalize the benefits to the baseline level. In other words, the NPV index for the baseline scenario is 100%. The simulations ran for 100 years and used a 3% discount rate.

Given the number of scenarios a description of each outcome is relegated to Appendix E. Tables 20 and 21 summarize the economic performance of the models. In addition, tables 20 and 21 provide information regarding the number of years that are required to achieve the same pre-policy (scenario) revenue in nominal terms. This number of years provides an indication of short-term sacrifices the industry must endure for adopting a given policy. We also provide the number of years needed under the current scenario needed to generate the same amount of discounted benefits than the baseline scenario.

Table 1: Summary of technological change policies

Scenarios	Description	Parameter change
Scenario I	Reduction in the roundfish species selectivity	All roundfish supply parameters by 5,10,15, and 20%
Scenario II	Reduction in the flatfish species selectivity	All flatfish supply parameters by 5,10,15, and 20%.
Scenario III	Increase in the elasmobranch species selectivity	All elasmobranch supply parameters by 5,10,15, and 20%.
Scenario IV	Reduction in the elasmobranch species selectivity	All elasmobranch supply parameters by 5,10,15, and 20%.
Scenario V	Increase in the pelagic species selectivity	All pelagic supply parameters by 5,10,15, and 20%.
Scenario VI	Reduction in the pelagic species selectivity	All pelagic supply parameters by 5,10,15, and 20%.
Scenario VII	Reduction in the roundfish species selectivity and increase in elasmobranch species selectivity	All roundfish supply parameters by 10 and elasmobranch supply parameters by 5,10, 15, and 20%.
Scenario VIII	Reduction in the roundfish and elasmobranch species selectivity	All roundfish supply parameters by 10 and elasmobranch supply parameters by 5,10, 15, and 20%.
Scenario IX	Reduction in the roundfish species selectivity and increase in pelagic species selectivity	All roundfish supply parameters by 10 and pelagic supply parameters by 5,10, 15, and 20%.
Scenario X	Reduction in the roundfish and pelagic species selectivity	All roundfish supply parameters by 10 and pelagic supply parameters by 5,10, 15, and 20%.

Table 2: Summary of market-based policies.

Scenarios	Description	Parameter change*
Scenario XI	Tax on roundfish catches	Roundfish catches taxed at 5, 10, 15, and 20 %
Scenario XII	Tax on flatfish catches	Flatfish catches taxed at 5,10, 15, and 20 %
Scenario XIII	Tax on elasmobranch catches	Elasmobranch catches taxed at 5, 10, 15, and 20 %
Scenario XIV	Subsidy on elasmobranch catches	Elasmobranch catches subsidized at 5, 10, 15, and 20 %
Scenario XV	Taxes on pelagic catches	Pelagic catches taxes at 5, 10, 15, and 20 %
Scenario XVI	Subsidy on pelagic catches	Pelagic catches subsidized at 5, 10, 15, and 20 %
Scenario XVII	Tax on roundfish catches and subsidy on elasmobranchs catches	Roundfish catches taxed at 10 % while elasmobranch catches are subsidized at 5, 10, 15, and 20
Scenario XVIII	Tax on roundfish catches and subsidy on pelagic catches	Roundfish catches taxed at 10 % while pelagic catches are subsidized at 5, 10, 15, and 20 %

(*) All taxes and/or subsidies are applied on the ex-vessel price.

Table 20: Summary of benefits under technological change policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
I.a.	5% reduction in roundfish selectivity	115.71	13	70
I.b.	10% reduction in roundfish selectivity	118.39	11	66
I.c.	15% reduction in roundfish selectivity	118.58	11	65
I.d.	20% reduction in roundfish selectivity	117.39	10	66
II.a.	5% reduction in flatfish selectivity	102.53	21	94
II.b.	10% reduction in flatfish selectivity	104.25	20	90
II.c.	15% reduction in flatfish selectivity	105.54	19	87
II.d.	20% reduction in flatfish selectivity	106.56	19	85
III.a.	5% increase in elasmobranch selectivity	101.01	21	98
III.b.	10% increase in elasmobranch selectivity	101.94	21	95
III.c.	15% increase in elasmobranch selectivity	102.8	20	93
III.d.	20% increase in elasmobranch selectivity	103.62	20	91
IV.a.	5% reduction in elasmobranch selectivity	98.90	23	>100
IV.b.	10% reduction in elasmobranch selectivity	97.68	23	>100
IV.c.	15% reduction in elasmobranch selectivity	96.29	24	>100
IV.d.	20% reduction in elasmobranch selectivity	94.66	25	>100

Table 20 (cont): Summary of benefits under technological change policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
V.a.	5% increase in pelagic selectivity	98.49	23	>100
V.b.	10% increase in pelagic selectivity	96.61	24	>100
V.c.	15% increase in pelagic selectivity	94.05	26	>100
V.d.	20% increase in pelagic selectivity	89.69	29	>100
VI.a.	5% reduction in pelagic selectivity	101.28	21	97
VI.b.	10% reduction in pelagic selectivity	102.40	21	94
VI.c.	15% reduction in pelagic selectivity	103.40	20	92
VI.d.	20% reduction in pelagic selectivity	104.30	20	90
VII.a.	10% reduction in roundfish selectivity and 5% increase in elasmobranch selectivity	118.66	11	66
VII.b.	10% reduction in roundfish selectivity and 10% increase in elasmobranch selectivity	118.92	11	66
VII.c.	10% reduction in roundfish selectivity and 15% increase in elasmobranch selectivity	119.18	11	65
VII.d.	10% reduction in roundfish selectivity and 20% increase in elasmobranch selectivity	119.43	11	65

Table 20 (cont.): Summary of benefits under technological change policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
VIII.a.	10% reduction in roundfish selectivity and 5% reduction in elasmobranch selectivity	118.12	11	67
VIII.b.	10% reduction in roundfish selectivity and 10% reduction in elasmobranch selectivity	117.85	11	67
VIII.c.	10% reduction in roundfish selectivity and 15% reduction in elasmobranch selectivity	117.57	11	67
VIII.d.	10% reduction in roundfish selectivity and 20% reduction in elasmobranch selectivity	117.28	12	68
IX.a.	10% reduction in roundfish selectivity and 10% increase in pelagic selectivity	118.17	11	67
IX.b.	10% reduction in roundfish selectivity and 10% increase in pelagic selectivity	117.95	11	67
IX.c.	10% reduction in roundfish selectivity and 15% increase in pelagic selectivity	117.73	11	67
IX.d.	10% reduction in roundfish selectivity and 20% increase in pelagic selectivity	117.50	11	67

Table 20 (cont.): Summary of benefits under technological change policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
X.a.	10% reduction in roundfish selectivity and 10% reduction in pelagic selectivity	118.61	11	66
X.b.	10% reduction in roundfish selectivity and 10% reduction in pelagic selectivity	118.83	11	66
X.c.	10% reduction in roundfish selectivity and 15% reduction in pelagic selectivity	119.06	11	66
X.d.	10% reduction in roundfish selectivity and 20% reduction in pelagic selectivity	119.26	11	65

Table 21: Summary of benefits under market-based policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
XI.a.	5% tax on roundfish catches	118.62	12	66
XI.b.	10% tax on roundfish catches	118.31	13	66
XI.c.	15% tax on roundfish catches	117.74	14	67
XI.d.	20% tax on roundfish catches	117.09	14	67
XII.a.	5% tax on flatfish catches	119.30	12	65
XII.b.	10% tax on flatfish catches	119.34	12	65
XII.c.	15% tax on flatfish catches	119.37	12	65
XII.d.	20% tax on flatfish catches	119.41	12	65
XIII.a.	5% tax on elasmobranch catches	119.26	11	65
XIII.b.	10% tax on elasmobranch catches	119.26	11	65
XIII.c.	15% tax on elasmobranch catches	119.26	11	65
XIII.d.	20% tax on elasmobranch catches	119.26	11	65
XIV.a.	5% subsidy on elasmobranch catches	119.26	11	65
XIV.b.	10% subsidy on elasmobranch catches	119.26	11	65
XIV.c.	15% subsidy on elasmobranch catches	119.27	11	65
XIV.d.	20% subsidy on elasmobranch catches	119.27	11	65

Table 21 (cont): Summary of benefits under market-based policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
XV.a.	5% tax on pelagic catches	119.28	11	65
XV.b.	10% tax on pelagic catches	119.30	11	65
XV.c.	15% tax on pelagic catches	119.32	11	65
XV.d.	20% tax on pelagic catches	119.35	11	65
XVI.a.	5% subsidy on pelagic catches	119.24	12	65
XVI.b.	10% subsidy on pelagic catches	119.22	12	65
XVI.c.	15% subsidy on pelagic catches	119.21	12	65
XVI.d.	20% subsidy on pelagic catches	119.19	12	65

Table 21 (cont.): Summary of benefits under market-based policies.

Scenario	Description	NPV Index Relative to Baseline Levels (%)	Years Needed to Met Pre-Policy Revenue Levels	Years Needed to Match Baseline Profit Levels
XVII.a.	10% tax on roundfish catches and 5% subsidy on elasmobranch catches	118.30	13	66
XVII.b.	10% tax on roundfish catches and 10% subsidy on elasmobranch catches	118.31	13	66
XVII.c.	10% tax on roundfish catches and 15% subsidy on elasmobranch catches	118.32	13	66
XVII.d.	10% tax on roundfish catches and 20% subsidy on elasmobranch catches	118.32	13	66
XVIII.a.	10% tax on roundfish catches and 5% subsidy on pelagic catches	118.29	13	66
XVIII.b.	10% tax on roundfish catches and 10% subsidy on pelagic catches	118.28	13	66
XVIII.c.	10% tax on roundfish catches and 15% subsidy on pelagic catches	118.27	13	66
XVIII.d.	10% tax on roundfish catches and 20% subsidy on pelagic catches	118.25	13	66

5.4. Discussion

In addressing the modification of the species selectivity properties of fishing gears, we attempted to address this issue theoretically and empirically. In chapter three, a stylized construct of this issue was developed. While theoretical treatment recognized two types of technology, namely perfectly selective and perfectly non-selective, it failed to recognize fishermen's ability to respond to relative prices. Several studies have shown that fishermen have a modicum of maneuverability to target one or more species.

To overcome this limitation, we adopted a more flexible specification. This new specification allowed us to examine this issue in detail. The scenarios investigated in the empirical section fell into two categories: market-based and technologically-based. The former focused on tax and/or subsidy programs while the latter focused on changing the gear's species selectivity properties.

An essential consideration for the study of tax and subsidy policies is that these mechanisms are commonly advocated in situations involving externalities. This situation is particularly relevant for the New England groundfish fishery where several studies have shown the need to significantly reduce fishing effort to ensure the biological and economic sustainability of the fishery. While one of the goals of this work was to investigate strategies for rebuilding groundfish stocks, this work did not investigate the socially optimal taxing policies. Clark (1990) observes that there are several difficulties associated with taxation in fisheries. First, fishermen unanimously oppose them because governments receive most of the rents, leaving fishermen with no

rents or, at best, inframarginal rents. Second, the estimation of the optimal tax requires managers to know the cost structure of the fleet and biological characteristics of the stock, which fluctuate unpredictably. Third, since the optimal tax would have to be calculated each year, new legislation would have to be passed for each fishing season.

The model was design so that the consequences of the various policies could be investigated in simulation experiments. Throughout we assume that the physical environment played no role in the system dynamics. The economic performance was evaluated by comparing the NPV indexes with the baseline case, which was set at 100%. The first set of policies investigated the impact of modifying the species selectivity properties of the gears (Table 20). The initial scenarios evaluated the impact of reducing the catchability of the overexploited stocks. Simulation results showed that reducing the catchability of roundfish yielded more benefits than reducing the catchability of flatfish. The economic performance of these scenarios is due to the harvest paths prior to reaching steady. Although, roundfish harvest rates are initially lower than baseline harvest levels, between years 15 and 20 (depending on the policy) they overtook baseline harvest levels. Since discounting favors present consumption over future consumption, it is not surprising that NPV indexes are higher than baseline levels.

An important feature of the model is the presence of predator-prey interactions. To examine the impact of changing the selectivity properties on these interactions, we initially modify the catchability of elasmobranchs species. Elasmobranchs are both prey

and predators of roundfish and flatfish. We found that by increasing the catchability of elasmobranch stocks we moderately increased the economic benefits relative to the baseline, whereas when we decreased the catchability of elasmobranch stocks we lowered the economic benefits relative to the baseline. These simulation experiments indicate that by decreasing the elasmobranch abundance we increase the economic performance of the fishery suggesting that elasmobranchs behave as a net predator.

Next, we examined policies that altered the catchability of pelagics stocks. Pelagics species are an important prey item for roundfish. Pelagic stocks were overexploited in the 1960's and 1970's, but since they have recovered to record levels. In recent years, this fishery has received considerable attention as possible substitute for the overexploited roundfish and flatfish fishery. Simulation results showed that by increasing the pelagic selectivity the economic performance of the fishery decreased, whereas when we decrease the pelagic selectivity the economic performance of the fishery increased. These results suggest that redirecting effort towards the pelagic stocks may have un-intended consequences, in spite of the record high stock levels.

