ABSTRACT

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The formation of harvest cooperatives has recently generated considerable interest among fishermen and regulators as an alternative to other rights-based systems such as individual transferable quotas. Many consider the promotion of self-governance to be essential to more sustainable, equitable and efficient management of commercial fisheries. This dissertation examines the incentives created by the allocation of collective fishing rights as a mechanism for inducing the creation of cooperatives (or sectors). A theoretical model of the fishery characterizes necessary and sufficient conditions for the formation of sectors when harvesters have incomplete information on how to organize collective fishing but instead must learn by doing. The equilibria of the dynamic sector-formation game played by the heterogeneous fishermen shows that sectors may fail to form if permit holders are unfamiliar with cooperative harvesting. Conversely, when sectors do organize, the

least skilled fishermen join first and the scope of their cooperation, as given by the number of tasks they choose to coordinate, increases progressively over time until the uncertainty is fully resolved. Profitability, in turn, benefits from enhanced cooperation.

I test the predictions of the model using a panel data set from the hook gear segment in the New England Multispecies Fishery to estimate a stochastic output distance function and a technical inefficiency model. The simultaneous estimation of both equations allows the full characterization of the underlying multi-output technology and the assessment of key determinants of technical efficiency such as vessel characteristics, congestion conditions and cooperation. The results show that the least efficient vessels were the first to join the Georges Bank Cod Hook sector in 2004, and present evidence of earlier cooperation among these vessels (i.e. previous to the institutionalization of the group as a sector), hence suggesting familiarity with collective harvesting when joining the sector. Additionally, the resulst demonstrate that technical efficiency was higher for sector vessels than common pool boats during the sector years and increased during this period.

AN ANALYSIS OF SECTOR ALLOCATIONS IN COMMERCIAL FISHERIES

By

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Dedication

To Catherine, Gabriela and Sofia, las chicas de mis ojos.

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Chapter 1: Introduction and Policy Background

The formation of harvest cooperatives and similar efficiency enhancing institutional changes have recently generated considerable interest among fishermen and regulators as an alternative to other individual rights-based systems such as individual transferable quotas (ITQs). Many consider the promotion of self-governance by increasing the scope of decisions assumed by the industry to be essential to achieving more sustainable, equitable and efficient management. Fishermen have incentives to increase the rents they extract from the resource, and the objective of self-governance is precisely to empower them to operationalize these incentives.

An illustration at hand is the recent expansion of sector-based management in the United States New England Multispecies Fishery and its likely adoption in other fisheries in the country. Following the success of initiatives like the Pacific Whiting Conservation Cooperative and the Alaskan Pollock Conservation Cooperative on the West Coast of the United States, the regulator (New England Fishery Management Council) has implemented Amendment 16 and approved nineteen industry groups in the multispecies fishery to opt out of the current effort control system of management in order to form harvesting cooperatives called *sectors*.[1] Sectors are groups of self-selecting permit holders who receive an annual allocation of each of the groundfish species they catch in

[1] A sector must comprise at least three permit holders. At this time, only the groundfish industry is authorized by regulation to create sectors; however, in a recent amendment to the scallop fishery management plan (Amendment 11), the New England Fishery Management Council agreed to allow the General Category fishery to form sectors. There are portions of the limited access fleet that are interested as well. Furthermore, harvesters in the herring fishery have shown interest in forming sectors (Scoping document for Amendment 4 to the Atlantic Herring Fishery Management Plan, Amendment 4 Scoping Comments, June 2008).

return for designing and implementing their own harvesting and enforcement rules to keep their total catch within the limits of their allocation. Each sector is also responsible for developing and implementing a system of monitoring and reporting measures that accounts for all catch. Amendment 16, which took effect on May of 2010, significantly expanded the role of sector allocations as a management tool. The amendment eliminates the 20% cap on the share of the total allowable catch (TAC) that a sector can hold, and allows intra-seasonal transfers of quota among sectors (Final Amendment 16, October 16, 2009).

Successful case studies of self-governance in fisheries have been extensively documented (see, for example, Townsend et al. 2008, Uchida 2007, Knapp 2007, Silva and Kitts 2006, Leal 2005, Asada et al. 1983) and the efficiency gains associated with cooperative harvesting are well established (Costello at al. 2009, Costello and Deacon 2006, Uchida and Wilen 2005, Gaspart and Seki 2003, Stollery 1998). Nevertheless, self-governance has emerged in relatively few of the world's fisheries.[2] Research on the obstacles to the adoption of self-regulation has traditionally focused on the number and heterogeneity of harvesters and the difficulties of enforcement (see, for example, Erdlenbruch et al. 2008, Burton 2003, Scott 1993, Ostrom 1990, and Johnson and Libecap 1982). Yet it is doubtful that these obstacles exhaust all the conditions under which fishermen's attempts to self-organize break down. Furthermore, the understanding of these obstacles to self-governance sheds little light on the actual functioning of fishing cooperatives once they have succeeded in forming. The question is whether there is a

[2] The comprehensive volume on self-governance in fisheries published in 2008 by FAO and edited by Townsend, Shotton and Uchida, for example, reports only 32 cases, in 12 different countries.

different rationale for the common failure of fishermen to self-organize, which can also provide insight into the likely path of cooperation once the harvesting group has formed.

This dissertation examines how incomplete information on the optimal implementation of collective harvesting affects the incentives to undertake cooperation. Hence, the analysis understands “self-governance as a learned behavior” (Townsend et al. 2008, p.17) and assumes that the transition from independent, competitive fishing to collective harvesting can present a challenge to fishermen accustomed to the ‘race for fish’ under input controls or total allowable catch limits. This is an aspect of cooperation in the commons that has been overlooked by the existing literature.

In Chapter 2, I develop a theoretical model of the fishery and characterize necessary and sufficient conditions for the formation of sectors when harvesters have incomplete information on how to organize collective fishing but learn-by-doing. The equilibria of the dynamic sector-formation game played by the heterogeneous fishermen shows that least skilled fishermen have incentives to join sectors first, and that sectors may fail to form if permit holders are unfamiliar with cooperative harvesting. Conversely, when sectors do organize, the scope of their cooperation, as given by the number of tasks they choose to coordinate, increases progressively over time until the uncertainty is fully resolved. Profitability and sector membership benefit from enhanced cooperation.

In the empirical section of the dissertation I test some of the conclusions of the theoretical model using panel data obtained from the National Marine Fisheries Service on the New England Multispecies Fishery. The data is described in Chapter 4. Chapter 3 presents the empirical framework, namely the simultaneous estimation, for the hook gear segment, of a stochastic output distance function and a technical inefficiency model. The estimation of this system of equations allows me to fully characterize the underlying multi-output technology and to study the impact of vessel characteristics and fleet conditions (i.e. such as crowding of fishing grounds and cooperative interactions) on vessels' technical efficiencies. Thus, unlike most empirical studies of commercial fisheries' production frontiers, which implicitly assume input-output separability and estimate a weighted aggregate measure of output as a function of inputs, this dissertation uses a multi-output approach, allowing for the testing of the separability assumption and the derivation of the ability of fishermen to alter their output mix. Second, the analysis is applied to panel data and, unlike short-term studies, explicitly incorporates the variability of stocks biomasses over time into the estimation. Third, the study explicitly accounts for the effect of fishermen's interactions on efficiency in order to identify cooperation among harvesters.

Results of the econometric analyses are presented in Chapter 5. They show that the least efficient vessels were indeed the first to join the Georges Bank Cod Hook sector in 2004 and present evidence of earlier cooperation among these vessels (i.e. previous to the institutionalization of the group as a sector), hence suggesting familiarity with collective harvesting when joining the sector. Furthermore, the results demonstrate that technical efficiency was higher for sector vessels than common pool boats during the sector years of 2004-2008 and that it actually increased during this period.

1.1 Policy Background

1.1.1 Federal Regulation of US Fisheries

In 1976, the U.S. Congress passed the Magnuson Fishery Conservation and Management Act, the main law governing marine fisheries management in federal waters, to protect both the American fishing industry as well as a number of species of fish found off the U.S. coast. The Act, reauthorized as the Magnuson-Stevens Act (MSA) in 1996, officially gave the federal government the authority to manage fisheries and claimed the area between 3 and 200 miles from shore, an area known today as the Exclusive Economic Zone (EEZ). The Act created eight Regional Fishery Management Councils: New England, Mid-Atlantic, South Atlantic, Gulf of Mexico, Caribbean, Pacific, North Pacific, and Western Pacific. Each Council's area of responsibility is the EEZ adjacent to its constituent states. Councils develop and recommend fishery management plans and amendments for fisheries within their area of responsibility. NOAA's National Marine Fisheries Service (NMFS) approves and implements these plans and measures.

The New England Region includes the states of Maine, New Hampshire, Massachusetts, Rhode Island, and Connecticut. Federal fisheries in this region are managed by the New England Fishery Management Council (NEFMC). The management authority of the NEFMC extends to the Gulf of Maine, Georges Bank, and southern New England, and overlaps with the Mid-Atlantic Council for some species in that region. Voting members include the coastal state directors responsible for marine fisheries, the NMFS Regional Administrator, and citizens nominated by the coastal state governors and appointed by the Secretary of Commerce. Non-voting members include one representative each from the US Department of State, the US Fish and Wildlife Service, the US Coast Guard, and the Atlantic States Interstate Marine Fisheries Commission. Presently, the Council has nine fishery management plans (FMPs) in effect: Northeast Multispecies (Groundfish), Scallop, Monkfish, Herring, Small Mesh Multispecies (whiting and two stocks of hake), Red Crab, and a plan for the Northeast Skate Complex, as well as two additional plans that are prepared jointly with the Mid-Atlantic Council, Monkfish and Spiny Dogfish.

1.1.2 Rebuilding Targets and Catch Shares

The Magnuson Act has been amended in several occasions over the years. Two major recent sets of amendments to the law are the Sustainable Fisheries Act of 1996 and the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006. The Fisheries Act of 1996 focused on rebuilding overfished fisheries, protecting essential fish habitat, and reducing bycatch. Concretely, it mandated the end of overfishing and the rebuilding within 10 years of depleted populations to levels able to support the maximum amount of fish that can be sustainably caught, if biologically possible. The Reauthorization Act of 2006 mandated the use of annual catch limits and accountability measures to end overfishing, provided for widespread market-based fishery management through limited access privilege programs, and called for increased international cooperation.

Despite the mandate of the Sustainable Fisheries Act, the rebuilding targets for many depleted stocks have yet to be met. According to the “2009 Status of US Fisheries” report, 46 stocks still have an overfished status and 38 stocks are currently subject to overfishing (and 319 stocks are unknown with respect to their overfished status, and 272 are unknown with respect to their overfishing status). Of these, 17 overfished stocks and 8 populations currently subject to overfishing are in the Northeast region.

By 2006, when the Reauthorization Act was passed, the challenges facing US fishery managers made clear that additional tools to improve management effectiveness needed to be considered. The 2006 amendment to the MSA recognized catch shares as one of such tools. Catch share is a general term used to describe several fishery management strategies that allocate a specific portion of the total allowable fishery catch (TAC) to individuals, cooperatives, communities or other entities. Each recipient of a catch share is directly accountable to stop fishing when his specific quota is reached. The term includes specific programs such as Individual Fishing Quota (IFQ) programs, Sector Quota programs, and Territorial Use Rights Fisheries (TURFs) that grant an exclusive privilege to harvest in a geographically designated fishing ground. Catch shares programs have been in use in the US since 1990 and now include 13 different fisheries from Alaska to Florida, which are managed by six different Councils. In order to expand the use of these programs, NOAA released a draft policy on the use of catch share programs in fishery management plans in December 2009. The draft NOAA policy encourages the use of catch share programs to help rebuild fisheries and sustain fishermen, communities and working waterfronts. The fishery-wide implementation of sector-based management in the Northeast Multispecies Fishery during year 2010 is a reflection of NMFS's commitment to the adoption of catch shares in order to rebuild depleted fish populations.

1.1.3 The New England Multispecies Fishery

The New England groundfish fishery exploits demersal marine resources off the east coast of the U.S. from Maine to Connecticut. The fixed gear fleet uses gillnets, longlines and handlines, while the mobile gear fleet utilizes otter trawls. Many of the most productive stocks in this fishery have collapsed due to an ever-improving harvesting technology and failure of the management system to take the necessary steps to rebuild the populations. As a result, landings have fallen and fish prices increased, fueled by meager catches and increasing demand by health-conscious consumers.[3] Groundfish landings reached 34 million metric tons in 2008, with total revenues of over US$65 million.

Groundfish stock management under the Magnuson-Stevens Act began with the adoption of a plan for cod, haddock, and yellowtail flounder in 1977. This plan, which relied on hard quotas (total allowable catches, or TACs), proved unworkable due to the inability of the regulator to enforce the TACs. The quota system was rejected in 1982 with the adoption of the Interim Groundfish Plan, which relied on minimum fish sizes and mesh regulations for the Gulf of Maine (GOM) and Georges Bank (GB) to control fishing mortality. The interim plan was replaced by the Northeast Multispecies Fishery Management Plan (FMP) in 1986, which established biological targets in terms of maximum spawning potential yet continued to rely on gear restrictions and minimum mesh size to control fishing mortality. Amendment 5 was a major revision to the FMP. Adopted in 1994, it implemented reductions in time fished (days-at-sea, or DAS) for

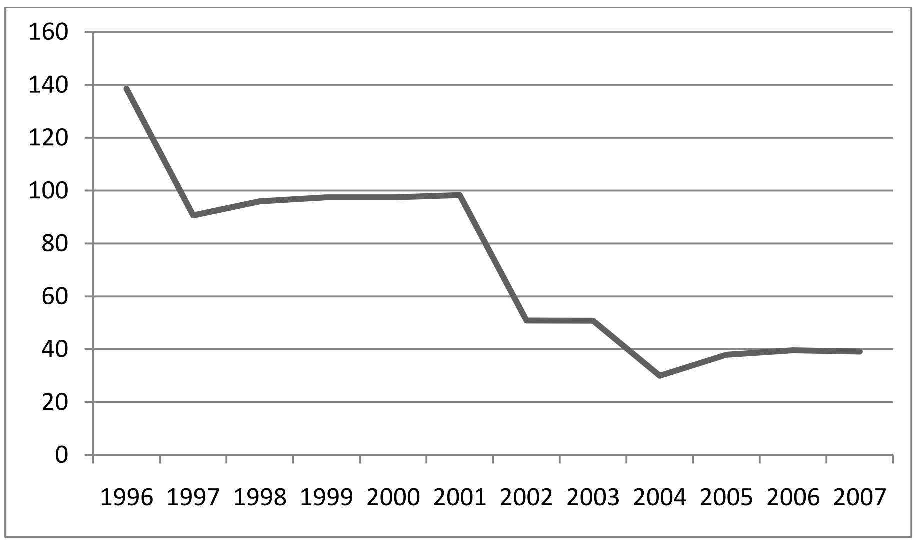
[3] "Brief history of the groundfishing industry in New England", available at http://www.nefsc.noaa.gov/history/stories/groundfish/grndfsh1.html

some fleet segments and adopted year-round closures to control mortality. Amendment 7, adopted in 1996, expanded the DAS program and accelerated the reduction in DAS first adopted in Amendment 5, but failed to convey sufficient reduction in fishing mortality due to the large amount of latent effort that existed in the fishery. Vessel buybacks in 1996 and 1997, with $25 million in government funds targeted at active groundfish vessels, purchased 79 vessels and permits that had accounted for roughly 20% of the revenues in the fishery. Despite this, the number of active groundfish vessels remained relatively constant between 1996 and 2001, implying that previously inactive vessels had entered the fishery following the buybacks. In 2001 another federally funded buyback purchased 245 permits for $9.6 million. In spite of these reductions in active capacity, latent effort, increasingly strict limits on effort, and other safeguards such as year-round and seasonal closed areas and trip limits, fishing mortality on some key groundfish stocks continued to exceed overfishing thresholds and evidence of substantial latent effort remained.

The next major change to the FMP came with the Settlement Agreement of August 2002. The Settlement Agreement was the result of a lawsuit brought against NMFS by environmental groups for violating the federal Sustainable Fisheries Act of 1996 by allowing the continued overfishing of cod, haddock, yellowtail flounder and other groundfish off the coast of New England. The provisions in the Settlement Agreement included a freeze on DAS based on the highest annual level used from fishing years 1996-2000, reduced by 20%, a freeze on the issuance of new permits, increased gear restrictions for certain gear types, including gillnets, hook-gear and trawl nets, modifications and additions to the closure areas, and limits on yellowtail flounder catch.

Amendment 13, which was developed over a four-year period and became effective on May 1, 2004, adopted a broad set of management measures to achieve the fishing mortality targets necessary to rebuild overfished stocks and meet other requirements of the Magnusson-Stevens Act. Among the most relevant changes were to reduce DAS available to fishermen, cut trip possession limits for the majority of the species, and proscribe the reactivation of latent permits. Figure 1.1 shows the evolution of the average DAS per vessel for the period 1996-2007.

Figure 1.1: Average DAS per vessel, period 1996-2007



Amendment 13 also contained provisions that allowed groups of fishermen to voluntarily form coop-type organizations called “sectors”. A sector could apply for an allocation of catch of one or several regulated groundfish species. The allocation of each species would be based on the documented accumulated landings of sector members for the 5-year period prior to submission of a sector allocation proposal to the NEFMC. The group would then receive an annual allocation equal to the target TAC for that species multiplied by the ratio of the group's catch to the total commercial catch. If a sector requested an allocation for all regulated stocks, and submitted a operations plan that would limit their catches to that allocation, they could avoid input-control regulations such as DAS limits, trip limits and seasonal area closures. Permit holders that did not wish to join a sector could continue to fish under the common set of regulations. The sector regulations in the amendment specified that no sector could be allocated more than 20% percent of the TAC unless otherwise authorized by the Council. The Georges Bank Cod Hook sector, the first sector to start operations, was authorized and implemented with Amendment 13.

Since the adoption of the Amendment 13, four adjustments actions (Frameworks 40A, 40B, 41, and 42) of the Multispecies Fishery Management Plan have been implemented. Among the measures adopted by these actions were the creation of a Georges Bank yellowtail flounder rebuilding strategy, changes in trip limits, extension of the DAS leasing program and modifications of the DAS transfer program, changes in gear standards, and the establishment of the Georges Bank Fixed Gear sector (approved in November of 2006), the second sector to start operations.[4]

Amendment 16, implemented in May of 2010, is the latest major modification to the Multispecies Management Plan. It adopts a broad range of measures designed to achieve reduced mortality targets, provide opportunities to target healthy stocks, and improve the administration of the fishery. Among other measures, the amendment significantly expanded the role of sectors. It removed the 20% cap on an individual

[4] A third sector, the summer flounder sector, was approved in 2009 by the Rhode Island Department of Environmental Management as part of the Summer Flounder Sector Allocation Pilot Program.

sector's total quota and approved seventeen new sectors. Under Amendment 16, sectors receive exemptions from many of the common pool effort control measures in exchange for a sector TAC for each species in the management plan (the so-called Annual Catch Entitlements, ACE). Furthermore, sectors can conduct the fishing activity according to their own business plans. In order to assure that sector ACEs are not exceeded, Amendment 16 adopts a new system of at-sea and dockside catch monitoring. Sectors can carry up to 10 percent of unused quota forward into the next fishing year, and sectors are allowed to exchange ACE with other sectors.

1.1.4 The Georges Bank Cod Hook Sector

The Georges Bank Cod Hook sector is comprised of a small, day-boat hook-and-line (benthic longlines and rod-and-reel) fleet. Sector vessels operate primarily out of Cape Cod, Massachusetts, fishing in the Georges Bank and to a lesser extent the Gulf of Maine, with the majority of the landings by sector vessels occurring in Chatham and Harwichport. Most sector vessels range from 25 to 70 feet in length. The GB Cod Hook Sector, the first sector authorized under Amendment 13, began operations in July 2004. Sector vessels received an allocation of Georges Bank cod only but not for the other species they harvested. They remained subject to DAS controls but became exempt from trip limits and restrictions on transfer of DAS within the sector. The sector was reauthorized yearly in the period 2005-2008 and continued to operate in a fashion similar to that of its first season. The sector's cod quota is allocated for each month of the fishing year, and the quota that is not landed during a month is rolled over into the next one.

Once the aggregate monthly quota is reached, no sector vessel is authorized to use fishing gear capable of catching cod. In practice, however, catch has never reached the monthly quota, and the annual catch of the sector has remained well below the sector's TAC, largely due to low catch rates for cod and continued restrictions of DAS. The number of permits, GB cod allocations, and GB cod landings are shown in Table 1. 1.

Table 1.1: No. permits, cod allocation and landings for the GB Cod Hook Sector

	2004	2005	2006	2007	2008
Total number of members	58	52	49	35	19
Entry	3	3	0	0	7
Exit	9	6	14	16	2
Active members	47	36	27	18	12
Entry	1	2	1	2	n.a.
Exit	12	11	10	8	n.a.
Allocation (mt)	371	455	615	675	658
% GB cod TAC	12.60%	11.70%	10.03%	8.02%	6.44%
Reported landings (mt)	130	125	89	86	97
% of quota landed	35.0%	27.5%	14.5%	12.7%	14.7%

Note: entry to and exit from the sector occur at the end of each year. A total of sixty one permit holders became members during 2004-2008.

Since its formation this sector has seen a steady decline in the number of permits. This trend closely resembles the overall reduction in active permits in the groundfish fishery, where the number of vessels has halved in little more than a decade as a consequence of the steady tightening of input controls (see figure 1.1 above). Indeed, the fact that sector vessels remained subject to the same system of strict DAS restrictions and trip possession limits (with the exemption of cod) as the common pool, coupled with the growing scarcity of GB cod, limited the ability of members to benefit from the collective operation and to shield themselves from the economic hardships they anticipated from the dispositions of Amendment 13.[5] This is probably why these fishermen have chosen, under the provisions of the recently approved Amendment 16, to opt out of the input-control system by requesting quota allocations for each one of the species they harvest.

[5] GB Cod Hook Sector Annual Report Fishing Year 2004

Chapter 2: Theoretical Model

This chapter examines how incomplete information on the optimal implementation of collective fishing affects the incentives to undertake cooperation. Hence, the analysis understands “self-governance as a learned behavior” (Townsend et al. 2008, p.17) and assumes that the transition from independent, competitive fishing to collective harvesting can present a challenge to fishermen accustomed to the ‘race for fish’ under input controls or total allowable catch limits.

I develop a model of learning-by-doing, in which the choice of the number of tasks to coordinate each season critically depends on fishermen’s current information. I then study the equilibria of the sector-formation game played by the heterogeneous fishermen, to answer the following questions concerning fishing cooperatives: Under what conditions are sectors expected to form? Who will join? What types of harvesting schemes will emerge?

The model predicts that a lack of familiarity of fishermen with cooperative harvesting may entirely preclude sectors from forming. On the other hand, if sectors do organize, the least skilled permit holders in the fishery join first and the scope of their cooperation (i.e. the number of coordinated tasks) is expected to increase gradually over time. These results are consistent with a variety of stylized facts about fishing coops. They help explain why quota holders rarely pool their shares of the TAC and fish cooperatively despite the potential efficiency gains. Furthermore, the rationale offered in this chapter –incomplete information on how to organize and implement collective fishing– is essentially different from the familiar free-riding in teams, or from adverse selection arguments that rely on asymmetric information on permit holders' skills.

The remainder of the chapter is organized as follows. Section 2.1 reviews the relevant literature on coalitions and coordination in fisheries. Section 2.3 develops the model and solves the sector-formation game. Section 2.4 discusses some of the assumptions and outlines future extensions of the framework. Section 2.5 presents policy implications of the findings and offers concluding remarks.

2.1 Previous Literature

Cooperation in fisheries has been extensively studied. Most of the models on coalition formation, however, have been applied to the study of the stability of cooperative agreements in high seas fisheries (see, for example, Kaitala and Lindroos 2001, Pintassilgo 2000, and Duarte et. al. 2000).This line of research typically assumes that the gains from cooperation arise exclusively from effort regulation, and that players are either homogeneous, or heterogeneous but very limited in number. In this section I discuss papers on agreements that form fishing cooperatives.

Knapp (2007) presents a detailed account of the functioning of the Chignik Salmon Cooperative during 2002-2005. He describes how the coop came about, how it was organized and governed, some of its effects, and why it ended.[6] Knapp explains, for example, how the Chignik coop was able to reduce operating costs (such as insurance, maintenance, fuel, and crew costs) by drastically consolidating the fleet. In 2004, out of

[6] In March 2005, the Alaska Supreme Court reversed the authorization for the Chignik cooperative, holding that the coop regulation was fundamentally at odds with the Limited Entry Act (i.e. it allowed people who were not actually fishing to benefit from the resource).

87 members, only 19 boats fished for the coop. The coop gradually undertook other initiatives to further decrease costs. It placed fixed leads on either side of the Chignik River where it enters the Chignik Lagoon, the area where the coop carried out its harvest, in order to reduce fishing costs by channeling returning salmon towards a narrow opening between the leads. The coop often timed its harvesting to coincide with low tides, when the Chignik Lagoon shrinks to a fraction of its size at high water, in order to concentrate the fish to a greater extent than would occur naturally. Finally, the coop coordinated information on stock locations from its active members and used this information to dispatch vessels to the most productive sites.

Knapp also recounts how the Chignik coop developed new ways for delivering and holding live fish to improve the quality of the product. Coop members traveled to British Columbia in 2003 to gather information from the farmed salmon industry on their handling techniques and quality control measures in the transportation of live salmon, and continued to experiment with different methods of handling fish in the next few years. By the third season, and as a result of these efforts, they were able to negotiate a contract with the processor which incorporated specific price premiums in return for quality.

Knapp makes specific reference to how the coop fishermen had to learn an entirely new way of fishing –cooperating instead of competing–, and explicitly includes among the lessons from the Chignik case that "fisheries self-governance selects for a different set of skills [from competitive fishing]" (Knapp 2007, p.44). In the report, he quotes the coop's fleet manager to stress this point: "…there were some socialization issues at work among fishermen who had been aggressive competitors in the past…I was fascinated by how the Chignik guys really did not know how to 'team' fish…A few fathers and sons, and maybe some brothers, shared information on the radio, but essentially no one else had a formal group that shared strategy and information" (ibid, p.16).

Costello et al. (2009) use a two-stage game to analyze the formation of the Chignik cooperative and explain some of the outcomes described by Knapp (2007). They model the benefits derived from coop membership as given by the availability of a public good input that reduces cost per unit of effort. The authors characterize the subgame perfect equilibrium and show that it is consistent with the consolidation of the coop fleet, the extension of the fishing season length, and the fact that fishermen that remained independent had better fishing skills than coop members (as indicated by higher historical catch rates).

Costello and Deacon (2006) study the benefits of sharing information on the location of stocks for ITQ holders, and conclude that this type of cooperation could eliminate inefficiencies associated with redundant search by independent fishermen. In a similar vein, Lynham (2006) suggests that information sharing on productive fishing grounds may prevent information cascades and herding behavior. Recently, Evans and Weninger (2009) have suggested that an information sharing cooperative would be beneficial for its members, but faces a free-riding problem as each member prefers that others undertake the costly search for information.

Uchida (2007) studies Japan's co-management groups, called Fishery Management Organizations (FMO), to find that simply allocating the allowable harvest to an FMO does not necessarily generate appropriate incentives; more proactive management measures are needed. He identifies two essential measures for successful co-management, effort coordination and adoption of a pooling arrangement. With these two measures, FMOs are able to operate in quasi-corporate style (i.e. operations are determined centrally and members are paid in a form that is similar to a dividend). Particularly interesting is his account of the Walleye Pollack (*Suketoudara*) fishery management, in the Hiyama region of Hokkaido. Uchida not only describes the sophisticated fishing arrangements adopted by some fishermen in this fishery (i.e. voluntary seasonal closures, establishment of no-fishing areas, imposition of gear restrictions, three-layered fishing-ground rotation: groups, teams, and individuals, etc.) but also how these self-imposed regulations have evolved. For example, while in the early 1980s the season opened in early December and continued until late March, in recent years the fishery has opened in early November and closed in early February. The reason for this self-imposed seasonal restriction is twofold: to maximize the value of the product (roe, the most valuable product, peaks in quality in this period), and to enhance successful reproduction of the stock (as the survival of the fertilized eggs is enhanced when water temperature drops below 10° C, which typically occurs in early February). Similarly, Uchida describes how harvesters in the Nishi section have recently modified their rotation scheme –intended to avoid congestion and the consequent costs, such as gear damage– to eliminate the inefficiency associated with the fact that some vessels had to travel long distances to reach their assigned fishing areas. This inefficiency has become acute and apparent as fuel prices have soared.

Uchida and Wilen (2005) develop a simple model to show that revenue pooling systems may mimic collusion and allow decentralized coops with large number of members to benefit from better terms of trade. The reason for this result is that forcing individuals to pool and share their proceeds generates incentives to shirk and restricts landings. This reduction in decentralized and non-cooperative effort choices leads to a reduction in aggregate harvest and higher prices. The extent to which market gains are exploited depends on both the pooling ratio and the elasticity of demand.

Finally, Platteau and Seki (2001) and Gaspart and Seki (2003) study three distinct groups of fishermen that operate in the *shiroebi* (Japanese glass shrimp) fishery. In both papers, the authors show that only the two groups comprised of homogeneous harvesters (as given by individual catch performances) have adopted some type of pooling arrangement and coordinate effort. Of these, only the group that has being operating the longest pools 100% of its profits and has implemented a scheme of community fishing. They synchronize fishing hours and number of hauls, share the burden of net repair, systematically exchange information on stock location, collectively control access to fishing grounds, and diffuse knowledge and expertise about fishing techniques.

As the aforementioned papers make patent, once fishermen join harvesting cooperatives –and it remains an unresolved puzzle why so few do– they face strong incentives to actively engage in cooperation to both reduce cost of effort and increase the value of their catch. Cooperation can boost profitability and is typically achieved through the design of fishing rules that attempt to synchronize the activities of coop members. Moreover, these fishing rules do not remain unchanged but evolve through time, allowing groups to progressively broaden the scope of their cooperation.

