# THE INFLUENCE OF INDIVIDUAL TRANSFERABLE QUOTAS ON DISCARDING AND FISHING BEHAVIOR IN MULTISPECIES FISHERIES

Trevor A. Branch

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This is to certify that I have examined this copy of a doctoral dissertation by

Trevor A. Branch

and have found that it is complete and satisfactory in all respects,
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Chair of Supervisory Committee:

__________________________________
Ray Hilborn

Reading Committee:

__________________________________
Ray Hilborn

__________________________________
André E. Punt

__________________________________
Robert C. Francis

Date:____________________________

University of Washington

**Abstract**

The influence of individual transferable quotas on discarding
and fishing behavior in multispecies fisheries

Trevor A. Branch

Chair of the Supervisory Committee:
Professor Ray Hilborn
School of Aquatic and Fishery Sciences

Under individual transferable quotas (ITQs), participants receive a share of the total allowable catch (TAC), can choose when to fish, and can sell or lease their share. ITQs generally increase fishing flexibility, improve profitability, reduce overcapitalization, and may improve sustainability of the resource through increased stewardship incentives. However, ITQs may increase high-grading and discarding, and create social problems because quota owners have increased control compared to other stakeholders. The U.S. West Coast groundfish trawl fishery is managed under two-monthly landing limits (not ITQs) for each species and has generally high discard levels. The British Columbia groundfish trawl fishery (B.C. fishery) is an ITQ fishery with full observer coverage, where marketable discard mortality is deducted from quotas. Under this system, total discards declined for most species, and marketable discards declined from 0.20% to 0.10%, after an adjustment period. The B.C. system would likely reduce discards in the West Coast fishery, although severe catch restrictions on overfished West Coast species may limit these reductions. To predict fishing changes under fishery regulations, a method was developed for defining “fishing opportunities” for each vessel—groups of

trawls over the same portion of a fishing ground. This method uses simple clustering method on Euclidean distances between trawls, offers a more realistic way of defining fishing opportunities than grid cells, and is able to correctly classify simulated trawls into fishing opportunities. The top vessels in the B.C. fishery frequented a wide variety of fishing opportunities (mean 38, range 20–69), in which trawls generally caught similar species. The B.C. fishery is a multispecies fishery with TACs imposed on 22 species. Despite these constraints, skippers were able to adjust the species mixture in their catches to match changes in TACs. Skippers reduced catches of rougheye, shortraker, and yelloweye rockfish by more than 50% when TACs for those species were reduced. However, there was only weak evidence that skippers changed their fishing patterns based on the species mixture of all of the most important species. Instead, a variety of other factors were likely important in determining which fishing opportunities are preferred and avoided in the B.C. fishery.

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## ABBREVIATIONS

**Standard abbreviations**
CPUE: catch per unit of effort
IFQ: individual fishing quota
IQ: individual quota
IPQ: individual processing quota
ITQ: individual transferable quota
IVQ: individual vessel quota
MPA: marine protected areas
NMFS: National Marine Fisheries Service
NOAA: National Oceanic and Atmospheric Administration
NRC: National Research Council
TAC: total allowable catch

**Fisheries abbreviations**
B.C. fishery: British Columbia groundfish trawl fishery
BSAI crab fisheries: Bering Sea and Aleutian Island crab fisheries
SBT fishery: Australian southern bluefin tuna fishery
SCOQ fishery: U.S. surfclam and ocean quahog fishery
West Coast fishery: U.S. West Coast groundfish trawl fishery