We also investigated the impact of modifying the species selectivity properties concurrently. We considered the cases where we reduced the roundfish catchability by 10% and modified (either increasing or decreasing) the catchability of elasmobranchs and pelagics. Simulation results reinforced the direction of the results obtained when only one policy was applied. However, the changes in magnitude were small. A simultaneous reduction in the catchability of roundfish with an increase in

elasmobranch catchability marginally improves the economic performance compared to a policy that reduces the catchability of roundfish only. Similarly, simultaneously reducing the catchability of roundfish and decreasing the catchability of pelagics produces marginally better results than solely reducing the catchability of roundfish.

The second set of policies we considered were market-based programs. In selecting incentive-disincentive policies, we first examined taxing roundfish and flatfish catches. Based on the scenarios developed, simulation results indicated that a tax policy on flatfish catches yielded marginally higher benefits than a similar taxation plan on roundfish catches (Table 21). This was surprising since in the technology-based scenarios, roundfish generated higher benefits. A closer examination of the harvest paths shows that under the flatfish tax scenario, both roundfish and flatfish harvest levels exceed baseline levels in year 9; whereas under the flatfish technological change scenario, roundfish harvest levels exceed baseline levels in between years 9-84, while flatfish harvest levels exceeded baseline levels between years 32 and 36.

Increasing the tax and subsidies rates on elasmobranchs and pelagics did not appreciably change welfare indexes. However, the directions, if any, were comparable to our findings from the technological based scenarios. Lastly, we investigated the impact of simultaneously taxing roundfish at 10% and subsidizing elasmobranchs and pelagics at different rates. Increasing the subsidy rate on elasmobranchs increased welfare while increasing the subsidy rate on pelagics decreased welfare (Table 21).

Again, the welfare changes were minuscule and followed the same patterns than in the single policy case (and the technological based scenarios).

Chapter 6: Conclusions and Policy Implications

Advances in fishing technology have had profound consequences on the structure of marine ecosystems. In Georges Bank, technological change contributed to dramatic shifts in species composition. Commercially valuable demersal fish communities such as roundfish and flatfish have been displaced by commercially less valuable elasmobranch stocks. In recent years, elasmobranch stocks have begun to decline due to increasing harvesting pressure. Simultaneously, low-value pelagic species, previously overexploited, recovered to record levels.

In New England, an important policy priority to ensure the sustainable use of fisheries resources and the economic viability of the industry is the improvement of the species selectivity properties of fishing gears. The development of management measures to ensure the sustainable use of fish resources requires an understanding of the bioeconomic consequences of modifying the catchability of the gears.

To shed some light on this important policy concern, this research examines the bioeconomic implications of modifying the species selectivity properties of marine gears. This work addresses this issue both theoretically and empirically. In the theoretical section, a stylized model was developed to analyze the long-run equilibrium bioeconomic properties of modifying the species selectivity properties of the gears. The study examined two polar cases, namely when the gears were perfectly non-selective and perfectly selective. Within each case, the impact of biological interactions (i.e.,

predator-prey relationships) was considered. Three policies were considered: a reduction in the catchability of the target species, an increase in the catchability of the accompanying species, and the simultaneous combination of the above policies.

The analysis showed that there was a considerable amount of uncertainty regarding the impact of technological improvement. Policy prescriptions for rebuilding stocks varied dramatically depending on the type of technology employed. In the perfectly non-selective gear case, rebuilding strategies would benefit decreasing the catchability of the overexploited species as long as the stocks were biologically independent. In the presence of biological interrelationships, decreasing the catchability yielded ambiguous results. Other policies such as increasing the catchability of accompanying species and simultaneously decreasing the catchability of the target species and increasing the catchability of the accompanying species in the both the absence and presence of biological interrelationship generated ambiguous results.

In the perfectly selective case, overexploited stocks were shown to recover under any of the three policies considered both in the presence and in absence of biological interrelationships. However, the impact of these policies on the accompanying species and effort levels yielded different outcomes depending on the presence of biological interrelationships.

In the empirical section, a bioeconomic model of the New England groundfish fishery was constructed to investigate the dynamic behavior of the system when the species

selectivity properties of the gear were altered. The model incorporates key predator-prey relationship of Georges Bank as well as recent advances in dual formulations, which in fisheries applied work have been primarily used in a static context. The use of dual formulations adds an interesting dimension to this research in that there is growing evidence that fishermen who employ non-selective gears can choose the catch mix in response to relative prices.

Simulation results indicate that technology and market-based mechanisms can aid in the rebuilding process; however, by themselves are insufficient to recover the overexploited roundfish and flatfish stocks. Rebuilding these stocks will require substantial reductions in fishing effort.

The policy implications of our model are two-fold. First, policies that call for the use of subsidies to divert fishing effort away from the overexploited stocks do not necessarily increase the economic performance of the fishery. For instance, increasing the catchability of pelagics actually reduced the economic performance of the fishery. Second, attempts to modify predator-prey dynamics yielded modest results. For instance, decreasing the pelagic selectivity to increase forage availability modestly enhance the economic performance of the fishery. A similar conclusion is obtained from modifying the elasmobranchs catchability coefficients. Neither increasing the elasmobranch selectivity as a means to reduce predator concentration, nor decreasing the elasmobranch selectivity as a means of increase forage significantly augmented welfare.

These conclusions and policy implications are dependent on the degree to which the model is able to describe the interactions between the resource and the harvesting sector. In spite of evidence of significant trophic interactions, some predator-prey parameters estimates have a high degree of uncertainty (Collie and Delong, 1998). Recent stock assessments suggest that some species groups such as elasmobranchs, which during the study were underexploited are currently overexploited. Similarly, the roundfish group appears to be increasing in spite of its overexploited status. These results, while consistent with this model, may show different dynamics. The predator-prey relationships may be further refined as more data become available.

Another limitation of this model is that many of the stock parameters present in the input-compensated supply equations violated the theoretically proper curvature conditions. Imposing restrictions on the parameter estimates in many cases yielded parameters in the order $10E-8$. This made the input-compensated supply equations essentially insensitive to stock changes. Given the insensitivity level of these parameters and the uncertainty of some of the predator-prey relationships, further work needs to be conducted before these results can be incorporated into management decisions.

While this study extends earlier works by considering the impact of altering the species selectivity properties into a multispecies context, several aspects of this issue remain unexplored. For instance, no attempt has been made to incorporate uncertainty into the model. Stochastic variability in the form of red noise (variance as a decreasing function of frequency) a feature commonly observed in marine environments could be readily

incorporated into the predator-prey model. Spencer and Collie (1994) used this red noise specification to explain predator-prey interactions between haddock and spiny dogfish.

Similarly, other forms of stochastic variability could be incorporated on ex-vessel prices and the fleets harvest mix and cost structure. In addition to increasing the number of species being explicitly modeled, a possible extension of the model would be to incorporate spatial considerations such as the impact of closures and effort redistribution. Spatial models are likely to become increasingly important as essential habitat concerns catch the public officials' attention. Finally, while this piece has been focused on marine ecosystems, this type of analysis could be extended to land ecosystems. The relationship between wildlife game and hunting policies would be one example.

Appendix A

To analyze the short-run effect of modifying the catchability coefficient in a single species fishery we assume that the industry has the following profit function

$$\pi = pqex^\beta - c(e)$$

In addition, we assume that the effort dynamics is given by

$$\dot{e} = k(pqx^\beta - c_e)$$

Setting the effort dynamics equation to zero and differentiating with respect to the catchability coefficient we obtain

$$\frac{de}{dq} = \frac{px^\beta}{c_{ee}}$$

The above relationship states that an increase in the species selectivity properties of the gear in the short-run will be directly related to the price of the species, stock size, and harvest-stock size elasticity (β) and indirectly related to the rate of change of the marginal cost of effort.

To examine the impact on yield we differentiate the harvest function

$$\frac{dh}{dq} = ex^\beta \frac{dq}{dq} + \beta qex^{(\beta-1)} \frac{dx}{dq} + qx^\beta \frac{de}{dq}$$

Since in the short-run the impact $dx/dq=0$ then we obtain

$$\frac{dh}{dq} = \frac{x^\beta (pqx^\beta + c_{ee}e)}{c_{ee}}$$

Appendix B

To solve for the local stability conditions we need to estimate the characteristic roots or eigenvalues of a linearized dynamical system evaluated at its steady state. Assuming that our system is given by pair of first order differential equations

$$\dot{x} = F(x, y) \text{ and}$$

$$\dot{y} = G(x, y)$$

where the steady state solution is given by (x^*, y^*) such that $F(x^*, y^*) = G(x^*, y^*) = 0$.

Then the linearized differential equation at the neighborhood of the equilibrium is obtained by using Taylor series expansion and retaining the linear term such that

$$\dot{x} = F_x(x^*, y^*)(x - x^*) + F_y(x^*, y^*)(y - y^*)$$

$$\dot{y} = G_x(x^*, y^*)(x - x^*) + G_y(x^*, y^*)(y - y^*)$$

Rewriting the system in matrix form we obtain

$$|A| = \begin{bmatrix} F_x(x^*, y^*) & F_y(x^*, y^*) \\ G_x(x^*, y^*) & G_y(x^*, y^*) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

Solving for the characteristic equation we get that

$$\begin{aligned} \det|A - \lambda I| &= \begin{vmatrix} a_{11} - \lambda & a_{12} \\ a_{21} & a_{22} - \lambda \end{vmatrix} = 0 \\ &= \lambda^2 - (a_{11} + a_{22})\lambda + (a_{11}a_{22} - a_{12}a_{21}) \end{aligned}$$

Making use of the Routh theorem which states that the real parts of all of the roots of the n^{th} degree polynomial

$$b_0\lambda^n + b_1\lambda^{n-1} + \dots + b_{n-1}\lambda + b_n = 0$$

are negative if and only if the first n of the following sequence of determinants

$$[b_1], \begin{bmatrix} b_1 & b_3 \\ b_0 & b_2 \end{bmatrix}, \begin{bmatrix} b_1 & b_3 & b_5 \\ b_0 & b_2 & b_4 \\ 0 & b_1 & b_3 \end{bmatrix}, \dots > 0$$

are all positive. In our quadratic case

$$\lambda^2 + b_1\lambda + b_2 = 0$$

with real coefficients (b_1 and b_0) both have negative and real parts if and only if $b_1 > 0$ and $b_2 > 0$.

This implies that for the system to stable $(a_{11}+a_{22}) < 0$, and $|A| > 0$. These are sufficient and necessary conditions. Thus, in our case the following conditions must hold

$$A = \begin{bmatrix} -kc_{ee} & \beta k p q x^{(\beta-1)} \\ -qx^\beta & (G_x - \beta q e x^{(\beta-1)}) \end{bmatrix}$$

$$\text{tr } A = -kc_{ee} + (G_x - \beta q e x^{(\beta-1)}) < 0$$

$$|A| = k(\beta p q^2 x^\beta x^{(\beta-1)} - (G_x - \beta q e x^{(\beta-1)}) c_{ee}) > 0$$

In the case of a 3x3 matrix modified Routh-Hurwitz conditions require that

$$(a_{11}+a_{22}+a_{33}) < 0, |A| < 0, \text{ and}$$

$$|2A \cdot I| < 0 \text{ (Murata, 1977).}$$

Appendix C

This appendix reviews the biologically independent case for both the perfectly selective and perfectly non-selective technologies. The results show that in some instances the impact of changing the catchability coefficient is ambiguous. Thus, to derive some unambiguous results and make the analysis more tractable we introduce two additional assumptions

$$(G_{x_i} - \beta q_i e x_i^{(\beta-1)}) < 0$$

$$(H_{x_j} - \alpha q_j e x_j^{(\alpha-1)}) < 0$$

for any set of equilibrium values (e^*, x_1^*, x_2^*) . These assumptions ensure that the individual stock size equilibrium is dynamically stable.