The accumulation of experience in team fishing as permit holders work together seems to be a critical trigger in the development of more complex collective fishing schemes. Yet despite the empirical evidence provided by these case studies, none of the theoretical models in the articles specifically address the possibility that fishermen must learn to implement collective fishing. The model in the next section explicitly accounts for this possibility, providing a previously unexplored explanation for both the common failure of fishing coops to emerge, and for the gradual increase in the scope of fishermen coordination when cooperatives succeed to form.

2.2 The Model[7]

2.2.1 The Fishery

A limited entry commercial fishery (i.e. the number of harvesters who may participate is limited by statute or regulation) is comprised of N risk-neutral individual fishermen. Fishermen are assumed heterogeneous with respect to skill. Differential abilities may be attributed to acquired knowledge and innate skills. The catch of individual fisherman i in season t, h_{it}, depends on the current fish biomass B_t, his catching skill k_i, and the amount of time he spends fishing (i.e. days at sea) T_{it}.

(2.1) $$h_{it} = h(k_i, T_{it}, B_t)$$

The cost of effort (i.e. cost per day at sea), denoted by c_i, varies among fishermen because of differences in their fishing abilities.[8] Without any loss of generality, I index harvesters in increasing order of their fishing skills so that N denotes the most skilled

[7] The appendix presents a summary of the main variables in the model.

[8] Note that cost per unit of effort can also vary among fishermen if their opportunity costs are different.

permit holder in the entire fishery (i.e. $k_N > k_i$). I assume that the ratio c_i/k_i is decreasing in i (i.e. $c_N/k_N < c_i/k_i$, for all i).The ratio c/k can be thought of as an (inverse) efficiency parameter; the lower the unit cost of effort, or the higher the skill level, the lower the value of c/k.

In the first season a new regulation is passed, authorizing fishermen to organize in a sector and allowing them to design their own governing rules. Under this new rule, each member is allocated a *potential sector contribution* (PSC) based on his landings history. If the catch function in (2.1) is specified as $h(k_i, T_{it}, B_t) = k_i T_{it} \phi(B_t)$, where ϕ is an increasing function, it is possible to write vessel *i*'s PSC as proportional to his skill level:[9]

(2.2) $$\mathrm{PSC}_{it} = \left(\frac{k_i}{K}\right) \mathrm{TAC}_t$$

where $K = \sum_{j=1}^{N} k_j$, the summation of skill over all permit holders in the fishery, and TAC_t denotes the total allowable catch set by the regulator for season *t*. The combined PSCs from all sector members is then used to determine the sector's *annual catch entitlement*, meaning its quota, in the following way:

(2.3) $$Q_t^S = \sum_{i \in S_t} \mathrm{PSC}_{it} = \left(\frac{\sum_{i \in S_t} k_i}{K}\right) \mathrm{TAC}_t$$

If fishermen, on the other hand, decide to continue fishing independently as part of the common pool, they add their PSCs to the common pool's total quota but have to compete

[9] The curvature properties of ϕ will depend on the behavioral characteristics of the fish stock (i.e. sedentary versus pelagic schooling species); see Clark (2005) for details.

for their share of the catch. The total quota allocated to the common pool is calculated simply as $Q_t^{CP} = \mathrm{TAC_t} - Q_t^S$, where Q_t^S is given by (2.3) above. The fish stock each season is determined by its level in the previous period, its biological growth function, and the previous TAC. I assume there is no depletion within the season.

Once the sector is formed, its members need to agree on the particular fishing arrangement to adopt. This decision has to be revised each season, and the details of the fishing scheme specified in a sector's operations plan, which is submitted annually for the approval of the regulator. One possibility is for the sector to simply opt for independent fishing where each member catches his own quota. In an overcapitalized fishery, sector members may instead decide to pool their quota and rationalize the fleet in order to catch their share of the TAC at a lower cost employing their most skilled fishermen. In this latter scenario, the sector will further need to decide whether to allow fishermen in the consolidated fleet to operate independently of each other, or to alternatively engage them in active cooperation. The sector may decide, for example, to encourage them to share information on stock locations to avoid redundant search effort, coordinate their access to productive fishing spots, implement collective search for lost gear, etc. Under complete coordination, the sector effectively adopts a sole-owner approach, in which the operations are completely managed to maximize sector profits.

I characterize the specific fishing scheme adopted by the group by the number of tasks ω that must be coordinated in order to implement it. Examples of tasks to coordinate are the search for the stock, the access to the fishing grounds, and the tendering on the catch. Under independent fishing –with or without quota pooling– ω is trivially equal to zero. The sector will be assumed to be a single-minded entity administered by a sector manager.

Figure 1 below summarizes the sequence of events each season: first, fishermen decide whether to join the sector or remain independent as part of the common pool; in phase 2 the sector selects its fishing scheme; finally, fishermen in the common pool exert fishing effort, and the sector implements its fishing arrangement and assigns fishing times to catch its assigned quota. This sequence is repeated every season.

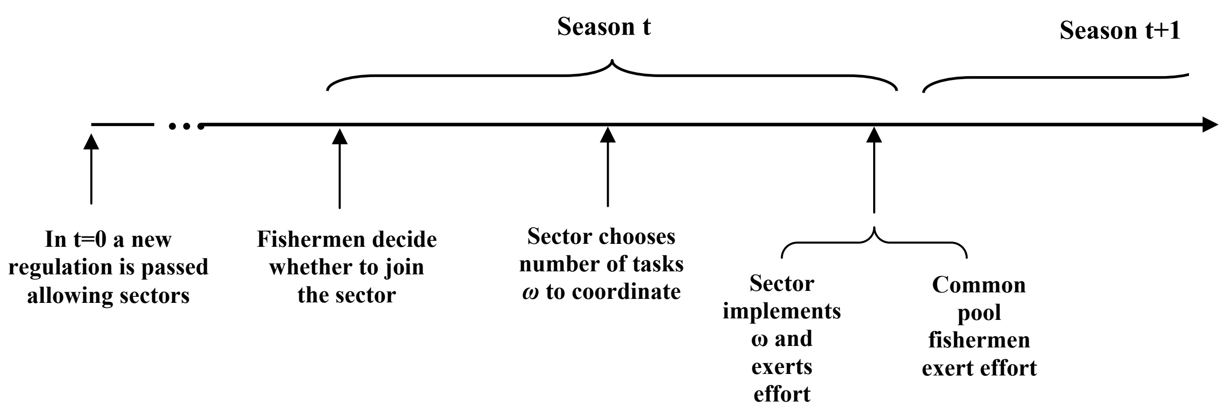


Figure 2.1: Sequence of moves each season

In what follows I suppose that fishermen select their strategies each season by myopic optimization. This means that permit holders care only about short-term (current) payoffs and ignore the impact of their actions on the evolution of the fishery. While this assumption may seem extreme, less plausible is the alternative of perfect farsightedness in which all economic decisions made by individual fishermen are globally optimal over an infinite horizon. As will be discussed later in the chapter, while this assumption substantially simplifies the analysis, it is not necessary for the derived results. The central reason for this is the requirement (an integral part of the new regulation itself) that fishermen ratify their decisions on an annual basis. This periodic opportunity to revise their decisions on sector membership and sector's fishing rules effectively makes permit holders' choices reversible.

2.2.2 The Sector: Internal Governance and Coordination of Tasks

In this section I introduce a stylized fishing sector that is fully characterized by i) simple contracts to distribute profits among members, and by ii) the degree of fishing cooperation its members decide to implement each season.

2.2.2.1. Distributing Profits

The payoff for a particular member of the sector will depend on how profits are distributed within the group. In the model the sharing rule ($\mathcal{S}$) is exogenously determined and thus taken as given. I assume that all profits are distributed as dividends each season and that each member receives a fixed share of total profits $\mathcal{s}_j$, which may or may not depend on individual skills. I will be interested here in discussing two alternative profit-sharing rules that are simple to implement and have been used before by fishing cooperatives:[10]

(i) equal sharing among members ($\mathcal{s}_j = \mathcal{s} = 1/\mathrm{N_t}$, where $\mathrm{N_t}$ denotes the sector's size in season *t*), and

[10] Equal sharing of profits is used, for example, by some groups in the *shiroebi* (Japanese glass shrimp) fishery (Gaspart and Seki, 2003), and was the formula adopted by the Chignik Salmon Cooperative in Alaska while it was in operation in 2002-2005 (Knapp 2007). Pooling arrangements in which the distribution rule incorporates the heterogeneity of both vessel and crew sizes are used by some groups in the *Suketoudara* (Walleye Pollack) fishery in the Hiyama region of Hokkaido, Japan (Uchida and Watanobe, in Townsend, 2008).

(ii) profit sharing proportional to potential sector contribution (PSC) (i.e. $s_j = k_j / \sum_{i \in S_t} k_i$).

While pooling arrangements of this type help to align the individual's incentive to maximize his return with the group's incentive, they may also encourage members to shirk. Since I am interested here in studying the effects of incomplete information on sector's formation and growth, in the rest of the chapter I disregard the enforcement problem and assume that members abide by the rules and norms accorded by the group. The penalties for violations stipulated in Amendment 16 are quite stringent and likely to deter, to some extent, shirking and cheating within sectors. Thus, for example, "…if a vessel is expelled from a sector, it cannot participate in the groundfish fishery for the remaining of the fishing year", (Final Amendment 16, October 16, p. 107), and "Sectors may be held jointly liable for violations of the following sector operations plan requirements: annual catch entitlement overages, discarding of legal-sized fish, and misreporting of catch (landings or discards)", (ibid, p. 107).

2.2.2.2. Implementing Cooperation

The transition from competitive and independent fishing to collective fishing is viewed here as the adoption of a new fishing technique. I characterize each cooperative fishing technique by the number of tasks ω that fishermen need to coordinate to implement it.[11] The larger the number of tasks ω to coordinate, the more cooperative the fishing scheme. Thus, for example, a quasi-corporate operation like the one run by the Chignik cooperative or by some Japanese groups (i.e. large ω), is deemed more

[11] The number of tasks can be interpreted as the degree of division of labor that describes the fishing scheme, with a higher degree of differentiation indicated by a higher ω.

cooperative than one where there is only coordination of access to fishing grounds to avoid congestion externalities (i.e. $\omega = 1$).

In the model, the benefits from cooperation come from the reduction in the unit cost of effort for sector members. Cooperation among fishermen, however, provides opportunities not only to coordinate fishing and reduce costs, but also to tailor product timing and mix to suit market conditions, to increase product quality and recovery rates, and to improve fishing safety. In the current model the learning-by-doing by the group determines the transition function regulating the evolution of the sector's profitability. That profitability is increased via cost reductions instead of product quality improvements is not critical for the results. I have opted to use the reduction in cost of effort as the modeling device for the benefits of cooperation, because it is in the design of new fishing schemes that Amendment 16 offers more opportunities (and challenges) to prospective sectors. The reduction in the cost of harvest will undoubtedly be a key determinant of the schemes that finally emerge. Furthermore, some harvest cooperatives have accomplished remarkable achievements in cost savings. For example, the cost savings as percentage of ex-vessel value attributable to the Chignik cooperative have been estimated to lie in the range 46%-61% (Knapp 2007).

Sectors will be able to design their own fishing rules without restrictions on the harvesting techniques they can adopt. Complex harvest strategies over space and time are available to sector members to maximize product value and to reduce harvesting costs. The present chapter explores an aspect of collective action unaddressed by previous research, by assuming that the transition to team fishing may be challenging if permit holders have historically 'raced for fish' and thus lack previous experience working cooperatively. This is, for example, the case of the New England groundfish fishery, which has been managed through input controls (such as limits on days at sea and trip possession) since the early eighties. It is precisely the overcapitalization of the fishery and the concomitant inefficiency that sector-based management is supposed to address. Concretely, I assume that upon adoption, sector members have incomplete information on how to coordinate the ω tasks that they have decided to implement. However, their knowledge increases as they experiment repeatedly with the new technique and gain familiarity with it. Pair trawling is a simple illustration of how demanding the transition to team fishing can be. This technique uses two vessels, each towing one warp, and keeps the net mouth open by the outward pull provided by correct lateral spacing of the boats, so that no otter boards are needed. While pair-trawling may be more efficient than single boat trawling (as it permits greater control of the net itself, and because engine noise from the boats is not directly over the fish and thus it does not scare them from the path of the net), the need of cooperation and finely-tuned coordination between the skippers, which becomes particularly challenging under adverse weather conditions, limits its use in commercial fisheries (Gabriel et al. 2005). Hazlehurst (1994) reports cases, in the island of Vind, Sweden, of costly coordination mistakes even among pair-trawling teams that had been working together for almost 20 years. When discussing fishermen' means of learning and knowing, he quotes the harvesters themselves as stating that "fishermen learn by doing" (ibid, p.16).

I draw on the work of Jovanovic and Nyarko (1996), and earlier research by Wilson (1975) and Prescott (1972), to model uncertainty about each new fishing scheme as an unknown target parameter. Using the simile in Mitchell (2000), the adoption of a new harvesting technique can be viewed as a problem in which the sector must choose not only the amount on inputs to hire, but also how to use those inputs. The choice of how to use the inputs can be understood as a dial-setting problem. The sector manager chooses inputs and a dial setting. The best dial-setting is unknown to the sector. The sector manager makes its best guess at the setting, observes the outcome, updates its beliefs about the optimal setting, and proceeds to the next fishing season.

Consider a sector faced with the decision of how to collectively harvest its allocation. The set of feasible collective fishing arrangements is given by Ω, where Ω is assumed to be finite subset of R_{++}.[12] Each $\omega \in \Omega$ defines a cooperative fishing scheme, namely, the scheme requiring the coordination of ω tasks among sector members. Thus, a higher ω indexes a higher number of tasks. Without loss of generality, I assume that the minimum number of tasks to coordinate is one (i.e. $\min\{\omega | \omega \in \Omega\} = 1$). Thus, the coordination of a single task defines the simplest of the cooperative schemes in Ω. To avoid notational complexity that does not add to the analysis, I leave it implicit how the specific tasks to coordinate in each scheme are chosen. Note that $0 \notin \Omega$, that is, independent fishing is not in the set of cooperative fishing schemes, and hence the choice $\omega = 0$ indicates that the sector has opted not to coordinate the harvesting activities of its members.

Successful cooperation requires that the sector manager actively coordinate members to perform their joint work (i.e. coordinate the tasks ω). I model the implementation decisions by the manager as the one-dimensional choice of $d_t \in \mathbb{R}$. The choice of d_t, however, may entail organizational considerations across many

[12] This assumption is in no way critical, and I could have alternatively defined Ω as a closed interval in R++.

dimensions. For example, how many exploratory vessels should be surveying for the distribution of fish schools? What is the optimal way to accomplish the orderly access to the fishing grounds, in order to avoid undesired congested conditions? How is the information on current market prices going to be used to determine the target mix of species for the catch? An alternative way to model the implementation decisions would be to treat d_t as a vector. However, that would mean dealing with multiple unknown parameters, which would limit the tractability of the model.

I adopt the specification in Jovanovic and Nyarko (1996) to model how deviations from optimal implementation reduce the return of a public input according to a quadratic loss function. Hence, the reduction in the unit cost of fishing effort for sector members in season *t* when coordinating ω tasks can be written as:

$$r_{\omega}(d_t, \theta_{\omega} + \varepsilon_t, X_t) = [\gamma_{\omega} - ((\theta_{\omega} + \varepsilon_t) - d_t)^2]X_t \tag{2.4}$$

where γ_{ω}, θ_{ω} are parameters specific to the fishing scheme ω, ε_t is a normally distributed independent disturbance with zero mean and variance σ_{ϵ}^2, and X_t is a public good input determined by members' contributions. While γ_{ω} is known by the fishermen, θ_{ω} is assumed unknown. In expression (2.4), for each set of tasks ω, it is the Euclidean distance between the sector manager's choice d_t and the realization of $\theta_{\omega} + \varepsilon_t$ that determines the actual return of the public input in reducing cost of effort. The larger the deviation from optimal implementation, the lower the return of input used. This deviation, in turn, depends on the random disturbance ε_t and on the information on θ_{ω}, that is, on the sector's accumulated knowledge on the fishing scheme. Hence, $y_{\omega_t} = \theta_{\omega} +$

ε_t can be viewed as a random target that the sector manager tries to anticipate when implementing the ω tasks. Under optimal implementation (i.e. when d_t is 'on target'), the reduction in the unit cost of effort is given simply by $\gamma_\omega X_t$. I assume that more coordination is desirable under perfect information, and thus $\gamma_{\omega+n} > \gamma_\omega$ for any $\omega, n \geq 0$.

Thus, in the framework of Buchanan (1965), the sector can be viewed as a club, and expression (2.4) as defining the provision of the club service, namely, the reduction in the unit cost of fishing effort for sector members.

Examples of the public good input in (2.4) are the stationary nets placed by the Chignik cooperative along the major migration route that funneled the migrating salmon stock towards the area where the purse seine were waiting, the artificial reefs (i.e. man-made objects specifically placed to attract fish, provide or improve fish or shellfish habitat, and increase fish biomass locally) installed by the Mugi Higashi Fishermen Cooperative Association in Japan, and fish aggregating devices (i.e. structures located at the surface or at midwater depths to take advantage of the attraction of pelagic fish to floating objects) used by some groups in the Philippines and Japan (FAO Fisheries Report No. 474, Supplement Volume 1, 1992).

As an illustration of (2.4), a collective fishing operation may entail investing in man-made reefs and similar devices (i.e. X_t), as well as coordinating the search for the stock in the artificial reef areas (i.e. ω = 1) by choosing the number of vessels to send searching each period (i.e. d_t= number of searching vessels in *t*). Sending an excessive number of boats would be wasteful due to the duplication of search effort, but too few may prevent the group from catching its entire quota. Furthermore, the optimal number of exploratory boats each period is likely to be subject to random variation due to changing tides, currents and weather conditions, among numerous other factors (i.e. $\theta_1 + \varepsilon_t$ =optimal number of searching vessels in *t*).

While θ_ω is unknown to fishermen, fishermen start the first season with prior beliefs about it, and those initial beliefs are common to all permit holders in the fishery. I assume that prior beliefs are normally distributed and that fishermen update beliefs following Bayes' rule. Each period the sector updates beliefs $\mu_t(\theta_\omega)$ upon realizing $y_{\omega_t} = \theta_\omega + \varepsilon_t$. Conditional on the signal y_{ω_t}, updated beliefs about θ_ω follow a normal distribution (De Groot 1970):

$$\mu_{t+1}(\theta_\omega) \sim N\left(\frac{y_{\omega_t}\sigma^2_{\theta_{\omega_t}} + \mathbb{E}_t(\theta_\omega)\sigma^2_\varepsilon}{\sigma^2_{\theta_{\omega_t}} + \sigma^2_\varepsilon}, \frac{\sigma^2_{\theta_{\omega_t}}\sigma^2_\varepsilon}{\sigma^2_{\theta_{\omega_t}} + \sigma^2_\varepsilon}\right) \quad (2.5)$$

where $\mathbb{E}_t(\theta_\omega)$ and $\sigma^2_{\theta_{\omega_t}}$ respectively denote expectation and variance of θ_ω with respect to beliefs $\mu_t(\theta_\omega)$. Notice that the updated mean is a convex combination of the prior belief and the signal y_{ω_t}, and that all signals reduce the posterior variance by the factor $\sigma^2_\varepsilon / (\sigma^2_{\theta_{\omega_t}} + \sigma^2_\varepsilon)$, which is smaller than one. Thus, the variance of the group's subjective beliefs falls through time and converges to zero, that is, in the long run the uncertainty about θ_ω is fully resolved[13]. This dynamic of belief formation will have important implications later on in the analysis.

I conclude this section by using the previous definitions to write the expected profit of the sector in season *t* as:

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[13] Note that while the precision of beliefs increases in a fixed, predetermined way, the value of $\mathbb{E}_t(\theta_\omega)$ each season will depend on the observed signals.

$$\text{(2.6)} \qquad \mathbb{E}\left[\Pi_t^S\right] = pQ_t^S - \sum_{i \in S_t} T_{it}(c_i - \mathbb{E}[\gamma_\omega - ((\theta_\omega + \varepsilon_t) - d_t)^2]X_t) - \mathrm{C}(X_t)$$

where p denotes the (exogenous) price of the catch, and $\mathrm{C}(X_t)$ the cost of providing the public good input $\mathrm{X_t}$. The function C is twice differentiable and strictly convex.

From (2.5) and (2.6) it can be seen that, in the model, the learning process is prompted by incomplete information, and that the transition function regulating the evolution of the sector's profitability is a result of Bayes' rule.

2.2.3 Solving the Season's Game

Myopic agents make their choices based on optimization of the season's payoffs. I analyze each season starting with the last stage. When deciding whether to become members of the sector, fishermen look forward in the season to anticipate that, once the fishing starts (stage 3), the sector manager will allocate harvesting times to its members, implement the selected scheme ω, and provide the public good input so as to catch the sector's quota at the minimum cost. Moreover, harvesters expect that, before the actual fishing starts, when selecting the number of tasks ω to coordinate (stage 2), the manager will optimally trade off the benefits from adopting cooperative schemes (i.e. large ω) against the costly implementation errors he foresees in light of his limited information.

It is by comparing the equilibrium profit he can earn in the common pool, as an independent, to his expected share of the sector's profits, that each permit holder decides, at the beginning of each season (stage 1), if it is worthwhile to join the sector. In this assessment, each agent anticipates the best responses of the remaining fishermen, as determined by their fishing skills and unit cost of effort. As will be shown later in this section, the unambiguous best response for everybody in the fishery is to stay out of the sector if harvesters anticipate that, given the manager's current knowledge on team fishing, he will opt not to coordinate any tasks (i.e. ω = 0).

2.2.3.1. Stage 3: Optimal Input Choices by Independents in the Common Pool

Each permit holder fishing independently in the common pool solves the following program:

$$\max_{T_{it}} ph(k_i, T_{it}, B_t) - c_i T_{it} = pk_i T_{it} \phi(B_t) - c_i T_{it} \tag{2.7}$$

subject to the condition that the common pool quota is not exceeded:

$$\phi(B_t) \sum_{i \in \mathrm{CP}} k_i T_{it} \leq Q_t^{CP} = \left(\frac{\sum_{i \in CP} k_i}{K}\right) \mathrm{TAC}_t \tag{2.8}$$

Equation (2.7) is linear and increasing in the days at sea T_{it} if $pk_i\phi(B_t) - c_i > 0$. Thus, the equilibrium condition for fishermen in the common pool is simply:

$$T_{it}^* = \begin{cases} \dfrac{\mathrm{TAC}_t}{\phi(B_t)K} & if \quad pk_i\phi(B_t) - c_i > 0 \\ \\ 0 & \text{otherwise} \end{cases} \tag{2.9}$$

Each active permit holder in the common pool will fish until the fraction of the TAC_t assigned to independents is caught. Thus, the equilibrium profit for the active fishermen in the common pool is:

(2.10) $$\pi_{it}^* = \left(pk_i - \frac{c_i}{\phi(B_t)}\right)\left(\frac{\text{TAC}_t}{K}\right)$$

This expression is clearly increasing in the skill level k_i (since the (inverse) efficiency ratio c_i/k_i decreases with skill). Note also that (2.10) is independent of the composition of the common pool. The reason for this result lies in the way potential sector contributions (PSCs) are calculated. An independent fisherman of skill k_i will catch $h_{it} = k_i T_{it}^* \phi(B_t)$ during season t. As a fraction of the common pool total catch, it amounts to $h_{it}/\sum_{j\in CP} h_{jt} = k_i/\sum_{j\in CP} k_j$. But this last expression coincides with his PSC_i. Thus, while a highly skilled permit holder may be able to land more fish than his independent counterparts, he does so only in proportion to his own contribution to the common pool quota. Therefore, his presence in the common pool does not undercut the profitability of the other independents.

Finally, observe that for those fishermen whose optimal choice in (2.9) is $T_{it}^* = 0$, the potential sector contribution equals zero. In the rest of the chapter I assume that only individuals contributing positive catch shares to the sector quota will be admitted as members. Under a profit-sharing rule proportional to PSC, inactive fishermen would have no incentives to join the sector. Under equal sharing, on the other hand, they would increase their profits by becoming members of the sector. However, it is reasonable to assume that, regardless of the sector's internal decision-making process, these individuals would not be accepted by the fishermen bringing positive quota to the group.

2.2.3.2. Stage 3: Optimal Input Choices by the Sector Manager

The objective of the sector manager is to maximize total expected profits each period. In the third stage, when both sector's membership and the fishing scheme are taken as given, the choice of fishing effort, public good provision, and optimal implementation can be found by solving the following maximization problem:

$$\text{(2.11)} \qquad \max_{T_{it},d_t,X_t} \mathbb{E}\left[\Pi_t^S|\omega_t,S_t\right] = pQ_t^S - \sum_{i\in S_t} T_{it}(c_i - \mathbb{E}[\gamma_\omega - ((\theta_\omega + \varepsilon_t) - d_t)^2]X_t) - \mathrm{C}(X_t)$$

$$\text{subject to } \sum_{i\in S_t} k_i T_{it}\phi(B_t) = Q_t^S$$

In (2.11) revenues depend on the price of the catch and the sector's share of the TAC_t. The sector's share, in turn, is fully specified by the number and skill profile of its members. Given the assumption of constant unit cost of effort, it is always optimal for the sector to harvest its entire quota (i.e. the constraint in (2.11) is binding). Thus, provided the entire quota Q_t^S is caught, the sector manager will minimize the cost of effort. He will do so by consolidating the fleet and assigning positive harvest times to the subset of lowest cost members such that the sector's season lasts the entire time the fish are available $\overline{\mathrm{T}}$.[14] When the marginal cost of effort is constant, this is always the optimal

[14] Note that for the actual unit cost of effort to be always positive, it is sufficient to impose that: $\lim_{X_t\to a} \frac{dC}{dX_t} = \infty$, where $a = c_{min}/(\gamma_{\overline{\omega}} - \sigma_\varepsilon^2)$, $c_{min} = \min(c_i \mid i \in S_t)$) and $\overline{\omega} = \max(\omega \mid \omega \in \Omega)$.

choice.[15] Otherwise, the costs could be further decreased simply by reducing the time allocated to the least skilled among the active fishermen in favor of a more highly skilled member. The optimal assignment of days at sea is defined by (2.12) bellow:

$$\{T_{it}^*\}_{i\in S_t} \in \text{argmin} \sum_{i\in S_t} c_i T_{it} \;\; \text{subject to} \;\; \sum_{i\in S_t} k_i T_{it}\phi(B_t) = Q_t^S \;\; \text{and} \;\; T_{it} \leq \bar{T} \;\; \text{for all } i \in S_t$$

Therefore, $T_{it}^* = \bar{T}$ for the subset of most skilled fishermen that ensures that the sector's quota is caught (i.e. $T_{it}^* = 0$ for the remaining members). This result is consistent with the increase in season length associated with the formation of cooperatives such as the Chignik Cooperative (the cooperative lengthened the season by an average of 32 days; Costello et al. 2009), the Pacific Whiting Conservation Cooperative (PWCC) (in 1998, the first year of PWCC operation, the season lasted 83 days, almost 60 days longer than previous years; Sylvia et al. 2008), and the cooperatives in the North Pacific Pollock fishery (the season length went from 75 days in 1998 to 149 days in 1999 after the creation of the cooperatives; Sanchirico 2008).

Note also that when the sector fleet is overcapitalized, that is, when $\sum_{i\in S_t} k_i\bar{T}\phi(B_t) > Q_t^S$, condition (12) implies that the least efficient members (such as fisherman 1) will not fish during the season.

From the first order condition of (2.11) with respect to d_t, it is immediate that the optimal implementation choice is given by:

[15] If marginal costs of effort are not constant, efficiency requires marginal costs of each effort type to be equal, and the marginal cost of the last unit of effort to be equal to the marginal product of aggregate effort.

$$(2.13) \qquad d_t^* = \mathbb{E}_t(\theta_\omega)$$

Not surprisingly, (2.13) sets the optimal implementation choice equal to the expected value of the technology specific parameter θ_ω. The rationale for this condition is that $\mathbb{E}[(\theta_\omega + \varepsilon_t) - d_t)^2]$ is a quadratic loss function, in which deviations above and below the target θ_ω reduce the return of the input used X_t. For example, if the sector is coordinating one task, namely the search for fish, then d_t corresponds to the number of searching vessels the sector manager sends to locate the stocks. Expression (2.13) indicates that what is relevant for the actual performance of the sector is not the optimal number of exploratory vessels to send searching for fish (i.e. θ_1), but how close the number of vessels the manager sends is to that optimal number of exploratory boats. Sending an excessive number of boats would be wasteful due to the duplication of search effort, but too few may prevent the group from catching its entire quota.

Substituting (2.12) and (2.13) into the first order condition of (2.11) with respect to X_t, we obtain:

$$(2.14) \qquad \left(\sum_{i \in S_t} T_{it}^*\right)\left[\gamma_\omega - (\sigma_{\theta_{\omega_t}}^2 + \sigma_\varepsilon^2)\right] - \frac{dC(X_t^*)}{dX_t} \leq 0$$

where $X_t^* \geq 0$ and (2.14) holds with equality if $X_t^* > 0$. Thus, at the optimum the Samuelson condition must be satisfied. For the public good input in question, the summation of each member's marginal benefits must be set equal to the marginal cost of provision. Note however, that equation (2.14) defines the optimal provision conditional on the current information on θ_ω, and it is lower than the optimal provision under perfect information. To see this notice that the first term in the left hand side of (2.14) is decreasing in $\sigma^2_{\theta_{\omega_t}}$ and $C(X_t)$ is strictly convex. Hence the lack of perfect information on θ_ω translates into a faulty decision d_t by the sector manager, and, for a given number of sector members, into under provision of the public good input.