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# INTRODUCTION

Individual transferable quotas (ITQs) have proved to be effective remedies for overcapitalization and the race for fish in many single-species fisheries, but are more problematic in multispecies fisheries. The underlying problem is that each of the many species in a multispecies fishery can sustain different maximum rates of harvest, but the species that are unproductive may be just as susceptible to fishing gear as species that are relatively more productive. Under ITQs, quotas for each species are allocated as shares of those species' total allowable catches (TACs), which are usually based on the productivity of each species and not on their relative catchability. Individual vessels will generally catch their quota share for some species before they catch their share of other species. This situation provides incentives to misreport, high-grade, or discard additional catches of some species in order to continue fishing for other species (e.g., Copes 1986). In existing multispecies fisheries, several approaches have been taken to address this problem, including leasing additional quota, carrying overages and underages forward to the next year, and forfeiting catches. These approaches are based on the assumption that it would be too difficult or expensive for fishers to change their fishing practices so that their catches closely match their quotas, and that it would be too costly to require full on-board observer coverage to account for discards. However, in the British Columbia groundfish fishery (B.C. fishery), mandatory on-board observer coverage has proved to be economically viable. In the B.C. fishery, in addition to full observer coverage, discard mortality of marketable fish is deducted from quotas, and vessels are required to stop bottom trawling if they are unable to lease quota to cover overages in excess of those allowed (Turris 2000). This suite of measures removes the incentives for fishers to misreport, high-grade and discard quota species, and provides strong incentives for them to alter their behavior so that their catches closely match their quotas. The B.C. fishery management system is of interest to the multispecies U.S. West Coast groundfish trawl fishery (West Coast fishery), which is considering moving from non-tradable two-monthly landing limits, to ITQs.

In this dissertation, the impacts of ITQs on fisheries other than the West Coast and B.C. fisheries are reviewed, with particular consideration paid to their effects on multispecies fisheries, and on the management of fisheries (Chapter 1). The current discarding patterns in the B.C. and in the West Coast fisheries are contrasted. It is suggested that if ITQs and the suite of management measures characteristic of the B.C. fishery were implemented in the West Coast fishery then discards (especially of marketable fish) might be reduced (Chapter 2). A clustering methodology is developed for defining “fishing opportunities”—vessel-specific groups of trawls conducted over the same portion of a fishing ground (Chapter 3). Finally, the B.C. fishery is examined for evidence that skippers changed their fishing patterns in order to match catches to quotas for each species (Chapter 4).

Figures and tables have been placed at the end of each chapter and scientific names for all species can be found in Appendix A.

# CHAPTER 1

# REVIEW OF INDIVIDUAL TRANSFERABLE QUOTA PROGRAMS

## Introduction

Fisheries management involves trade-offs between generally conflicting biological, economic, and social objectives. It is rare to hear of fisheries where the stocks are sustainably harvested, substantial economic rents are being generated, and participants (and ex-participants) consider the system to be equitable and fair. Instead, the most widely cited stories are those of failures: the collapse of the northern cod fishery (Hutchings and Myers 1994), 90% declines in large predatory fish (Myers and Worm 2003), the destruction of coastal ecosystems through long-term overfishing (Jackson et al. 2001), wasteful discarding (Alverson et al. 1994), and collateral damage caused by trawling on bottom ecosystems (Watling and Norse 1998), to cite just a few.

The simplest model of the underlying problem is based on an open-access fishery, which has no barrier to entry and no restrictions on fishing effort. Under open access, fisheries that are more profitable than alternative occupations will attract increasing numbers of fishers, until there is so much fishing effort that the fish stock is depleted to a level where profits are the same as in alternative opportunities (Gordon 1954, Scott 1955). This problem is often referred to as the "tragedy of the commons", in which each individual fisher has the incentive to increase effort and thus reap greater personal benefits, while the negative effects of a reduction in the fish stock are shared by all fishers (Hardin 1968).

The open-access system is no more than a caricature of industrial fisheries, despite the continuing fondness that economists have for modelling fisheries as open access problems (e.g., Sanchirico and Wilen 2001). Catches in most present-day fisheries are restricted in numerous ways, including limited entry, a cap on total allowable catch (TAC), closed areas, trip limits, mesh restrictions, limited boat size, gear restrictions, and closed seasons. These regulations have been imposed largely for biological reasons: to reduce catches so that the stock will remain at (or recover to) a level that will produce a socially acceptable optimum yield. However, none of these management tools addresses the underlying incentives to increase effort at the expense of others in the fishery in whichever dimension remains unregulated, leading to a "race for fish". Instead, these incentives unwittingly act to dissipate any economic rent that might be obtained from a fishery, and in turn cause ever-more restrictive regulations to be passed. Thus even if the stock is maintained at a biologically optimal level, the economic performance of a fishery is compromised by excessive effort and by restrictive regulations that cause inefficient fishing.