C.1. Perfectly Selective Technology Case

$$\frac{de_i}{dq_i} = \frac{k_i k_j [p_i x_i^\alpha G_{x_i} \overbrace{((H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)}) c_{e_j e_j} - \alpha p_j q_j e_j^{(\alpha-1)} q_j x_j^\alpha)}^{(-)} \underbrace{(H_{x_j} (G_{x_i} - \beta q_i e_i x_i^{(\beta-1)}) p_j x_j^\alpha c_{e_j e_j})}_{(-)} \frac{dq_j}{dq_i}]}{\underbrace{[H]}_{(+)}}$$

$$\frac{de_j}{dq_i} = \frac{k_i k_j [-p_i x_i^\beta G_{x_i} \overbrace{(H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)}) c_{e_j e_j}}^{(-)} + p_j x_j^\alpha H_{x_j} \overbrace{((G_{x_i} - \beta q_i e_i x_i^{(\beta-1)}) c_{e_i e_i} - \beta p_i q_i x_i^{(\beta-1)} q_i x_i^\beta)}^{(-)} \frac{dq_j}{dq_i}]}{\underbrace{[H]}_{(+)}}$$

$$\frac{dx_i}{dq_i} = \frac{k_i k_j [e_i x_i^\beta \overbrace{(H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)})}^{(-)} (c_{e_i e_i} c_{e_j e_j} - c^2_{e_i e_j}) + p_i x_i^\beta q_i x_i^\beta \overbrace{((H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)}) c_{e_j e_j} - \alpha p_j q_j x_j^{(\alpha-1)} q_j x_j^\alpha)}^{(-)}]}{\underbrace{[H]}_{(+)}} \\ \underbrace{(c_{e_i e_i} \alpha p_j q_j x_j^{(\alpha-1)} e_i x_i^\beta q_j x_j^\alpha + c_{e_i e_j} q_i x_i^\beta p_j x_j^\alpha H_{x_j} \frac{dq_j}{dq_i})}_{\underbrace{[H]}_{(+)}}$$

$$\frac{dx_j}{dq_i} = \frac{k_i k_j [((G_{x_i} - \beta q_i e_i x_i^{(\beta-1)}) e_j x_j^\alpha (c_{e_i e_i} c_{e_j e_j} - c^2_{e_i e_j}) - \beta p_i q_i x_i^{(\beta-1)} q_i x_i^\beta x_j^\alpha (p_j q_j x_j^\alpha + c_{e_j e_j} e_j) + \underbrace{[H]}_{(+)})]}{\underbrace{[H]}_{(+)}} \\ + \frac{p_j x_j^\alpha q_j x_j^\alpha c_{e_i e_i} \overbrace{(G_{x_i} - \beta q_i e_i x_i^{(\beta-1)})}^{(-)} \frac{dq_j}{dq_i}}{\underbrace{[H]}_{(+)}} - \frac{q_j x_j^\alpha p_i x_i^\beta c_{e_j e_i} G_{x_i}}{\underbrace{[H]}_{(+)}}$$

C.2. Perfectly Non-Selective Technology Case

$$\frac{de}{dq_i} = \frac{-k_i k_j [p_i x_i^\beta G_{x_i} \overbrace{(H_{x_j} - \alpha q_j e x_j^{(\alpha-1)})}^{(-)} + p_j x_j^\alpha H_{x_j} \overbrace{(G_{x_i} - \beta q_i e x_i^{(\beta-1)})}^{(-)} \frac{dq_j}{dq_i}]}{\underbrace{[D]}_{(-)}}$$

$$\frac{dx_i}{dq_i} = \frac{k_i k_j [\alpha p_j q_j x_j^{(\alpha-1)} e x_i^\beta q_j x_j^\alpha - x_i^\beta \overbrace{((H_{x_j} - \alpha q_j e x_j^{(\alpha-1)}) (p_i q_i x_i^\beta + c_{e e} e) - p_j x_j^\alpha q_i x_i^\beta H_{x_j} \frac{dq_j}{dq_i})}^{(-)}]}{\underbrace{[D]}_{(-)}}$$

$$\frac{dx_j}{dq_i} = \frac{k_i k_j [\beta p_i q_i x_i^{(\beta-1)} q_i x_i^\beta e x_j^\alpha \frac{dq_j}{dq_i} - p_i x_i^\beta q_j x_j^\alpha G_{x_i} - x_j^\alpha \overbrace{(G_{x_i} - \beta q_i e x_i^{(\beta-1)})}^{(-)} (p_j q_j x_j^\alpha + c_{e e} e) \frac{dq_j}{dq_i}]}{\underbrace{[D]}_{(-)}}$$

Appendix D

In this appendix, we review the biologically interdependent case for both the perfectly selective and perfectly non-selective technologies.

D.1. Perfectly Selective Technology Case

$$\begin{aligned}
 \frac{de_i}{dq_i} &= \frac{k_i k_j [p_i x_i^\beta G_{x_i} (\overbrace{(H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)})}^{(-)}) c_{e_i e_j} - \alpha p_j q_j x_j^{(\alpha-1)} q_j x_j^\alpha + H_{x_i} x_i^\beta (\alpha p_j q_j x_j^{(\alpha-1)}) c_{e_i e_j} e_i - p_i G_{x_i} c_{e_i e_j}]}{\underbrace{H}_{(+)}} + \\
 &\quad \frac{(c_{e_i e_j} p_j x_j^\alpha (H_{x_i} G_{x_j} - \overbrace{(G_{x_i} - \beta q_i e_i x_i^{(\beta-1)})}^{(-)}) H_{x_j})}{\underbrace{H}_{(+)}} - \frac{\beta p_i q_i x_i^{(\beta-1)} G_{x_j} x_j^\alpha (p_j q_j x_j^\alpha + c_{e_i e_j} e_j)}{\underbrace{H}_{(+)}} \frac{dq_j}{dq_i} \\
 \frac{de_j}{dq_i} &= \frac{k_i k_j [p_i x_i^\beta c_{e_i e_j} (G_{x_j} H_{x_i} - G_{x_i} (\overbrace{(H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)})}^{(-})) - H_{x_i} x_i^\beta \alpha p_j q_j x_j^{(\alpha-1)} (p_i q_i x_i^\beta + c_{e_i e_j} e_i)]}{\underbrace{H}_{(+)}} + \\
 &\quad \frac{(p_j x_j^\alpha H_{x_i} (\overbrace{(G_{x_i} - \beta q_i e_i x_i^{(\beta-1)})}^{(-)}) c_{e_i e_j} - \beta p_i q_i x_i^{(\beta-1)} q_i x_i^\beta) + G_{x_j} (\beta p_i q_i x_i^{(\beta-1)} c_{e_i e_j} e_j x_j^\alpha - H_{x_i} c_{e_i e_j} p_j x_j^\alpha)}{\underbrace{H}_{(+)}} \frac{dq_j}{dq_i} \\
 \frac{dx_i}{dq_i} &= \frac{k_i k_j [(H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)}) e_i x_i^\beta (c_{e_i e_j} c_{e_i e_j} - c_{e_i e_j}^2) - x_i^\beta \alpha p_j q_j x_j^{(\alpha-1)} q_j x_j^\alpha (p_i q_i x_i^\beta + c_{e_i e_j} e_i)]}{\underbrace{H}_{(+)}} \\
 &\quad + \frac{p_i x_i^\beta ((H_{x_j} - \alpha q_j e_j x_j^{(\alpha-1)}) q_i x_i^\beta c_{e_i e_j} + G_{x_j} q_j x_j^\alpha c_{e_i e_j})}{\underbrace{H}_{(+)}} - \frac{((c_{e_i e_j} c_{e_i e_j} - c_{e_i e_j}^2) e_j x_j^\alpha G_{x_i} + p_j x_j^\alpha (G_{x_j} c_{e_i e_j} q_j x_j^\alpha + c_{e_i e_j} q_i x_i^\beta H_{x_j}))}{\underbrace{H}_{(+)}} \frac{dq_j}{dq_i} \\
 \frac{dx_j}{dq_i} &= \frac{k_i k_j [e_j x_j^\alpha (G_{x_i} - \beta q_i e_i x_i^{(\beta-1)}) (c_{e_i e_j} c_{e_i e_j} - c_{e_i e_j}^2) \frac{dq_j}{dq_i} - \beta p_i q_i x_i^{(\beta-1)} q_i x_i^\beta x_j^\alpha (p_j q_j x_j^\alpha + c_{e_i e_j} e_j) \frac{dq_j}{dq_i}]}{\underbrace{H}_{(+)}} + \\
 &\quad \frac{p_j x_j^\alpha ((G_{x_i} - \beta q_i e_i x_i^{(\beta-1)}) q_j x_j^\alpha c_{e_i e_j} + H_{x_i} q_i x_i^\beta c_{e_i e_j}) \frac{dq_j}{dq_i} - e_i x_i^\beta H_{x_i} (c_{e_i e_j} c_{e_i e_j} - c_{e_i e_j}^2) - p_i x_i^\beta (q_j x_j^\alpha G_{x_i} c_{e_i e_j} + q_i x_i^\beta H_{x_i} c_{e_i e_j})}{\underbrace{H}_{(+)}}
 \end{aligned}$$

D.2. Perfectly Non-Selective Technology Case

$$\begin{aligned} \frac{de}{dq_i} &= k_i k_j \left[\frac{H_{x_i} (\alpha p_j q_j x_j^{(\alpha-1)} ex_i^\beta + p_i x_i^\beta G_{x_j}) - p_i x_i^\beta G_{x_i} \overbrace{(H_{x_j} - \alpha q_j ex_j^{(\alpha-1)})}^{(-)}}{D^{(-)}} + \right. \\ &\quad \left. \frac{(G_{x_j} (\beta p_i q_i x_i^{(\beta-1)} ex_j^\alpha + p_j x_j^\alpha H_{x_i}) - p_j q_j^\alpha H_{x_j} \overbrace{(G_{x_i} - \beta p_i q_i x_i^{(\beta-1)})}^{(-)}) \frac{dq_j}{dq_i}}{D^{(-)}} \right] \\ \\ \frac{dx_i}{dq_i} &= k_j k_i \left[\frac{-x_i^\beta \overbrace{(H_{x_j} - \alpha q_j ex_j^{(\alpha-1)})}^{(-)} (p_i q_i x_i^\beta + c_{ee} e) + q_j x_j^\alpha (p_i x_i^\beta G_{x_j} + \alpha p_j q_j x_j^{(\alpha-1)} ex_i^\beta)}{D^{(-)}} + \right. \\ &\quad \left. \frac{(G_{x_j} x_j^\alpha (c_{ee} e + p_j q_j x_j^\alpha) - q_i x_i^\beta p_j x_j^\alpha H_{x_j}) \frac{dq_j}{dq_i}}{D^{(-)}} \right] \\ \\ \frac{dx_j}{dq_i} &= \frac{k_j k_i [(H_{x_i} x_i^\beta (p_i q_i x_i^\beta + c_{ee} e) - p_i x_i^\beta q_j x_j^\alpha G_{x_i})}{D^{(-)}} + \frac{(ex_j^\alpha (\beta p_i q_i x_i^{(\beta-1)} q_i x_i^\beta - \overbrace{(G_{x_j} - \beta q_j ex_j^{(\beta-1)})}^{(-)}) c_{ee}) \frac{dq_j}{dq_i}}{D^{(-)}} \end{aligned}$$

Appendix E

Baseline scenario

To gauge the suite of proposed management policies a baseline scenario was developed. The baseline scenario assumed that the current limited entry regime remains in place for the duration of the simulation. As mentioned earlier, to ensure that the valuable demersal stocks (i.e., roundfish and flatfish) do not collapse, the overall effort level is reduced by 58 %. Under this scenario, roundfish biomass continues to decline until year 14 reaching minimum biomass level of 55 million tons, then rising rapidly and stabilizing at 840.1 million tons. Flatfish and pelagic stocks increase stabilizing at 76 and 2,221.8 million tons, respectively. Elasmobranch stocks collapse in year 87. The collapse of elasmobranch stocks is not surprising given that dogfish constitute a larger proportion of this assemblage. Dogfish grow slowly, mature late, and produce a small number of offspring, leaving them vulnerable to overexploitation.

In terms of harvesting, roundfish stocks initially yield 28.5 million tons rapidly dropping to 25.15 million tons in year 14. Subsequently, roundfish stocks increased stabilizing at 180.9 million tons. Flatfish catches increase from 2.1 million tons to 4 million tons. Similarly, pelagic and miscellaneous species catches increased from 9 and 16.4 million tons to 42.8 and 21.8 million tons, respectively. In contrast, elasmobranch stocks yield decreased from 2.16 million tons to zero in year 87. In terms of economic

performance, the net present value of discounted quasi rents is normalized to one for policy comparison purposes.²⁶

Technological change scenarios

Scenario I: Reduction in the catchability of roundfish stocks.

This scenario considers reducing the gear's roundfish selectivity by 5, 10, 15 and 20%. Under this scenario, roundfish profile is shifted to the left in respect to the baseline case. Steady state roundfish biomass levels increase with larger reduction in catchability. With a 5% reduction in catchability, roundfish steady state levels reached 856.8 million tons while with a 20% reduction roundfish steady state levels reached 907.3million tons. Flatfish biomass profile under the reduced catchability cases shift upwards around year 18 in respect to the baseline scenario. At year 80, flatfish biomass profiles converge slightly above the baseline benchmark around 76 million tons. Similarly, reducing the catchability of roundfish shifted up the pelagic biomass profile between years 18 and 85 in respect to the benchmark pelagic biomass. After year 85, pelagic biomass profiles converge to the baseline scenario. At a 5% roundfish reduction, pelagic long run stock size reached 2,223.7 million tons while at a 20% reduction pelagic stocks stabilized at 2,230.3million tons. Reducing the roundfish catchability accelerated the collapse of the elasmobranch stocks.

²⁶ The estimated NPV was US\$ 4,141.6 million. Assuming a 100-year horizon at a 3 percent discount rate.

In harvesting terms, reducing roundfish selectivity shifts roundfish harvesting paths to the left of the baseline scenario. Roundfish steady state harvest levels decrease with increased reductions in catchability. At a reduction of 5%, roundfish stocks stabilize at 108.70 million tons while at a 20% reduction roundfish stocks stabilize at 93.94 million tons. Flatfish catches exhibit a similar pattern to roundfish stocks. At a 5% reduction, flatfish harvest levels stabilized at 3.96 million tons while at a 20% reduction flatfish harvest levels stabilized at 3.82 million tons. With decreasing catchability, elasmobranch catches exhibit decreasing harvest levels. With a 5% reduction in roundfish catchability, pelagic and miscellaneous species yielded 5.6353 and 21.7913 million tons, respectively while with a 20% reduction they yielded 5.3941 and 21.6923 million tons, respectively.