Finally, using expressions (2.12)-(2.14), the sector's maximized profit in the third stage can be written as:

$$(2.15) \qquad \mathbb{E}\left[\Pi_t^S|\omega_t, S_t\right] = \left[pQ_t^S - \sum_{i\in S_t} c_i T_{it}^*\right] + \left[\left(\sum_{i\in S_t} T_{it}^*\right)\left[\gamma_\omega - \left(\sigma^2_{\theta_{\omega_t}} + \sigma^2_\varepsilon\right)\right] X_t^* - C(X_t^*)\right]$$

The first term in the right hand side of (2.15) equals the profits of fishing the quota with a rationalized fleet, and the second term corresponds to the expected net gains from adopting cooperative fishing when the sector implements ω tasks. These latter gains are realized as further reductions in the unit costs of fishing. Note that $\mathbb{E}_t(\theta_\omega)$ does not enter in equation (2.15), since the size of θ_ω does not affect sector's success. As it was mentioned above, it is only the Euclidean distance between $\mathbb{E}_t(\theta_\omega)$ and the true θ_ω that matters. In (2.15) the posterior precision on θ_ω can be viewed as the stock of social capital of the group. As sector members use the new fishing technique, they also observe $y_{\omega_t} = \theta_\omega + \varepsilon_t$ and learn more about θ_ω, which allows the sector manager to make a better decision d_t. This reduces the posterior variance $\sigma^2_{\theta_{\omega_{t+1}}}$ and raises the expected profit of the sector. Note that in the model the choice of inputs by the sector manager does not affect the realization of $y_{\omega_t} = \theta_\omega + \varepsilon_t$. Thus, the decisions of the sector manager, like the allocation of fishing times among members, have no effect on the evolution of beliefs (i.e. in this sense learning is passive).

2.2.3.3. Stage 2: Selecting the Fishing Scheme

Each season the sector manager selects the number of tasks to coordinate, learns from that experience, and then chooses a new set of tasks to implement the following season.

The link between different cooperative schemes is informational. Concretely, if the sector is coordinating ω tasks, and the alternative is to coordinate $\omega + n$ tasks, with $\omega + n \in \Omega$, I define $\theta_{\omega+n} = \sqrt{z_{\omega+n}/z_\omega}\,\theta_\omega$. The parameters z_ω and $z_{\omega+n}$ are specific to the fishing schemes ω and $\omega + n$, respectively, and define the closeness of both techniques. From this definition it follows that $\sigma^2_{\theta_{\omega+n}} = (z_{\omega+n}/z_\omega)\sigma^2_{\theta_\omega}$, and the ratio $z_{\omega+n}/z_\omega$ can be viewed as measuring the transferability of the sector's information to a different set of tasks. If, for example, $z_{\omega+n} = z_\omega = z$ for any $\omega, n \geq 0$, information is fully transferrable across fishing techniques. If, conversely, $z_{\omega+n} > z_\omega$, the sector's previously acquired knowledge on θ_ω is only partially transferrable to schemes with more tasks. In this later case, the increasing organizational complexity associated with the coordination of larger number of tasks translates into poor guesses on $\theta_{\omega+n}$ and faulty implementation choices d_t.

In a derby fishery where permit holders have historically raced for their share of the catch, fishermen are likely to have had little previous experience with cooperative collective fishing. Consequently, I assume that the larger the number of tasks to coordinate under a particular fishing scheme (i.e. the more cooperative the scheme), the less familiar fishermen are with it (i.e. $z_{\omega+n} > z_{\omega}$ for any $\omega, n \geq 0$).

Recalling that one is the minimum number of tasks in Ω, it is possible to rewrite the definition of $\theta_{\omega+n}$ above as $\theta_{\omega+n} = \sqrt{z_{\omega+n}}\theta_1$, where z_1 has been normalized to one. In this last expression, $z_{\omega+n}$ can be interpreted as the specificity of the fishing technique $\omega + n$.

Using these definitions, expression (2.15) can be rewritten as function of the beliefs on θ_1, that is, as a function of fishermen's information on the least cooperative of the fishing schemes in Ω:

$$\text{(2.16)} \qquad \mathbb{E}\left[\Pi_t^S|\omega_t, S_t\right] = \left[pQ_t^S - \sum_{i\in S_t} c_i T_{it}^*\right] + \left[\left(\sum_{i\in S_t} T_{it}^*\right)\left[\gamma_\omega - \left(z_\omega \sigma_{\theta_{1_t}}^2 + \sigma_\varepsilon^2\right)\right] X_t^* - \mathrm{C}(X_t^*)\right]$$

where $\sigma_{\theta_{1t}}^2$ denotes the variance of beliefs about θ_1 in season *t*. In (2.16), for each ω ∈ Ω, the pair $(\gamma_\omega, z_\omega)$ determines the return of the fishing scheme in reducing unit cost of effort. The actual return of the inputs used on cost reduction depends not only on γ_ω but also on the deviations from optimal implementation. These deviations, in turn, will depend on the sector's accumulated knowledge on θ_1, and the transferability of this knowledge, as measured by z_ω .

Define the following function $\Gamma_\omega\left(\sigma_{\theta_{1_t}}^2\right) = \gamma_\omega - \left(z_\omega \sigma_{\theta_{1t}}^2 + \sigma_\varepsilon^2\right)$, and rewrite equation (2.16) as:

$$\text{(2.17)} \qquad \mathbb{E}\left[\Pi_t^S|\omega_t, S_t\right] = \Pi_{Q_t^S}^* + \left(\sum_{i\in S_t} T_{it}^*\right)\Gamma_\omega X_t^* - \mathrm{C}(X_t^*)$$

By the envelope theorem on (2.17) it is immediate that $\mathbb{E}\left[\Pi_t^S|\omega_t, S_t\right]$ is increasing in Γ_ω.[16] Hence, the choice, in the second stage, of the optimal number of tasks to coordinate in season *t* can be obtained by solving:

$$(2.18) \qquad \max_{\omega\in\Omega} \Gamma_\omega(\sigma^2_{\theta_{1_t}}) = \gamma_\omega - \left(z_\omega \sigma^2_{\theta_{1_t}} + \sigma^2_\varepsilon\right)$$

There is a basic trade-off built into expression (2.18). Upgrading fishing techniques allows the sector to make more efficient use of the public good input, as $\gamma_{\omega+n} > \gamma_\omega$ for any $\omega, n \geq 0$. However, upgrading implies a loss of information as well, as $z_{\omega+n} > z_\omega$, and implies larger expected errors in implementation. Which effect dominates critically depends on the current knowledge on θ_1 and the characteristics of the fishing schemes in $\omega \in \Omega$. To see this, note that, according to (2.18), the sector manager prefers a scheme with $\omega + \mathrm{n}$ tasks over the coordination of ω tasks, as long as $(\gamma_{\omega+n} - \gamma_\omega) \geq (z_{\omega+n} - z_\omega)\sigma^2_{\theta_{1_t}}$.[17]

Figures 2.2 and 2.3 below, illustrate the selection of the optimal set of tasks when $\Omega = \{1, n, n+M\}$ for two possible cases: (i) $\frac{\gamma_{\omega+n}-\sigma_\varepsilon^2}{\gamma_\omega-\sigma_\varepsilon^2} < \frac{z_{\omega+n}}{z_\omega}$ for all *n*, with $\omega, \omega+n \in \Omega$, and (ii) $\frac{\gamma_{\omega+n}-\sigma_\varepsilon^2}{\gamma_\omega-\sigma_\varepsilon^2} \geq \frac{z_{\omega+n}}{z_\omega}$ for all *n*, with $\omega, \omega+n \in \Omega$,

In (i), the loss of information when upgrading to a more cooperative harvesting scheme outweighs the efficiency gains from coordinating more tasks. Thus, in case (i) the fishing

[16] Note that by the time the sector chooses the optimal level of contribution to the public good input $\mathrm{X_t}$, the fishing scheme ω and the current beliefs $\mu_t(\theta_\omega)$ are taken as given, so in equation (2.17) Γ_ω can be viewed as a parameter.
[17] If γ and z had been defined, instead, as continuous variables of ω, the corresponding first order condition for the maximization of $\Gamma(\omega, \sigma^2_{\theta_{1t}})$ with respect to ω, would be $\sigma^2_{\theta_{1t}} z \geq \gamma$, with equality for a positive optimal ω.

techniques in Ω exhibit 'decreasing returns to tasks' due to incomplete information. This is likely to be the case when the schemes in Ω differ substantially from one another, as when incorporating new tasks calls for the reorganization of the collective operation. In other words, limited information in the face of growing coordination difficulty limits the scope of the sector. For example, the transition from a decentralized operation that prevents congestion externalities by rotating access to the fishing grounds, to a scheme where a fleet manager coordinates both the collective search and harvest of the stock, assigning who fishes where and when based on weather conditions and stock distribution (indeed the role of the fleet manager in the case of Chilean fishing companies; Oshe Consultores S.A. 2006), entails a substantial reorganization of the sector's day-to-day activities. In figure 2.2, it is this assumption and the linearity of Γ_ω that guarantee the existence (and uniqueness) of the intersection points labeled E, F, G and H.[18]

Assume first that the sector manager's current beliefs $\mu_t(\theta_1)$ are such that $\sigma^2_{\theta_{1_t}} \in (f, e)$ where $f = (\gamma_n - \gamma_1)/(z_n - 1)$ and $e = (\gamma_1 - \sigma^2_\varepsilon)$. In this case, the optimal choice is to coordinate $\omega_t = 1$ task, as this is the fishing technique that returns the largest expected reduction in unit cost of effort per dollar contributed by sector members. In figure 2.2 this is patent from the fact that, within that range of $\sigma^2_{\theta_1}$, Γ_ω is highest along $\overline{\text{EF}}$. Note that the manager makes his choice entirely aware of the superior efficiency of the alternative schemes (i.e.$\gamma_{n+M} > \gamma_n > \gamma_1$). It is his current lack of information (i.e. $\sigma^2_{\theta_1} > 0$), and the attendant implementation errors ($z_{n+M}\sigma^2_{\theta_{1_t}} > z_n\sigma^2_{\theta_{1_t}} > \sigma^2_{\theta_{1_t}}$) that leads the manager to disregard more cooperative schemes and choose one task instead. In other words, fishing

[18] Adding fishing schemes to Ω would increase the number of intersection points (i.e. such as F and G) in figure 2.2, but it would not change the analysis. In the limit, as Ω becomes an interval in the positive real numbers, the path equivalent to $\overline{\text{EFGH}}$ would become smooth.

schemes involving larger number of tasks are more informationally intensive, and that limits their use by the sector. Indeed, in figure 2.2, both Γ_n and Γ_{n+M} are actually negative for $\sigma^2_{\theta_{1_t}} \in (l, e)$, where $l = (\gamma_n - \sigma^2_\varepsilon)/z_n$.

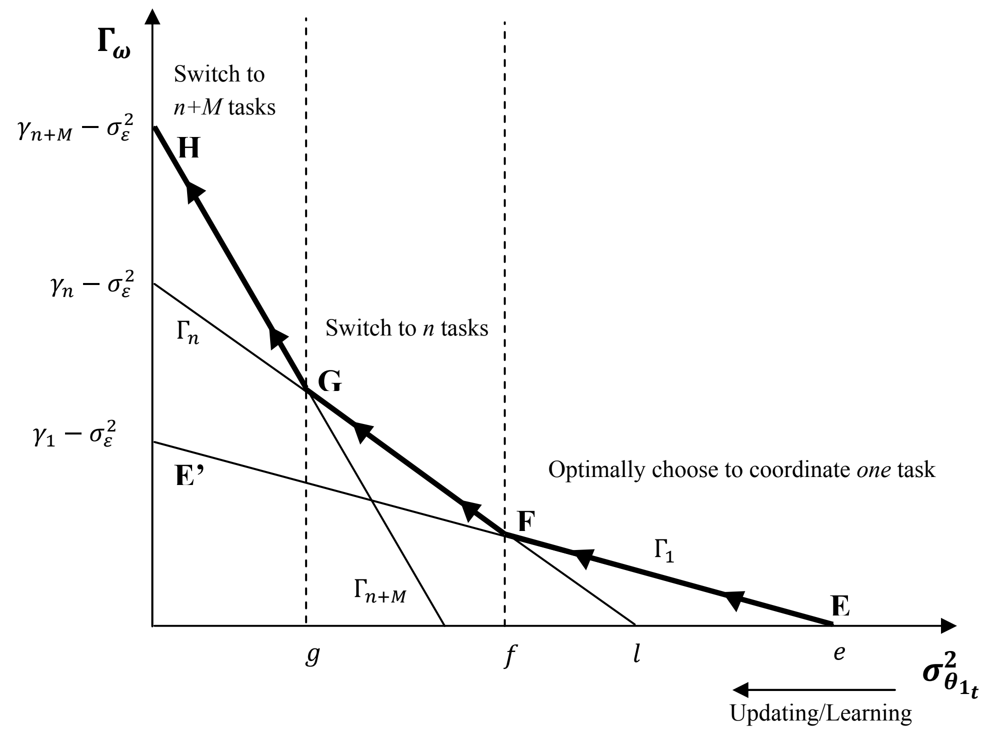


Figure 2.2: Task-choice path as a function of accumulated knowledge

While σ^2_ε is constant in the model, beliefs are dynamic and defined each season by (2.5). In (2.5), beliefs' precision increases gradually and the variance converges to zero as sector members observe new signals. If in season t the sector is coordinating *one* task, then there are three possibilities for the operation the following season: (1) the updated variance $\sigma^2_{\theta_{1_{t+1}}} = (\sigma^2_\varepsilon \sigma^2_{\theta_{1_t}})/(\sigma^2_\varepsilon + \sigma^2_{\theta_{1_t}})$ is such that $\sigma^2_{\theta_{1_{t+1}}} > f$, and there is no upgrading (i.e. the sector continues to coordinate *one* task in season t+*1*); (2) $g < \sigma^2_{\theta_{1_{t+1}}} < f$, where

$g = (\gamma_{n+M} - \gamma_n)/(z_{n+M} - z_n)$, and the manager's optimal choice in season *t+1* is to coordinate *n* tasks (i.e. a move along $\overline{\text{FG}}$ in figure 2.2); or (3) $\sigma^2_{\theta_{1_{t+1}}} < g$, and the sector coordinates *n+M* tasks (i.e. a move along $\overline{\text{GH}}$). Once *n+M* tasks have been selected, no further upgrading is possible and the sector manager job's reduces to perfecting the implementation of those *n+M* tasks as he acquires additional information each period. In the long-run, the uncertainty on θ_1 is fully resolved and the return of the input used in reducing the cost of effort is maximized and given by $\gamma_{n+M} - \sigma^2_\varepsilon$ (i.e. point H in figure 2.2).

In the absence of decreasing return to tasks (i.e. case (ii)) there is no trade off –regardless of beliefs– involved in the choice of a larger number of tasks to coordinate. This situation is illustrated in figure 2.3. Incomplete information remains costly (i.e. $z_{n+M} > z_1 = 1$), but the loss of knowledge upon upgrading is outweighed by the efficiency gains from coordinating a larger number of tasks (i.e. $\gamma_{n+M} - \gamma_1$). Contrary to case (i), this is likely to happen when the schemes in Ω are similar, as when upgrading simply adds tasks to the existing operation, without reorganization. If, for example, the sector manager already coordinates information on targeted stock locations, the extension of the scheme to sharing and coordinating data on bycatch should be fairly straightforward. Under a TAC management system that assigns quotas to all the species caught (targeted and non-targeted) and non-selective fishing gear, the identification of areas where high bycatch is likely to occur may have an important impact on profitability.[19] Graphically this means that the functions Γ_ω do not intersect in the first quadrant as before. Under these

[19] Both the Pacific Whiting Conservation Cooperative and the Alaskan Pollock Conservation Cooperative report catch and bycatch data electronically to Sea State, a private firm specializing in fisheries data collection and analysis. Sea State assembles the data and reports back to coop vessels on a real-time basis, advising vessel captains to avoid areas in which high bycatch is likely to occur.

circumstances, the sector manager always prefers the choice of $n+M$ tasks over the alternatives of n and *one* tasks (move along $\overline{\text{EH}}$ in figure 2.3).

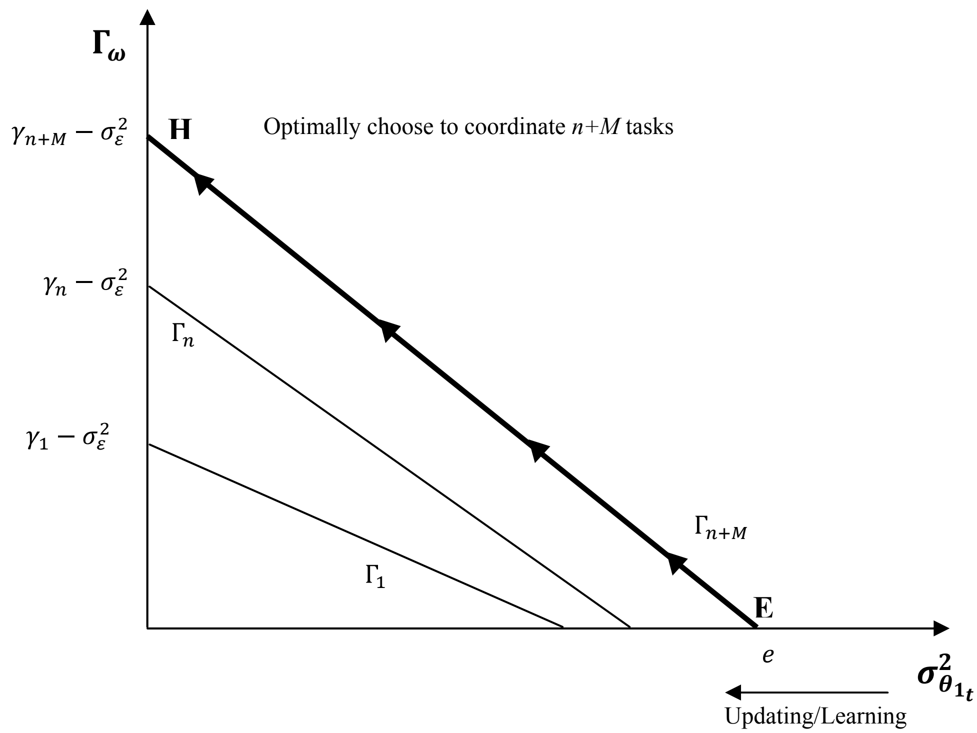


Figure 2.3: Task-choice path as a function of accumulated knowledge

(case of no upgrading)

Note that the two cases in (i) and (ii), illustrated respectively in figures 2.2 and 2.3, have been presented separately only for exposition purposes. However, it is likely that in the same set Ω, some of the harvesting schemes exhibit property (i) (i.e. they differ substantially, and hence the transferability of information among them is limited) while others are characterized by (ii) (i.e. they are very much alike).

Finally, neither in figure 2.2 nor in figure 2.3 is cooperation in the sector guaranteed. To see this, note that point *e*, defined in the general case by

$e = \max_{\omega \in \Omega} (\gamma_\omega - \sigma_\varepsilon^2)/z_\omega$, characterizes a threshold for the initial prior's variance, beyond which none of the schemes $\omega \in \Omega$ generates positive returns in the reduction of cost of effort. Indeed, for priors such that $\sigma^2_{\theta_{1(t=0)}} > e$, the benefits from cooperation are outweighed by the expected losses associated with implementation errors. Therefore, if initial beliefs are characterized by a low precision prior, a myopic manager maximizes expected (current) profits by consolidating the fleet and letting active members fish independently from one another (i.e. by selecting $\omega_t = 0$). This, however, is an undesirable outcome from a welfare standpoint, as it entails a suboptimal long-run equilibrium for the fishery. By selecting $\omega_t = 0$, the sector forsakes valuable signals each season, renounces to learning by doing, and effectively limits its choice set each season to the mere consolidation of the fleet.

The following proposition formalizes the previous discussion.

<u>Proposition 1</u>:

(i) *The sector manager chooses to coordinate a positive number of tasks $\omega \in \Omega$ if and only if his initial beliefs are such that $\sigma^2_{\theta_{1(t=0)}} \in [0, max_{\omega \in \Omega} (\gamma_\omega - \sigma_\varepsilon^2)/z_\omega]$, where θ_1 denotes the unknown parameter corresponding to the least cooperative (i.e. coordination of a single task) fishing scheme in Ω.*

(ii) *If the sector chooses to coordinate a positive number of tasks and there exists $\omega \in \Omega$ such that $\frac{\gamma_{\varpi} - \sigma_\varepsilon^2}{\gamma_\omega - \sigma_\varepsilon^2} < \frac{z_{\varpi}}{z_\omega}$, where $\varpi = max\{\omega | \, \omega \in \Omega\}$, then the manager's optimal choice is characterized by the coordination of a progressively larger number of tasks over time. ω^* in the first season is defined by the initial beliefs*

according to the condition $\gamma_{\omega^*} - \gamma_n > (z_{\omega^*} - z_n)\sigma^2_{\theta_{1(t=0)}}$ *for all* $n \in \Omega$, *and endogenous upgrading guarantees that* $\omega^*_{t\to\infty} = \varpi = max\{\omega |\ \omega \in \Omega\}$.

(iii) *If the sector chooses to coordinate a positive number of tasks and* $\frac{\gamma_{\varpi} - \sigma^2_{\varepsilon}}{\gamma_{\omega} - \sigma^2_{\varepsilon}} > \frac{z_{\varpi}}{z_{\omega}}$ *for all* $\omega \in \Omega$, *then the manager's optimal choice is given by the largest number of available tasks* $\varpi = max\{\omega |\ \omega \in \Omega\}$, *regardless of* $\sigma^2_{\theta_{1(t=0)}}$.

The proof of results (i)-(iii) follows immediately from the specification of Bayes' rule in (2.5) and pointwise optimization on (2.18). Indeed, as it was pointed out earlier, it is the learning process as defined by the updating of beliefs that prompts the evolution of the sector's profitability.

Results (i)–(iii) highlight the importance, for sector operations, of fishermen's expectations concerning the possibility of boosting profitability through collective fishing. These expectations, in turn, depend critically on the knowledge permit holders have about how to organize and implement team-fishing. When sector members hold little previous information on how to coordinate the group operation and thus expect to make costly mistakes in implementation, they may choose to disregard any coordination of tasks (result (i)). As mentioned before, pair-trawling, as used in Scandinavia and Southern Europe, is an example of a cooperative harvesting technique whose use is limited by the need for finely-tuned coordination between vessels (Gabriel et al. 2005). Pair trawling may increase the profitability of the cooperating boats and allow small-scale fishermen to compete with larger trawlers. However, this fishing technique requires that vessels match their actions and maneuvers closely (i.e. so as to keep a constant distance between the vessels during towing, and then come adequately close for hauling the catch or for shooting the net) and that skippers coordinate their efforts continuously, acting as a single unit. This coordination is challenging for captains, especially at night or during bad weather conditions, and mistakes resulting in loss or damaged gear can be expensive (Gabriel et al 2005, National Research Council 1988). Proposition 1.(i) states that fishermen will adopt pair-trawling if and only if they expect this fishing scheme to be more profitable than individual trawling. Their beliefs in the possibilities of coordination will be critical in this assessment.

Alternatively, sector members may decide to start with a simple fishing operation, (i.e. one that calls for the coordination of a few tasks) and only gradually expand the scope of their cooperation as the group builds up experience with team harvesting. Result (ii) shows that this is indeed the optimal strategy when permit holders have had little previous experience with collective fishing and the harvesting schemes become progressively difficult to implement as more tasks are added (i.e. there exists $\omega \in \Omega$ such that $\frac{\gamma_{\varpi}-\sigma_{\varepsilon}^2}{\gamma_{\omega}-\sigma_{\varepsilon}^2} < \frac{z_{\varpi}}{z_{\omega}}$). Not surprisingly, some of the most sophisticated collective fishing arrangements have evolved in Japan, where fishing cooperatives associated with coastal communities have a tradition of centuries (Uchida 2007). Only in the absence of tradeoffs associated with the adoption of complex schemes, will sectors opt for the coordination of a large number of tasks from the outset (result (iii)).

2.2.3.4. Stage 1: Committing to the Sector

Using the results of stages 2 and 3, the maximized expected profit for the sector in season *t,* conditional on its composition S_t, can be written as:

$$(2.19) \qquad \mathbb{E}\left[\Pi_t^S | S_t\right] = \Pi^*_{Q_t^S} + \left(\sum_{i \in S_t} T^*_{it}\right) \Gamma_{\omega^*} X_t^* - \mathrm{C}(X_t^*)$$

where T^*_{it}, X^*_t and ω^*_t are defined by (2.12), (2.14) and (2.18), respectively. Expression (2.19) is weakly increasing each season, because learning over time translates into progressively smaller errors in the implementation of tasks[20]. The actual path of sector profits, however, will depend on the draws of ε_t. The expected profit for sector member *j* in season *t* can be written as:

$$(2.20) \qquad \mathbb{E}\left[\pi_{jt} | S_t\right] = \mathscr{s}_j \Pi^*_{Q_t^S} + \mathscr{s}_j \left[\left(\sum_{i \in S_t} T^*_{it}\right) \Gamma_{\omega^*} X_t^* - C(X_t^*)\right]$$

where $\mathscr{s}_j$ is member *j*'s fraction of sector profits under sharing rule $\mathcal{S}$. Note that, everything else equal, identical shares $\mathscr{s} = 1/\mathrm{N_t}$ will tend to be favored by low skilled sector members (i.e.$j \in S_t |\, k_j < \left(\sum_{i \in S_t} k_i\right)/\mathrm{N_t}$). Different sharing rules, however, will typically result in equilibria with different sector membership's profiles.

According to proposition 1, there are two possible cases to consider in stage 1.

The Case of No Coordination ($\boldsymbol{\omega_t^* = 0}$)

I first analyze the case where $\sigma^2_{\theta_{1(t=0)}} > \max_{\omega \in \Omega} (\gamma_\omega - \sigma^2_\varepsilon)/z_\omega$. By proposition 1-(i), the optimal choice of tasks is given by $\omega^*_t = 0$, for all *t*. Thus, under the two profit-sharing rules considered in this chapter, equation (2.20) can be rewritten simply as $\mathbb{E}\left[\pi_{jt} | S_t\right] =$

[20] For expression (2.19) to weakly increase each period, theTAC_t must either remain at the same level or increase each season, but not decrease.

$\mathscr{s}_j \Pi^*_{Q_t^S}$, where $\mathscr{s}_j$ is defined either as $1/\mathrm{N_t}$ or as $k_j/\sum_{i \in S_t} k_i$. Using the definition of $\Pi^*_{Q_t^S}$ and $\mathscr{s}_j = k_j/\sum_{i \in S_t} k_i$ write:

$$(2.21) \qquad \mathscr{s}_j \Pi^*_{Q_t^S} = p\left(\frac{k_j}{K}\right)\mathrm{TAC}_t - \left(\frac{k_j}{\sum_{i \in S_t} k_i}\right)\sum_{i \in S_t} c_i T^*_{it}$$

By comparing (2.21) with the profit fisherman j can make as an independent in the common pool, $\pi^*_{jt} = \left(pk_j - \frac{c_j}{\phi(B_t)}\right)\left(\frac{\mathrm{TAC}_t}{K}\right)$, it is clear that in both cases revenues coincide with the value of his PSC_j. Thus, it is the comparison of the costs under the two alternatives that finally determines whether fishermen join the sector.

When evaluating the convenience of committing to the sector, fisherman N (i.e. the most skilled permit holder in the fishery) is aware of the fact that, regardless of the skills of other members in S_t, it is optimal for the sector manager to allocate him a positive fishing time. Thus, he anticipates that: either he is able to catch the entire sector quota by himself (i.e. his is the only active vessel in the sector fleet), or he catches the sector quota together with other members. If he catches the entire sector quota, his profit in (2.21) becomes:

$$(2.22) \qquad \mathscr{s}_N \Pi^*_{Q_t^S} = p\left(\frac{k_N}{K}\right)\mathrm{TAC}_t - \left(\frac{k_N}{\sum_{i \in S_t} k_i}\right)\left[\frac{c_N}{k_N}\left(\frac{\sum_{i \in S_t} k_i}{K}\right)\frac{\mathrm{TAC}_t}{\phi(B_t)}\right]$$

which reduces to:

$$(2.23) \qquad \mathscr{s}_N \Pi^*_{Q_t^S} = p\left(\frac{k_N}{K}\right)\mathrm{TAC}_t - \left(\frac{c_N}{\phi(B_t)K}\right)\mathrm{TAC}_t$$

Expression (2.23) coincides with the profit he would make in the common pool, and thus fisherman N has no incentives to join the sector if he expects to be the only active member in the fleet. The other possibility, namely that he catches the sector quota together with other members, is however, unambiguously inferior for fisherman N. To see this, recall that for an individual fisherman the cost of a catch q is proportional to his c/k ratio (i.e. for fisherman i it is equal to $(q/\phi(B_t))\,(c_i/k_i)$). Thus, the assignment of positive fishing times to less skilled members than N, necessarily increases the total cost of effort above the level in (2.23), as this cost becomes a weighted average of c/k that are higher than c_N/k_N. This makes it suboptimal for N to join the sector.

So far I have shown that the most skilled fishermen will always stay in the common pool as long as it is optimal for the sector not to coordinate any tasks, $\omega_t^* = 0$. The equilibrium for the entire fishery can now be derived as follows: foreseeing N's dominant strategy, the next most skilled fishermen, harvester N-1, faces an identical problem as N's. Hence, with fisherman N in the common pool, the best response for fisherman N-1 is always to stay out of the sector. As this reasoning unravels, it becomes obvious that, with the exception of the least skilled permit holder in the fishery (i.e. fisherman 1), every agent's best reply is to remain independent. Therefore, when fishermen anticipate $\omega_t^* = 0$, the sector is effectively prevented from forming.

The same reasoning is trivially extended to the case of identical shares (i.e. $s_j = s = 1/\mathrm{N_t}$) and therefore I omit it here.

I formalize the previous discussion in the following proposition.

Proposition 2:

If fishermen's initial beliefs are characterized by $\sigma^2_{\theta_{1(t=0)}} > max_{\omega \in \Omega} \, (\gamma_\omega - \sigma^2_\varepsilon)/z_\omega$*, where* θ_1 *denotes the unknown parameter corresponding to the least cooperative (i.e. coordination of a single task) fishing scheme in* Ω*, and the sharing rule* $\mathscr{s}_j$ *is defined by either* $\mathscr{s}_j = \mathscr{s} = 1/N_t$ *or* $\mathscr{s}_j = k_j / \sum_{i \in S_t} k_i$*, then every permit holder in the fishery remains in the common pool and the sector does not form.*

If indeed "almost miraculously, fishers who move on from ITQs to a self-regulatory-regime are likely to succeed" (Scott 2000, p.116), one would expect to see the spontaneous emergence of cooperation among catch-share holders to be the norm in commercial fisheries with defined property rights. However, it is infrequent today to find quota holders pooling their shares of the TAC and fishing cooperatively, despite the potential efficiency gains associated with this strategy (Townsend et al., 2008). What is the reason for this apparent anomaly? Proposition 2 states that it suffices for fishermen to be unfamiliar enough with cooperative collective harvesting for them to (optimally) choose independent fishing. This is a relevant result as it helps to explain why fishermen fail to cooperate even when nobody is expected to cheat on the group's agreed upon rules. Note also that this conclusion is obtained in a fishery in which harvesters' skills are common knowledge, and thus it differs from adverse selection arguments that rely on asymmetric information on permit holders' types. It is not incomplete information on individual fishing skills that drives the result, but the lack of perfect knowledge on how to profitably organize and implement group fishing.