Individual Transferable Quotas (ITQs) were proposed as a way of breaking this cycle of economic deficiency (Christy 1973, Moloney and Pearse 1979). Under this system, each participant receives a share of the TAC, and is free to choose when, where, and how to harvest that share. ITQs (in their purest form) are divisible and transferable. Proponents argued that ITQs would result in incentives to minimize the cost of harvesting fish, maximize quality, and reduce the harvesting overcapacity in the fishery. While ITQs can solve (in theory) the issues of biological sustainability (by keeping catches within TACs) and economic efficiency, social issues were not considered initially. Nevertheless, social issues are important, and the success or failure of ITQ systems may hinge on whether the system is perceived to be equitable and to provide for social welfare.

ITQs are referred to in a variety of ways: in the U.S.A. they are often called individual fishing quotas (IFQs), while in Canada they may be allocated to vessels and be termed individual vessel quotas (IVQs), or allocated to companies and termed enterprise allocations (EAs). If transferability is not allowed, they are called individual quotas (IQs) or individual non-transferable quotas (INTQs). The common thread to all these systems is that the TAC is allocated among recipients in a manner that grants those allocated quota the privilege (or right) to harvest a certain percentage of the TAC that year.

IQ programs have been in existence for decades, among the earliest being in Iceland for summer-spawning herring (1975), capelin (1980) and demersal fisheries (1984) (Arnason 1993, Jakobsson and Stefánsson 1999). The earliest ITQ programs were implemented in the 1980s, including those for Canadian Atlantic herring in 1983 (Crowley and Palsson 1992) and Australian southern bluefin tuna in 1984 (Geen and Nayar 1988). Several countries have since adopted ITQs as the standard option for fisheries regulation, including New Zealand (in 1986), Iceland (in 1990), the Netherlands (1996), and Australia (various years) (Annala et al. 1991, Arnason 1993, Davidse et al. 1999, Young 1999). The governments of Canada, Chile, Namibia, Russia, South Africa, and the U.S.A. have also implemented some form of IQ or ITQ program in many fisheries (Crowley and Palsson 1992, Bernal et al. 1999, Hersoug and Holm 2000, Wertheimer and Swanson 2000, Eikeland and Riabova 2002).

There are, however, many complaints about ITQs. The long-term effects of ITQs are not always regarded as desirable, because granting fishing privileges to a few fishers changes power structures within the fisheries. Processors may be left worse off (Matulich and Clark 2003), crew members may face a reduction in wages and bargaining power (Eythórsson 2000), fishing communities may be affected (Skaptadóttir 2000), and some object to the perceived give-away of public resources to a privileged few (Macinko and Bromley 2002). Furthermore, it has been pointed out that fishers have increased incentives under ITQs to fish illegally, misreport catches, and increase discarding (Copes 1986). Care needs to be taken to minimize these potential negative effects when designing ITQ programs.

In this chapter I review the impacts of ITQs in fisheries, starting with issues arising from their initial allocation, and then moving on to biological, economic, social and management impacts, before touching on some special problems that arise in multispecies fisheries.

**Initial allocation**

Initial allocation is important because ITQs usually become valuable assets. In the majority of cases, ITQs are granted to vessel owners free of charge. Fishing privileges (or rights) are assigned to vessel owners because it is argued that they bore the risk of making a capital investment in the fishery and should therefore be rewarded, whereas other participants were paid for their work. They are generally granted free of charge to ensure that existing participants will support the change to ITQs.

Typically, allocations are based on a combination of catch history, vessel characteristics, and equal shares. For example, in the British Columbia groundfish fishery, ITQs were based 70% on catch history and 30% on vessel length (Turris 2000). In the Tasmanian rock lobster fishery, allocation was based on an equal per-pot share with a small allowance for catch history (Bradshaw et al. 2000), while in Alaska the allocation was based solely on catch history, with vessel owners choosing the best five out of seven years of catches for halibut, and the best five out of six years for sablefish (Hartley and Fina 2001a).