Scenario II: Reduction in the catchability of flatfish stocks.

The second scenario evaluates reducing the flatfish catchability. As in other scenarios, we considered a reduction of 5, 10, 15 and 20%. Reducing the catchability of flatfish shifts the roundfish and flatfish biomass profiles to the left. Roundfish, flatfish and pelagic long run biomass levels exceeded baseline levels. At a 5 % reduction, roundfish, flatfish, and pelagic stocks stabilize at 840.1, 76.64, and 2,222.6 million tons, respectively, while at a 20% reduction, roundfish, flatfish, and pelagic stocks stabilize at 841.16, 77.5, and 2,225.1 million tons, respectively. Elasmobranch stocks collapse sooner in the presence of policies that curtail the catchability of flatfish.

At a 5 % reduction, roundfish, flatfish, pelagic and miscellaneous species catches stabilized at 113.03, 3.79, 5.67, and 21.79 million tons, respectively, while at a 20 % reduction the catches of these stocks stabilized at 112.93, 3.18, 5.58, and 21.76 million tons, respectively.

Scenario III: Increase in the catchability of elasmobranch stocks

The third scenario evaluates increasing the catchability of the elasmobranchs. With a 5% increase in the elasmobranch selectivity, roundfish, flatfish, and pelagic stocks stabilized at 840.2, 76.1, and 2,222 million tons, whereas with a 20% increase they stabilized at 840.3, 76, and 2,222.6 million tons, respectively.

Under the 5 % increase scenario, roundfish, flatfish, pelagic and miscellaneous species landings reached stabilized at 113.07, 4.0, 5.70, and 21.81 million tons, respectively whereas with a 20% increase these stocks stabilized at 113.07, 4.0, 5.678, and 21.8123 million tons, respectively.

Scenario IV: Reduction in the catchability of elasmobranch stocks.

The four scenario investigates reducing the elasmobranch species selectivity. With a 5% reduction, the roundfish, flatfish, and pelagic stocks stabilized at 840.1, 76, and 2,221 million tons, respectively. With a 20% reduction, they reached steady state level of 839.7, 76.0, and 2,220.7 million tons, respectively.

With a 5% reduction in elasmobranch selectivity, the harvest of roundfish and miscellaneous species stabilized at 113.0686 and 21.8037 million tons, respectively; while with a 20% reduction they stabilized at 113.0547 and 21.7982 million tons, respectively. In contrast, a 5% reduction resulted in flatfish and pelagic stocks reaching a long-term steady state harvest rate of 4 and 5.7152 million tons, respectively. While with a 20% reduction, flatfish and pelagic stocks reached a steady state harvest rate of 4.0028 and 5.7360 million tons, respectively.

Scenario V: Increase in the catchability of pelagic stocks.

The fifth scenario considers increasing the pelagic species selectivity by 5, 10, 15, and 20%. Increasing the catchability from 5 to 20%, reduces the stock size of roundfish from 838.9 to 853.3 million tons. Analogously, the pelagic steady state stock size drops from 2,214.3 to 2,191.8 million tons. The flatfish stock size increases from 75.9 to 76.3 million tons.

In harvesting terms, augmenting the pelagic catchability from 5 to 20% reduced the roundfish steady state harvest level from 112.8673 to 112.2719 million tons and increased the flatfish steady state harvest rate from 3.99 to 4.0 million tons, respectively. Likewise, steady state pelagic harvest levels increases from 5.98 to 6.79 million tons while miscellaneous species steady state harvest level decreased from 21.8 to 21.79 million tons

Scenario VI: Decrease in the catchability of pelagic stocks.

The sixth scenario investigates decreasing the catchability of pelagic species. As in other scenarios, we considered a reduction of 5, 10, 15 and 20%. At a 5 % reduction, roundfish, flatfish, and pelagic stocks stabilized at 841.3, 76.5, and 2,229.2 million tons, respectively, while at a 20% reduction, roundfish, flatfish, and pelagic stocks stabilized at 844.9, 75.9, and 2,251.5 million tons, respectively.

In terms of harvesting, reducing the pelagic catchability increased the steady state roundfish and miscellaneous species harvest levels, and reduced steady state flatfish and pelagic harvest levels. At a 5% reduction, roundfish and miscellaneous species harvest levels stabilized at 113.27 and 21.8 million tons, respectively, while at a 20% reduction, roundfish and miscellaneous species steady state harvest levels stabilized at 113.86 and 21.81 million tons, respectively. On other hand, a similar catchability reduction, decreases flatfish and pelagic steady state harvest levels from 3.99 and 5.4 million tons to 3.98 and 4.6 million tons, respectively.

Scenario VII: Reduction in the catchability of roundfish stocks with an increase in the catchability of elasmobranch stocks.

The seventh scenario explores the impacts of simultaneously reducing the catchability of roundfish and improving the catchability of elasmobranchs. For the purposes of the

scenario, the roundfish catchability is reduced by 10% while the elasmobranch catchability is increased between 5-20%.

With a 5 %increase in elasmobranch catchability, roundfish, flatfish and pelagic stocks stabilized at 873.36, 75.9, and 2,226.0 million tons, respectively; whereas with a 20% increase in the elasmobranch catchability, roundfish, flatfish, and pelagic stocks stabilized at 873.8, 76.7, and 2,226.6 million tons, respectively.

With 5% increase, the long-run roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.05, 3.9179, 5.55, and 21.77 million tons, respectively; whereas with a 20% increase, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.06, 3.9172, 5.5296, and 21.7754 million tons, respectively.

Scenario VIII: Reduction in the catchability of roundfish and elasmobranch stocks.

The eighth scenario considers simultaneously reducing the gears ability to target roundfish and elasmobranchs. This scenario assumed that roundfish catchability was reduced by 10% whereas the elasmobranch catchability was reduced between 5 and 20%.

In the long-run with a 5% reduction, roundfish, flatfish, and pelagic stocks stabilized at 873.5, 76.5, and 2,225.6 million tons respectively. With a 20% decrease in the

elasmobranch catchability, roundfish, flatfish, and pelagic stocks stabilized at 873.4, 76.4, and 2,225 million tons, respectively.

In harvesting terms, an decrease of 5% results in roundfish, flatfish, pelagic, and miscellaneous species steady state catch rates reaching 104.0566, 3.9211, 5.5661, and 21.76 million tons, respectively. With a 20% decrease, roundfish, flatfish, pelagic, and miscellaneous species long run catch rates stabilize at 104.0539, 3.9261, 5.5881, and 21.7625 million tons, respectively.

Scenario IX: Reduction in the catchability of roundfish stocks with an increase in the catchability of pelagic stocks.

The ninth scenario considers simultaneously reducing the gears ability to target roundfish and increasing the ability to target pelagics. In the long run with 5% change, roundfish, flatfish, and pelagic stock sizes stabilized at 872.4, 76.6, and 2,218.5 million tons while with a 20% change they stabilized at 868.8, 76.5, and 2,196.5 million tons, respectively.

Roundfish and miscellaneous species steady state harvest levels decreased from 103.88 to 103.35 million tons and from 21.76 to 21.75 million tons, respectively as the pelagic selectivity was increased from 5 to 20%. In contrast, long-run flatfish, pelagic catch levels increased from 3.9257 to 3.9269 million tons and from 21.765 to 21.7541 million tons, respectively.

Scenario X: Reduction in the catchability of roundfish and pelagic stocks.

The tenth scenario studies the effects of simultaneously reducing the catchability of roundfish and pelagic. The roundfish catchability reduction was fixed at 10% while the pelagic catchability reduction varied between 5 and 20%.

Under the 5 % reduction scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 874.8, 76.3, and 2,233.1 million tons; whereas under the 20% reduction scenario, they stabilized at 878.3, 75.9, and 2,254.8 million tons, respectively.

With a 5% reduction, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 104.23, 3.92, 5.29, and 21.77 million tons, respectively. With a 20% reduction, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized 104.75, 3.91, 4.47, and 21.78 million tons, respectively.

Market-based scenarios

Scenario XI: Tax scheme on roundfish catches

The eleventh scenario analyzed was imposing a tax on roundfish landings. The cases considered included a 5, 10, 15, and 20 percent tax on ex-vessel prices. Under the 5 % tax scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 882.1, 76.0, and 2,256.4 million tons; whereas under the 20% tax scenario, they stabilized at 894.9, 76.9, and 2,261.5 million tons, respectively.

With a 5% tax, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 103.7359, 3.8521, 4.4153, and 21.7231 million tons, respectively; while with a 20% tax, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized 100.2338, 3.6670, 4.2199, and 21.4518 million tons, respectively.

Scenario XII: Tax scheme for flatfish catches

The twelfth scenario investigates the impact of a tax on flatfish catches. Under the 5 % tax scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 878.6, 75.9, 2,255.3 million tons; whereas under the 20% tax scenario, they stabilized at 879.5, 76.0, and 2,256.9 million tons, respectively.

Under a 5% tax, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 104.6478, 3.8910, 4.4357, and 21.7485 million tons, respectively; while with a 20% tax, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.5429, 3.8700, 4.3956, and 21.7146 million tons, respectively.

Scenario XIII: Tax scheme for elasmobranch catches

The thirteenth scenario considers a tax on elasmobranch catches. Under the 5 % tax scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 878.3, 76.0,

and 2,254.7 million tons; whereas under the 20% tax scenario, they stabilized at 878.2, 76, and 2,254.5 million tons, respectively.

Under a 5% tax, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 104.7559, 3.9136, 4.4784, and 21.7812 million tons, respectively; while with a 20% tax, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.7674, 3.9185, 4.4877, and 21.7792 million tons, respectively.

Scenario XIV: Subsidy scheme for elasmobranch catches

The fourteenth scenario evaluates a subsidy on elasmobranch catches. Under the 5 % subsidy scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 878.4, 75.9, and 2,254.9 million tons; whereas under the 20% subsidy scenario, they stabilized at 878.4, 75.9, and 2.2551 million tons, respectively.

Under a 5% subsidy, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 104.7477, 3.9104, 4.4726, and 21.7824 million tons, respectively; while with a 20% subsidy, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.7351, 3.906, 4.4644, and 21.7840 million tons, respectively.

Scenario XV: Tax scheme for pelagic catches

The fifteenth scenario investigates a tax scheme on pelagic catches. Under the 5 % tax scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 878.4, 75.9, and 2,255.2 million tons; whereas under the 20% tax scenario, they stabilized at 878.7, 75.9, and 2,256.4 million tons, respectively.

Under a 5% tax, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 104.7524, 3.9091, 4.4613, and 21.7782 million tons, respectively; while with a 20% tax, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.7560, 3.9003, 4.4154, and 21.7679 million tons, respectively.

Scenario XVI: Subsidy scheme for pelagic catches

The sixteenth scenario investigates a subsidy scheme on pelagic catches. Under the 5 % subsidy scenario, roundfish, flatfish and pelagic steady state stock sizes stabilized at 878.2, 76.0, and 2,254.4 million tons; whereas under the 20% subsidy scenario, they stabilized at 878, 76.0, and 2,253.4 million tons, respectively.

Under a 5% subsidy, roundfish, flatfish, pelagic and miscellaneous species steady state harvest levels stabilized at 104.7515, 3.9150, 4.4892, and 21.7855 million tons,

respectively; while with a 20% subsidy, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 104.7515, 3.9238, 4.5283, and 21.797 million tons, respectively.

Scenario XVII: Tax scheme for roundfish and subsidy scheme for elasmobranchs catches

The seventeenth scenario considers tax/subsidy scheme where roundfish catches are tax at a 10 percent while the subsidy level on elasmobranch catches was allowed to vary between 5 and 20 percent at 5 % increments.

Under the 5% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species biomass stabilized at 886.2, 76.2, and 2,258.1 million tons, respectively. Under the 20% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species biomass stabilized at 886.3, 76.4, and 2,258.3 million tons, respectively.

Under the 5% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species catches stabilized at 102.6450, 3.7896, 4.3499, and 21.65 million tons, respectively.

Under the 20% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 102.6331, 3.7866, 4.3420, and 21.6511 million tons, respectively.

Scenario XVIII: Tax scheme for roundfish and subsidy scheme for pelagic catches

The eighteenth scenario considered was a tax/subsidy scheme where roundfish catches could be taxed at 10% while the subsidy on pelagic catches was allowed to vary between 5 and 20 percent at 5% increments. Under the 5% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species biomass stabilized at 886.0, 76.2, 2,257.6 million tons, respectively. Under the 20% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species biomass stabilized at 885.8, 76.1, and 2, 256.5 million tons, respectively.

Under the 5% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species catches stabilized at 102.6487, 3.7932, 4.3675, and 21.654 million tons, respectively. Under the 20% subsidy policy, roundfish, flatfish, pelagic and miscellaneous species harvest rates stabilized at 102.6497, 3.8016, 4.4094, and 21.6677 million tons, respectively.