The Case of Coordination ($\boldsymbol{\omega_t^*} > 0$)

I transcribe equation (2.19) here:

$$\text{(2.24)} \qquad \mathbb{E}\left[\Pi_t^S | S_t\right] = \Pi_{Q_t^S}^* + \left(\sum_{i \in S_t} T_{it}^*\right) \Gamma_{\omega^*} X_t^* - \mathrm{C}(X_t^*)$$

Using the definition of $\Pi_{Q_t^S}^*$ and $\mathcal{s}_j$ proportional to PSC, individual *j*'s profit from joining the sector is:

$$\text{(2.25)} \qquad \mathbb{E}\left[\pi_{jt} | S_t\right] = \left(\frac{k_j}{\sum_{i \in S_t} k_i}\right) \left[p Q_t^S - \sum_{i \in S_t} c_i T_{it}^*\right] + \left(\frac{k_j}{\sum_{i \in S_t} k_i}\right) \left[\left(\sum_{i \in S_t} T_{it}^*\right) \Gamma_{\omega^*} X_t^* - \mathrm{C}(X_t^*)\right]$$

The second term on the right hand side of (2.25) is simply the share of the net benefits from coordination that accrues to each member. This term is always nonnegative and adds to the profits obtained from harvesting the sector quota with a consolidated fleet.

First note that, for fisherman 1, it is a dominant strategy to join the sector. Being the least skill harvester, he is always better off joining other fishermen (i.e. even if $\omega_t^* = 0$). Fisherman 2 knows this fact.[21] Thus, if the initial beliefs lead him to expect $\omega_t^* > 0$, he will join the sector only if: (a) he expects to be the most skilled fisherman to join, but even in this case coordination makes sector membership more profitable than independent fishing (i.e. $\mathbb{E}[\pi_{2t} | S_t = \{1,2\}] > \pi_{2t}^*$), or (b) if, upon him joining, he expects x additional fishermen to become members (i.e. it is a best response for the remaining of the first $x + 2$ harvesters to join in *t*, and for the rest to stay independent) and $\mathbb{E}[\pi_{2t} | S_t =$

[21] I assume, as it is customary, that the equilibrium strategies are common knowledge.

$\{1,2,3,\ldots,x+2\}] > \pi^*_{2t}$. Fishermen $i > 2$ reason in a similar manner. Recalling that the profits fishermen can make in the common pool (equation (2.10)) are increasing in skill k_i, the previous reasoning results in the successive joining of higher skilled harvesters. If m denotes the marginal independent, the equilibrium of the sector-formation game each season can be written as the following partition of the set of fishermen between the sector and the common pool: $\mathrm{S}_t = \{i|\, k_i < k_m\}$ and $\mathrm{CP}_t = \{i|\, k_i \geq k_m\}$ for $i = 1,\ldots,N$. To see that this is indeed the case, notice from (2.10) and (2.25) that it is never a best response for a harvester of skill k_i to remain in the common pool if the equilibrium strategy of any higher skill fisherman is to join the sector.

Since sector members' expected profit, as given by (2.25), is weakly increasing due to learning, it is never optimal for a member to abandon the sector. Furthermore, as the posterior variance of θ_1 decreases each period, additional fishermen are expected to be attracted to the group in the 'continuation games'. The specific dynamics for the sector's expected profits, however, will depend on whether it is optimal for the manager to gradually upgrade techniques or to select the largest number of tasks immediately (see section 3.3.3.). Since the learning process is bounded ($\lim_{t\to\infty} \sigma^2_{\theta_{1_t}} = 0$), the sector's size will stabilize in the long run, after a steady increase in membership in previous seasons.

Identical arguments can be applied to derive the equilibrium of the fishery each season when $s_j = s = 1/\mathrm{N_t}$). With identical shares, the sector will tend to be smaller than under sharing based on quota contributions, and the average skill level lower. The reason, as it was pointed out before, is that, everything else equal, identical shares are preferred by low skilled fishermen (i.e.$j \in S_t|\, k_j < \left(\sum_{i\in S_t} k_i\right)/\mathrm{N_t}$).

I formalize the previous discussion in the following proposition.

Proposition 3:

If fishermen's initial beliefs are characterized by $\sigma^2_{\theta_{1(t=0)}} \in [0, max_{\omega\in\Omega}\,(\gamma_\omega - \sigma^2_\varepsilon)/z_\omega]$, *where* θ_1 *denotes the unknown parameter corresponding to the least cooperative (i.e. coordination of a single task) fishing scheme in* Ω, *and the sharing rule* $\mathcal{s}_j$ *is defined by either* $\mathcal{s}_j = \mathcal{s} = 1/N_t$ *or* $\mathcal{s}_j = k_j/\sum_{i\in S_t} k_i$, *then the fishery's equilibrium each season is given by the partition:* $S_t = \{i|\, k_i < k_m\}$ *and* $CP_t = \{i|\, k_i \geq k_m\}$, *where the marginal independent m is uniquely defined by the conditions* $\mathbb{E}\left[\pi_{(m-1)t}|S_t = \{1,2,3,\ldots,m-1\}\right] > \pi^*_{(m-1)t}$ *and* $\mathbb{E}[\pi_{mt}|S_t = \{1,2,3,\ldots,m\}] \leq \pi^*_{mt}$.

For the sharing rule $\mathcal{s}_j = k_j/\sum_{i\in S_t} k_i$, the conditions defining the marginal independent *m* can be rewritten as:

$$(2.26)\qquad \left(\frac{k_{m-1}}{\sum_{i=1}^{m-1} k_i}\right)\left[\left(\sum_{i=1}^{m-1} T^*_{it}\right)\Gamma_{\omega^*}X^*_t - \mathrm{C}(X^*_t)\right] > \left(\frac{k_{m-1}}{\sum_{i=1}^{m-1} k_i}\right)\sum_{i=1}^{m-1} c_i T^*_{it} - \frac{c_{m-1}}{\phi(B_t)}\left(\frac{\mathrm{TAC}_t}{K}\right)$$

and

$$(2.27)\qquad \left(\frac{k_m}{\sum_{i=1}^{m} k_i}\right)\left[\left(\sum_{i=1}^{m} T^*_{it}\right)\Gamma_{\omega^*}X^*_t - \mathrm{C}(X^*_t)\right] < \left(\frac{k_m}{\sum_{i=1}^{m} k_i}\right)\sum_{i=1}^{m} c_i T^*_{it} - \frac{c_m}{\phi(B_t)}\left(\frac{\mathrm{TAC}_t}{K}\right)$$

The left hand side in (2.26) and (2.27) represents the fisherman's share of the net benefits from cooperation within the sector, when its members coordinate ω^* tasks. The specific composition of the sector defines the optimal allocation of fishing times T^*_{it} among harvesters.

Under a sharing rule proportional to quota contribution, each sector member receives as revenue the value of his quota, which coincides with the revenue he would earn as an independent in the common pool. Fishermen share the cost of harvesting the sector's quota as well. As shown in the previous section, for the most skilled fisherman in the sector, this cost share is larger than the cost of catching his quota as an independent. The right hand side in (2.26) represents fisherman *m-1*'s expected increase in the cost of catching his quota upon joining the sector. The same holds for fisherman m in (2.27).

Thus, m is the first permit holder in the fishery for whom the net benefits from coordination are insufficient to compensate for the increase he expects in the cost of earning his quota as a sector member.

The proof of proposition 3 follows immediately from the equilibrium strategies identified above for fisherman 1 and fishermen $j \geq 2$, and the definitions of π_{jt}^* and $\mathbb{E}[\pi_{jt}|S_t]$ in (2.10) and (2.20).

Proposition 3 indicates that, in the scenario that sectors do form, the least skilled permit holders in the fishery are expected to join first. These fishermen benefit the most from cooperation, as they are unlikely to fish for the sector (i.e. the sector fleet is rationalized) and hence expect to profit from the higher skills of other members. As sectors experiment with collective fishing and extend the scope of their cooperation, their expected profits increase, attracting progressively more skilled fishermen. In the long run equilibrium, only the most skilled permit holders remain in the common pool and fish independently. This result is consistent with, for example, evidence from the Chignik salmon fishery, where the historic catch shares for fishermen who remained independent (highliners) exceeded that of coop joiners (Knapp, 2007, Costello et al., 2009).

2.3 Discussion

The results in the previous section have been derived under the assumption that fishermen behave myopically and make their choices to optimize current season profits. The long-run equilibrium derived for the fishery under this assumption coincides with the long-term equilibrium supported by farsighted harvesters. Here I discuss the rationale for this result.

One of the requirements of Amendment 16 is that fishermen ratify their decisions regarding sector affiliation on an annual basis. It is precisely this built-in flexibility to adjust their decisions on sector membership and sector's fishing rules that makes permit holders' choices reversible. Indeed, once sectors have formed, and unless sector members themselves decide to incorporate restrictions to new membership in the bylaws, this periodic opportunity to revise the choices made in the previous season makes it optimal for farsighted harvesters to behave as myopic agents. To see this, recall that in the model learning in the sector only depends on the repeated experimentation with collective fishing (i.e. on the decision to coordinate a positive number of tasks) but not on the specific member composition of the sector. Thus, a harvester facing the decision to join the group, knows that by staying in the common pool for another period he does not compromise the learning (and hence, the optimal choice of tasks) within the sector. This means that, by choosing to stay out of the sector for one more season, the permit holder is not limiting his choice set in the future, as the next season he will face the same decision problem as this period. In the meantime, however, he will have gained the difference between this period's profits in the common pool and what he would have earned as a member of the sector. In other words, for this fisherman there is no tradeoff in the decision to postpone joining the sector by one period. In these conditions, the optimization over the entire horizon effectively reduces to an infinite series of independent, one-season optimization problems, and the optimal solution reduces to choosing the most profitable option each period.

There is, however, an important caveat to the above argument. If fishermen start with a low precision prior, $\sigma^2_{\theta_{1(t=0)}} > \max_{\omega\in\Omega}(\gamma_\omega - \sigma^2_\varepsilon)/z_\omega$, it is known from proposition 2 that the sector will fail to form. This outcome, in turn, reduces the future choice set of all the permit holders in the fishery. Under these circumstances, it may be optimal for farsighted fishermen to join the sector and invest in learning for one or several seasons, even if this means giving up higher profits in the common pool in the meantime. Future profits resulting from active cooperation within the sector may make this investment worthwhile. Unfortunately, this strategy is not a best response for any permit holder. To see this, assume that farsighted players join the sector in the first period if the infinite stream of payments associated with this strategy is higher than the payoffs from fishing in the common pool. Then, the following deviation increases the payoff for any of them: remain in the common pool and postpone joining the sector until the next period. By doing so, a fisherman earns the difference between his profits in the common pool and those he would have obtained as a sector member in the current season, yet still benefits from the investment in learning undertaken by others. Hence, the formation of the sector is not a Nash equilibrium for low precision priors, regardless of the agents' horizon of optimization.

2.4 Concluding Remarks

That race for fish is wasteful and dangerous is well documented. This harvesting strategy leads to overinvestment in fishing inputs and induces such behavior as fishing in bad weather and delaying needed repairs. Derby fishing also shortens the fishing season, which generates shortages and gluts in the market. The rationale for this dissipation of rent lies in the fact that limited licensing assigns only a right to fish, not a property right to the fish resource. Individual catch-shares, especially ITQs, are frequently hailed as the best-suited management tool to align the economic interests of fishermen with ecological and safety concerns. However, ITQs have shortcomings. They may exacerbate "highgrading", the tendency of fishers to discard smaller fish in hope of catching larger, more valuable ones, they create no incentives for quota holders to coordinate fishing effort or share information, and they are highly contentious in the political arena, especially when it comes to agreeing on the initial allocation of individual quotas. Sector allocations are an attractive alternative to ITQs and it is therefore worth studying the conditions that make their implementation viable.

Sector allocations may contribute to rebuilding depleted stocks and increasing industry profits, thereby improving the quality of life of permit holders as well as the marine ecosystem. However, the transition from independent, competitive fishing to collective harvesting may be challenging for fishermen, especially if they have had little earlier experience with cooperative initiatives.

The success of sectors is likely to rest partly on the strength of the relationships among fishermen, including their degree of trust and collaboration. It is reasonable to think that successful sectors will build norms and networks that enable collective action and learning over time. This may represent an opportunity for fishing communities (i.e. port-based, fishing-dependent communities). Indeed, community-based sectors could provide the means for a community and its fishermen to retain or regain access to the fishery and to ensure that the community benefits from this access (Holland 2007). This possibility contrasts with the feared marginalization of fishing communities usually associated with the adoption of an ITQ system (Dolsak and Ostrom 2003).

The analysis in this chapter highlights the relevance of addressing the question of what types of training programs would help accelerate the learning process and boost the adoption of collective arrangements of self-governance. Building capacity among fishermen to organize and administer sectors will likely entail documenting previous experiences to encourage learning from successful case studies, and coaching and guidance on institutional design. The regulator should pay attention to this matter, as it could have serious policy implications in terms of reducing the long-term economic and environmental costs of the transition. It is ultimately in the public interest for the regulator to ensure that sector allocations work.

Chapter 3: Empirical Framework

The main objective of this third chapter is to present the empirical framework that will be used to test some of the implications of the model introduced in chapter 2. Specifically, I focus on the following predictions of the theoretical model: i) previous experience with team harvesting facilitates the formation of cooperative-type business arrangements (i.e. sectors), ii) least-skilled fishermen have incentives to join sectors first, and iii) learning-by-doing increases the returns of cooperation over time within sectors. Using technical efficiency as a proxy for fishing skill (Kirkley et al. 1998, Viswanathan et al. 2002, Hoff and Frost 2005) and utilizing a panel data set from the hook gear fleet in the New England Multispecies Fishery, I estimate a system of equations comprised of stochastic output distance function and a technical inefficiency model (Battesse and Coelli 1992, 1995). The framework allows for the simultaneous characterization of the underlying technology and the determination of the key factors impacting efficiency.

The contribution of this chapter to the applied fisheries economics literature is threefold. First, and unlike most empirical studies of fisheries production frontiers which implicitly assume input-output separability and estimate a weighted aggregate measure of output as function of inputs, this study uses a primal multi-output distance function approach, allowing for the testing of the separability assumption and the derivation of the ability of fishermen to alter their output mix. Second, the analysis is applied to a long panel data, and unlike short-term studies, it explicitly incorporates the variability of stocks biomasses over time into the estimation. Third, the study explicitly accounts for the effect of fishermen's interactions on efficiency in order to identify cooperation among harvesters.

3.1 Previous Literature

The literature on productivity and efficiency in fisheries and cooperation in the commons is extensive and this review is not intended as a comprehensive assessment of the research conducted in these areas. Rather, it reviews articles that deal specifically with three topics that are pertinent to the empirical methodology discussed later in the chapter: i) empirical evidence on the connection between technical efficiency and skipper characteristics, ii) characterization of technical efficiency in multispecies fisheries, and iii) empirical research investigating cooperative behavior in the commons.

Technical Efficiency and Skipper Skills

Kirkley et al. (1998) represented the first attempt in the fisheries economics literature to relate technical efficiency with management (skippers) skill. To this end, the authors used a two-stage approach: first, they estimated a stochastic production function to determine technical efficiency (TE) scores, and subsequently they regressed (using a truncated model) TE scores on variables that proxy for skill level, skipper's years of education and years of experience in the Mid-Atlantic sea scallop fishery. Using trip level data for the years 1987-1990 for the dredge fleet, they found a positive relationship between both skipper's education and experience and vessel performance, as given by technical efficiency. A shortcoming of the study is the use of two stages in the estimation instead of the single-stage approach introduced by Coelli and Battese (1993). This later methodology is preferred, as it avoids the inconsistency of assumptions implied by the uses of two separate steps.[22]

Viswanathan et al. (2002) analyzed the Kedah trawl fishery in Malaysia using season-level (i.e. normal, peak and off season) data for the year 1995. The authors estimated a stochastic production function and an inefficiency model to assess the influence on vessels' technical efficiencies of boat size, skipper's years of experience, ethnicity and similar factors. While vessel size indeed proved to be a determinant of efficiency, the results provided inconclusive support to the hypothesis that the skipper's experience greatly impacts efficiency. A limitation of the methodology used in the paper is the adoption of a single-output specification (a production function in which output was measured as the geometric mean of all species landed, where revenue shares served as weights) for the analysis of a multispecies fishery. This approach imposes restrictions on the technology (such as input-output separability on the transformation function; see Pascoe and Mardle (2003)) that may be at odds with the underlying data generating process.

Hoff and Frost (2003) studied the link between technical efficiencies and skipper characteristics for different gear segments of the Danish commercial fleet. They used monthly data for the year 2002 and the multi-stage approach introduced by Fried et al. (1999) to conclude that, for the three major trawl segments of the Danish fishing fleet,

[22] In the first stage, the production frontier is estimated and the technical efficiency of each unit derived. These are subsequently regressed against the set of variables which are hypothesized to influence the unit's efficiency. There is an inconsistency, however, in this two-stage approach. As noted by Battese and Coelli (1995), the stochastic production frontier is estimated in the first stage under the assumption that the inefficiency effects (error term) are identically distributed, while in the second stage the predicted technical efficiencies are regressed upon a number of unit (i.e. firm, vessel, etc) specific factors, hence suggesting the inefficiency effects are not identically distributed.

exogenous factors beyond the control of the skipper are the major reasons for high inefficiencies, rather than skippers' skill. Standard input-oriented (output-oriented) DEA models assume that inputs (outputs) are discretionary or controllable. The approach in Fried et al. (1999) deals with nondiscretionary or environmental factors in four-stages. The first phase consists of solving a basic DEA model without environmental factors. In a second-stage, regression equations are estimated for each input, where the dependent variable is, in each equation, the total amount of input (radial plus non-radial) slack and the independent variables are environmental. In a third phase, the actual input levels are adjusted by a factor that equals the difference between the maximum predicted slack minus the predicted slack value. In a final stage, these adjusted values are included in a basic DEA model whose results take environmental factors into account. This approach is supposed to effectively deal with non-discretionary variables, but there is little consensus among researchers.[23]

Squires et al. (2003) studied artisanal gillnet fisheries in the east and west coasts of Malaysia to examine which factors were constraining technical efficiency. They used cross-sectional data corresponding to the year 1988 to estimate two separate translog stochastic production frontiers models, one for each of the coasts. To test for the factors that may have been contributing to technical inefficiency, they simultaneously estimated

[23]For details on this approach, see the volume "The Measurement of Productive Efficiency and Productivity Growth" (2008), edited by Fried, Lovell and Schmidt. Note also that the popular two-stage DEA procedure, an alternative approach to handle nondiscretionary factors, has been shown to exhibit substantial bias. In this method DEA is first conducted using only traditional (discretionary) inputs and outputs, and then the first-stage DEA efficiency scores are regressed on the environmental (non-discretionary) inputs of interest. Variants of this approach use tobit models rather than traditional regression models in the second stage to account for the fact that efficiency scores are bounded between 0 and 1. One problem of the two-stage approach relates to the possible correlation between input-output factors used to calculate the efficiency scores and the independent variables used in the second stage model. Another problem is that DEA efficiency scores are dependent on each other, which "violates a basic assumption required by regression analysis: the assumption of independence within sample" (Xue and Harker, quoted in Fried et. al 2008). See also Simar and Wilson (2007) and Barnum and Gleason (2008).

a technical inefficiency model in which, among other independent variables, the captain's years of fishing experience and his family size were included. For the east coast vessels, both explanatory variables were shown to have a significant effect on efficiency, suggesting that additional experience and the extra responsibility associated with a larger number of family-dependents tended to increase vessel's performance.

Tingley et al. (2005) analyzed the effect of vessel and skipper characteristics on the technical efficiency (TE) of different segments (mobile gear, potters and net-liners) of the English Channel fisheries. The authors used two alternative methodologies to study the determinants of TE. First, they estimated a single-output translog stochastic production frontier model with technical efficiency effects, and secondly they calculated TE scores using non-stochastic, linear-programming Data Envelopment Analysis (DEA) and used a tobit-regression of the DEA-derived scores to assess the influence of factors such as formal education and the availability of navigational aid devices. The authors used yearly catch data for the period 1993-1998 and information from a skipper's survey to show that for some of the gear segments, skippers' experience (for potters) and a family history in the fishing industry (for net-liners) had a significant and positive effect on efficiency. These results were found to be consistent across the DEA and stochastic frontier models. Since the authors analyzed a multispecies fishery, a potential limitation of their approach, as the authors themselves acknowledged, was the use of a single-output specification. Furthermore, the use of revenue per vessel as output is problematic, because: i) changes in prices are accounted for as changes in output, and ii) it implies the assumption that output prices do not differ across vessels. In their paper, the authors did not account for changes in stock abundance.

Esmaeili (2006) studied the Iranian fisheries in the Northern Persian Gulf in order to identify the key determinants of technical efficiency. The author used data on vessels operating in 1993 to estimate a stochastic production function and an inefficiency model in which technical inefficiencies depended on both vessel and skipper characteristics. The results of the analysis confirmed that vessel instrumentation (i.e. presence of GPS and a two-way radio) and skipper's level of education and years of experience in the fishery had a significant impact on efficiency. As in the cases of Viswanathan et al. (2002) and Tingley et al. (2005) discussed above, a potential limitation of the approach is the specification of a single output model to analyze a multispecies fishery (Esmaeili used aggregated catch across species as a measure of output).

Multi-output Specifications and Technical Efficiency

Weninger (2001) analyzed changes in productivity in the Mid-Atlantic surf clam and quahog fishery. To this end, the author used data envelopment analysis to characterize the technology (using the directional distance function representation) and study the shifts in the efficient production frontier (EPF) over time (what the author referred to as changes in the bioeconomic productivity of the fishery). His findings confirmed claims that surf clam stock had increased in the 1980-1994 and ocean quahog biomass declined over the period 1991-1994. The author concluded that the clam harvesting technology was flexible and thus input-output substitution possibilities allowed fishermen to adjust production activities in response to regulations imposed by management. Lacking stock biomass information, however, the author is unable to disentangle, in the shifts in the EPF, stock effects from pure productivity changes.

Furthermore, the use of deterministic DEA in the context of a fishery (in which random variation in catch is significant) and the assumption of constant returns of scale for the technology (an assumption rejected at the 1% level in Weninger and Strand (2003)) may limit the scope of the findings.

Fousekis (2002) used trip-level data for the inshore fleet in Greece corresponding to fishing year 2000 to estimate two alternative representations of a multi-output technology: the stochastic output distance function and the stochastic ray production function. A technical inefficiency model was also specified and estimated simultaneously with both the distance function and the ray production function. In this equation, technical efficiencies were hypothesized to depend on characteristics of vessel (gross registered tons and horse power) and captain (age and level of formal education). The empirical results obtained with both specifications were consistent and indicated the same technology structure (exhibiting non-separability of inputs and outputs and increasing returns to scale) and provided similar relative rankings of efficiency scores. Furthermore, both models agreed that the vessel and skipper characteristics considered in the study had significant influence on technical efficiency levels. The author used seasonal dummies to control for the effects of changes in resource abundance over the year, and dealt with zero-harvest trips by replacing the zeros with very small positive numbers.

Weninger and Waters (2003) studied the northern Gulf of Mexico reef fish fishery. Specifically, they used daily data for the year 1993 to estimate the economic benefits of replacing controlled access management (which includes vessel entry restrictions, per-trip limits and periodic fishery closures) with tradable quotas. Their methodology was to characterize the input-output feasible sets under both management regimes using directional distance functions. The authors concluded that the adoption of tradable quotas would create significant benefits for the fishery due to the elimination of market gluts caused by seasonal closures and cost savings associated with the removal of per-trip catch limits.

Orea et al. (2005) used daily data to estimate alternative primal stochastic models for measuring technical efficiency for the Northern Spain hake fishery in 1999. Fishermen in this industry primarily target hake, but they catch a variety of other species as well. The authors then compared the resulting efficiency scores from the different specifications, that is, from the aggregate-output production function, the distance function, and the multi-output production functions (for different base outputs). They found that production patterns seemed better represented by multi-output models than by an aggregate output production function (i.e. substitutability between outputs was significant), but that relative efficiency estimates were not substantially affected by model specification. Furthermore, they concluded that the distance function is the most appropriate representation of the technology, since it recognizes output substitution, and generates efficiency scores invariant to the output selected as the dependent variable.

Felthoven et al. (2005) studied capacity utilization and technical efficiency among catcher-processor vessels operating in the Bering Sea and Aleutian Islands flatfish fishery. They estimated an output distance function using weekly data for the years 1994-2004 and calculated measures of fleet capacity and vessel-specific capacity utilization. In their analysis, the authors allowed for heterogeneous production technology (for the different fleet segments), and explicitly used distributional information on technical efficiency rankings (i.e. their measure of fleet capacity incorporates the probability that a given vessel is the most efficient one in the fleet). In their final specification of the distance function, the authors decided not to incorporate information on stocks biomass due to problems of collinearity, but included the month in which each fishing trip took place in an attempt to capture seasonal variation in the migration of flatfish.

Pascoe et al. (2007) estimated a stochastic output distance function for two North Sea fleet segments (the UK beam trawl and the English otter trawl segments) to derive output elasticities of substitution and thus assess the ability of vessels to target different species and change harvest composition. Using monthly data for the period 1990-2000, the authors not only showed that there exists the potential for limited substitution between species, but also that the ability to influence catch composition is not homogeneous across the fleet and is linked to the size of the vessel. Larger vessels can access a wider range of fishing grounds and can thus take advantage of differences in local relative abundance of species. In contrast, smaller boats are less able to modify the composition of their catch through their fishing strategy. Interestingly, the authors departed from earlier research and explicitly accounted for the stock biomass of each of the four species considered. They did so by using partial fishing mortality (i.e. catch over stock) instead of catch in their specification of the distance function.

Empirical Research on Cooperation in the Commons

A substantial experimental literature has focused on the conditions under which cooperative behavior is likely to occur among actors providing public goods or extracting common-pool resources (see for example, Mason and Phillips (1997), Ostrom (1999), Walker et al. (2000), Fischbacher et al. (2001)). A different line of research has empirically investigated the determinants of cooperation in the field when cooperation is known to be in place. See for example, Marshall (2004) that studied the propensity to cooperate among Australian farmers in the Murray-Darling Basin, or Fujiie et al. (2005), which used ordinary least squares to identify key factors for the success of collective action among irrigators' associations in the Philippines. Very few papers, however, have attempted to empirically test whether cooperation in the commons exists in the first place.

Haynie et al. (2009) empirically examined the cooperative behavior of commercial fishermen in the Bering Sea. Concretely, they studied the level of provision of a public good, bycatch avoidance, in the Alaskan flatfish fishery. This fishery operates under a two-tiered total allowable catch (TAC) system, in which TACs are defined over target and bycatch species (i.e. pacific halibut, a species of zero value to trawl fishermen due to regulations that require it to be discarded). Once either TAC is reached all fishing ceases, effectively closing the fishery. Such closures often occur with significant remaining quota for the target species. Thus, avoiding bycatch benefits everybody via an extended fishing season. Avoidance, however, comes with a large individual opportunity cost since the marketable species, yellowtail sole and other flatfish, share similar habitat with the bycatch species, making them complements of production. Part of the catcher processor fleet contracted with Sea State Inc. in 1995 to begin analyzing government observer-collected bycatch information. Sea State provides spatial advisories to the fleet, which provide non-mandatory recommendations of areas to avoid in order to reduce bycatch. The authors combined catch and bycatch data with information from Sea State to estimate a mixed logit model of spatial fishing behavior. In their empirical model, the probability of visiting a site was specified as a function of, among other variables, a bycatch information signal (i.e. information received from Sea State) and the amount of bycatch remaining in the fishery (i.e. before reaching the bycatch TAC) at each point in time. The authors found that fishermen predominantly avoided regions with high bycatch rates early in the season, but that, as the season progressed, they reduced their degree of aversion. This suggested that fishermen were utilizing the bycatch information to enhance their performance later in the season, presumably because the target species and halibut are complements in production.

Abbott and Wilen (2010) revisited the Sea State program studied by Haynie et al. (2009). The authors used the vessels that initially elected not to participate in the Sea State program as a control group to provide the counterfactual of what bycatch levels Sea State members would have shown in absence of their participation in the program. To this end, they estimated both a reduced form model (using difference-in-differences estimation) and a structural model of bycatch avoidance (a variant of a random utility model of fishing location choice), which allowed them to use the spatial choices made by skippers to uncover their willingness to pay for bycatch avoidance. The findings of both approaches proved consistent and indicated that Sea State had no discernible impact on bycatch rates in the first three years of its inception, and that from 1998 onwards, bycatch rates were higher on average for the initial Sea State participants than for those who opted out. The authors attributed the tendency observed after 1998 to the deterioration in the incentives for bycatch avoidance among Sea State members. A substantial portion of the halibut bycatch TAC is designated for the targeting of yellowfin sole, meaning that vessels must retain and process large quantities of yellow sole to utilize this bycatch quota. Yellowfin sole prices crash after 1998, however, substantially reducing the implicit value of holding halibut quota. The authors speculate that non-joiners may have had long term contracts for yellowfin sole, effectively isolating them from this price decrease. This fact would help to explain the different patterns of bycatch avoidance among the fleets after 1998.

Although not dealing with common pool resources, the study closest in spirit to the empirical approach adopted in this dissertation is Battese and Tveteras (2006). In their paper the authors studied the salmon aquaculture industry in Norway and found evidence of positive effects on technical efficiency associated with agglomeration externalities such as knowledge spillovers and shared industry infrastructure. Using panel data they estimated a stochastic frontier production function and a technical inefficiency model, in which inefficiencies were specified as functions of, among other variables, salmon industry size (measured by industry employment) and salmon farm density (farms per km^2) in the region, and their corresponding square terms (i.e. to capture second-order effects). Their results showed a significant (but decreasing) positive effect of industry size and farm density on efficiency.