*Windfall gains*

Initial recipients can choose to remain in the fishery, or sell their quota, often for a huge “windfall gain.” Regardless of whether the initial allocation is perceived as the creation of wealth where none existed before, or the giveaway of public resources, ITQs certainly represent a valuable asset that approximates the present value of the economic rents from the fishery. In New Zealand, ITQs were valued at close to US$1 billion in 1992 (Johnson 1995). These high values present a barrier for future entry, and may create a division between haves and have-nots, marginalizing processors, crew members, and non-fishing members of fishing communities.

*Allocating ITQs to broader groups of interest*

Allocating ITQ shares more widely may alleviate windfall gains and their associated impacts. The U.S. National Research Council (NRC) conducted a wide-ranging review of ITQs (NRC 1999). It recommended that hired skippers, crew members and fishing communities should be included in the initial allocation where appropriate, but found no compelling reason to include or exclude processors. There are many different options for initial allocation which attempt to spread the wealth, of which the British Columbia groundfish (BC) fishery, and the Bering Sea and Aleutian Island (BSAI) crab fisheries, offer two good examples. The BC fishery allocates 10% of the annual TAC to Community Development Quotas, which are awarded to proposals made by joint processor and vessel-owner groups which best aid regional development (Turris 2000). An additional 10% of the TAC is allocated as Code of Conduct Quota that may be withheld from vessels if crew members are treated unfairly, although no complaints have been raised in the first eight years of the program. The Code of Conduct Quota is problematic because withholding it would penalize the crew that complained by reducing the quota associated with the vessel on which they work, and would perhaps jeopardize their future job prospects (Turris 2000). The BSAI crab fisheries will implement a quite different “two-pie” system in January 2005 (Fina in press). Under this system, ITQs are allocated to harvesters, and Individual Processing Quotas (IPQs) are allocated to processors. Harvesters must deliver 90% of their catch to IPQ holders, and the remaining 10% can be delivered to any processors. Processors argue that this system prevents harvesters from dominating negotiations. Communities are given the first right to purchase IPQs if a local processor decides to shut down operations. In addition, to provide additional leverage for salary and crew share negotiations, crew and captains will be granted 3% of the TAC as a separate class of shares that can only be owned by those who are actively fishing.

*Allocation by auctions*

Another method of alleviating windfall gains is by appropriating the value of ITQs through auctions (e.g., Clark and Munro 2002, Macinko and Bromley 2002). It has been argued that valuable resources should not be given away to a particular group of people involved in the fishery, but that the public should benefit from the resource (Macinko 1993, Morgan 1995, NRC 1999, Macinko and Bromley 2002, Weitzman 2002). Extensive experience auctioning off other valuable public resources, like airport landing slots, and television, radio, and cell phone spectrum rights could be applied to fisheries (Morgan 1995). In general, regulators have been reluctant to employ auctions where they might disenfranchise the participants currently in the fishery, although there are several examples where fishing rights are auctioned—annual auctions in the Washington state geoduck (clam) fishery bring in $7 million for one-year harvest privileges (Hilborn et al. 2004), while Namibia auctions off IQs to (often foreign) companies which are required to carry observers and employ some Namibian labor. Russia auctioned off the fishing rights to Barents Sea cod in the mid-1990s (Eikeland and Riabova 2002), and Chile auctioned rights to Chilean sea bass, squat lobster, and yellow prawn under ITQ programs with the interesting twist that 10% of the quota reverts to the Government each year and is re-auctioned (Bernal et al. 1999, González et al. 2001). Auctions may be attractive to the public, but can be unpopular with those involved in the fishery. In general, investors and outsiders can easily gain control over the fishery under an auction system if they have more ready access to capital than current participants.

*Cost recovery and taxing economic rents*

One final option for reducing windfall gains is by taxing ("capturing") part or all of the economic rent obtained in ITQ fisheries (Grafton 1992, 1994, 1995, Johnson 1995, Weitzman 2002). Typically, taxing the economic rent is strongly opposed by fishers, although limiting the taxes to "cost recovery" is more palatable. Most ITQ fisheries recover part or all of their costs from levies on catches or quota shares. For example, New Zealand recovers most of their fishery management costs through levies on quotas and catches (Annala 1996). It should be noted that complete rent capture would reduce the value of ITQ holdings to zero, while maintaining economic efficiency (Grafton 1992), but may affect the incentives of quota holders to maximize quota value through stewardship of the resource.