Appendix F

Matlab Code

```
a1=.42;%0.39
close;
CCC=[28.55969857 (8.428721918*0.46) 3.891659726 2.349503273
     25.45322923]';

%Starting values

T=100; %time span

x=[ 88.6 5.8 171.97 382 0]'; %initial stock size 5.4165 6.366
y=[ 88.6 2.28 170 382 0]'; %lagged initial stock size
%y=[ 68 5.47 147.21 239.2 0]';
%x=[ 68 5.47 147.21 239.2 0]';
%x=[737 80 199 2367 1]'
%=====
===
%List of parameters
%Biological (order: groundfish, flatfish, elasmobranchs, pelagics and
misc. species)
%-----
% intrinsic growth00954043

r=[ 0.557 1.108 (0.409) 0.314 0]'; % ms species original model
%r=[0.72 1.01 3.95 0.01 0]'; %single species
%1.108
% carrying capacities
K=[(737) 80 199 2367 1]'; %original model
%K=[308.8 60 30 2000 1]'; %single species

% multispecies interaction coefficient (i.e., predator-prey)*.94116
alpha=1*[ 0.000000 0.000000 -0.001561 0.000132
0.000000 ;
0.000000 0.000000 0.000000 -0.002890 0.000000
0.000000 ;
-0.000359 -0.000927 0.000000 0.000000
0.000000 ;
0.000000 0.000000 -0.000248 0.000000
0.000000 ;
0.000000 0.000000 0.000000 0.000000
0.000000 ];

% alpha=zeros(5,5);

% vector of ones to sum multispecies interaction coefficients
I=ones(5,1);%I=[1 1 1 1 1]';

%Economic
%-----
```

```

% Fish prices
pr=1.71*(1-0.1); %price roundfish
pf=2.73*(1-0); %price flatfish
pe=0.25*(1+0.0); %price elasmobranch
pp=0.36*(1+0.2); %price pelagics
po=2.47*(1-0); %price miscellaneous species

pprime=[1.71 2.73 0.25 0.36 2.47]';
p=[pr pf pe pp po]';
xprice=sqrt([1 pf/pr pe/pr pp/pr po/pr;
              pr/pf 1 pe/pf pp/pf po/pf;
              pr/pe pf/pe 1 pp/pe po/pe;
              pr/pp pf/pp pe/pp 1 po/pp;
              pr/po pf/po pe/po pp/po 1]);

price=sqrt([pr^2 pr*pf pr*pe pr*pp pr*po;
            pf*pr pf^2 pf*pe pf*pp pf*po;
            pe*pr pe*pf pe^2 pe*pp pe*po;
            pp*pr pp*pf pp*pe pp^2 pp*po;
            po*pr po*pf po*pe po*pp po^2]);

%Techoonology
%-----

% Otter Trawl Fleet (5-50 GRT)
% -----

%alphaotc1=[(-659.93-1.5*356) (-546.779+1.35*253.1) (-274.925-
0.55*332) (-54.7771+.15*274.925) (-824.601+0.8*360.2)]';
alphaotc1=[(-659.93-1*356.1) (-546.779+.3*253.1) (-274.925-.9*332)
(-54.7771+.07*274.925) (-824.601-0*360.2)]'.*adjust_alpha;
%2.3* %1.7* %0.75 %0*.15* %0*0.55*
betaotc1= [ (26921.27-.55*3638.6) 0 0 0
0;
0 (40380.04-.0*2553.0) 0 0
0;
0 0 7379.488 0 0;
0 0 0 (28.40943) 0;
0 0 0 0
30550.69].*adjust;

portotc1=[21911.55 25713.97 (8200.672) -18699.6 -22369.5 -
24313.3 ;
-21471.2 -38339.4 -38353.7 -39095.5 -39216.9 -39297.4;
1371.342 -8978.88 -10299.8 260.6731 -6632.91 6152.152;
31950.25 2026.795 251.8448 130.0317 174.6506 156.981;
39377.56 4686.713 1737.626 -24967.3 -29039.9 -
29219.2].*adjust_portotc1;

wtportotc1=[0.0105960 0.0145695 0.0145695 0.3165563 0.4993377
0.0092715];
%wtportotc1=[0.0463576 0.0384106 0.0516556 0.5470199 1.6529801
0.0238411]; effort adj.

stockotc1=diag(adjust_stock'*[(11.56475) 1.01E-6 1.01E-6 1.01E-6
0])';

seasonrotc1=adjust_seasonr.*[ -3775.79 -1931.54 -4870.19 0]';

```

```

seasonfotc1=adjust_seasonf.*[ 1361.836 1924.967 2425.395 0]';
seasoneotc1=adjust_seasonf.*[ -1932.66 -1573.72 8197.782 0]';
seasonpotc1=adjust_seasonp.*[ 292.3569 41.45193 -261.264 0]';
seasonootc1=adjust_seasono.*[ 1234.596 4668.148 1294.316 0]';
seasonotc1=[seasonrotc1 seasonfotc1 seasoneotc1 seasonpotc1
seasonootc1]';
wtotc1=[0.2278146 0.2927152 0.1880795 0.2913907]';

%wtotc1=[0.2913907 0.2278146 0.2927152 0.1880795]'; effort adj.

ntripotc1= a1*[172 221 142 220]'/5;    %average number of trips per
season

% Otter Trawl Fleet (51-100 GRT)
% -----
ss2=[9.90778476    1.75279266    0.78444012    0.344831133 8.83936159]';

alphaotc2=[ (-1729.61-1*520.7) (-63.9323+1*49.0634) (-247.058-
1*100.9) (-17.1677-1*26.0975) (-795.385-1*324.8) ]'.*adjust_alpha;
%alphaotc2=[ (-1729.61-0.1*520.7) (-63.9323-.8*49.06) (-
247.058+.37*100.9) (-17.1677-.445*26.09) (-795.385-1.51*324.8) ]';
betaotc2=[(8952.302-0.75*5318.7)      0      0      -1E-8
0;
0      (1496.814+.1*394.5) 0      0      0;
0      0      (1886.48-0.52*811.1) 0      0;
-1E-8 0      0      (53.55962+0.15 *281.6)
0;
0      0      0      0      (10343.87-
1*2611.8)].*adjust;

portotc2=[26464.14 35096.26 10847.09 -6645.04 -4399.6 941.309
63407.32 -2784.6;
-2784.6 -96.8927 195.9616 -337.673 615.788 369.314
8376.546 -538.854;
-1020.93 -772.462 -912.496 333.6045 -1082.12 206.7435
1881.722 -653.107;
205.3809 963.1371 45.38551 -28.038 119.6609 45.31248
2930.358 -134.8;
40697.95 20681.01 11251.17 -1664.65 1922.778 3969.381
56209.89 -4185.23].*adjust_portotc2;

%wtportotc2=[0.0452656    0.2600462    0.2494226    0.4743649 ...
%      0.0364896    0.2092379    0.2272517    0.0175520];
effort adj

wtportotc2=[ 0.0087760 0.0748268 0.0438799 0.2000000 ...
0.0064665 0.0309469 0.0595843 0.0032333];

stockotc2=diag(adjust_stock'*[51.53025 1.01E-6 1.01E-6 0.36138 0])';

seasonrotc2=adjust_seasonr.*[ -7380.46 -3957.21 2563.43 0]';
seasonfotc2=adjust_seasonf.*[ -622.643 -935.603 -740.094 0]';
seasoneotc2=adjust_seasonf.*[ -533.294 -509.005 1273.239 0]';
seasonpotc2=adjust_seasonp.*[ -1.3904 -88.0273 -269.77 0]';
seasonootc2=adjust_seasono.*[ -5721.34 -7925.34 -6119.54 0]';

```

```

seasonotc2=[seasonrotc2 seasonfotc2 seasoneotc2 seasonpotc2
seasonootc2]';
%wtotc2=[0 1.0267898 1.5819861 1.5510393 ]';
wtotc2=[0.1912240 0.2969977 0.3113164 0.2004619]';

ntripotc2=a1*[414 643 674 434]/5';
% Otter Trawl Fleet (101-150 GRT)
% -----

ss3=[8.306704424 3.045217508 0.394546029 0.436494722 8.541146952]';

alphaotc3=[(-150.617-1*63.1506) (-12.5852+1*6.4888) (-11.0942-
1*2.7057) (-2.8268+1*10.5648) (-108.411-
1*53.7672)]'.*adjust_alpha;%alphaotc3=[(-150.617+ .5*63.15) (-
12.5852+0*6.488) (-11.0942+2*2.7) (-2.8268+0*10.56) (-
108.411+0*53.7672)]';

betaotc3=[ (1551.076-0.1 *569) 36.33482 18.26466 -222.818
42.17843;
36.33482 (594.1454+1*58.58) -20.6377 214.923 -
105.15;
18.26466 -20.6377 (164.076-1*41.65) -56.8824
14.97303;
-222.818 214.923 -56.8824 (-173.267+1.97*128) -
17.4571;
42.17843 -105.15 14.97303 -17.4571 (1793.494-
.55*494.6) ].*adjust;

portotc3=[9264.756 3276.413 568.2496 30.25201 -165.465 4.779799
8477.559 -233.803 415.5655;
-40.6156 -234.302 -304.044 -121.602 815.9928 -130.159
520.8881 -231.88 -296.462;
72.48458 -49.3124 -42.4398 106.966 -85.2506 11.75669
236.0714 -8.335 15.52872;
376.5949 15.30252 35.31837 35.26444 73.82621 -12.6042
885.6881 -79.0295 -53.0907;
13715.49 1441.897 740.4387 37.86365 683.1054 220.2205
7199.631 10156.92 267.8108 ].*adjust_portotc3;

%wtportotc3=[ 0.1889297 0.2907371 0.7507766 0.1358373
0.0043773...
% 0.7293138 0.2664502 0.0014120 0.0035301 ];

wtportotc3=[ 0.0199096 0.0618469 0.0972889 0.0320531 0.000847218
0.1060435 ...
0.0667890 0.000282406 0.000282406];

stockotc3=diag(adjust_stock'*[ 1.01E-6 1.01E-6 1.01E-6 0.569556
0])';

seasonrotc3=adjust_seasonr.*[-497.485 -160.796 -393.287 0]';
seasonfotc3=adjust_seasonf.*[-122.004 -152.171 -215.427 0]';
seasoneotc3=adjust_seasone.*[-22.9753 -13.0393 23.56345 0]';
seasonpotc3=adjust_seasonp.*[-54.0362 72.01692 -162.66 0]';
seasonootc3=adjust_seasono.*[-547.66 -893.579 -1504.45 0]';

```

```

seasonotc3=[seasonrotc3 seasonfotc3 seasoneotc3 seasonpotc3
seasonootc3]';
%wtotc3=[1.7158995    1.8469359    1.8047162]'; adj effort

wtotc3=[0.2438577    0.2661677    0.2780288    0.2119458]';

ntripotc3=a1*[ 1727 1885 1969 1501]'/5;

% Otter Trawl Fleet (150+ GRT)
% -----
ss4=[6.57140044    0.608171078    0.094608867    1.329113896    4.245116304]';

alphaotc4=[(-213.25-1*24.2797)    (-1.21341+1*3.1227)    (-5.69854-
1*2.1972) ...
(-22.5351+0*23.8834)    (-126.73+1*46.3863)
]'.*adjust_alpha;

betaotc4=[ (1026.124+0*343.9)    87.31942    58.96083    333.404    -237.842
87.31942    (336.8175+0.1 *59.0625)    -76.322    -110.215    -
6.29598
58.96083    -76.322    (115.0486-1.7*86.5968)    -
19.9323    29.50682
333.404    -110.215    -19.9323
(54.05242+0*374.4)    -155.197
-237.842    -6.29598    29.50682    -155.197
(885.4309+0*497.6)].*adjust;

portotc4=[ 2363.51    1330.166    612.0636    736.3775    6625.9
1073.427    -1114.42;
-284.436    -307.38    -316.57    -109.969    -170.433    -
302.223    -293.547;
-56.0717    -69.563    -72.1222    -45.3105    65.85736    -
39.1166    108.9576;
32.46466    9.759805    -24.1633    72.96831    376.976
30002.83    207.8199;
3864.671    798.8908    876.8434    387.4356    1125.521
8280.735    2652.55].*adjust_portotc4;

wtportotc4=[0.0993361    0.2152707    0.2885598    0.0311542    0.1355975
0.0071502    0.000255363 ];
stockotc4=diag(adjust_stock'*[ 3.572765    8.643869    0.139085    1E-8
0])';

seasonrotc4=adjust_seasonr.*[473.7387    302.4815    876.1154    0]';
seasonfotc4=adjust_seasonf.*[-4.07991    -36.2135    -61.1493    0]';
seasoneotc4=adjust_seasone.*[-12.1515    -5.99297    -17.0164    0]';
seasonpotc4=adjust_seasonp.*[27.35761    316.5499    -14.0539    0]';
seasonootc4=adjust_seasono.*[1059.278    -156.693    -401.777    0]';
seasonotc4=[seasonrotc4 seasonfotc4 seasoneotc4 seasonpotc4
seasonootc4]';

wtotc4=[0.2247191    0.2842186    0.2918795    0.1991828 ]';
ntripotc4=a1*[880 1113 1143 780 ]'/5;