As the articles is this review make clear: i) there is empirical support for the "skipper effect" hypothesis, namely, that operators' skills have a tangible impact on fishing performance, ii) harvesting in multispecies fisheries is more properly characterized by a multi-output specification of the technology, but controlling for stock biomass variation remains challenging; and iii) there has been little empirical research to date testing the very existence of cooperation among resource extractors in the commons.

The empirical approach developed in the remainder of this chapter uses panel data to identify early traces of cooperation among the vessels that later joined the Georges Bank Cod Hook sector. The model is specified as a system of equations comprised of a stochastic distance function in which stocks abundances are explicitly accounted for, and an inefficiency equation, in which technical inefficiency depends on vessel characteristics, congestion externalities and the degree of cooperation among vessels. Furthermore, drawing from the literature linking skipper skills and efficiency, differences (across sector joiners and non-joiners) in the effect of unobserved characteristics on technical efficiency are interpreted as differences in fishing skill.

3.2 Multi-Output Distance Functions and Technical Efficiency

Output distance functions

When multiple inputs are used to produce multiple outputs, Shephard's (1970) distance functions provide a characterization of the structure of production technology. Consider a process that transforms an input vector $\mathbf{x}^t = (x_1^t, \dots, x_K^t) \in R_+^K$ into an output vector $\mathbf{y}^t = (y_1^t, \dots, y_M^t) \in R_+^M$ in every time period t $(t = 1, \dots, T)$. In the case of a commercial fishery, for example, inputs such as crew and bait, among others, are used to catch different species (i.e. outputs). Let $P(\mathbf{x}^t)$ represent the set of all output vectors that are feasible for each input vector $\mathbf{x}^t \in R_+^K$ of period t, i.e. the producible output set. The output distance function $D_o(\mathbf{x}^t, \mathbf{y}^t)$ is defined as the largest proportional increase in the observed output vector $\mathbf{y}^{\mathrm{t}}$ such that the expanded vector is still an element of the original output set:

$$(3.1) \qquad D_o(\boldsymbol{x}^t, \boldsymbol{y}^t) = min\{\theta: (\boldsymbol{y}^t/\theta) \in P(\boldsymbol{x}^t)\}$$

Where

$$(3.2) \qquad P(\boldsymbol{x}^t) = \{\boldsymbol{y}^t \in R_+^M: \boldsymbol{x}^t \; can \; produce \; \boldsymbol{y}^t\}$$

Since the output distance function in (3.1) is defined in terms of the producible output set $P(\boldsymbol{x}^t)$, it inherits its properties. If $P(\boldsymbol{x}^t)$ satisfies the standard axioms P.1.-P.6 listed below, the distance function satisfies the following, equivalent, properties: $D_o(\boldsymbol{x}^t, \boldsymbol{y}^t)$ is nonincreasing in $\mathbf{x}^{\mathrm{t}}$ and nondecreasing, homogenous of degree +1, and convex in $\mathbf{y}^{\mathrm{t}}$. Furthermore, under these assumptions the output set can be written as: $P(\boldsymbol{x}^t) = \{\boldsymbol{y}^t: D_o(\boldsymbol{x}^t, \boldsymbol{y}^t) \leq 1\}$. The output set is customarily assumed to satisfy the following axioms (Kumbhakar and Lovell 2000):

P.1 $P(\mathbf{0}) = \{0\}$

P.2 $P(\boldsymbol{x}^t)$ is bounded for $\boldsymbol{x}^t \in R_+^K$.

P.3 $P(\boldsymbol{x}^t)$ is a closed set.

P.4. $P(\lambda\boldsymbol{x}^t) \supseteq P(\boldsymbol{x}^t)$ for $\lambda \geq 1$ (weak disposability of inputs)

P.5. $\boldsymbol{y}^t \in P(\boldsymbol{x}^t) \Longrightarrow \lambda\boldsymbol{y}^t \in P(\boldsymbol{x}^t)$ for $\lambda \in [0,1]$ (weak disposability of outputs)

P.6 $P(\boldsymbol{x}^t)$ is a convex set for $\boldsymbol{x}^t \in R_+^K$.

Axiom P.1 states that any nonnegative input vector can produce at least zero output and that there is no free lunch. P.2 simply says that finite amounts of inputs can only produce finite amounts of outputs. By axioms P.2 and P.3 $P(\boldsymbol{x}^t)$ is a compact set. Axiom 4, weak disposability of inputs, states that if inputs are proportionally increased, outputs do not decrease. Weak disposability of outputs, axiom 5, states that a proportional reduction of outputs is feasible. P.5 allows for the fact that disposal of some outputs may be costly in terms of opportunity cost of forgone output of other commodities. This is a convenient property for modeling production technologies in commercial fisheries where bycatch is frequently regulated. Suppose, for example, that output 1 represents catch of a targeted species while output 2 is bycatch. Property 5 implies that a b% reduction in bycatch is possible if accompanied by a b% decrease in the catch of the targeted species, holding the input vector constant (Färe and Primont 1995).

Distance Functions and Technical Efficiency

An output oriented measure of technical efficiency $\mathrm{TE_o}$ is defined as:

(3.4) $$TE_o(\boldsymbol{x}^t, \boldsymbol{y}^t) = [max\{\phi : \phi\boldsymbol{y}^t \in P(\boldsymbol{x}^t)\}]^{-1}$$

comparing (3.1) and (3.4), it follows that:

(3.5) $$TE_o(\boldsymbol{x}^t, \boldsymbol{y}^t) = D_o(\boldsymbol{x}^t, \boldsymbol{y}^t)$$

so that $\mathrm{TE_o}(\mathbf{x}^t, \mathbf{y}^t) \leq 1$. This function is illustrated in Figure 3.1 for the simple case of two outputs (i.e. species harvested). In the example both vessels A and B operate on the interior of $\mathrm{P}(\mathbf{x})$, and the measure of their technical efficiency is given by $\mathrm{TE_o}(\mathbf{x}^i, \mathbf{y}^i) = \|\mathbf{y}^i\| / \|\varphi^i \mathbf{y}^i\| = 1/\varphi^i$ for i=A,B. Note that one advantage of this efficiency measure is that $\mathrm{TE_o}(\mathbf{x}^i, \mathbf{y}^i)$ is invariant with respect to the units in which **x** and **y** are measured (Khumbhakar and Lovell 2000, Coelli et al. 2005).

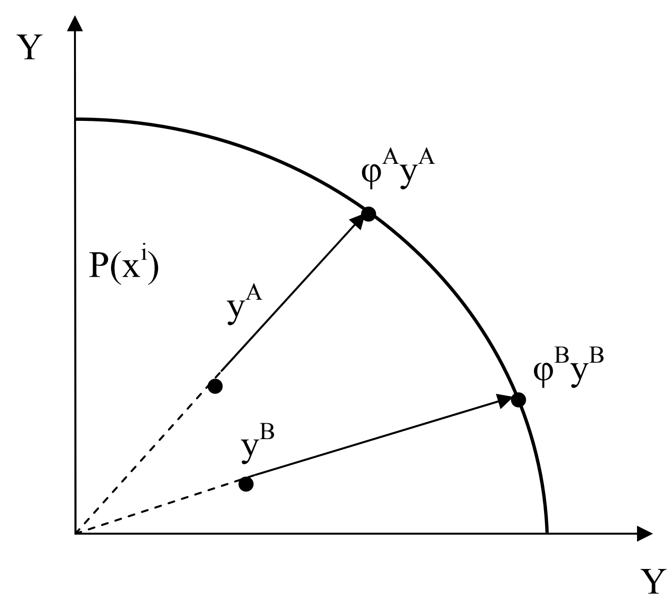


Figure 3.1: An output-oriented measure of technical efficiency (M=2)

3.3 Stochastic Frontiers and the Estimation of Technical Efficiency

In the single-output case, a production frontier model can be written as:

$$(3.6) \qquad y_{it} = f(\boldsymbol{x}_{it}; \boldsymbol{\beta}) TE_{it}$$

where y_{it} is the scalar output of producer *i* in period t, $\mathbf{x}_{it}$ is a vector on inputs used by producer *i* in period t, $f(\boldsymbol{x}_{it}; \boldsymbol{\beta})$ is the production frontier, $\boldsymbol{\beta}$ is a vector of technology parameters to be estimated, and TE_{it} denotes (output-oriented) technical efficiency on producer i in period t. Equation (3.6) can be written as:

$$(3.7) \qquad TE_{it} = \frac{y_{it}}{f(\boldsymbol{x}_{it}; \boldsymbol{\beta})}$$

which defines technical efficiency as the ratio of observed output to maximum feasible output. y_{it} achieves its maximum feasible value of $f(\boldsymbol{x}_{it}; \boldsymbol{\beta})$ if, and only if, $TE_{it} = 1$. Otherwise, $TE_{it} < 1$ measures the shortfall of observed output from maximum feasible output. In equation (3.6) the production frontier $f(\boldsymbol{x}_{it}; \boldsymbol{\beta})$ is deterministic and the entire shortfall of observed output from maximum feasible output is attributable to technical efficiency. To incorporate producer-specific random shocks, equation (3.6) can be rewritten as:

$$(3.8) \qquad y_{it} = f(\boldsymbol{x}_{it}; \boldsymbol{\beta}) exp\{v_{it}\} TE_{it}$$

where $f(\boldsymbol{x}_{it};\boldsymbol{\beta})exp\{v_{it}\}$ is the stochastic production frontier. Thus, the stochastic production frontier comprises a deterministic part $f(\boldsymbol{x}_{it};\boldsymbol{\beta})$ common to all producers and a producer-specific part $\exp\{v_{it}\}$, which captures the effects of random shocks in each producer. Equation (3.8) can be rewritten as:

$$TE_{it} = \frac{y_{it}}{f(\boldsymbol{x}_{it};\boldsymbol{\beta})exp\{v_{it}\}} \tag{3.9}$$

In (3.9) technical efficiency is defined as the ratio of observed output to maximum feasible output in an environment characterized by $exp\{v_{it}\}$. As before, y_{it} achieves its maximum feasible value of $f(\boldsymbol{x}_{it};\boldsymbol{\beta})exp\{v_{it}\}$ if, and only if, $TE_{it} = 1$.

Defining,

$$TE_{it} = exp\{-u_{it}\} \tag{3.10}$$

Equation (3.8) can be rewritten:

$$y_{it} = f(\boldsymbol{x}_{it};\boldsymbol{\beta})exp\{v_{it} - u_{it}\}, \text{ or} \tag{3.11}$$

$$\frac{y_{it}}{f(\boldsymbol{x}_{it};\boldsymbol{\beta})} = exp\{v_{it} - u_{it}\} \tag{3.12}$$

Since $TE_{it} \leq 1$, it follows that $u_{it} \geq 0$. Thus, in (3.12) u_{it} are viewed as one-sided errors representing technical efficiency. In the next section, distributional assumptions are made for the two error terms (v_{it} and u_{it}) to allow for the estimation of the parameters using maximum likelihood. The intuition behind the error component specification in (3.12) is that any deviation from the frontier caught by the technical efficiency term, u_{it}, is the result of factors under the vessel's control, such as the will and effort of the skipper and his crew, and factors such as defective gear. However, the frontier itself can vary randomly across vessels due to the random error v_{it}. On this specification, the frontier is stochastic, with random disturbance v_{it} being the result of favorable and unfavorable external events such as luck and climate. Morever, errors of observation and on measurement of production also justify the presence of v_{it} on the frontier model (Coelli et al. 1999).

3.3.1. Stochastic Distance Functions

From the definition of the output distance function in (3.1), it follows that for the single output case $D_o(\mathbf{x}_{it}, y_{it}; \boldsymbol{\beta}) = y_{it}/f(\mathbf{x}_{it}; \boldsymbol{\beta})$. Consequently, the multi-output version of equation (3.12) is given by (Kumbhakar and Lovell 2000):

$$(3.13) \qquad D_o(\boldsymbol{x}_{it}, \boldsymbol{y}_{it}; \boldsymbol{\beta}) = exp\{v_{it} - u_{it}\}$$

This can be rewritten as a stochastic distance function model:

$$(3.14) \qquad 1 = D_o(\boldsymbol{y}_{it}, \boldsymbol{x}_{it}; \boldsymbol{\beta})\, exp(u_{it} - v_{it})$$

Equation (3.14) can be converted into an estimable regression model by exploiting the linear homogeneity property of $D_o(\mathbf{y}_{it}, \mathbf{x}_{it}; \boldsymbol{\beta})$. For $\tau > 0$, it holds that:

(3.15) $$D_o(\tau \boldsymbol{y}_{it}, \boldsymbol{x}_{it}; \boldsymbol{\beta}) = \tau D_o(\boldsymbol{y}_{it}, \boldsymbol{x}_{it}; \boldsymbol{\beta})$$

Setting $\tau = 1/y_{M_{it}}$, the reciprocal of one of the outputs, equation (3.15) can be rewritten as:

(3.16) $$D_o(\boldsymbol{y}_{it}/y_{M_{it}}, \boldsymbol{x}_{it}; \boldsymbol{\beta}) = \frac{1}{y_{M_{it}}} D_o(\boldsymbol{y}_{it}, \boldsymbol{x}_{it}; \boldsymbol{\beta})$$

Substituting $D_o(\mathbf{y}_{it}, \mathbf{x}_{it}; \boldsymbol{\beta})$ from (3.16) into (3.14) and taking logs:

(3.17) $$ln y_{M_{it}} = -ln D_o(\boldsymbol{y}_{it}/y_{M_{it}}, \boldsymbol{x}_{it}; \boldsymbol{\beta}) + v_{it} - u_{it}$$

In what follows it is assumed the v_{it}, the random disturbances accounting for noise, are i.i.d. $N(0, \sigma_v^2)$. The objective of the empirical strategy outlined in the next sections is to obtain estimates of the stochastic frontier in (3.17), i.e. estimates of β's and σ_v^2, and also to obtain estimates of u_{it}, which can be used to calculate technical efficiencies TE_{it}, and to assess how these TE_{it} are influenced by vessel-specific characteristics.

3.4 Model Specification

In parametric empirical analysis, the standard practice of estimating an output distance function is to approximate it via a flexible functional form. Ideally, this would be a functional form that can characterize all the economically relevant information, in terms of both first and second-order relationships. That is, it can be used to estimate the full vector of marginal products and rates of transformation. One such candidate is the translog function, which provides a second-degree approximation to the true $\mathrm{D_o}(\mathbf{x^t}, \mathbf{y^t})$ in (3.1). Thus, using the translog (TL) specification, equation (3.17) can be rewritten as:

$$(3.18) \qquad lny_{M_{it}} = -TL\left(\frac{\boldsymbol{y}_{it}}{y_{M_{it}}}, \boldsymbol{x}_{it}, \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\delta}\right) + v_{it} - u_{it}$$

If regulatory and other shifters $\mathrm{w_{st}}$ that may affect the shape of the frontier are included, equation (3.18) becomes:

$$(3.19) \qquad lny_{M_{it}} = -\left[TL\left(\frac{\boldsymbol{y}_{it}}{y_{M_{it}}}, \boldsymbol{x}_{it}, \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\delta}\right) + \sum_{s=1}^{S} \phi_s w_{st}\right] + v_{it} - u_{it}$$

The inclusion of $\mathrm{w_{st}}$ in the specification of (3.19), that is, the inclusion of variables aside from the production factors and outputs, assumes that the regulatory environment has a direct influence on the production structure. In the context of the highly regulated New England commercial fisheries, in which effort controls, seasonal closures and additional restrictions very much determine how, where and when vessels fish, this is indubitably the case.

For estimation purposes, the negative sign on equation (3.19) can be ignored. This results in the signs of the estimated coefficients for the distance function (i.e. α′s, β′s, δ's, and Φ's) being reversed, which facilitates interpreting the estimates more comparably to standard production function models (as noted in Coelli and Perelman 1996). Thus, for example, the first-order coefficients corresponding to inputs should be positive (i.e. non-negative marginal productivity of inputs), while the first-order coefficients corresponding to outputs are expected to be negative (which is consistent with a positive opportunity cost of reallocating scarce resources from one output to another, i.e. consistent with a downward sloping production possibilities frontier). Equation (3.19) for vessel *i* in week t can be rewritten as equation (3.20) below:

$$lny_{M_{it}} = \alpha_0 + \sum_{m=1}^{M-1} \alpha_m lny^*_{m_{it}} + \frac{1}{2}\sum_{m=1}^{M-1}\sum_{n=1}^{M-1} \alpha_{mn} lny^*_{m_{it}} lny^*_{n_{it}} + \sum_{k=1}^{K} \beta_k lnx_{k_{it}}$$

$$+\frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K} \beta_{kl} lnx_{k_{it}} lnx_{l_{it}} + \sum_{m=1}^{M-1}\sum_{k=1}^{K} \delta_{mk} lny^*_{m_{it}} lnx_{k_{it}} + \sum_{s=1}^{S} \phi_s w_{st} + v_{it} - u_{it}$$

where $y^*_{m_{it}} = y_{m_{it}}/y_{M_{it}}$. Given the interpretation of the translog model as a second-order approximation to an arbitrary function, it follows that the symmetry restrictions required by Young's theorem are $\alpha_{mn} = \alpha_{nm}$ and $\beta_{kl} = \beta_{lk}$ for m, n=1,2,…,M-1 and k, l=1,2,…,K. In the estimation of equation (3.20), both symmetry and homogeneity of degree +1 are imposed.

To allow for technical efficiency effects, that is, to account for the influence that vessel-specific characteristics may have on technical efficiency, the one-sided error in (3.20), u_{it}, is specified as:

(3.21) $$u_{it} = \psi(\boldsymbol{z}_{it}) + \eta_{it}$$

where $\mathbf{z}_{it}$ is a Rx1 vector of vessel-specific factors affecting the TE levels, and η_{it} are i.i.d random variables defined by the truncation of the normal distribution with mean zero and variance σ_u^2, so that at the point of truncation $\eta_{it} \geq -\psi(\boldsymbol{z}_{it})$. The latter is consistent with u_{it} being a non-negative truncation of the $N(\mu_{it}, \sigma_u^2)$ distribution, with $\mu_{it} = \psi(\boldsymbol{z}_{it})$ (Fousekis 2002). Letting $\psi(z_{it}) = \theta_0 + \sum_{r=1}^{R} \theta_r z_{r_{it}}$, equation (3.21) can be rewritten as:

(3.22) $$u_{it} = \theta_0 + \sum_{r=1}^{R} \theta_r z_{r_{it}} + \eta_{it}$$

where the parameter θ_r indicates the impact of variable z_r on technical inefficiency deviation from the frontier for vessel *i* in period t. A negative value of the parameter suggests a positive influence on efficiency and vice versa (Coelli and Battese 1993).

Equations (3.20) and (3.22) are estimated simultaneously using maximum likelihood (MLE) and the prediction of fisherman-specific technical efficiencies TE_{it} in (3.10) is based on the point estimator proposed by Coelli et al. (1999):[24]

(3.23) $$TE_{it} = E[exp(-u_{it})|\ \varepsilon_{it} = v_{it} - u_{it}]$$

[24] $TE_{it} = E[\exp(-u_{it}|\varepsilon_{it})] = \left\{\exp\left[-\zeta_{it} + \frac{1}{2}\sigma_*^2\right]\right\}\left\{\Phi\left[\frac{\zeta_{it}}{\sigma_*} - \sigma_*\right]/\Phi\left[\frac{\zeta_{it}}{\sigma_*}\right]\right\}$, where $\Phi(.)$ denotes the distribution function for the standard normal variable, $\sigma_*^2 = \gamma(1-\gamma)(\sigma_v^2 + \sigma_u^2)$, $\gamma = \sigma_u^2/(\sigma_u^2 + \sigma_v^2)$, and

$\zeta_{it} = (1-\gamma)\left[\theta_0 + \sum_{r=1}^{R} \theta_r z_{r_{it}}\right] - \gamma\varepsilon_{it}$. By replacing the unknown parameters in the equation for TE_{it} above with the maximum likelihood estimates, the operational predictor for the technical efficiency of the i-th vessel in the t-th time period is obtained.

3.4.1 Variables used in the Stochastic Frontier

3.4.1.1. The Earlier Years: 1994-2003

The 386 vessels in the hook gear category harvested more than 40 different species during the period of study. The primarily targeted species were cod, which comprised 37% of the total pounds harvested (41% of revenues), and haddock, which represented 9% of the total (12% of revenues). The remaining 54% of the catch was made up of dogfish and small fractions of pollock, white hake, summer flounder, redfish, bluefish and black sea bass, among other species. Empirical tractability requires that harvested species be aggregated into output groups. Thus, the three outputs included in the model are cod, haddock and "other" species.

A key determinant of catch is the size of the fish stock, and changes in composition may represent changes in relative stock abundance rather than changes in the behavior of fishermen. In single-output production models, stock abundance is generally incorporated directly as an input in the production function. A particular problem exists for the use of stock measures in multi-output production models in that each stock measure relates directly to only one of the outputs. Further, a composite stock variable cannot effectively capture the stock changes of the different species, which do not follow a consistent pattern. Note also that since some of the outputs are effectively treated as inputs in the estimation process (i.e. on the right hand side of equation (3.20)), a high correlation between catch levels and stock size of individual species (as would be expected) may lead to problems of multi-collinearity. An alternative is to derive measures of partial fishing mortality rather than catch levels per se (Hilborn and Waters 1992, Fox et al. 2003, Pascoe et al. 2007). These represent the proportion of the stock removed by each fishing vessel, and are calculated simply by dividing the catch in each time period by the stock estimate in that time period. This allows the effects of changes in stock size on catch of each species to be incorporated into the analysis, but implicitly imposes unitary output elasticity with respect to stock size (Pascoe et al. 2007). This is a reasonable assumption provided that the stocks are widely dispersed and fairly uniform in density across their areas of distribution (Hilborn and Walters 1992). This is the case for cod, haddock and the other species under consideration in the Northeast region. Once partial fishing mortalities were computed, the fishing mortalities corresponding to cod and haddock were normalized by the partial fishing mortality of "other" species[25]. This latter output was selected since the aggregated catch for the species in this category was nonzero for all observations.

In several trips, the harvested quantities of cod and/or haddock equal zero. To allow for logarithmic estimation with a number of zero values of output observations, I follow the procedure proposed by Battese (1997), who uses dummy variables associated with the incidence of these observations to eliminate bias in estimating a production frontier.[26] Particularly, I replace output variables (i.e. the normalized partial fishing mortalities described in the previous paragraph) $y_m^{i,t}$ (where m=cod, haddock) with $y_m^{*i,t} = \max(y_m^{i,t}, D_m^{i,t})$, where D_m are dummy variables. The dummy D_m takes a value of one if the variable $y_m^{i,t}$ is equal to zero and a value of zero if the variable is greater than

[25] The results are invariant to the choice of the normalizing output (Coelli and Perelman 2000).

[26] Limiting the analysis to the subset of fishing trips with strictly positive outputs for the three output groups may be problematic as those trips may not be representative of the whole industry. On the other hand, the practice of including the zero-observation cases in the analysis by using the value of an arbitrarily small number greater than zero may result in seriously biased estimators of the parameters of the production function if the number of zero-cases is a significant proportion of the total number of observations (see Battese (1997)). For some concrete applications of this technique, see Tsekouras et al. (2003), Samakovlis (2003), Brännlund and Lundgren (2004), González and Lopez (2007) and Okello and Swinton (2010).

zero. For example, for those trips in which the normalized partial mortality of cod is zero, that is $y_{\mathrm{cod}}^{\mathrm{i,t}} = 0$ (i.e. trips for which the log-transformation $\ln y_{\mathrm{cod}}^{\mathrm{i,t}}$ is undefined), $y_{\mathrm{cod}}^{\mathrm{i,t}}$ is replaced by a one (so that now $\ln y_{\mathrm{cod}}^{*\mathrm{i,t}} = 0$), and the dummy variable $\mathrm{D}_{\mathrm{cod}}$ takes the value of one, allowing for a different intercept. Thus, in terms of equation (3.20) above, Battese's approach is to specify a slightly different frontier for trips without landings of cod. Indeed, the approach (i) assumes the same elasticities for trips that did not catch cod as those corresponding to trips that landed cod, (ii) but it allows equation (3.20) to accommodate a different intercept for trips without cod. The dummy $\mathrm{D}_{\mathrm{cod}}$ captures the differential effect on partial mortality of "other species" associated to trips with zero landings of cod. Therefore, a statistically significant dummy $\mathrm{D}_{\mathrm{cod}}$ indicates that not including it in the model would have introduced bias in the estimation of the parameters in (3.20). Identical rationale holds for trips with zero landings of haddock.

As a result of the transformations described above, the output in the left-hand-side of (3.20) corresponds to partial mortality of "other species", while the outputs in the right-hand-side are defined by $y_{\mathrm{cod}}^{*\mathrm{i,t}}$=max{partial mortality cod/partial mortality "other species", $\mathrm{D}_{\mathrm{cod}}$} and $y_{\mathrm{haddock}}^{*\mathrm{i,t}}$=max{partial mortality haddock/partial mortality "other species", $\mathrm{D}_{\mathrm{haddock}}$}.

Vessel size, as measured by the hull water displacement (gross registered tonnage) was used to represent "fixed inputs". Crew, defined by the number of workers (including the captain) on board the vessel, number of days absent from port, and number of hooks, were used as variable inputs in the model, that is, as proxies for the numerous inputs that are exhausted within a trip. Both crew size and number of hooks correspond to averages per trip, calculated over the trips taken each week, while days at sea are calculated as weekly totals. The number of hooks was included in the specification, as it is a key determinant of catch for fixed gear such as bottom longline and handline.

Various external shift factors (w_{st} in equation (3.20)) likely affect catch in the New England Multispecies fishery. One such productivity determinant is the regulatory regime. For this fishery, for the period 1994-2003, the primary regulatory changes are Amendment 7, implemented in July of 1996, and the Settlement Agreement of August 2002. Amendment 7 accelerated the DAS reduction called for originally in Amendment 5, eliminated the exemptions to the DAS program, increased the number and duration of area closures, and established rebuilding programs for five overfished stocks. The Settlement Agreement was the result of a lawsuit brought against NMFS by environmental groups for violating the federal Sustainable Fisheries Act of 1996 by allowing the continued overfishing of cod, haddock, yellowtail flounder and other groundfish off the coast of New England. The provisions in the Settlement Agreement included a freeze on DAS based on the highest annual level used from fishing years 1996-2000, reduced by 20%, a freeze on the issuance of new permits, increased gear restrictions for certain gear types, including gillnets, hook-gear and trawl nets, modifications and additions to the closure areas, and limits on yellowtail flounder catch. To facilitate consideration of the resulting productivity effects I include in the **w** vector the dummy variables D_{amend7} (equal to zero from 1994 to 1995 and one thereafter) and $D_{settlement}$ (equal to zero from 1994 to 2001 and one thereafter) reflecting these regulatory changes. The gear specific dummy variable $D_{longline}$ was also included in **w** to test for the effect of bottom longlining on harvest.

3.4.1.2. The Sector Years: 2004-2008

The stochastic production frontier for years 2004-2008 differs from that described in the previous section in two ways: (i) given that biomass data is not available for this period, output is specified as catch not as partial fishing mortality, and year dummies are added to the vector of shifters **w** in equation (3.20) in an attempt to control for inter-annual variation in stocks abundance; (ii) the regulatory dummies D_{amend7} and $D_{settlement}$ are dropped from the model. Note that since the econometric specifications are different for the periods 1994-2003 and 2004-2008, the models, and hence the estimated technical efficiencies, are not comparable across the two periods.

3.4.2 Determinants of Inefficiency

3.4.2.1. The Earlier Years: 1994-2003

To allow for technical inefficiency effects, the one-sided error u_{it} is specified as a function of vessel and fleet characteristics, and sector membership. In particular, the inefficiency model can be written as equation (3.24) below:

$$u_{it} = \theta_0 + \theta_1 D_{toc} + \theta_2 D_{sector_i} + \theta_3 N_{other\ vessels_{it}} + \theta_4 N_{sector\ vessels_{it}} + \theta_5 D_{sector_i} N_{sector\ vessels_{it}} + \eta_{it}$$

where D_{toc} is a dummy variable whose value depends on the vessel's type of construction (1 if wood, 0 if fiberglass or steel) and attempts to control for vessel's age (i.e. as newer vessels tend to be made of fiberglass or steel), and D_{sector_i} is a dummy that equals one if the vessel *i* later became part of the sector under Amendment 13. The variable

$N_{\text{sector vessels}_{it}}$ represents the number of vessels, out of those that later joined the sector, that fished contemporaneously with vessel *i* in the Georges Bank and Gulf of Maine region. It is calculated as the average (over *i*'s trips in week t) of the number of (future) sector vessels that fished simultaneously with *i*. In constructing this variable, vessels are considered to fish contemporaneously if there is an overlap on the time span defining their trips (i.e. if, for example, vessel *j* departed at an earlier date and arrived back to port at a later date than *i*'s departure). Similarly, $N_{\text{other vessels}_{it}}$ represents the average number of vessels, excluding those that later became sector boats, that fished contemporaneously with vessel *i* in week t. It includes those vessels –otter trawls, sink gillnets, bottom longlines, and handlines– that hold a multispecies permit and hence target the same species as vessel *i*.

The variables $N_{\text{sector vessels}_{it}}$ and $N_{\text{other vessels}_{it}}$ attempt to identify any negative effects on efficiency that may result from crowding externalities, local depletion and information cascades[27]. As shown in maps 1 and 2 in appendix A, the significant overlap in areas fished by fixed and mobile gears in the groundfish fishery suggests at least the possibility of congestion externalities in the form of gear conflicts. Anecdotal evidence indicates that gear conflicts do occur in the Northeast groundfish fishery (Holland 2004). A common example of this type of conflict occurs when a towed gear (i.e. trawl) cuts across static gear (i.e. gillnet and longlines), resulting in entanglement and loss of nets and longlines. Altering the manner (location, speed, course) of deployment of gear to avoid direct interactions like gear entanglement adds an additional constraint to fishing

[27] "…the efficiency of each boat may be lowered by congestion over fishing grounds" (V. Smith 1968, p. 413). See also Lynham (2006) for an analysis of information cascades in fisheries, and Larson et al. (1999) for empirical evidence of these information effects on the Bering Sea/Aleutian Islands trawl fisheries.

that could result in reduced catch rates. For this reason, it is reasonable to assume that there are negative influences of increasing vessel density on fishing success, beyond simple exploitation effects.

Lastly, the interaction term between future sector membership ($\mathrm{D}_{\mathrm{sector}_\mathrm{i}}$) and the number of future sector boats ($\mathrm{N}_{\mathrm{sector\ vessels}_{\mathrm{it}}}$) seeks to identify any differential effect that the presence of these vessels on the water may have on the performance of its peers that later joined the sector. If, for vessel *i*, the presence of additional sector boats adversely impacts its efficiency, unless vessel *i* is itself a future sector peer, then it is possible to infer that these vessels may have engaged in some type of cooperative behavior (such as information-sharing) before the group formally became a sector under Amendment 13.

Thus, in specification (3.24), the full effect of future sector participation on observed vessels' technical efficiencies u_{it} is captured by the expression $\theta_2 D_{sector_i} + \theta_5 D_{sector_i} N_{sector\ vessels_{it}}$. The first term represents, for those vessels that later became sector members, the effect of skipper's and crew's skills on their boat's efficiency. In other words, this is the effect of future sector participation on technical efficiency when the vessel fishes by itself, without its future sector partners. If this first term turns out to be positive, it would confirm the assertion that future sector vessels were less efficient (i.e. when fishing under identical conditions) than independents. The second term, in turn, corresponds to the effects on vessels' technical efficiencies of sector vessels interaction. A negative second term would hint to cooperation and team work among the skippers that later became GB Cod Hook sector members. In summary, equation (3.24) attempts to disentangle, from the observed levels of vessel technical efficiency, the influences of fishermen skill, vessel characteristics, cooperation among crews, and negative externalities such as congestion.

3.4.2.2. The Sector Years: 2004-2008

The model developed in chapter 2 shows that cooperation and learning within the sector are beneficial for its members as they increase the group's profitability. Increasing levels of technical efficiency over 2004-2008 for the GB Hook sector vessels would provide some support to the claim that learning to 'team fish' is indeed relevant. This result, combined with the finding that sector vessels were already cooperating before the sector formed (i.e. combined with the expected signs for the coefficients in specification (3.24)), would strongly support the relevance of learning for the formation and development of sectors. Furthermore, high efficiency scores for sector vessels relative to independents would indicate that cooperation pays, that is, it improves individual performance. To study the path of technical efficiency in the hook fleet during years 2004-2008 (i.e. after Amendment 13 was implemented and sectors approved) and to compare efficiency scores between sector and common pool vessels, a time-varying efficiency model is specified by replacing equation (3.24) with the following expression (Battese and Coelli 1992):

$$(3.25) \qquad u_{it} = u_i exp\{-\lambda(t - T_i)\}$$

where u_i are non-negative random variables accounting for technical inefficiency in production and are assumed to be i.i.d as truncations at zero of the $N(\mu, \sigma_u^2)$ distribution, and λ is a parameter to be estimated. The last period for vessel *i* contains the base level of inefficiency for that boat (i.e. for $t=T_i$, $u_{it}=u_i$). If $\lambda>0$, then the level of inefficiency decays toward the base level. If $\lambda<0$, then the level of inefficiency increases to the base level, and if $\lambda=0$, then the level of inefficiency remains constant.

Chapter 4: The Data

4.1 Description of data

Data was obtained from the Commercial Fisheries Database System maintained at the National Marine Fisheries Service Northeast Fisheries Science Center through Agreement #NEFSC-09-001. The primary data source is the logbook information required of all vessels with federal limited-entry groundfish permits. Logbooks record information on each trip and tow, including species and estimated catch weight, gear used, location of fishing, and departure and arrival times. Supplementary data on vessel characteristics was obtained from the Permit Application Database and the Observer Database System.

Trip-level data was aggregated at the weekly level, resulting in an unbalanced panel of 25,603 observations corresponding to 386 vessels using hook gear (benthic longlines and handlines).[28] Only vessels that operated a minimum of three time periods were included in the analysis.

Information on stock abundance –spawning stock biomass– for cod, haddock and the other species considered, for the period 1994-2003, came from NMFS's stock assessments and biomass surveys for the Northeast region.[29] The stocks of redfish, bluefish, dogfish, white hake, pollock and summer flounder were aggregated to compute the biomass of "other species", as they are the main species harvested besides cod and haddock and account for 92% of the catch of other species that is broken down by

[28] At the weekly level, as over 10% of the 69,000 trips are longer than a day. The results are robust to the level of aggregation and remain unchanged when the model is estimated at the monthly or yearly level.
[29] The reports referred to in this section are available at http://www.nefsc.noaa.gov.

species, and 70% of the total catch of other species.[30] This aggregation procedure assumes that optimal input choices and aggregate output levels can be chosen independently of the mix of species within this group. Inclusion of additional species in this "other species" category was precluded by unavailability of data on their stocks biomass. Nevertheless, none of the remaining species (with the exception of skate that made up 0.49% of the catch) represented individually more than 0.3% of total harvest.

Stock information for cod, haddock, white hake and redfish was obtained from the "Report of the 3rd Groundfish Assessment Review Meeting" (2007), which details the results of the latest stock assessment for the 19 stocks in the groundfish complex. Information on pollock came from the report "Status of the Fishery off the Northeastern United States" (NOAA Technical Memorandum NMFS-NE-108, 1995) and was complemented with biomass indices in "Report of the 3rd Groundfish Assessment Review Meeting". Data on the summer flounder came from "The Summer Flounder Assessment and Biological Reference Point Update for 2006". Finally, information on dogfish came from "The 43rd Northeast Regional Stock Assessment Workshop Summary Report" (2006), while data on bluefish was obtained from "The 41st Northeast Regional Stock Assessment Workshop (SAW) Assessment Summary Report" (2005). These stock assessments use a combination of data from periodical research vessel surveys, observer programs, sea-based sampling of discards, and dockside sampling of commercial and recreational landings to estimate trends in fish populations. Table 4.1 presents a summary with the evolution of stock biomass over 1994-2004 by species.

[30] Landings data include information for 26 species and also a general category of other.

Table 4.1: Stock abundance per species (MT)

	1994	1995	1996	1997	1998
Bluefish	67,007	67,728	65,644	64,727	70,600
Cod GB	18,540	18,503	19,697	19,050	19,130
Cod GOM	10,755	13,566	11,949	9,856	10,814
Dogfish	460,932	519,920	520,782	489,233	406,287
Haddock GB	20,406	26,991	36,012	44,106	51,502
Haddock GOM	1,300	2,157	2,887	4,457	5,952
Pollock	51,903	79,754	103,490	158,716	122,163
Redfish	12,015	12,366	17,675	25,225	35,062
Summer flounder	15,100	18,976	20,067	20,413	22,245
White hake	22,000	31,133	24,650	18,227	17,734

Table 4.1 (continued): Stock abundance per species (MT)

	1999	2000	2001	2002	2003
Bluefish	72,900	80,300	87,700	88,200	92,200
Cod GB	20,744	22,290	25,305	20,078	14,694
Cod GOM	11,246	14,285	17,848	18,673	16,539
Dogfish	358,185	343,602	337,686	371,200	293,538
Haddock GB	60,500	75,111	90,118	104,085	126,003
Haddock GOM	5,834	6,501	10,517	13,667	11,757
Pollock	242,426	133,556	387,376	293,538	347,657
Redfish	46,798	60,380	75,578	92,938	113,478
Summer flounder	22,551	26,130	33,835	39,051	44,786
White hake	13,773	25,165	29,023	24,770	16,933

Data on the stock status of bluefish, dogfish and summer flounder was unavailable for the period 2004-2008. As the purpose of the empirical investigation is to test a different set of hypotheses for the pre-sector years than for the years in which the GB Cod Hook sector was formally in operation, and considering this limited availability of biomass information, two different stochastic frontier models were estimated: (i) for seasons 1994-2003 (the pre-sector years), and (ii) for the years following the approval of Amendment 13, that is, the period 2004-2008. The first model, which explicitly controlled for fish stock variation, was used to test whether vessels that later joined the sector were indeed less efficient than the boats that remained independent and to identify traces of early cooperation among sector joiners. The second model was used to estimate and compare efficiency scores for the sector and the independent fleets.

Summary statistics describing the data are presented in table 4.2. Homogeneity in both vessel characteristics and activity levels (i.e. DAS/week) between the independent and the sector fleets is a conspicuous feature of the data. Yet there is considerable difference in the quantity of gear (# of hooks and, presumably, bait) utilized by the two fleets and, as a result, in their respective average catches per week. In the early years 1994-2001 all hook fishermen operated under identical regulatory restrictions, and variation in the quantity of gear used responds exclusively to skippers' choices. The Settlement Agreement of August 2002 set limits on the maximum number of hooks that a vessel could set and haul in the Georges Bank (3,600 hooks) and the Gulf of Maine (2,000 hooks) in a trip. This regulation impacted the two fleets differently as over 90% of the trips of the sector fleet took place in the Georges Bank, compared with 51% of those of the independent fleet. The situation changed again in 2004, when Amendment 13 confirmed the restrictions established in the Settlement Agreement but exempted GB Hook sector vessels from the Georges Bank hook limit.

Table 4.2: Summary statistics for the New England groundfish hook gear fleet

	Independent Fleet		Sector Fleet[a]	
Variable	**Mean**	**SD**	**Mean**	**SD**
Seasons 1994-2003				
Vessel gross registered tonnage (tons)	15.08	13.39	14.38	7.14
Crew size[b]	1.84	0.84	1.72	0.56
Number of hooks[b]	1,010	1,566	2,102	2,074
DAS/week	1.42	1.68	1.34	1.04
Cod landings/week (pounds)	886	2,123	1,999	2,723
Haddock landings/week (pounds)	97	427	130	633
Other species landings/week (pounds)	1,373	4,561	2,120	7,134
Number of vessels	325		61	
Type of construction: *wood*	41		0	
Type of construction: *fiberglass or steel*	284		61	
Longliners	155		31	
Number of observations	11,898		6,836	
Seasons 2004-2008				
Vessel gross registered tonnage (tons)	13.51	12.58	14.38	7.14
Crew size[b]	1.85	0.69	1.81	0.88
Number of hooks[b]	572	1,797	2,806	3,341
DAS/week	1.16	1.45	1.33	1.01
Cod landings/week (pounds)	320	767	647	1,501
Haddock landings/week (pounds)	372	1,527	2,513	5,165
Other species landings/week (pounds)	758	2,842	760	1,477
Number of vessels	219		48[c]	
Type of construction: *wood*	12		0	
Type of construction: *fiberglass or steel*	207		48	
longliners	89		27	
Number of observations	5,542		1,327	

(a) Throughout the chapter I refer to the vessels that later joined the GB Cod Hook sector as the "sector fleet".
(b) Average crew size and number of hooks per week.
(c) Not all members were active during the sector years.

Table 4.2 also highlights a change in the targeting behavior of the fleets during the period 2004-2008. From its first season in 2004, sector members made significant progress in shifting from overfished stocks (cod) to healthy stocks by participating in the Closed Area I (CAI) Haddock Special Access Program (SAP). The CAI Haddock SAP allows hook vessels to target haddock in the northwestern corner of the so-called Closed Area I in the Georges Bank during a three-month season that runs from October to December. Each year the SAP is allocated a haddock TAC which is paired with a hard TAC on cod bycatch. The program was initiated in 2004, after an experimental season in which hook vessels showed that they were able to target haddock, an underutilized resource, while minimizing cod mortality. The program was initially approved as a Hook Sector-only CAI Haddock SAP, making it possible for Hook Sector members to access the SAP a full fishing year sooner than non-sector hook fishermen. Additionally, non-sector participants were more likely to have access to the SAP limited by their incidental catch cod TAC than sector members, who could apply bycatch toward their entire sector allocation of cod. These facts help explain both the change in the composition of the catch after 2003, and the increasing difference in catch of haddock between the fleets.[31]

As mentioned in chapter 3, two new variables, $\mathrm{N}_{\mathrm{sector\ vessels}_{it}}$ and $\mathrm{N}_{\mathrm{other\ vessels}_{it}}$, were created and included in the technical inefficiency model for years 1994-2003 to test for the presence of crowding externalities and cooperation. For each vessel, these variables were computed using the package MATLAB, conducting a search for all those vessels that held a groundfish permit (i.e. that targeted the same species as the hook fleet) and fished on the Georges Bank or the Gulf of Maine at the same time as the vessel in question. The logbooks include the dates of departure and arrival to port, which characterize the time span of each trip. A count was added to the number of "other vessels" fishing simultaneously with *i*, during a specific trip, each time that a non-sector

[31] Indeed, haddock revenues were the largest share of groundfish revenues for this sector in every year of the period 2004-2008. As stated in the GB Cod Hook sector 2007 Annual Report: "The unavailability of GB cod to hook fishermen continues to hamper efforts to harvest the Hook Sector's GB cod allocation. Participation of Hook Sector vessels in the Haddock SAP was critical to the economic survival of several members…"

vessel was found on the water between the dates characterizing *i*'s trip. The average of these numbers over the trips taken by boat *i* in week *t* corresponds to $\mathrm{N}_{\mathrm{other\ vessels}_{it}}$. The variable $\mathrm{N}_{\mathrm{sector\ vessels}_{it}}$ was constructed in similar manner. Table 4.3 presents summary statistics for these two variables.

Table 4.3: Distribution of contemporaneous trips

	Independent Fleet		**Sector Fleet**	
Variable	**Mean**	**SD**	**Mean**	**SD**
Seasons 1994-2003				
$\mathrm{N}_{\text{sector vessels}}$	11.5	7.6	13.2	7.1
$\mathrm{N}_{\text{other vessels}}$	334.4	94.7	329.4	66.2

From table 4.3 it can be seen that, on average, vessels in both fleets harvested under similar conditions of crowdedness. The next chapter shows, however, that the presence of sector vessels on the water had a different impact for boats in each of these fleets.

Chapter 5: Results

This chapter discusses the results for the two empirical models specified for the period 1994-2003 and for the sector years. The empirical findings are widely consistent with the predictions of the model developed in chapter 2. Concretely, the results 1) show that the least efficient vessels were the first to join the Georges Bank Cod Hook sector in 2004, 2) present evidence of earlier cooperation among these vessels (i.e. previous to the institutionalization of the group as a sector), hence suggesting familiarity with collective harvesting when joining the sector, and 3) demonstrate that technical efficiency was higher for sector vessels than common pool boats during the sector years and that it in fact increased during this period.

5.1 The Earlier Years: 1994-2003

The system defined by equations (3.20) and (3.24) was estimated by maximum likelihood (see appendix B, section I, for the derivation of the log-likelihood function) using FRONTIER 4.1 (Coelli 1996). Parameters estimates, standard errors, and asymptotic t-ratios associated with the final specification for the period 1994-2003 are shown in table 5.1. Most of the coefficients were found to be significant at the 1% level. Table 5.2 presents Generalized Likelihood Ratio Tests concerning the structure of the production technology and the nature of technical inefficiency.

The model was originally specified as a translog production frontier, but tested for the alternative Cobb-Douglas specification (element-wise separability). The result of the specification test in table 5.2 shows that the translog is indeed the preferred functional form for the model.

The estimated coefficients on both right-hand side output variables (cod and haddock) are significant and have the expected negative sign for the slope of a production possibility frontier. They indicate that substitutability among the outputs is a key productive characteristic. The second order coefficients for these variables are also negative and statistically different from zero, and the interaction between cod and haddock is positive and significant. Overall these estimates indicate that at least some inputs are allocable.[32] This result is consistent, for example, with the successful development of techniques for targeting haddock while minimizing cod bycatch (by using herring-based fabricated baits instead of squid), which allowed fishermen using hook gear to gain access to the CAI Haddock SAP.

In addition to the information about output relationships embodied in equation (3.20), evaluation of the input-output links may provide some insight into the validity of the separability assumption implicit in the aggregate production function models. Input-output separability can be analyzed by testing the joint significance of the cross-terms between input and output variables. As shown in table 5.2, the null hypothesis of input-output separability is strongly rejected, suggesting that a multi-output model (i.e. distance function) is more appropriate than the frequent approach of combining harvest into a composite index and then proceeding to estimate an aggregate output production function.

[32] If inputs are non-allocable (i.e. vessels and their crews harvest several species in a manner that is joint), substitution is not possible and an aggregate-output production function completely represents the technology. In this case, cross $y_i - y_j$ parameters would be zero.

The significance of the estimated first-order coefficients for days at sea, crew size, registered tonnage and hooks indicates that extending the duration of a trip, adding new crew, increasing the number of hooks and/or using a larger boat does enhance catch quantity.

The direct impact of the regulatory changes on harvest is represented by the significantly negative coefficients for D_{amend7} and $D_{settlement}$, which is consistent with the initial intent of both Amendment 7 and the Settlement Agreement. The coefficient on $D_{longline}$, on the other hand, is insignificant, indicating that, after controlling for the number of hooks (a main difference between handliners and longliners), the type of gear has a negligible effect on catch. Furthermore, the coefficients associated with the zero output variables (D_{cod} and $D_{haddock}$) are statistically significant at the 1% level, which confirms that bias would be introduced in the parameters if the output distance function was estimated without explicitly addressing the problem of zero values.

Technical Efficiency

Turning now to the nature of technical efficiency, table 5.2 presents the results of two tests of hypotheses. The first null hypothesis is whether or not technical inefficiency is absent; i.e., $H_0\colon \sigma_u^2 = \theta_0 = \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = 0$. This null hypothesis is specified as: $\gamma = \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = 0$, where γ is defined by the reparameterization $\gamma = \sigma_u^2/(\sigma_v^2 + \sigma_u^2)$, and lies between 0 and 1. This hypothesis was rejected at the 1% level of significance, which confirms that technical inefficiency effects exist in the data. The second test (table 5.2, under "Vessel characteristics do not affect TE") established whether or not the technical inefficiency effects are influenced by the explanatory variables (**z**) under the null hypothesis $H_0: \theta_j = 0$ for all *j*'s. The likelihood ratio test indicated that the explanatory variables included in the inefficiency model are jointly significant at the 1% level.

The parameters of the inefficiency equation (3.24) are presented in table 5.1. All the coefficients have the expected signs and are statistically significant at the 1% level. The positive coefficient for D_{toc} indicates that the type of construction is indeed a determinant of efficiency. Either wooden vessels are less efficient because of the type of construction itself, or alternatively, if in fact this variable works as a proxy for a boats' age, this result confirms the intuition that older vessels tend to underperform those built more recently. Likewise, the positive coefficients for both $N_{\text{other vessels}}$ and $N_{\text{sector vessels}}$ suggest that, as more vessels congregate on the fishing grounds, fishermen's interference with each other becomes more severe and, as a result, the mutual detrimental effect on individual boats' efficiencies increases. This finding supports the anecdotal evidence mentioned above on crowding and related externalities arising from spatial concentration and excessive quantities of fishing gear.

The significantly positive coefficient for D_{sector} shows that, as predicted by the model in the second chapter, fishermen that later became members of the Georges Bank Cod Hook Sector exhibit lower technical efficiency than their independent peers after controlling by type of construction and fleet conditions. While this coefficient captures the effect on technical efficiency of characteristics that are common to this specific group of vessels, to fully account for the impact of future sector participation on efficiency during 1994-2003, it is necessary to analyze the interaction term in (3.24). If these vessels were behaving cooperatively before the GB Cod Hook sector was officially constituted in

2004 (acting, for example, as an information-sharing clique or coordinating the search for the schools of fish), additional sector boats on the water would most likely have had a beneficial effect on team vessels' efficiencies. The negative coefficient on the interaction term in the inefficiency equation confirms this conjecture, and identifies the anticipated positive effect on performance. Indeed, as can be readily ascertained from the values of the estimated coefficients in table 5.1, the average sector vessel required twelve of its peers fishing simultaneously with it in order to achieve the level of efficiency of an independent operating under similar conditions. In the data, of the total trips undertaken by sector vessels in the period 1994-2003, in 38% of them the number of sector boats simultaneously on the water exceeded thirteen.

Table 5.1: Distance function parameter estimates, 1994-2003

Parameter	Coefficient	Standard Error	Asymp. t-ratio
α_0 ; Intercept	-4.9990	0.0540	-92.66**
α_1 ; ln(cod)	-0.4802	0.0067	-71.44**
α_2 ; ln(haddock)	-0.2071	0.0054	-38.28**
α_{11} ; $[\ln(\text{cod})]^2$	-0.0379	0.0003	-113.6**
α_{22} ; $[\ln(\text{haddock})]^2$	-0.0524	0.0003	-154.9**
α_{12} ; ln(haddock)*ln(cod)	0.0774	0.0006	130.4**
δ_{11} ; ln(cod)*ln(crew)	0.0082	0.0029	2.87**
δ_{12} ; ln(cod)*ln(DAS)	0.0087	0.0017	5.22**
δ_{13} ; ln(cod)*ln(GRT)	0.0006	0.0017	0.34
δ_{14} ; ln(cod)*ln(hooks)	0.0027	0.0005	5.31**
δ_{21} ; ln(haddock)*ln(crew)	-0.0167	0.0028	-5.93**
δ_{22} ; ln(haddock)*ln(DAS)	-0.0409	0.0015	-27.70**
δ_{23} ; ln(haddock)*ln(GRT)	-0.0080	0.0017	-4.81**
δ_{24} ; ln(haddock)*ln(hooks)	-0.0062	0.0004	-16.96**
β_{11} ; $[\ln(\text{crew})]^2$	0.0188	0.0133	1.41
β_{12} ; ln(crew)*ln(DAS)	0.0397	0.0094	4.25**
β_{13} ; ln(crew)*ln(GRT)	0.0183	0.0098	1.87
β_{14} ; ln(crew)*ln(hooks)	-0.0022	0.0026	-0.82
β_{22} ; $[\ln(\text{DAS})]^2$	0.0433	0.0035	12.46**
β_{23} ; ln(DAS)*ln(GRT)	-0.0147	0.0054	-2.71**
β_{24} ; ln(DAS)*ln(hooks)	0.0174	0.0012	13.91**
β_{33} ; $[\ln(\text{GRT})]^2$	-0.0069	0.0040	-1.73
β_{34} ; ln(GRT)*ln(hooks)	0.0001	0.0015	0.08
β_{44} ; $[\ln(\text{hooks})]^2$	0.0011	0.0006	1.82
β_1 ; ln(crew)	0.0880	0.0349	2.52**
β_2 ; ln(DAS)	0.4328	0.0195	22.24**
β_3 ; ln(GRT)	0.0914	0.0216	4.23**
β_4 ; ln(hooks)	0.0630	0.0069	9.16**

** Significant at the 1% level; * significant at the 5% level

Table 5.1 (continued): Distance function parameter estimates, 1994-2003

Parameter	Coefficient	Standard Error	Asymp. t-ratio
Φ_1 ; $D_{longline}$	0.0109	0.0224	0.49
Φ_2 ; D_{amend7}	-0.0977	0.0085	-11.46**
Φ_3 ; $D_{settlement}$	-0.0405	0.0066	-6.09**
Φ_4 ; D_{cod}	1.3313	0.0124	107.2**
Φ_5 ; $D_{haddock}$	2.1659	0.0160	135.6**
$\sigma^2 = \sigma_u^2 + \sigma_v^2$	3.6412	0.1618	22.51**
$\gamma = \sigma_u^2/\sigma^2$	0.9909	0.0006	1,786**
Inefficiency Model			
θ_0 ; Intercept	-16.7532	0.3765	-44.49**
θ_1 ; D_{toc}	3.0125	0.1263	23.85**
θ_2 ; D_{sector}	2.5254	0.0689	36.66**
θ_3 ; $N_{other\ vessels}$	0.0190	0.0004	46.49**
θ_4 ; $N_{sector\ vessels}$	0.0592	0.0036	16.23**
θ_5 ; D_{sector}*$N_{sector\ vessels}$	-0.2242	0.0076	-29.52**

** Significant at the 1% level; * significant at the 5% level

Table 5.2: Generalized Likelihood Ratio Tests of hypotheses, 1994-2003

Null Hypothesis, H_0	LR statistic	df	Critical Value (1%)	
Input-output separability: $\delta_{11}=\delta_{12}=\delta_{13}=\delta_{14}=\delta_{21}=\delta_{22}=\delta_{23}=\delta_{24}=0$	1,190	8	20.09	Reject H_0
Cobb-Douglas frontier:	18,829	21	38.93	Reject H_0
Technical inefficiency is absent: $\gamma=\theta_0=\theta_1=\theta_2=\theta_3=\theta_4=\theta_5=0$	6,286	7	17.76	Reject H_0
Vessel characteristics do not affect TE: $\theta_1=\theta_2=\theta_3=\theta_4=\theta_5=0$	4,235	5	15.09	Reject H_0

Note: As γ takes values between 0 and 1, in H_0: $\gamma = \theta_0 = \ldots = \theta_5 = 0$ the statistic is distributed according to a mixed χ^2 whose critical value is obtained from Kodde and Palm (1986).

5.2 The Sector Years: 2004-2008

Parameter estimates, standard errors, and asymptotic t-ratios for the period 2004-2008 are shown in table 5.3 (see appendix B, section II, for the derivation of the log-likelihood function). As in the model fitted for the earlier years, most of the coefficients were found to be significant at the 1% level. Furthermore, with the exception of a few second-order effects and the dummy $D_{longline}$, the coefficients had identical sign as those in the distance function estimated for 1994-2003.

The year dummies, included in the vector of shifters **w** in (3.20) in order to try to control for stock biomass, were significant and negative, likely capturing the detrimental effect of lower stocks and adverse climatic conditions on catch over this period. The coefficient on $D_{longline}$ identified a positive, non-negligible effect on catch of using benthic longlines instead of handlines. Lastly, the parameters associated with the zero output variables (D_{cod} and $D_{haddock}$) remained statistically significant.

Table 5.4 presents Generalized Likelihood Ratio Tests on the structure of the production technology and the presence of technical inefficiency. Input-output separability is once again strongly rejected and the translog specification preferred over the Cobb-Douglas functional form.

Technical Efficiency

The hypothesis test in table 5.4 (third row, under "Technical inefficiency is absent") confirms that technical inefficiency exists in the data for 2004-2008. This null hypothesis is specified as: $H_0: \gamma = \lambda = \mu = 0$ (refer to equation (3.25)) and is rejected at the 1% level. Furthermore, λ was found to be positive and statistically significant, implying an upward trend on efficiency for hook fishermen. The rationale behind this improvement is twofold: the ability of fishermen to gradually adapt their behavior to the newly introduced requirements of Amendment 13 since its implementation in May of 2004, and the steady flow of vessels that left the fishery during seasons 2004-2008. Amendment 13 created categories of DAS, introduced both leasing and a permanent transfer programs of DAS, allowed groups of fishermen to form sectors, and introduced new input controls. Therefore, it is reasonable to infer that after an initial phase of adaptation, fishermen became familiar with the new rules and were able to deal more effectively with them. On the other hand, only 139 vessels operated in season 2008. The vessels that remained active exhibited higher efficiency levels than the boats that exited the fishery.

Table 5.5 shows the yearly average technical efficiencies for the GB Cod Hook sector vessels and the independent fleet (i.e. the common pool). Table 5.6 presents the same results as table 5.5, but only for those vessels that remained in the fishery over the period 2004-2008. Mean efficiencies are considerably higher for sector boats. This fact remains true if the comparison is conducted instead only among vessels that remained in the fishery over the whole period 2004-2008. These figures imply a beneficial effect of sector membership on fishing performance. In fact, as the mean efficiencies for sector vessels account for the positive influences of cooperation and team harvesting, they suggest that investing in a platform for collective action has a positive return on technical efficiency. Furthermore, technical efficiencies increased over the period, hinting to the possible impacts of learning within the sector. These facts are consistent with the predictions of the theoretical model introduced in chapter 2.

Table 5.5: Yearly average efficiencies for hook fleet, years 2004-2008

	2004	2005	2006	2007	2008
Sector vessels	0.692	0.749	0.777	0.784	0.847
Independent fleet	0.584	0.618	0.675	0.699	0.739

Table 5.6: Yearly average eff. for vessels that remained in the fishery

	2004	2005	2006	2007	2008
Sector vessels	0.760	0.767	0.8102	0.833	0.851
Independent fleet	0.600	0.641	0.676	0.707	0.743

This conclusion is tempered, however, by two facts. First, mean technical efficiency also improved over 2004-2008 in the independent fleet, suggesting the possibility that the improvements observed in table 5.6 for both fleets were, as mentioned above, simply the result of the gradual adaptation of fishermen's behavior to the newly introduced Amendment 13. Lacking further information, it is not possible to ascertain what part of the improvement in sector vessels' efficiencies is sector-specific. Second, the theory in chapter 2 anticipates entry to the sector as its profitability improves. As table 1.1 in chapter 1 shows, there has indeed been entry to the sector, as anticipated, but also exit. Recall, however, that in 2004-2008 the GB Cod Hook sector operated under a different set of rules than those specified in Amendment 16, the regulatory framework under which the results in chapter 2 were derived. Specifically, the GB Hook sector only received allocation of cod quota and remained subject to DAS limits and similar effort restrictions. Amendment 16 replaced input controls (such as the individual allocation of DAS) with a system of fishery-wide TACs and quota allocations that are only appropriated through sector membership. These regulatory changes will undoubtedly alter the relative attractiveness of common pool and sector membership with respect to that of the period 2004-2008. Note also that, lacking cost information, it is not licit to make conclusive statements on the relative profitability of the two sets of vessels, as technical efficiency is a necessary but not sufficient condition for economic efficiency. Undoubtedly, there were economically unviable operators in the two groups, as suggested by the fact that vessels from both fleets exited the fishery during this period.