```

```

%Gillnet
%-----
ss5=[0.80603796    0.058431624 1.53939396    0.007941179 0.002646416]';
alphagill=[(-103.265+0.5*46.7833)    1.732504    (-195.958+1*130.6) ...
          (-1.09329-1*1.0864    )    (-202.296-1*75.9669)]'.*adjust_alpha;
betagill=[ (1322.798-0.01*1322.798) 0    0    0    0;
           0    (-144.553+0.14*451.0)    0    0    0;
           0 0    (22184.87+.10*7483.1)    0    0;
           0 0    0    (35.67559-.19*64.2565)    0;
           0 0    0    0    (3946.528-.6918*4353.9)
].*adjust;

portgill=[ 3490.731  2942.576 -8.15234  -245.772  -79.7915  -937.362
-1296.92;
          97.61999  614.7927  49.34266 137.0019  -41.4263
145.0877 -96.9041;
          -10445   -13822.9  -21450.1  -21579   -20353.6  -
21988.9  -6981.9;
          43.93175  8.127567  -10.1377  -21.6092  51.84492  -
53.6602  -37.4023;
          9232.385   4441.841 -1236.13  -2072.63  -1243   -3739.7
-3044.59 ].*adjust_portgill;
wtportgill=[0.1115385    0.1423077    0.0102564 0.7256410 0.0051282
0.0012821 0.0538462];
%wtportgill=[0.7256410 0.5641026 0.0653846  2.3230769  0.0102564
0.0012821 0.2935897 ];%adj. effort
stockgill=diag(adjust_stock'*[ 1.885822  1E-8  1E-8  0.049063 0]');
seasonrgill=adjust_seasonr.*[-869.171 -941.022  302.2671  0]';
seasonfgill=adjust_seasonf.*[-53.8486 267.6565  -14.2891 0]';
seasonegill=adjust_seasone.*[ -2317.36  -1146.69  3291.115 0]';
seasonpgill=adjust_seasonp.*[-25.5854  -48.2157  -40.3738 0]';
seasonogill=adjust_seasono.*[ 128.5754 -2481.87  -1089.11 0]';
seasongill=[seasonrgill seasonfgill seasonegill seasonpgill
seasonogill]';
wtgill=[0.1358974 0.1756410    0.3256410 0.3628205    ]';

%wtgill=[0.5153846  0.7423077  1.3064103 0]'; %adj effort
ntripgill=a1*[106 137 254 283 ]'/5;

%Longline
%-----
ss6=[0.198396252  9.68278E-05 0.025768891 3.49617E-05 0.640749996]';

alphalong=[ -34.9293    -0.0879 2.116814 0.023613  (-40.0317-
.12*38.3677)    ]'.*adjust_alpha;
betalong=[(749.6613-.5*606.9)    0    0    0    0;
          0    (1.88109-.38*3.0679)    0    0
0;
          0    0    (-64.7747+.04*229.5)    0    0;
          0    0    0    (-0.6927+.13*0.6779)    0;
          0    0    0    0    3917.334].*adjust;

```

```

portlong=[ 136.4355  1346.681  -319.43  -20.0979 -216.241 188.2733
-631.917 ;
          0.083945  0.247839  -0.93487  0.207043 -0.37719 0.099133
-0.22718;
          50.68681  371.0619  68.13725  38.57052 27.3486 55.62657
8.658852 ;
          -0.21353  0.04008  0.149255 0.219146  0.167524 -0.03112
-0.07961 ;
          714.8744  2645.186  -2658.44  -3477.52 -3636.59  963.258
-2561.15].*adjust_portlong;

wtportlong=[0.2514620  0.1169591  0.0058480  0.5555556 0.0380117
0.0087719  0.2777778];

stocklong=diag(adjust_stock'*[ 2.324345  0.054482  1E-8 0.00101 0]');

seasonrlong=adjust_seasonr.*[-15.1093  26.63872  18.91855 0]';
seasonflong=adjust_seasonf.*[-1.52695  -1.09072  -1.5428 0]';
seasonelong=adjust_seasons.*[-25.7652  10.66658  220.8819 0]';
seasonplong=adjust_seasonp.*[ 0.068626  0.318993  -0.03712 0]';
seasonolong=adjust_seasono.*[-264.197  -527.815  183.4074 0]';
seasonlong=[seasonrlong seasonflong seasonelong seasonplong
seasonolong]';

wtlong=[ 0.3274854 0.2426901 0.1111111 0.3187135 ]';

ntriplong=a1*[112 83 38 109]'/5;

% Counter information
biomass=x';

effort_otc1=[0];
harvest_otc1=[0 0 0 0 0];
allboat_otc1=[1];
Nboat_otc1=allboat_otc1;
profit_otc1=[10];

effort_otc2=[0];
harvest_otc2=[0 0 0 0 0];
allboat_otc2=[1];
Nboat_otc2=allboat_otc2;
profit_otc2=[10];

effort_otc3=[0];
harvest_otc3=[0 0 0 0 0];
allboat_otc3=[1];
Nboat_otc3=allboat_otc3;
profit_otc3=[10];

effort_otc4=[0];
harvest_otc4=[0 0 0 0 0];
allboat_otc4=[1];
Nboat_otc4=allboat_otc4;
profit_otc4=[10];

effort_gill=[0];

```

```

harvest_gill=[0 0 0 0 0];
allboat_gill=[1];
Nboat_gill=allboat_gill;
profit_gill=[10];

effort_long=[0];
harvest_long=[0 0 0 0 0];
allboat_long=[1];
Nboat_long=allboat_long;
profit_long=[10];

allprofits=[0];

zharvest_otc1=[0 0 0 0 0];
zharvest_otc2=[0 0 0 0 0];
zharvest_otc3=[0 0 0 0 0];
zharvest_otc4=[0 0 0 0 0];
zharvest_gill=[0 0 0 0 0];
zharvest_long=[0 0 0 0 0];
ss1=[ 2.76937473  2.96401222  1.05290186  0.23108738  3.18420797]';

%Cost
theta_otc1=0;
fcost_otc1=0;
c_otc1=2111.686;
d_otc1=100+20*73;%1E-8  2966
lr_cost_otc1=1861.973+1*508.0;%; %31900

theta_otc2=0;
fcost_otc2=0;
c_otc2=2195.559 ;
d_otc2=5000;%1E-8  2462.947
lr_cost_otc2= 2462.947+1*361.3;

theta_otc3=0; %own parameter SAS params suck
fcost_otc3=0;
c_otc3=7051.611 ;
d_otc3=1E-8 ;
lr_cost_otc3=4707.881-0.1*1836.8;%4000

theta_otc4=0;%own parameter SAS params suck
fcost_otc4=0;
c_otc4=3157.229;
d_otc4=150;
lr_cost_otc4= 3061.426+(1* 343.9);%7000;

theta_gill=0;
fcost_gill=300;
c_gill=1150.91;
d_gill=0;
lr_cost_gill=1153.749+1*11.248 ;%8000;

theta_long=0; .
fcost_long=0;
c_long= 1187.303;

```



```

d_long= 40.51+1*10.66;%40.51478
lr_cost_long=1187.303+1*102;%3000;

%intermediate variables
ei_otc1=[0];
hi_otc1=[0 0 0 0 0];
s_otc1=(p'*seasonotc1)';

ei_otc2=[0];
hi_otc2=[0 0 0 0 0];
s_otc2=(p'*seasonotc2)';

ei_otc3=[0];
hi_otc3=[0 0 0 0 0];
s_otc3=(p'*seasonotc3)';

ei_otc4=[0];
hi_otc4=[0 0 0 0 0];
s_otc4=(p'*seasonotc4)';

ei_gill=[0];
hi_gill=[0 0 0 0 0];
s_gill=(p'*seasonogill)';

ei_long=[0];
hi_long=[0 0 0 0 0];
s_long=(p'*seasonlong)';

%call program
%» close; plot(2:t+1, b(2:t+1,1), 'O-', 2:t+1, B1(2:t+1,1))
myproblem

for t=1:T; %annual timer

    for i=1:4; %seasonal timer

        for ii=1:5 % sets stock size equal to zero in event of negative
stocks sizes
            if x(ii)<= 0;
                x(ii)=0;
            end;
        end;

        % Selects for individual seasonal effort

        ef_otc1= max((1/(p'*alphaotc1*2-d_otc1*2))*(lr_cost_otc1-
(I'*(betaotc1.*price')*I+stockotc1*(p.*x)...
+s_otc1(i,1)*wtotc1(i,1)+p'*(portotc1*wtportotc1'))),0);

        ei_otc1=[ei_otc1, ef_otc1];

        ef_otc2= max((1/(p'*alphaotc2*2-d_otc2*2))*(lr_cost_otc2-
(I'*(betaotc2.*price')*I+stockotc2*(p.*x)...

```

```

+s_otc2(i,1)*wtotc2(i,1)+p'*(portotc2*wtportotc2'))),0) ;

ei_otc2=[ei_otc2, ef_otc2];

ef_otc3= max((1/(p'*alphaotc3*2-d_otc3*2))*(lr_cost_otc3-
(I'*(betaotc3.*price')*I+stockotc3*(p.*x)...
+s_otc3(i,1)*wtotc3(i,1)+p'*(portotc3*wtportotc3'))),0) ;

ei_otc3=[ei_otc3, ef_otc3];

ef_otc4= max((1/(p'*alphaotc4*2-d_otc4*2))*(lr_cost_otc4-
(I'*(betaotc4.*price')*I+stockotc4*(p.*x)...
+s_otc4(i,1)*wtotc4(i,1)+p'*(portotc4*wtportotc4'))),0) ;

ei_otc4=[ei_otc4, ef_otc4] ;

ef_gill= max((1/(p'*alphagill*2-d_gill*2))*(lr_cost_gill-
(I'*(betagill.*price')*I+stockgill*(p.*x)...
+s_gill(i,1)*wtgill(i,1)+p'*(portgill*wtportgill'))),0) ;

ei_gill=[ei_gill, ef_gill];

ef_long= max((1/(p'*alphalong*2-d_long*2))*(lr_cost_long-
(I'*(betalong.*price')*I+stocklong*(p.*x)...
+s_long(i,1)*wtlong(i,1)+p'*(portlong*wtportlong'))),0) ;

ei_long=[ei_long, ef_long] ;

% Selects for individual seasonal harvest

harv_otc1=(ntripotc1(i)*max((alphaotc1*ef_otc1^2+diag(betaotc1*xprice')
)*ef_otc1+(stockotc1'.*x)*ef_otc1...

+(seasonotc1(:,i)*wtotc1(i,1))*ef_otc1+(portotc1*wtportotc1')*ef_otc1
,0)/10^6);

for iii=1:4
    if x(iii)<= 0
        harv_otc1(iii)=0;
    end
end

hi_otc1=[hi_otc1, harv_otc1'];

ntripotc2=[414 643 674 434]/5';
harv_otc2=
(ntripotc2(i)*max((alphaotc2*ef_otc2^2+diag(betaotc2*xprice')*ef_otc2+
(stockotc2'.*x)*ef_otc2...

+(seasonotc2(:,i)*wtotc2(i,1))*ef_otc2+(portotc2*wtportotc2')*ef_otc2
,0)/10^6);

```

```

for iii=1:4
    if x(iii)<= 0
        harv_otc2(iii)=0;
    end
end
hi_otc2=[hi_otc2,harv_otc2'];

harv_otc3= (ntripotc3(i)*
max((alphaotc3*ef_otc3^2+diag(betaotc3*xprice')*ef_otc3+(stockotc3'.*x)
)*ef_otc3...

+(seasonotc3(:,i)*wtotc3(i,1))*ef_otc3+(portotc3*wtportotc3')*ef_otc3)
,0)/10^6);

for iii=1:4
    if x(iii)<= 0
        harv_otc3(iii)=0;
    end
end
hi_otc3=[hi_otc3,harv_otc3'];

bb4=[376.1 222.6 228.6 156]';

harv_otc4= (ntripotc4(i)*
max((alphaotc4*ef_otc4^2+diag(betaotc4*xprice')*ef_otc4+(stockotc4'.*x)
)*ef_otc4...

+(seasonotc4(:,i)*wtotc4(i,1))*ef_otc4+(portotc4*wtportotc4')*ef_otc4)
,0)/10^6);

for iii=1:4
    if x(iii)<= 0
        harv_otc4(iii)=0;
    end
end
hi_otc4=[hi_otc4,harv_otc4'];

harv_gill=(ntripgill(i)*
max((alphagill*ef_gill^2+diag(betagill*xprice')*ef_gill+(stockgill'.*x)
)*ef_gill...

+(seasongill(:,i)*wtgill(i,1))*ef_gill+(portgill*wtportgill')*ef_gill)
,0)/10^6);
for iii=1:4
    if x(iii)<= 0
        harv_gill(iii)=0;
    end
end
hi_gill=[hi_gill,harv_gill'];

harv_long= (ntriplong(i)*
max((alphalong*ef_long^2+diag(betalong*xprice')*ef_long+(stocklong'.*x)
)*ef_long...

+(seasonlong(:,i)*wtlong(i,1))*ef_long+(portlong*wtportlong')*ef_long)
,0)/10^6);