Table 5.3: Distance function parameter estimates, 2004-2008

Parameter	Coefficient	Standard Error	Asymp. t-ratio
α_0 ; Intercept	4.3554	0.0826	52.74**
α_1 ; ln(cod)	-0.1988	0.0146	-13.62**
α_2 ; ln(haddock)	-0.7269	0.0168	-43.30**
α_{11} ; $[\ln(\text{cod})]^2$	-0.0097	0.0009	-10.85**
α_{22} ; $[\ln(\text{haddock})]^2$	-0.0114	0.0010	-11.78**
α_{12} ; ln(haddock)*ln(cod)	0.0128	0.0017	7.42**
δ_{11} ; ln(cod)*ln(crew)	-0.0188	0.0083	-2.28*
δ_{12} ; ln(cod)*ln(DAS)	-0.0110	0.0041	-2.69**
δ_{13} ; ln(cod)*ln(GRT)	-0.0012	0.0042	-0.27
δ_{14} ; ln(cod)*ln(hooks)	-0.0293	0.0015	-19.24**
δ_{21} ; ln(haddock)*ln(crew)	0.0292	0.0101	2.89**
δ_{22} ; ln(haddock)*ln(DAS)	0.0340	0.0050	6.75**
δ_{23} ; ln(haddock)*ln(GRT)	0.0011	0.0053	0.20
δ_{24} ; ln(haddock)*ln(hooks)	0.0372	0.0018	20.67**
β_{11} ; $[\ln(\text{crew})]^2$	-0.0165	0.0449	-0.37
β_{12} ; ln(crew)*ln(DAS)	0.0225	0.0258	0.87
β_{13} ; ln(crew)*ln(GRT)	0.0629	0.0353	1.78
β_{14} ; ln(crew)*ln(hooks)	0.0060	0.0104	0.58
β_{22} ; $[\ln(\text{DAS})]^2$	0.0341	0.0099	3.45**
β_{23} ; ln(DAS)*ln(GRT)	-0.0430	0.0139	-3.09**
β_{24} ; ln(DAS)*ln(hooks)	0.0911	0.0046	19.90**
β_{33} ; $[\ln(\text{GRT})]^2$	-0.0231	0.0207	-1.12
β_{34} ; ln(GRT)*ln(hooks)	0.0036	0.0071	0.51
β_{44} ; $[\ln(\text{hooks})]^2$	-0.0061	0.0021	-2.92**
β_1 ; ln(crew)	0.0280	0.1011	0.28
β_2 ; ln(DAS)	0.3720	0.0376	9.88**
β_3 ; ln(GRT)	0.0953	0.0721	1.32
β_4 ; ln(hooks)	0.1571	0.0225	6.98**

** Significant at the 1% level; * significant at the 5% level

Table 5.3 (continued): Distance function parameter estimates, 2004-2008

Parameter	Coefficient	Standard Error	Asymp. t-ratio
Φ_1 ; $D_{longline}$	0.7101	0.0664	10.69**
Φ_2 ; D_{2005}	-0.0623	0.0201	-3.10**
Φ_3 ; D_{2006}	-0.0755	0.0240	-3.15**
Φ_4 ; D_{2007}	-0.2249	0.0277	-8.13**
Φ_5 ; D_{2008}	-0.1909	0.0335	-5.69**
Φ_6 ; D_{cod}	-1.2952	0.0494	-26.21**
Φ_7 ; $D_{haddock}$	-2.0718	0.0437	-47.39**
$\sigma^2 = \sigma_u^2 + \sigma_v^2$	1.2798	0.1707	7.50**
$\gamma = \sigma_u^2/\sigma^2$	0.7985	0.0298	26.77**
μ	-2.0218	0.3854	-5.25**
λ	0.0017	0.0003	5.64**

** Significant at the 1% level; * significant at the 5% level

Table 5.4: Generalized Likelihood Ratio Tests of hypotheses, 2004-2008

Null Hypothesis, H_0	LR statistic	df	Critical Value (1%)	
Input-output separability:				
$\delta_{11}=\delta_{12}=\delta_{13}=\delta_{14}=\delta_{21}=\delta_{22}=\delta_{23}=\delta_{24}=0$	797	8	20.09	Reject H_0
Cobb-Douglas frontier:	3,024	21	38.93	Reject H_0
Technical inefficiency is absent:				
$\gamma=\lambda=\mu=0$	1,551	3	7.05	Reject H_0

Note: As γ takes values between 0 and 1, in H_0: $\gamma = \lambda = \mu = 0$ the statistic is distributed according to a mixed χ^2 whose critical value is obtained from Kodde and Palm (1986).

5.3 Concluding Remarks

This chapter has attempted to test the main predictions of the theoretical model introduced in the second chapter on the formation of voluntary harvesting cooperatives in commercial fisheries. Building on earlier research that establishes links between technical efficiency and fishing skill (Kirkley et al. 1998, Viswanathan et al. 2002, Hoff and Frost 2005), the analysis uses technical efficiency to study the formation of the Georges Bank Cod Hook Sector, the first sector to start operations in the New England groundfish fishery. The approach has been to estimate a system of equations defining a stochastic output distance function with technical inefficiency effects (Battese and Coelli 1992, 1995) using maximum likelihood estimation. The empirical results confirm that indeed the least efficient vessels later became Hook Sector members and that this subset of vessels seemed to have engaged in some kind of cooperative behavior prior to the constitution of GB Cod Hook sector in 2004. In fact, the results suggest that the coordination of the harvesting may have helped these vessels to overcome their lower skill level. This was certainly the case for the seasons 2004-2008 when the GB Hook sector was officially in operation, as is clear from the estimated efficiency scores for that period. These findings are consistent with the claims that 1) familiarity with team fishing increases the likelihood of sector adoption by fishermen, since it lessens the uncertainty on the profitability of the collective operation, and that 2) returns from cooperation increase over time as a result of learning and accumulation of social capital.

A limitation of the approach adopted in this study is that it has relied exclusively on the analysis of technical efficiency. The unavailability of cost data has precluded the estimation of profit or cost frontiers. Economic efficiency, however, has technical and allocative components. While the technical component refers to the ability to avoid waste by producing as much output as technology and inputs allow, the allocative component is equally important as it refers to the ability to combine inputs and outputs in optimal proportions in light of prevailing prices. Thus, while the findings of this chapter seem to support the predictions presented in the theoretical model introduced in the previous chapter, they should be interpreted with some caution.

Chapter 6: Conclusion

The adoption of market-based rationalization programs in commercial fisheries has been met by a great deal of success in countries like Australia, Canada and New Zealand. Drawing on these previous experiences, the U.S. National Marine Fisheries Service has endorsed in 2010 the adoption of rights-based systems by releasing a "NOAA Catch Share Policy", in which it encourages regional councils to consider the use individual or collective harvesting quotas. Rights-based systems give fishermen a stake in the health of the fishery, often reducing the adversarial nature of fisheries regulation and management and creating stewardship incentives among participants. The allocation of quota shares to harvest cooperatives, in particular, has recently generated considerable interest among fishermen and regulators. Many consider the promotion of self-governance by increasing the scope of decisions assumed by the industry to be essential to achieving more sustainable, equitable and efficient management.

Successful case studies of self-governance in fisheries have been extensively documented and the efficiency gains associated with cooperative harvesting are well established. Nevertheless, self-governance has emerged in relatively few of the world's fisheries. Research on the obstacles to the adoption of self-regulation has traditionally focused on the number and heterogeneity of harvesters and the difficulties of enforcement and free-riding. Yet it is doubtful that these obstacles exhaust all the conditions under which fishermen's attempts to self-organize break down. Furthermore, once fishermen do decide to join harvesting cooperatives they face strong incentives to actively engage in cooperation to both reduce the cost of fishing effort and increase the value of their catch.

Cooperation can boost profitability and is typically achieved through the design of fishing rules that attempt to coordinate the activities of coop members. Anecdotal evidence shows these fishing rules do not remain unchanged but evolve through time, allowing groups to progressively broaden the scope of their cooperation. Thus, the accumulation of experience in team fishing as permit holders work together seems to be a critical trigger in the development of more complex collective fishing schemes.

This dissertation adopts a different perspective from the earlier literature by examining how incomplete information on the optimal implementation of collective fishing: i) affects the incentives to undertake cooperation, and ii) determines the likely path of coordination of activities within the group when cooperation emerges. I begin by developing a theoretical model of the fishery in which fishers have limited previous experience with team fishing, but learn-by-doing. Each season fishermen must decide whether to harvest competitively in the common pool, or instead join a cooperative group (a sector) and choose the number of tasks to coordinate based on fishermen's current information on collective fishing. Only upon joining the sector do harvesters receive as allocation a share of the total allowable catch (TAC). In the dissertation I study the equilibria of the sector-formation game played by the heterogeneous fishermen, to answer the following questions concerning fishing cooperatives: Under what conditions are harvesting cooperatives or sectors expected to form? Who will join? What types of harvesting schemes will emerge?

The model predicts that a lack of familiarity of fishermen with cooperative harvesting may entirely preclude cooperatives from forming. On the other hand, if sectors do organize, the least skilled permit holders in the fishery have incentives to join first and the scope of their cooperation (i.e. the number of coordinated tasks) is expected to increase gradually over time. The model also shows that sector members have incentives to consolidate their fleet when there is overcapacity (i.e. excess capacity to catch the sector's quota) and extend the duration of the season. These results are consistent with a variety of stylized facts about fishing coops. They help explain, for example, the increase in season length associated with the formation of cooperatives such as the Chignik Cooperative and the Pacific Whiting Conservation Cooperative, and why it is rather infrequent to see quota holders pooling their shares of the TAC and fishing cooperatively despite the potential efficiency gains. Furthermore, the rationale offered in the model – incomplete information on how to organize collective fishing– is essentially different from the familiar free-riding in teams, or from adverse selection arguments that rely on asymmetric information on permit holders' skills.

The empirical component of this dissertation examines the predictions of the theoretical model using information on the fishermen that in 2004 voluntarily joined the first sector to start operations in the New England Multispecies Fishery, the Georges Bank Cod Hook sector. Concretely, the empirical section studies whether these fishermen were less skilled than those that chose to remain independent, whether they had actively engaged in cooperation (i.e. hence, acquiring familiarity with team fishing) before the sector was formally constituted, and if learning occur during the sector operation years. Lacking cost information on the fishery, I build on the existing literature linking harvesting skill and technical efficiency and conduct the analysis using a primal approach. Concretely, I estimate a stochastic output distance function and a technical inefficiency model for the hook gear fleet. The simultaneous estimation of this system of equations allows the characterization of the underlying multi-output technology and the assessment of the impact of vessel characteristics and fleet conditions (i.e. such as crowding of fishing grounds and cooperative interactions) on vessels' technical efficiencies. Unlike most empirical studies of fisheries production frontiers, which implicitly assume input-output separability and estimate a weighted aggregate measure of output as function of inputs, this dissertation uses a multi-output approach, allowing for the testing of the separability assumption and the derivation of the ability of fishermen to alter their output mix. Second, the analysis is applied to panel data, and unlike short-term studies, it explicitly incorporates the variability of stocks biomasses over time into the estimation. Third, the study explicitly accounts for the effect of fishermen's interactions on efficiency in order to identify cooperation among harvesters. The results show that indeed the least efficient vessels were the first to join the Georges Bank Cod Hook sector in 2004, present evidence of earlier cooperation among these fishermen and demonstrate that technical efficiency was higher for sector vessels than common pool boats during the sector years and increased during this period.

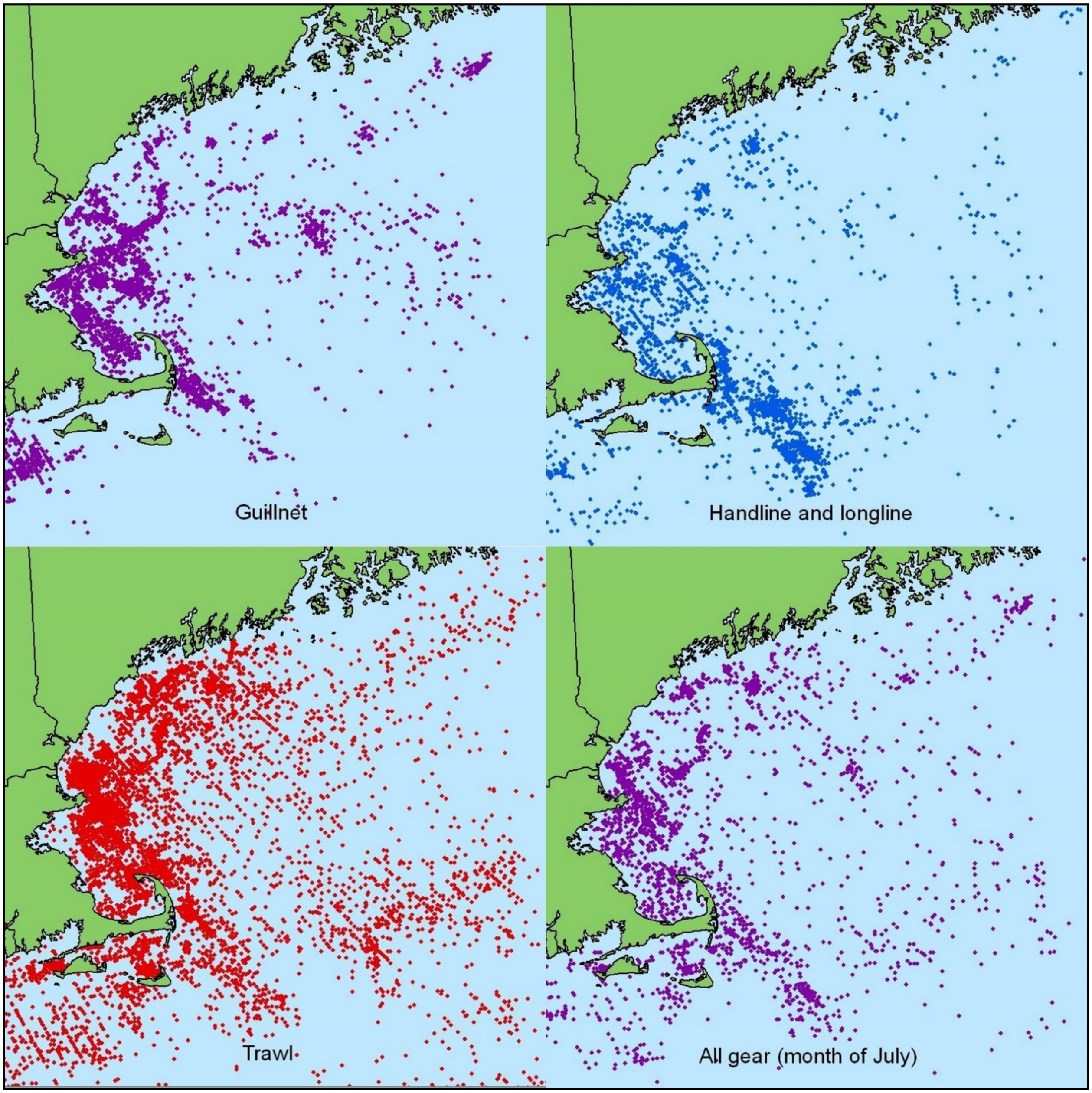
The success of harvesting cooperatives or sectors is likely to rest partly on the strength of the relationships among fishermen, including their degree of trust and collaboration. It is reasonable to think that successful sectors will build norms and networks that enable collective action and learning over time. The analysis in this dissertation highlights the role of human capital, conceived here as fishermen's stock of shared-experience with collective harvesting, in the formation of cooperatives. This research shows that the regulator should explicitly address questions concerning the type of infrastructure, supporting institutions and training programs that would help accelerate the learning process regarding this new way of fishing and thus boost the adoption of collective arrangements of self-governance.

Building capacity among fishermen to organize and administer sectors will likely entail empowering existing platforms for collective action such as fishermen's associations, documenting previous experiences to encourage learning from successes in other fisheries, and coaching and guidance on business planning and management. Not surprisingly, thirteen of the nineteen recently approved sector plans were submitted by the same institution, the Northeast Seafood Coalition, a membership organization that represents fishermen interests. This dissertation shows that, from a policy standpoint, building capacity among harvesters is an essential and irreplaceable complement to the assignment of property rights when the end objective is to promote self-governance. Furthermore, this research demonstrates that management agencies should not expect the efficiency gains stemming from fishermen's cooperation to be realized immediately but rather gradually over time if harvesters must first learn to coordinate their activities. The regulator should pay attention to these matters, as it could have serious policy implications in terms of reducing the long-term economic and environmental costs of the transition to catch shares.

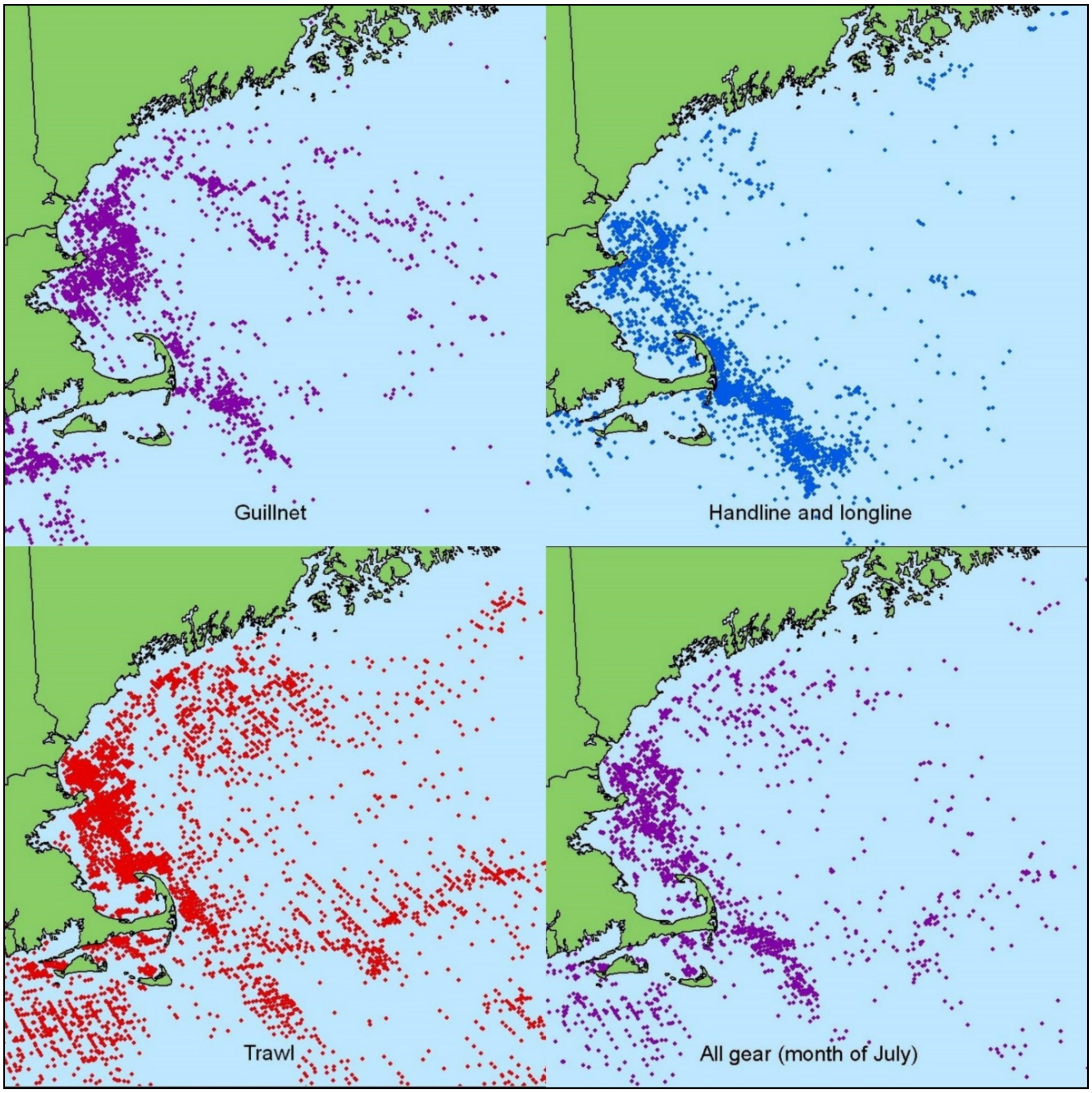
There are a number of potential extensions of this dissertation research. In the current analysis, many of the problems of the internal governance structure of the cooperative (such as free-riding, bargaining and moral hazard) are assumed away. In the theory section the sector manager is modeled as implementing all of the decisions for the group, and hence frictions within the team activity are absent. Future work should explore the implications of relaxing this assumption. Furthermore, in the analysis in this dissertation, the regulator is in the "background" and its only role is to set the TAC each season. Hence, problems of monitoring of landings and enforcement of quotas are ruled out. However, if compliance requires costly enforcement, it is worthwhile exploring under what conditions the regulator is better off dealing with fewer players (i.e. sectors) that have incentives to police each other, rather than with individual fishermen. Further, how do the incentives to join the sector change when overages of the common TAC undermine the sectors' allocations the following period? Further research should investigate these and similar questions. Ultimately, the successful implementation of catch shares, with their intended benefits in terms of higher industry profits and sustainability of the resource, depend on the answers to such questions.

APPENDIX A: Spatial Distribution of Trips by Gear

Map 1: Distribution of 1995 Groundfish Season Trips by Gear (GB and GOM region)



Map 2: Distribution of 2001 Groundfish Season Trips by Gear (GB and GOM region)



APPENDIX B: Derivation of Log-Likelihood Functions

I. The earlier years: 1994-2003[33]

For simplicity of exposition and in order to avoid cumbersome notation, I rewrite the inefficiency stochastic frontier model defined by equations (3.20) and (3.24) as:

$$(\mathrm{A.B.1}) \qquad y_{it} = \boldsymbol{x}_{it}\boldsymbol{\beta} + \varepsilon_{it}$$

$$(\mathrm{A.B.2}) \qquad u_{it} = \boldsymbol{z}_{it}\boldsymbol{\theta} + \eta_{it}$$

where $\varepsilon_{it} = v_{it} - u_{it}$, i=1,2,3,…,N, and t=1,2,3,…,T. It is assumed that the v_{it} are i.i.d $\mathrm{N}(0, \sigma_V^2)$ random variables, independent of the u_{it}'s, which are assumed non-negative truncations of the $\mathrm{N}(\boldsymbol{z}_{it}\boldsymbol{\theta}, \sigma_u^2)$ distribution.

Thus, equation (3.20) is rewritten as equation (A.B.1), where y_{it} represents, in fact, the logarithm of "other species" partial mortality for the i[th] vessel in the t[th] time period, and $\boldsymbol{x}_{it}$ and $\boldsymbol{\beta}$ denote, respectively, the vectors of independent variables and parameters in (3.20).

The density function for v_{it} is given by:

$$(\mathrm{A.B.3}) \qquad f_v(v_{it}) = \frac{1}{\sqrt{2\pi}\sigma_v} \cdot exp\left\{-\frac{{v_{it}}^2}{2\sigma_v^2}\right\}, \quad -\infty < v_{it} < \infty$$

The truncated normal density function for u_{it} is given by:

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[33] For additional details, see Coelli and Battese (1993), and Kumbhakar and Lovell (2000).

$$\text{(A.B.4)} \qquad f_u(u_{it}) = \frac{1}{\sqrt{2\pi}\sigma_u \, \Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)} \cdot exp\left\{-\frac{(u_{it} - z_{it}\boldsymbol{\theta})^2}{2\sigma_u^2}\right\}, \quad u_{it} \geq 0$$

where $\boldsymbol{z}_{it}\boldsymbol{\theta}$ is the mean of the normal distribution, which is truncated below at zero, and $\Phi(\cdot)$ the standard normal cumulative distribution function. Thus $f_u(u_{it})$ is the density function of a normally distributed variable with nonzero mean $\boldsymbol{z}_{it}\boldsymbol{\theta}$, truncated below at zero. Given the independence assumption, the joint density function of u_{it} and v_{it} is simply the product of their individual density functions, and so:

$$\text{(A.B.5)} \qquad f_{u,v}(u_{it}, v_{it}) = \frac{1}{2\pi\sigma_u\sigma_v \, \Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)} \cdot exp\left\{-\frac{(u_{it} - \boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2\sigma_u^2} - \frac{{v_{it}}^2}{2\sigma_v^2}\right\}$$

Since from (A.B.2) $\varepsilon_{it} = v_{it} - u_{it}$, the joint density function of u_{it} and ε_{it} is:

$$\text{(A.B.6)} \qquad f_{u,\varepsilon}(u_{it}, \varepsilon_{it}) = \frac{1}{2\pi\sigma_u\sigma_v \, \Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)} \cdot exp\left\{-\frac{(u_{it} - \boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2\sigma_u^2} - \frac{(\varepsilon_{it} + u_{it})^2}{2\sigma_v^2}\right\}$$

which, upon defining $\mu_{it*} = (\sigma_v^2\boldsymbol{z}_{it}\boldsymbol{\theta} - \varepsilon_{it}\sigma_u^2)/(\sigma_u^2 + \sigma_v^2)$ and $\sigma_*^2 = \sigma_u^2\sigma_v^2/(\sigma_u^2 + \sigma_v^2)$, can be rewritten as:

$$\text{(A.B.7)} \quad f_{u,\varepsilon}(u_{it}, \varepsilon_{it})$$
$$= \frac{1}{2\pi\sigma_u\sigma_v \, \Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)} \cdot exp\left\{-\frac{(u_{it} - \mu_{it*})^2}{2\sigma_*^2} - \frac{\varepsilon_{it}^2}{2\sigma_v^2} - \frac{(\boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2\sigma_u^2} - \frac{\mu_{it*}^2}{2\sigma_*^2}\right\}$$

The marginal density of ε_{it} is obtained by integrating u_{it} out of $f_{u,\varepsilon}(u_{it}, \varepsilon_{it})$:

$$(\mathrm{A.B.8}) \qquad f_\varepsilon(\varepsilon_{it}) = \int_0^\infty f_{u,\varepsilon}(u_{it}, \varepsilon_{it}) du_{it}$$

which yields (A.B.9):

$$f_\varepsilon(\varepsilon_{it}) = \frac{1}{\sqrt{2\pi}\sigma_u\sigma_v \, \Phi(\boldsymbol{z\theta}/\sigma_u)} \cdot exp\left\{-\frac{{\varepsilon_{it}}^2}{2\sigma_v^2} - \frac{(\boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2\sigma_u^2} + \frac{\mu_{it*}^2}{2\sigma_*^2}\right\} \int_0^\infty \frac{1}{\sqrt{2\pi}} \cdot exp\left\{-\frac{(u_{it} - \mu_{it*})^2}{2\sigma_*^2}\right\} du_{it}$$

or,

$$(\mathrm{A.B.10}) \quad f_\varepsilon(\varepsilon_{it}) = \frac{1}{\sqrt{2\pi} \, (\sigma_u^2 + \sigma_v^2)^{1/2} [\Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)/\Phi(\mu_{it*}/\sigma_*)]} \cdot \; exp\left\{-\frac{{\varepsilon_{it}}^2}{2\sigma_v^2} - \frac{(\boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2\sigma_u^2} + \frac{\mu_{it*}^2}{2\sigma_*^2}\right\}$$

which can be rewritten as:

$$(\mathrm{A.B.11}) \quad f_\varepsilon(\varepsilon_{it}) = \frac{1}{\sqrt{2\pi} \, (\sigma_u^2 + \sigma_v^2)^{1/2} [\Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)/\Phi(\mu_{it*}/\sigma_*)]} \cdot \; exp\left\{-\frac{(\varepsilon_{it} + \boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2(\sigma_u^2 + \sigma_v^2)}\right\}$$

Substituting $\varepsilon_{it} = y_{it} - \boldsymbol{x}_{it}\boldsymbol{\beta}$ into (A2.11), yields the density function for y_{it}:

$$(\mathrm{A.B.12}) \quad f_y(y_{it})$$

$$= \frac{1}{\sqrt{2\pi}\ (\sigma_u^2 + \sigma_v^2)^{1/2} [\Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u)/\Phi(\mu_{it}^{**}/\sigma_*)]}$$

$$\cdot\, exp\left\{-\frac{(y_{it} - \boldsymbol{x}_{it}\boldsymbol{\beta} + \boldsymbol{z}_{it}\boldsymbol{\theta})^2}{2(\sigma_u^2 + \sigma_v^2)}\right\}$$

where $\mu_{it}^{**} = [\sigma_v^2 \boldsymbol{z}_{it}\boldsymbol{\theta} - \sigma_u^2(y_{it} - \boldsymbol{x}_{it}\boldsymbol{\beta})]/(\sigma_u^2 + \sigma_v^2)$.

If there are T_i observations for the i^{th} vessel, and denoting $\boldsymbol{y}_i = (y_{i1}, y_{i2}, \dots, y_{iT_i})'$ the vector of the T_i partial fishing mortalities in equation (A.B.1), then the logarithm of the likelihood function for the whole sample, $\boldsymbol{y} = (\boldsymbol{y}_1', \boldsymbol{y}_2', \dots, \boldsymbol{y}_N')$, is given by:

$$(\mathrm{A.B.13}) \qquad \mathcal{L}(\boldsymbol{\vartheta}; \boldsymbol{y}) = -\frac{1}{2}\left(\sum_{i=1}^{N} T_i\right)\{ln\ 2\pi\ + ln\ (\sigma_u^2 + \sigma_v^2)\}$$

$$-\frac{1}{2}\sum_{i=1}^{N}\sum_{t=1}^{T_i}\left[\frac{(y_{it} - \boldsymbol{x}_{it}\,\boldsymbol{\beta} + \boldsymbol{z}_{it}\boldsymbol{\theta})^2}{\sigma_u^2 + \sigma_v^2}\right]$$

$$-\sum_{i=1}^{N}\sum_{t=1}^{T_i}[ln\ \Phi(\boldsymbol{z}_{it}\boldsymbol{\theta}/\sigma_u) - ln\ \Phi(\mu_{it}^{**}/\sigma_*)]$$

where $\boldsymbol{\vartheta} = (\boldsymbol{\beta}', \boldsymbol{\theta}', \sigma_v^2, \sigma_u^2)'$ is the vector of parameters to estimate.