```

```

for iii=1:4
    if x(iii)<= 0
        harv_long(iii)=0;
    end
end

hi_long=[hi_long,harv_long'];

end;

e_otc1=sum(ei_otc1) ;
h_otc1=sum(reshape(hi_otc1, 5,5)')' ;
ei_otc1=[0];
hi_otc1=[0 0 0 0 0];

e_otc2=sum(ei_otc2) ;
h_otc2=sum(reshape(hi_otc2, 5,5)')' ;
ei_otc2=[0];
hi_otc2=[0 0 0 0 0];

e_otc3=sum(ei_otc3) ;
h_otc3=sum(reshape(hi_otc3, 5,5)')' ;
ei_otc3=[0];
hi_otc3=[0 0 0 0 0];

e_otc4=sum(ei_otc4) ;
h_otc4=sum(reshape(hi_otc4, 5,5)')' ;
ei_otc4=[0];
hi_otc4=[0 0 0 0 0];

e_gill=sum(ei_gill) ;
h_gill=sum(reshape(hi_gill, 5,5)')' ;
ei_gill=[0];
hi_gill=[0 0 0 0 0];

e_long=sum(ei_long) ;
h_long=sum(reshape(hi_long, 5,5)')' ;
ei_long=[0];
hi_long=[0 0 0 0 0];

%fleet profit
prof_otc1=(p'*h_otc1*10^6-lr_cost_otc1*e_otc1)/10^6;
prof_otc2=(p'*h_otc2*10^6-lr_cost_otc2*e_otc2)/10^6;
prof_otc3=(p'*h_otc3*10^6-lr_cost_otc3*e_otc3)/10^6;
prof_otc4=(p'*h_otc4*10^6-lr_cost_otc4*e_otc4)/10^6;
prof_gill=(p'*h_gill*10^6-lr_cost_gill*e_gill)/10^6;
prof_long=(p'*h_long*10^6-lr_cost_long*e_long)/10^6;

%fleet size
Nboat_otc1=max(Nboat_otc1+theta_otc1*prof_otc1,0);
Nboat_otc2=max(Nboat_otc2+theta_otc2*prof_otc2,0);
Nboat_otc3=max(Nboat_otc3+theta_otc3*prof_otc3,0);
Nboat_otc4=max(Nboat_otc4+theta_otc4*prof_otc4,0);
Nboat_gill=max(Nboat_gill+theta_gill*prof_gill,0);
Nboat_long=max(Nboat_long+theta_long*prof_long,0);

% Catch proportionality

```

```

prop1=[1.6 1.0 1.0 7.5 1.0]'; % 3 gears to total landings

Htran=(h_otc1*Nboat_otc1+h_otc2*Nboat_otc2+h_otc3*Nboat_otc3+h_otc4*Nb
oat_otc4...
      +h_gill*Nboat_gill+h_long*Nboat_long);

H=Htran.*prop1;

z_otc1=h_otc1 ;
z_otc2=h_otc2;
z_otc3=h_otc3;
z_otc4=h_otc4;
z_gill=h_gill;
z_long=h_long;

for n=1:4
    if H(n) > x(n); %; +r(n).*x(n) -
        ((r(n)./K(n)).*x(n).^2)+(alpha(n).*(y(n)*y'))*I ;

        HH(n)      = H(n);
        H(n)       = x(n); %; +r(n).*x(n) -
        ((r(n)./K(n)).*x(n).^2)+(alpha(n).*(y(n)*y'))*I;
        beta(n)    = max(H(n)/(HH(n)),0);
        h_otc1(n)  = beta(n)*h_otc1(n);
        h_otc2(n)  = beta(n)*h_otc2(n);
        h_otc3(n)  = beta(n)*h_otc3(n);
        h_otc4(n)  = beta(n)*h_otc4(n);
        h_long(n)  = beta(n)*h_long(n);
        h_gill(n)  = beta(n)*h_gill(n);

    else
        h_otc1(n)  = h_otc1(n);
        h_otc2(n)  = h_otc2(n);
        h_otc3(n)  = h_otc3(n);
        h_otc4(n)  = h_otc4(n);
        h_long(n)  = h_long(n);
        h_gill(n)  = h_gill(n);

    end
end

%stock dynamics

x=max(x+r.*y-((r./K).*y.^2)+(alpha.*(y*y'))*I-
(h_otc1*Nboat_otc1+h_otc2*Nboat_otc2...
+h_otc3*Nboat_otc3+h_otc4*Nboat_otc4+h_gill*Nboat_gill+h_long*Nboat_lo
ng).*prop1,0);

%counters

biomass = [biomass, x'];
xbiomass= [biomass, x']';
y=xbiomass(1+(5*(t-1)):5+5*(t-1));

effort_otc1 = [effort_otc1, e_otc1' ];

```

```

harvest_otc1 = [harvest_otc1, h_otc1' ];
allboat_otc1 = [allboat_otc1, Nboat_otc1];
profit_otc1 = [profit_otc1, prof_otc1 ];

effort_otc2= [effort_otc2, e_otc2'];
harvest_otc2=[harvest_otc2, h_otc2'];
allboat_otc2=[allboat_otc2, Nboat_otc2];
profit_otc2= [profit_otc2, prof_otc2];

effort_otc3= [effort_otc3, e_otc3'];
harvest_otc3=[harvest_otc3, h_otc3'];
allboat_otc3=[allboat_otc3, Nboat_otc3];
profit_otc3= [profit_otc3, prof_otc3];

effort_otc4= [effort_otc4, e_otc4'];
harvest_otc4=[harvest_otc4, h_otc4'];
allboat_otc4=[allboat_otc4, Nboat_otc4];
profit_otc4= [profit_otc4, prof_otc4];

effort_gill= [effort_gill, e_gill'];
harvest_gill=[harvest_gill, h_gill'];
allboat_gill=[allboat_gill, Nboat_gill];
profit_gill= [profit_gill, prof_gill];

effort_long= [effort_long, e_long'];
harvest_long=[harvest_long, h_long'];
allboat_long=[allboat_long, Nboat_long];
profit_long= [profit_long, prof_long];

zharvest_otc1=[zharvest_otc1, z_otc1'];
zharvest_otc2=[zharvest_otc2, z_otc2'];
zharvest_otc3=[zharvest_otc3, z_otc3'];
zharvest_otc4=[zharvest_otc4, z_otc4'];
zharvest_gill=[zharvest_gill, z_gill'];
zharvest_long=[zharvest_long, z_long'];

allprofits=[allprofits,
(prof_otc1+prof_otc2+prof_otc3+prof_otc4+prof_gill+prof_long)];
end;

b=reshape(biomass,5,T+1)';

zotc1=Nboat_otc1*reshape(zharvest_otc1,5,T+1)';
zotc2=Nboat_otc2*reshape(zharvest_otc2,5,T+1)';
zotc3=Nboat_otc3*reshape(zharvest_otc3,5,T+1)';
zotc4=Nboat_otc4*reshape(zharvest_otc4,5,T+1)';
zgill=Nboat_gill*reshape(zharvest_gill,5,T+1)';
zlong=Nboat_long*reshape(zharvest_long,5,T+1)';

hotc1=Nboat_otc1*reshape(harvest_otc1,5,T+1)';
hotc2=Nboat_otc2*reshape(harvest_otc2,5,T+1)';
hotc3=Nboat_otc3*reshape(harvest_otc3,5,T+1)';
hotc4=Nboat_otc4*reshape(harvest_otc4,5,T+1)';
hgill=Nboat_gill*reshape(harvest_gill,5,T+1)';
hlong=Nboat_long*reshape(harvest_long,5,T+1)';