Finally, using the reparameterization suggested by Battese and Corra (1977), $\gamma = \sigma_u^2/\sigma^2$, with $\sigma^2 = \sigma_u^2 + \sigma_v^2$, the log likelihood function in (A2.12) can be rewritten as:

$$(\mathrm{A.B.14}) \qquad \mathcal{L}(\boldsymbol{\vartheta}^*;\boldsymbol{y}) = -\frac{1}{2}\left(\sum_{i=1}^{N} T_i\right)\{ln\, 2\pi \;+ ln\, \sigma^2\}$$

$$-\frac{1}{2}\sum_{i=1}^{N}\sum_{t=1}^{T_i}\left[\frac{(y_{it} - \boldsymbol{x}_{it}\,\boldsymbol{\beta} + \boldsymbol{z}_{it}\boldsymbol{\theta})^2}{\sigma^2}\right]$$

$$-\sum_{i=1}^{N}\sum_{t=1}^{T_i}[ln\,\Phi(d_{it}) - ln\,\Phi(d_{it}^*)]$$

where $d_{it} = \boldsymbol{z}_{it}\boldsymbol{\theta}/(\gamma\sigma^2)^{1/2}$, $d_{it}^* = [(1-\gamma)\boldsymbol{z}_{it}\boldsymbol{\theta} - \gamma(y_{it} - \boldsymbol{x}_{it}\,\boldsymbol{\beta})]/[\gamma(1-\gamma)\sigma^2]^{1/2}$, and $\boldsymbol{\vartheta}^* = (\boldsymbol{\beta}', \boldsymbol{\theta}', \gamma, \sigma^2)'$ is the vector of model parameters to estimate.

II. The sector years: 2004-2008[34]

As in the previous section, rewrite the system of equations (3.20) and (3.25) as:

$$(\mathrm{A.B.15}) \qquad y_{it} = \boldsymbol{x}_{it}\boldsymbol{\beta} \;+ \varepsilon_{it}$$

$$(\mathrm{A.B.16}) \qquad u_{it} = \lambda_{it} u_i$$

where $\lambda_{it} = exp\{-\lambda(t - T_i)\}$ and $\varepsilon_{it} = v_{it} - \lambda_{it}u_i$. It is assumed that the v_{it} are i.i.d $\mathrm{N}(0, \sigma_V^2)$ random variables, independent of the u_i's, which are assumed non-negative truncations of the $\mathrm{N}(\mu, \sigma_u^2)$ distribution

The density function for u_i is:

[34] For additional details, see Coelli and Battese (1992), and Kumbhakar and Lovell (2000).

(A. B. 17)
$$f_u = \frac{1}{\sqrt{2\pi}\sigma_u\,[1 - \ \Phi(-\mu/\sigma_u)]} \cdot exp\left\{-\frac{(u_i-\mu)^2}{2\sigma_u^2}\right\}, \quad u_i \geq 0$$

where, as before, $\Phi(\cdot)$ represents the standard normal cumulative distribution function. Using the independence assumption between u_i and v_{it}, write their joint density function as:

(A. B. 18)
$$f_{u,v}(u_i, v_{it}) = \frac{1}{2\pi\sigma_u\sigma_v\,[1 - \ \Phi(-\mu/\sigma_u)])} \cdot exp\left\{-\frac{(u_i-\mu)^2}{2\sigma_u^2} - \frac{{v_{it}}^2}{2\sigma_v^2}\right\}$$

Since $\varepsilon_{it} = v_{it} - \lambda_{it}u_i$, the joint density function of u_i and ε_{it} is given by:

(A. B. 19)
$$f_{u,\varepsilon}(u_i, \varepsilon_{it})$$
$$= \frac{1}{2\pi\sigma_u\sigma_v\,[1 - \ \Phi(-\mu/\sigma_u)])} \cdot exp\left\{-\frac{(u_i-\mu)^2}{2\sigma_u^2} - \frac{(\varepsilon_{it}+\lambda_{it}u_i)^2}{2\sigma_v^2}\right\}$$

Defining $\mu_{it*} = (\sigma_v^2\mu - \lambda_{it}\varepsilon_{it}\sigma_u^2)/(\sigma_v^2 + \lambda_{it}^2\sigma_u^2)$ and $\sigma_{it*}^2 = \sigma_u^2\sigma_v^2/(\sigma_v^2 + \lambda_{it}^2\sigma_u^2)$, the joint density function in (A2.19) can be rewritten as:

(A. B. 20)
$$f_{u,\varepsilon}(u_i, \varepsilon_{it})$$
$$= \frac{1}{2\pi\sigma_u\sigma_v\,[1 - \Phi(-\mu/\sigma_u)]} \cdot exp\left\{-\frac{(u_i-\mu_{it*})^2}{2\sigma_{it*}^2} - \frac{\varepsilon_{it}^2}{2\sigma_v^2} - \frac{\mu^2}{2\sigma_u^2} - \frac{\mu_{it*}^2}{2\sigma_{it*}^2}\right\}$$

The density function for ε_{it} is obtained by integrating $f_{u,\varepsilon}(u_i, \varepsilon_{it})$ with respect to the range for u_i, namely $u_i \geq 0$, to yield (A.B.21),

$$f_\varepsilon(\varepsilon_{it}) = \frac{1}{\sqrt{2\pi}\sigma_u\sigma_v\,[1-\Phi(-\mu/\sigma_u)]}\cdot exp\left\{-\frac{{\varepsilon_{it}}^2}{2\sigma_v^2}-\frac{\mu^2}{2\sigma_u^2}+\frac{\mu_{it*}^2}{2\sigma_{it*}^2}\right\}\int_0^\infty \frac{1}{\sqrt{2\pi}}$$

$$\cdot\, exp\left\{-\frac{(u_i-\mu_{it*})^2}{2\sigma_{it*}^2}\right\}du_i$$

or,

$$(\mathrm{A.B.22})\qquad f_\varepsilon(\varepsilon_{it})$$

$$= \frac{[1-\Phi(-\mu_{it*}/\sigma_*)]}{\sqrt{2\pi}\;(\sigma_v^2+\lambda_{it}^2\sigma_u^2)^{1/2}[1-\Phi(-\mu/\sigma_u)]}\cdot\; exp\left\{-\frac{{\varepsilon_{it}}^2}{2\sigma_v^2}-\frac{\mu^2}{2\sigma_u^2}+\frac{\mu_{it*}^2}{2\sigma_{it*}^2}\right\}$$

Denoting by $\boldsymbol{\varepsilon}_i$ the (T_ix1) vector of the ε_{it}'s (with $\varepsilon_{it} = v_{it} - \lambda_{it}u_i$) associated with the T_i observations for the ith vessel, the density function for $\boldsymbol{\varepsilon}_i$ can be written as (A.B.23) below:

$$f_\varepsilon(\boldsymbol{\varepsilon}_i) = \frac{[1-\Phi(-\mu_{i*}/\sigma_{i*})]}{(2\pi)^{T_i/2}\sigma_v^{(T_i-1)}\;(\sigma_v^2+\lambda_i{}'\lambda_i\sigma_u^2)^{1/2}[1-\Phi(-\mu/\sigma_u)]}$$

$$\cdot\;\, exp\left\{-\frac{\boldsymbol{\varepsilon}_i{}'\boldsymbol{\varepsilon}_i}{2\sigma_v^2}-\frac{\mu^2}{2\sigma_u^2}+\frac{\mu_{it*}^2}{2\sigma_{i*}^2}\right\}$$

where $\mu_i^* = (\sigma_v^2\mu - \boldsymbol{\lambda}_i{}'\boldsymbol{\lambda}_i\boldsymbol{\varepsilon}_i\sigma_u^2)/(\sigma_v^2+\boldsymbol{\lambda}_i{}'\boldsymbol{\lambda}_i\sigma_u^2)$ and $\sigma_{i*}^2 = \sigma_u^2\sigma_v^2/(\sigma_v^2+\boldsymbol{\lambda}_i{}'\boldsymbol{\lambda}_i\sigma_u^2)$.

The density function for $\boldsymbol{y}_i$, the (T_ix1) random vector of y_{it}'s for the ith vessel, is obtained from (A.B.23) by substituting $\boldsymbol{y}_i - \boldsymbol{x}_i\boldsymbol{\beta}$ for $\boldsymbol{\varepsilon}_i$, where $\boldsymbol{x}_i$ is the ($T_i$xk) matrix of x_{it}'s for the ith vessel, where k is the dimension of the vector of parameters $\boldsymbol{\beta}$**.** The log-likelihood function for the sample of observations, $\boldsymbol{y} = (\boldsymbol{y}_1', \boldsymbol{y}_2', \dots, \boldsymbol{y}_N')$, is thus:

$$(\mathrm{A.B.24}) \qquad \mathcal{L}(\boldsymbol{\vartheta};\boldsymbol{y}) = -\frac{1}{2}\left(\sum_{i=1}^{N} T_i\right) ln\ 2\pi - \frac{1}{2}\sum_{i=1}^{N}(T_i - 1) ln\sigma_v^2$$

$$-\frac{1}{2}\sum_{i=1}^{N} ln\ (\sigma_v^2 + \boldsymbol{\lambda}_i{}'\boldsymbol{\lambda}_i\sigma_u^2) - Nln[1 - \Phi(-\mu/\sigma_u)]\ + \sum_{i=1}^{N} ln[1 - \Phi(-\mu_i^*/\sigma_i^*)]$$

$$-\frac{1}{2}\sum_{i=1}^{N}\frac{[(\boldsymbol{y}_i - \boldsymbol{x}_i\boldsymbol{\beta}\,)'(\boldsymbol{y}_i - \boldsymbol{x}_i\boldsymbol{\beta}\,)]}{\sigma_v^2} - \frac{1}{2}N(\mu/\sigma_u)^2 + \frac{1}{2}\sum_{i=1}^{N}(\mu_i^*/\sigma_i^*)^2$$

where $\boldsymbol{\vartheta} = (\boldsymbol{\beta}', \sigma_v^2, \sigma_u^2, \mu, \lambda)'$ is the vector of model parameters to estimate.

Finally, using the reparameterization suggested by Battese and Corra (1977), $\gamma = \sigma_u^2/\sigma^2$, with $\sigma^2 = \sigma_u^2 + \sigma_v^2$, the log likelihood function in (A.B.20) can be rewritten as:

$$(\mathrm{A.B.25}) \qquad \mathcal{L}(\boldsymbol{\vartheta}^*;\boldsymbol{y}) = -\frac{1}{2}\left(\sum_{i=1}^{N} T_i\right)\{ln\ 2\pi + ln\sigma^2\} - \frac{1}{2}\sum_{i=1}^{N}(T_i - 1)ln(1-\gamma)$$

$$-\frac{1}{2}\sum_{i=1}^{N} ln\ [1 + (\boldsymbol{\lambda}_i{}'\boldsymbol{\lambda}_i - 1)\gamma] - Nln[1 - \Phi(-z)]\ - \frac{1}{2}Nz^2\ + \sum_{i=1}^{N} ln[1 - \Phi(-z_i^*)]$$

$$+\frac{1}{2}\sum_{i=1}^{N} z_i^{*2} - \frac{1}{2}\sum_{i=1}^{N}\left[\frac{(\boldsymbol{y}_i - \boldsymbol{x}_i\boldsymbol{\beta}\,)'(\boldsymbol{y}_i - \boldsymbol{x}_i\boldsymbol{\beta}\,)}{(1-\gamma)\sigma^2}\right]$$

where $\boldsymbol{\vartheta}^* = (\boldsymbol{\beta}', \sigma^2, \gamma, \mu, \lambda)'$, $z = \mu/(\gamma\sigma^2)^{1/2}$ and, $z_i^* = \frac{\mu(1-\gamma) - \gamma\boldsymbol{\lambda}_i{}'((\boldsymbol{y}_i - \boldsymbol{x}_i\boldsymbol{\beta}\,)}{\{\gamma(1-\gamma)\sigma^2[1 + (\boldsymbol{\lambda}_i{}'\boldsymbol{\lambda}_i - 1)\gamma\}\}^{1/2}}$.

Glossary

Summary of the Variables in the Theoretical Model of Chapter 2:

Variable	Description
B_t	Fish biomass in *t*
c_i	Unit cost of effort of fisherman *i*
d_t	Implementation of fishing scheme ω in season *t*
h_{it}	Catch of individual fisherman *i* in season *t*
k_i	Catching skill of fisherman *i*
K	Summation of skill over all permit holders in the fishery
N	Number of permit holders in the fishery
p	Catch price
ε_t	Random disturbance in *t*
σ_ε^2	Variance of ε_t
PSC_{it}	Fisherman *i*'s quota in *t*
Q_t^S	Sector's quota in *t*
Q_t^{CP}	Common pool's quota in *t*
s_i	Member *i*'s share of sector profits
Ω	Set of collective fishing schemes
ω	Number of tasks to coordinate under fishing scheme $\omega \in \Omega$
$\overline{\omega}$	$\max\{\omega \mid \omega \in \Omega\}$
θ_ω	Target parameter for fishing scheme ω
γ_ω	Unit cost of effort reduction per input used under perfect implementation of ω
TAC_t	Total allowable catch for season *t*
T_{it}	Fishing time for fisherman *i* in season *t*
$\bar{T}$	Time the stock is available each season
X_t	Public good input provision in *t*
$\mu_t(\theta_\omega)$	Beliefs on θ_ω in season *t*
$\sigma_{\theta_{\omega t}}^2$	Variance of beliefs $\mu_t(\theta_\omega)$
$z_\omega/z_{\omega+n}$	Transferability of information on θ_ω to $\theta_{\omega+n}$

Bibliography

"2009 Status of U.S. Fisheries", National Marine Fisheries Service, 2009.

Abbott, J.K., and Wilen, J. (2010). "Voluntary Cooperation in the Commons? Evaluating the Sea State Program with Reduced Form and Structural Models". *Land Economics*, 86 (1): 131-154.

Amendment 13 to the Northeast Multispecies Fishery Management Plan, April 27, 2004, National Marine Fisheries Service.

Asada, Y., Hitasawa, Nagasaki, F. "Fishery Management in Japan". FAO Fisheries Technical Papers 238, 1983.

Barnum, D.T., and Gleason, J.M. (2008), "Bias and Precision in the DEA Two-Stage Method". *Applied Economics*, 40, 2305-2311.

Battese, G.E. (1997), "A Note on the Estimation of Cobb-Douglas Production Functions when some Explanatory Variables have Zero Values", *Journal of Agricultural Economics*, 48 (2), 250-252.

Battese, G.E., and Coelli, T.J. (1992), "Frontier Production Functions, Technical Efficiency and Panel Data: With Application to Paddy Farmers in India", Journal of Productivity Analysis 3:1/2 (June), 153-69.

Battese, G.E., and Coelli, T.J. (1995), "A model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data", *Empirical Economics*, 20, 325-332.

Battese, G.E., and Corra, G.S. (1977), "Estimation of a Production Function Frontier Model: with Application to the Pastoral Zone of Eastern Australia". *Australian Journal of Agricultural Economics*, 21 pp. 169-179.

Battese, G.E., Tveteras, R. (2006), "Agglomeration Externalities, Productivity and Technical Efficiency", *Journal of Regional Science*, Vol. 46, No., pp. 605-625.

Brännlund, R. and Lundgren, T. (2005), "A Dynamic Analysis of Interfuel Substitution for Swedish Heating Plants", *Energy Economics*, 26 (2004) 961– 976.

Buchanan, J.M., "An Economics Theory of Clubs", *Economica*, 32 (1965), pp. 1-14.

Burton, P.S. "Community Enforcement of Fisheries Effort Restrictions", *Journal of Environmental Economics and Management*, vol. 45, Issue 2, Supplement 1, March 2003, Pages 474-491

Chambers, R. (1994). "Applied Production Analysis: A Dual Approach". Cambridge University Press.

Clark, C.W., "Mathematical Bioeconomics: the Optimal Management of Renewable Resources". 2005, Wiley-Interscience.

Coelli, T.J. (1996) "A Guide to FRONTIER Version 4.1: A Computer Program for Frontier Production Estimation". CEPA Working Paper 96/07. Armidale, Australia: Department of Econometrics, University of New England.

Coelli, T.J., Rao, D.S.P., and Battese, G.E. (1998), "An Introduction to Efficiency and Productivity Analysis", Kluwer Academic Publishers, USA.

Coelli, T.J., and Perelman, S. (1996), "Efficiency Measurement, Multi-Output Technologies and Distance Functions: With Application to European Railways", CREPP Working Paper #96/05, Universite de Liege, Belgium.

Coelli, T.J., Perelman, S., and Romano, E. (1999), "Accounting for Environmental Influences in Stochastic Frontier Models: With Application to International Airlines", Journal of Productivity Analysis, 11: 251-273.

Coelli, T.J., and Perelman, S. (2000), "Technical Efficiency of European Railways: A Distance Function Approach", *Applied Economics*, 32(15): 1967-76.

Coelli, T.J., Rao, D.S.P., Battese, G.E. (2005). "An Introduction to Efficiency and Productivity Analysis". Springer.

Conlisk, J., "Why Bounded Rationality?", *Journal of Economic Literature*, Vol. 34, No. 2 (Jun., 1996), pp. 669-700.

Costello, C., Deacon, R.. (2007). "The Efficiency Gains from Fully Delineating Rights in an ITQ Fishery", *Marine Resource Economics*, Volume 22, pp. 347–361

Costello, C. Parker, D., Deacon, R. (2009). "The Efficiency Gains from Coordination Effort in a Fishery: Evidence from the Chignik Salmon Cooperative". Working Paper, UC, Santa Barbara.

Da Silva, P., Kitts, A. "Collaborative fisheries management in the Northeast US: Emerging initiatives and future directions", Marine Policy, 30 (2006), pp. 832–841.
De Groot, M.H., "Optimal statistical decisions", McGraw- Hill, Inc., 1970.

Dolsak, N., Ostrom, E., "The Commons in the New Millennium: Challenges and Adaptation". 2003, MIT press.

Duarte, C., Brasao, A., Pintassilgo, P. (2000). “Management of the Northern Atlantic Bluefin Tuna: an application of C-games”, *Marine Resource Economics*, vol. 15: 21-36.

Erdlenbruch, K., Tidball, M., van Soest, D. “Renewable Resource Management, User Heterogeneity, and the Scope for Cooperation”, *Ecological Economics*, vol. 64, Issue 3, 15 January 2008, pp. 597-602.

Esmaeili, A. (2006), “Technical Efficiency Analysis for the Iranian Fishery in the Persian Gulf”. *ICES Journal of Marine Science*, 63: 1759-1764.

Evans, K.S., Weninger, Q., “Information Sharing and Cooperative Search in Fisheries”. Working Paper, Iowa State University, 2009.

FAO Fisheries Report No. 474 Supplement Volume 1: papers presented at the FAO/Japan expert consultation on the development of community-based coastal fishery management systems from Asia and the Pacific, 1992.

Färe, R., Primont, D., “Multi-output Production and Duality: Theory and Applications”, 1995, Kluwer Academic Publishers.

“Final Amendment 16 to the Northeast Multispecies Fishery Management Plan”, October 16, 2009, National Marine Fisheries Service.

Fleet Manager’s job description, Oshe consultores S.A, 2006.

Fischbacher, U., Gächter, S., and Fehr, E. (2001). “Are People Conditionally Cooperative? Evidence from a Public Goods Experiment”. *Economics Letters*, 71, 397–404.

Fousakis, P. (2002), “Distance vs. Ray Functions: An Application to the Inshore Fishery of Greece”, *Marine Resource Economics*, Vol. 7. pp. 251-267.

Fox, K.J, Grafton, R.Q., Kirkley, J, and Squires, D. (2003), “Property Rights in a Fishery: Regulatory Change and Firm Performance”, *Journal of Environmental Economics and Management*, 46 (1): 156-77.

Fried, O., Lovell, C.A.K., and Schmidt, S., (2008). “The Measurement of Productive Efficiency and Productivity Growth” (2008), Oxford University Press.

Fujiie, M., Hayami, Y., and Kikuchi, M., (2005). “The Conditions of Collective Action For Local Commons Management: the Case of Irrigation in the Philippines”. *Agricultural Economics*, 33, 179-189.

Gaspar, F., Seki, E., (2003). “Cooperation, Status Seeking and Competitive Behavior: Theory and Evidence”, Journal of Economic Behavior and Organization, 51, 51-77.

Gabriel, O., Lange, K., Dahm, E., Wendt, T., "Fish Catching Methods of the World". Blackwell Publishing, 2005.

Georges Bank Cod Hook Sector Annual Reports, years 2004-2007.

Gonzalez, M.A. and Lopez, R.A (2007), "Political Violence and Farm Household Efficiency in Colombia", Economic Development and Cultural Change, University of Chicago Press, vol. 55(2), pp. 367-92.

Haynie, A.C., Hicks, R.L, and Schnier, K.E. (2009). "Common Property, Information, and Cooperation: Commercial Fishing in the Bering Sea". *Ecological Economics*, 69, 406-413.

Hazelhurst, B.L. (1994). "Fishing for Cognition: An Ethnography of Fishing Practice in a Community on the West Coast of Sweden." Unpublished PhD dissertation. UC, San Diego. Available at http://www.dcog.net

Heintzelman, M.D., Salant, S.W., Schott, S., "Putting Free-riding to Work: A Partnership Solution to the Common-Property Problem", *Journal of Environmental Economics and Management*, vol. 57, Issue 3, May 2009, pp. 309-320.

Hilborn, R., and Walters, C. (1992), "Quantitative Fisheries Stock Assessment". London: Chapman and Hall.

Holland, D. S. (2007). "Community-based sectors for the New England groundfish fishery", A Gulf of Maine Research Institute Report.

Hoff, A. and Frost, H. (2005), "Efficiency and Skipper Skill in the Danish Fishing Fleet", FOI, Report 177.

Holland, D.S. (2004), "Spatial Fishery Rights and Marine Zoning: A Discussion with Reference to Management of Marine Resources in New England", *Marine Resource Economics*, Vol. 19, pp. 21-40.

Johnson, R.N., Libecap, G.D., "Contracting Problems and Regulation: The Case of the Fishery". *American Economic Review*, Vol. 72, No. 5 (Dec., 1982), pp. 1005-1022.

Jovanovic, Boyan and Nyarko, Yaw, (1996). "Learning by Doing and the Choice of technology". *Econometrica*, Econometric Society, vol. 64(6), pages 1299-1310

Kaitala, V., Lindroos, M., (2001). "Nash Equilibria in a Coalition Game of the Norwegian Spring-spawning Herring fishery", *Marine Resource Economics*, vol. 15: 321-339.

Knapp, G. (2002). "Effects of the Chignik Salmon Cooperative: A survey of Chignik Salmon permit holders". Working paper, University of Alaska.

Kirkley, J.E., and Strand, I.E. (1988), “The Technology and Measurement of Multi-Species Fisheries”. *Applied Economics*, 20: 1279-92.

Kirkley, J.E., Squires, D. and Strand, I.E. (1998), “Characterizing Managerial Skill and Technical Efficiency in a Fishery”. *Journal of Productivity Analysis*, 9: 145-160.

Knapp, G. (2007). “The Chignik Salmon Cooperative: A Case Study of Allocation to a Voluntary Self-Governance Organization”. Working paper, University of Alaska.

Kumbhakar, C., and Lovell, C.A.K. 2000. “Stochastic Frontier Analysis”. Cambridge University Press.

Kodde, D., and Palm, F. (1986), ‘Wald Criteria for Jointly Testing Equality and Inequality Restrictions”. *Econometrica* 54(5), 1243-1248.

Larson, D.M., Sutton, W.R., and Terry, J.M. (1999), “Toward Behavioral Modeling of Alaska Groundfish Fisheries: A Discrete Choice Approach To Bearing Sea/Aleutian Islands Trawl Fisheries”. *Contemporary Economic Policy*, Vol. 17 (2), 267-277.

Leal, D.R., “Evolving Property Rights in Marine Fisheries”. 2004, Rowman and Littlefield.

Lynham, J. (2006), ”Schools of fishermen: a theory of information sharing in spatial search”. Working Paper, UC Santa Barbara.

Marshall, G.R. (2004). “Farmers Cooperating in the Commons? A Study of Collective Action in Salinity Management”. *Ecological Economics*, 51, 271-286.

Mason, C.F., Phillips, O.R. (1997). “Mitigating the Tragedy of the Commons through Cooperation; An Experimental Evaluation”. *Journal of Environmental Economics and Management*, 34, 148-172.

Mitchell, M.F., “The Scope and Organization of Production: Firm Dynamics over the Learning Curve”, *RAND Journal of Economics*, Vol. 31, No. 1 (Spring, 2000), pp. 180-205.

National Research Council, Office of International Affairs, “Fisheries technologies for developing countries: report of an Ad Hoc Panel of the Board on Science and Technology for International Development”, Washington, D.C. 1988.

Okello, J.J., and Swinton, S.M, From Circle of Poison to Circle of Virtue: Pesticides, Export Standards and Kenya’s Green Bean Farmers”, *Journal of Agricultural Economics*, Vol. 61, No. 2, 2010, 209–224.

Orea, L., Alvarez, A., and Morrison Paul, C. J., "Modeling and Measuring Production Processes for a Multi-Species Fishery: Alternative Technical Efficiency Estimates for the Northern Spain Hake Fishery". *Natural Resource Modeling*, V.18, number 2, summer 2005.

Ostrom, E., "Governing the Commons".1990, Cambridge University Press.

Ostrom, E. (1999). "Coping with the Tragedies of the Commons". *Annual Review of Political Science*, 2, 493-535.

Pascoe, S., Koundouri, P., and Bjorndal, T. (2007), "Estimating Targeting Ability in Multi-species Fisheries: A Primal Multi-Output Distance Function Approach". *Land Economics* 83(3), 382-397.

Pascoe, S., and Mardle, S. (2003), "Efficiency Analysis in EU Fisheries: Stochastic Production Frontiers and Data Envelopment Analysis". Centre for the Economics and Management of Aquatic Resources (CEMARE) Report 60, University of Portsmouth, UK.

Pintassilgo, P."A Aoalition Approach to the Management of High Seas Fisheries in the Presence of Externalities". *Natural Resource Modeling*, vol. 16, Number 2, Spring 2003, pp.175-197.

Platteau, J-P., Seki, E. "Community Arrangement to Overcome Market Failures: Pooling Groups in Japanese Fisheries", in "Communities and Markets in Economic Development", 2001, Oxford University Press.

Prescott, E., (1972). "The Multi-period Control Problem Under Uncertainty", *Econometrica*, 40, pp. 1043-1058.

Samakovlis, E., "The Relationship between Waste Paper and Other Inputs in the Swedish Paper Industry", *Environmental and Resource Economics,* 25: 191–212, 2003.

Sanchirico, J., (2008). "An Overview of the Economic Benefits of Cooperatives and Individual Fishing Quota Systems". Written testimony prepared for the Senate Subcommittee for Oceans, Atmosphere, Fisheries and Coast Guard of the Senate Committee on Commerce, Science, and Transportation.

Scott, A., "Obstacles to Fishery Self-Government", *Marine Resource Economics*, vol 8, pp.187-199, 1993.

Scott, A., (1999). "Moving through the Narrows: from Open Access to ITQs and Self-government, p. 105-117 in Shotton R, editor. "Use of property rights in fisheries management", FAO fisheries technical paper 404/2.Rome, FAO, 2000.

Sen, A. “Labour Allocation in a Cooperative Enterprise”, *Review of Economic Studies*, Vol. 33, No. 4 (Oct., 1966), pp. 361-371.

Shephard, R.W. (1970), “The Theory of Cost and Production Functions”. Princeton: Princeton University Press.

Simar, L., and Wilson, P.W. (2007), “Estimation and inference in two-stage, Semiparametric Models of Production Processes”. *Journal of Econometrics*, 136, 31-64.

Smith, V.L. (1968), “Economics of Production from Natural Resources”. *American Economic Review* N.3, 409-431.

Stollery, K.R. “Cooperatives as an Alternative to Regulation in Commercial Fisheries”, *Marine Resource Economics*, vol. 4. pp. 289-304. 1988

Sylvia, G., Munro Mann, H., Pugmire, C. (2008) “Achievements of the Pacific Whiting Conservation Cooperative: Rational Collaboration in a Sea of Irrational Competition”, p. 425-440 in Townsend, R., R. Shotton and H. Uchida, eds. “Case studies in Fisheries Self-Governance”, FAO Fisheries Technical No. 504, Rome, FAO, 2008.

Tsekouras, K.D., Pantzios, C.J. and Karagiannis, G. (2004), “Malmquist Productivity Index Estimation with Zero-Value Variables: The case of Greek Prefectural Training Councils”, *International Journal of Production Economics*, 89, 95-106.

Tingley, D., Pascoe, S., and Coglan L. 92003), “Factors Affecting Technical Efficiency in Fisheries: Stochastic Production Frontier versus Data Envelopment Analysis Approaches”, *Fisheries Research* 73, 363-376.

Townsend, R.., Shotton, R.., Uchida, H. (Eds). (2008). “Case studies in fisheries self-governance”. FAO Fisheries Technical Paper. No. 504. Rome, FAO.

Uchida, H, Wilen, J. (2005). “Harvester cooperative, pooling arrangements and market power”. Working paper, Department f Agricultural and Resource Economics UC, Davis.

Uchida, H. (2007). “Collective Fishery Management in TURFs: the Role of Effort Coordination and Pooling Arrangements”. Unpublished PhD. dissertation, UC Davis.

Viswanathan, K.K., Omar, I.H., Jeon, Y., Kirkley, J.E., Squires, D., Susilowati, I. (2002), “Fishing Skill in Developing Country Fisheries: The Kedah, Malaysia Trawl Fishery”. *Marine Resource Economics*, Vol. 16, pp. 293-314.

Walker, J.M., Gardner, R., Herr, A., and Ostrom, E. (2000). “Collective Choice in the Commons: Experimental Results on Proposed Allocation Rules and Votes”. *The Economic Journal*, No. 460, 212-234.

Weninger, Q. (2001). “An Analysis of the Efficient Production Frontier in the Fishery: Implications for Enhanced Fisheries Management”. *Applied Economics*, 33, 71-79.

Weninger, Q., Strand, I.E. (2003). “An Empirical Analysis of Production Distortions in the Mid-Atlantic Surf Clam and Ocean Quahog Fishery”. *Applied Economics*, 1191-1197.

Weninger, Q., Waters, J.R. (2003). “Economic Benefits of Management Reform in the Northern Gulf of Mexico Reef Fish Fishery”. *Journal of Environmental Economics and Management*, 46, 207-230.

Wilson, R., (1975). “Informational Economies of Scale”, *Bell Journal of Economics*, 6, pp. 184-195.