```

```

effortotc1=effort_otc1';
effortotc2=effort_otc2';
effortotc3=effort_otc3';
effortotc4=effort_otc4';
effortgill=effort_gill';
effortlong=effort_long';

TT=(hotc1+hotc2+hotc3+hotc4+hlong+hgill);
HARVEST=(prop1*ones(1,t+1)).*TT;
EFFORT=[effortotc1 effortotc2 effortotc3 effortotc4 effortgill
effortlong];
PROFIT=[profit_otc1' profit_otc2' profit_otc3' profit_otc4'
profit_gill' profit_long'];

%figure (1), title 'Hola',
%SUBPLOT(2,2,1),plot(b,'-');title('Biomass');
%SUBPLOT(2,2,2),plot(effort_otc1(2:t+1),'o');title('Effort from
otc1');
%SUBPLOT(2,2,3),plot(effort_otc2(2:t+1),'o');title('Effort from
otc2');
%SUBPLOT(2,2,4),plot(effort_otc3(2:t+1),'o');title('Effort from
otc3');

%figure (2), title 'Roundfish',
%SUBPLOT(2,2,1),plot(b(2:t+1,1),'-');title('Biomass of roundfish');
%SUBPLOT(2,2,2),plot(hotc1(2:t+1,1),'o');title('Harvest from otc1');
%SUBPLOT(2,2,3),plot(hotc2(2:t+1,1),'o-r');title('Harvest from otc2');
%SUBPLOT(2,2,4),plot(hotc3(2:t+1,1),'o-b');title('Harvest from otc3');

%figure (3), title 'Flatfish',
%SUBPLOT(2,2,1),plot(b(2:t+1,2),'-');title('Biomass of flatfish');
%SUBPLOT(2,2,2),plot(hotc1(2:t+1,2),'o');title('Harvest from otc1');
%SUBPLOT(2,2,3),plot(hotc2(2:t+1,2),'o-r');title('Harvest from otc2');
%SUBPLOT(2,2,4),plot(hotc3(2:t+1,2),'o-b');title('Harvest from otc3');

%figure (4), title 'Elasmobranchs',
%SUBPLOT(2,2,1),plot(b(2:t+1,3),'-');title('Biomass of
elasmobranchs');
%SUBPLOT(2,2,2),plot(hotc1(2:t+1,3),'o');title('Harvest from otc1');
%SUBPLOT(2,2,3),plot(hotc2(2:t+1,3),'o-r');title('Harvest from otc2');
%SUBPLOT(2,2,4),plot(hotc3(2:t+1,3),'o-b');title('Harvest from otc3');

%figure (5), title 'Pelagics',
%SUBPLOT(2,2,1),plot(b(2:t+1,4),'-');title('Biomass of pelagics');
%SUBPLOT(2,2,2),plot(hotc1(2:t+1,4),'o');title('Harvest from otc1');
%SUBPLOT(2,2,3),plot(hotc2(2:t+1,4),'o-r');title('Harvest from otc2');
%SUBPLOT(2,2,4),plot(hotc3(2:t+1,4),'o-b');title('Harvest from otc3');

%figure (6), title 'Pelagics',
%SUBPLOT(2,2,1),plot(b(2:t+1,5),'-');title('Biomass of all other');
%SUBPLOT(2,2,2),plot(hotc1(2:t+1,5),'o');title('Harvest from otc1');
%SUBPLOT(2,2,3),plot(hotc2(2:t+1,5),'o-r');title('Harvest from otc2');
%SUBPLOT(2,2,4),plot(hotc3(2:t+1,5),'o-b');title('Harvest from otc3');
% plot(1:t-1, b(1:t-1,1), 'o-r', 1:t-1, TT(2:t,1),'-ob')
%plot(allboat_otc1);title('allboat');

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Bibliography

Acheson, J., 1984. Government Regulation and Exploitative Capacity: The Case of the New England Groundfishery. *Human Organization*, Vol. 43, No. 4, pp. 319-329.

Aguirre International, 1996. *An appraisal of the Social and Cultural Aspects of the Multispecies Groundfish Fishery in New England and the Mid-Atlantic Regions*. Report submitted to the NOAA. Bethesda, MD.

Anderson, L. G., 1986. *The Economics of Fisheries Management*. 2nd edition. Baltimore, MD. John Hopkins University Press.

Appolonio, S., 1978. The New England Fishery Council: Problems and Prospects. In: *Formulating Marine Policy: Limitations to Rational Decision-making*. Proceedings of the Second Annual Conference held by the Center for Ocean Management Studies, University of Rhode Island, Kingston, June 1978.

Beattie, B. R., and C. R. Taylor, 1993. *The Economics of Production*. Krieger Publishing Company. Malabar, Florida.

Bell, W., 1978. *Food from the sea: the economics and politics of ocean fisheries*. Westview Press. Boulder, Colorado.

Beddington, J. R., and R. M. May, 1980. Maximum sustainable yields in systems subject to harvest at more than one trophic level. *Mathematical Biosciences*, Vol. 51, pp. 261-281.

Brewer, D., Eayrs, A., Mounsey, R., and Y. Wang, 1994. An assessment of an environmentally friendly, semi pelagic fish trawl. *Fisheries Research*, Vol. 26, No. 3-4, pp. 225-237.

Campbell, H.F., and R. B. Nicholl, 1994. Can Purse Seiners Target Yellowfin Tuna? *Land Economics*, August 1994, Vol. 70, No. 3, pp. 345-53.

Campbell, H. F., and R. B. Nicholl, 1995. Allocating Yellowfin Tuna Between Multispecies Purse Seine and Longline Fleets. *Marine Resource Economics*, Vol. 10, No. 1, pp. 35-58.

Campbell, H. F., 1995. Modeling ITQ Markets in Multispecies Fisheries. *Proceedings of the 7th Biennial Conference of the International Institute of Fisheries Economics and Trade*. David S. Liao (ed.). Vol. 1, pp. 258-271.

Canfield, Clark, 1997. More Hearthache Ahead. *National Fisherman*, Vol. 77, No. 11, pp. 30-37.

- Clark, C. W., 1985. *Bioeconomic Modelling and Fisheries Management*. Wiley, New York.
- Chambers, R. G., 1988. *Applied production analysis: A dual approach*. Cambridge University Press. New York.
- Christie, D. R., 1987. The Georges Bank/Gulf of Maine Boundary Dispute Between The United States and Canada. In: *Georges Bank*. R. H. Backus (ed.). The MIT Press, Cambridge, Massachusetts, pp. 469-473.
- Collie, J. S., and A. K. DeLong, 1999. Multispecies interactions in the Georges Bank Fish Community. In: *Ecosystem Approaches for Fisheries Management*. Alaska Sea Grant College Program. Pp. 187-210. AK-SG-99-01.
- Costa Duarte, C., 1992. Targeted versus Non-Targeted Multispecies Fishing. *Environmental and Resource Economics*, Vol. 2, pp. 259-281.
- Cunningham, S., M. R. Dunn, and D. Whitmarsh, 1985. *Fisheries Economics: An Introduction*. London. Mansell.
- DeAlteris, J. T., and D. L. Morse, 1997. Fishing Gear Management. In: *Northwest Atlantic Groundfish: Perspective on a Fishery Collapse*. J. Boreman, B. S. Nakashima, J. A. Wilson, and R. L. Kendall. American Fisheries Society. Bethesda, Maryland.
- Diewert, W. E., and T. J. Wales, 1987. Flexible Functional Forms and Global Curvature Conditions. *Econometrica*, Vol. 55, pp. 43-68.
- Diewert, W. E., and L. Ostensoe, 1988. Flexible functional forms for profit functions and global curvature conditions. *Proceedings from the Third International Symposium in Economic Theory and Econometrics*. W. Barnett, E. Berndt, and H. White (eds.). Cambridge University Press.
- Doeringer, P. B., and D. G. Terkla, 1995. *Troubled Waters: Economic Structure, Regulatory Reform, and Fisheries Trade*. University of Toronto Press. Toronto.
- Doeringer, P. B., D. G. Terkla, and A. Watson, 1995. *Regulation, Industry Structure, and the Future of the North Atlantic Fishing Industry*. Occasional Paper No. 22, Canadian-American Center, The University of Maine, Orono, Maine.
- Edwards, S. F. and S. A. Murawski, 1993. Potential Economic Benefits from Efficient Harvest of New England Groundfish. *North American Journal of Fisheries Management*, Vol. 13, pp. 437-449.
- Eide, A., F. Skjold, F. Olsen, and O. Flaaten, 1998. Production Functions of the Norwegian bottom trawl fisheries of cod in the Barents Sea. *Proceedings of the 9th*

International Conference of the International Institute of Fisheries Economics and Trade, A. Eide and T. Vassdal (eds.) pp.357-362, Tromsø, Norway, 1998.

FAO, 1997. Bycatch management and the economics of discarding. *FAO Fisheries Technical Paper*, No. 370, 137 pp. FAO, Rome, Italy.

Feldman, M., and D. Colson, 1981. The maritime boundary of the United States. *American Journal of International Law*. Vol. 75 pp. 729-763.

Flaaten, O., 1987. *Production Functions with seasonal variations in the catchability coefficients-the case of the Lofoten cod fisheries*. Report. In Norwegian.

Flaaten, O., 1988. *The Economics of Multispecies Harvesting: Theory and Application to the Barent Sea Fisheries*. Springer-Verlag, Berlin.

Flaaten, O., 1991. The Bioeconomics of Sustainable Harvest of Competing Species. *Journal of Environmental Economics and Management*. Vol. 20, pp. 163-180.

Fogarty, M., Cohen, M., Michaels, W., and Morse, W., 1991. Interactions among herring, mackerel, and sand lance in the Northwest Atlantic. *ICES Mar. Sci. Symp. Multispecies Models Relevant to Management of Marine Living Resources*. Vol. 193, pp. 120-124. International Council for the Exploration of the Sea. Copenhagen.

Fogarty, J. M., and S. A. Murawski, 1998. Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. *Ecological Applications* 8(1) Supplement, pp. S6-S22.

Gates, J. M., 1974. Demand price, fish size, and the price of fish. *Canadian Journal of Agricultural Economics*. Vol. 22, pp. 1-12.

Grevobal, D. F., 1985. *Fisheries Management Under Stochastic Conditions: A Bioeconomic Simulator of the New England Groundfish Fishery*. Unpublished Dissertation, University of Rhode Island, Kingston, Rhode Island.

Grosslein, M. D., R. Langton, and M. P. Sissenwine, 1980. Recent fluctuations in pelagic fish stocks in the Northwest Atlantic, Georges Bank region in relations to species interactions. *Rapports et Proces-verbaux des Reunion de Conseil International de Exploration of de la Mer*. Vol. 74, pp. 374-405.

Gudmundsson, E. and J.G. Sutinen, 1998. Challenges of Marine Biodiversity. *Marine Resource Economics*, Vol. 13, pp. 75-83.

Halliday, R.G., and A.T. Pinhorn, 1997. Policy Frameworks. In: *Northwest Atlantic Groundfish: Perspective on a Fishery Collapse*. J. Boreman, B. S. Nakashima, J. A. Wilson, and R. L. Kendall. American Fisheries Society. Bethesda, Maryland.

Hall, R. E., 1973. The specification of technology with several kinds of outputs. *Journal of Political Economy*, Vol. 82, pp. 878-892.

Hanna, S., 1990. Mesh size regulations and bycatch in the west coast groundfish fishery. In: *Effects of different fishery management schemes on bycatch, joint catch and discards: Summary of a national workshop*. Dewees, C. M., and Ueber, E., (eds.). California Sea Grant College Report No. T-CSGCP-019, California Sea Grant College, University of California, La Jolla, 30-31.

Hannesson, R., 1983. Bioeconomic Production Function in Fisheries: Theoretical and Empirical Analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 40, pp. 969-982.

Hennemuth, R.C. and S. Rockwall, 1987. History of Fisheries Conservation and Management. In: *Georges Bank*, R. H. Backus (ed.). MIT Press. Cambridge, Massachusetts.

Hennessey, T. M., 1983. Managing Fishery Resources: The Political Economic of Fishery Regulation. In: *The U.S. Fishing Industry and Regulatory Reform*, Proceedings from the Fifth Annual Conference held June 22-24, 1981, Center for Ocean Management Studies, University of Rhode Island, Kingston, Rhode Island.

Herbert, G. J., 1995. Fisheries relations in the Gulf of Maine: Implications of an Arbitrated maritime boundary. *Marine Policy*, Vol. 19, No. 4, pp. 301-316.

International Court of Justice, 1984. Case concerning delimitation of the maritime boundary in the Gulf of Maine area (Canada/ United States of America). *International Court of Justice Reports* 246.

Kirkley, J. E. and I.E. Strand, 1988. The Technology and Management of Multispecies Fisheries. *Applied Economics*, Vol. 20, pp. 1279-1292.

MAFMC, 1993. Report, Part 2, Phase 1, *Fishery Impact Management* Project, submitted to the Mid-Atlantic Fishery Management Council. Prepared by B. McCay, B. Blinkoff, R. Blinkoff, and D. Bart. December 31, 1993.

McFadden, D., 1978. Cost, revenue, and profit functions. In: *Production Economics: A dual approach to theory and applications*. M. Fuss and D. McFadden, (eds.). North-Holland, Netherlands.

Murata, Y., 1977. *Mathematics for Stability and Optimization of Economic Systems*. Academic Press.

Murawski, S. A., 1990. Mesh size regulations and discards: some observations from the North Atlantic. In: *Effects of different fishery management schemes on bycatch, joint catch and discards: Summary of a national workshop*, Dewees, C. M., and Ueber, E.,

(eds.). California Sea Grant College Report No. T-CSGCP-019, California Sea Grant College, University of California, La Jolla, 30-31.

NMFS, 1995. *Status of the Fishery Resources off the Northeastern United States for 1994*. NOAA Technical Memorandum NMFS-NE-108.

NMFS, 1998. *Status of the Fishery Resources off the Northeastern United States for 1994*. NOAA Technical Memorandum NMFS-NE-108.

NMFS, 1996. *Our Living Oceans. Report on the Status of U.S. living marine resources, 1995*. U.S. Department of Commerce, NOAA Tech. Memo. NMFS-F/SPO-19, 160 p.

Overholtz, W. J. and A. V. Tyler, 1986. An exploratory simulation model of competition and predation in a demersal fish assemblage on Georges Bank. *Transactions of the American Fisheries Society*. Vol. 115, pp. 805-817.

Overholtz, W. J., S. F. Edwards, and J. K. T. Brodziak, 1995. Effort control in the New England groundfish fishery: a bioeconomic perspective. *Canadian Journal of Fisheries and Aquatic Sciences*, Vol. 52, pp. 1944-1957.

Parks, R., 1971. Price responsiveness to factor utilization in Swedish manufacturing. *Review of Economics and Statistics*, Vol. 53, pp. 129-139.

Parsons, L. S., 1993. Management of Marine Fisheries in Canada. *Canadian Bulletin of Fisheries and Aquatic Sciences*, Vol. 225, pp. 321-336.

Rothschild, B. J., and A. F. Sharov, and M. Lambert, 1997. Single species and multispecies management. In: *Northwest Atlantic groundfish: perspectives on a fishery collapse*. B.S. Nakashima, J. A. Wilson, and R. L. Kendall, (eds.). Pp. 141-152. American Fisheries Society, Bethesda, Maryland.

Samuelson, P., 1947. *Foundations of Economic Analysis*. Harvard University Press, Cambridge, Massachusetts.

Siegel, R.A., 1981. *Federal Regulatory Policy for Marine Fisheries*. In: *Economic Analysis for Fisheries Management Plans*. L. G. Anderson (ed.). Ann Arbor Science Publications, Ann Arbor.

Sissenwine, M. P., and G.D. Marchesseault, 1984. New England Groundfish Management: A Scientific Perspective on Theory and Reality. In: *Proceedings of the Conference on Fisheries Management: Issues and Options*, T. Frady, ed. November 13-16, 1984, Anchorage, Alaska, Alaska Sea Grant Report 85-2.

Sissenwine, M. P., E. B. Cohen, and M.D. Grosslein, 1984. Structure of the Georges Bank ecosystem. *Rapp. P.V. Reun. Cons. Int. Explor. Mer*, Vol 183, pp. 243-254.

Spencer, P. D., and Collie, J. S., 1994. Modeling seasonally dependent predation in marine environments. *ICES Council Meeting Paper*.

Spencer, P. D., and J. S. Collie, 1995. A simple predator-prey model of exploited marine fish populations incorporating alternative prey. *ICES Journal of Marine Science*, 53:615-628.

Squires, D., 1987. Public Regulation and the Structure of Production in Multiproduct Industries: An Application to the New England Otter Trawl Industry. *Rand Journal of Economics*, Vol. 18, No. 2, pp. 232-247.

Squires, D., and J. E. Kirkley, 1991. Production Quota in Multiproduct Pacific Fisheries. *Journal of Environmental Economics and Management*. Vol. 21, pp. 109-126.

Squires, D., and J. Kirkley, 1995. Resource rents from single and multispecies individual transferable quota programs. *ICES Journal of Marine Science*, Vol. 52, pp. 153-164.

Thunberg, E.M., E.W. Bresnayan, and C.M. Adams, 1995. Economic Analysis of Technical Interdependencies and the Value of Effort in a Multispecies Fishery. *Marine Resource Economics*, Vol. 10, No. 1, pp. 59-76.

Thunberg, E. M., T.E. Hesler, R. K. Mayo, 1998. Bioeconomic Analysis of Alternative Selection Patterns in the United States Atlantic Silver Hake Fishery. *Marine Resource Economics*, Vol. 13, pp. 51-74.

Ueber, E., 1990. Using mesh sizes to reduce discards. In: *Effects of different fishery management schemes on bycatch, joint catch and discards: Summary of a national worksho*. Dewees, C. M., and Ueber, E. (eds.). California Sea Grant College Report No. T-CSGCP-019, California Sea Grant College, University of California, La Jolla, 30-31.

von Glahn, Gerhard, 1986. *Law Among Nations: An Introduction to Public International Law*. Fifth edition. MacMillan Publishing Company, New York.

Wang, S. D. H., M. Miller, P. Logan, and D. Lipton, 1987. U.S. Fishing Affected by the 1984 U.S.-Canada East Coast Maritime Boundary Decision. In: *East Coast Fisheries Law and Policy*. J. L. Bubier and A. Rieser (eds.). Marine Law Institute, University of Maine School of Law, Portland, Maine.

Whitmarsh, D., 1990. Technological Change and Marine Fisheries Development. *Marine Policy*, Vol. 14, pp. 15-22.

Whitmarsh, D., 1998. The Fisheries Treadmill. *Land Economics*, August 1998. Vol, 74, No. 3, pp. 422-427.

Wiley, D. E., W. H Schmidt, and W. J. Bramble, 1973. Studies of a class of covariance structure models. *Journal of the American Statistical Association*, Vol. 68, pp. 317-323.

Wyman, E., 1995. Selective groundfish pots offer solutions to bycatch problems. In: *Solving bycatch: considerations for today and tomorrow*. Alaska Sea Grant College Program Report No. 96-03, University of Alaska, Fairbanks, pp. 169-173.