*Potential litigation costs*

Initial allocation is typically the component of ITQ systems that is most likely to lead to lawsuits. A mechanism for legal challenges to quota allocation formulae is needed, to ensure that allocations are calculated fairly. In several cases, legal challenges have derailed the efficient operation of ITQ systems (Kaufman and Geen 1998). For example, in the Australian South-East Trawl fishery, the initial allocation rule was deemed to produce an "absurd result" and was overturned. While the case was being decided, transferability of ITQs was prohibited, which resulted in considerable inefficiency and discarding because fishers were unable to lease quota to match their multispecies catches to their quota holdings (Pascoe 1993, Grieve and Richardson 2001). Appeals continued for six years.

**Biological impacts**

ITQs are designed primarily to address the economic and not the biological problems in fisheries, but may have biological impacts. From a biological point of view, fisheries success is characterized by sustainable catches with minimal ecosystem impacts. In an ITQ system, the total catch is controlled by the TAC, and thus overfishing is related to the magnitude of the TAC, not to ITQs. ITQs are only a method of allocating and harvesting the TACs. If TACs are set too high because of uncertainty in survey estimates and stock assessments, or for non-biological reasons by the management authority, then the resulting catches may result in overfishing. There is always assessment uncertainty when recommending TACs, suggesting that conservative quota setting may be required (Walters and Pearse 1996), although this limitation applies to any management system. Putting aside the argument over what the "best" TAC is, it is possible ITQs may have some impact on the ability to stay within the TAC, and on the amount of damage caused to non-target species while catching the TAC.

*Restricting catches to TACs*

For the target species, staying within the TAC is of critical importance. If an ITQ system is well- monitored and regulated, the TAC is only rarely over-caught and may more often be under-caught. Even with minimal at-sea monitoring in the New Zealand ITQ fisheries, only 22 (12%) of 179 TACs were over-caught in 1993-4, six by less than 2% (Annala 1996). Of the remaining stocks, legal provisions allow overruns up to 10% to be subtracted from the following year's quota (12 stocks), and over-catches can also be surrendered, and a deemed value paid, or traded for bycatch of another species (10 species). Under-catching the quota is common in ITQ fisheries, and will generally help to conserve or rebuild the stock at the expense of some loss of income to the industry. In New Zealand, TACs were under-caught (by mass) by 33% in 1986-87, by 24% in 1987-88 and by 22% in 1993-94 (Annala et al. 1991, Annala 1996). Under-runs may be caused by multispecies limits if insufficient ITQ is possessed for all bycatch species, by natural variability in the stocks, and because of poor market prices. In contrast to ITQs, alternative management systems generally struggle to restrain catches to TACs. For example, before ITQs the derby fishery for Alaskan halibut exceeded the TAC in 13 out of 15 years, but in none of the three years after ITQs were implemented (Wertheimer and Swanson 2000). The biological benefits of staying within TACs cannot be overstated.

*Incentives for increased stewardship*

One perceived benefit of ITQs is that they should encourage long-term stewardship of the resource. Fishers may be aware that a resource is being overfished, but have little incentive to reduce fishing pressure unless they reap the benefits. In an open access or competitive fishery, improved catch rates will merely encourage increased effort, dissipating the gains of the original fishers. In ITQ fisheries, fishers will reap the benefits of any rebuilding, and their ITQ holdings will be worth far more. An example of this is the New Zealand Gisborne red rock lobster fishery (Breen and Kendrick 1997). ITQs were imposed in 1990, but catch rates continued to decline due to illegal harvesting by non-quota holders and high mortality of abundant sub-legal size rock lobster from octopus predation in the pots. In 1993, the ITQ holders proposed moving the legal harvest period to winter (when illegal harvesting is difficult and prices are higher), landing only male rock lobsters, reducing the minimum tail width from 54 mm to 52 mm (to reduce pot mortality of sublegal lobsters by octopus), and reducing the TAC from 330 t to 164 t. The results were dramatic: CPUE increased fivefold (Figure 1.1), the size and numbers of lobsters increased substantially (Figure 1.2), and quota value increased from NZ$30,000–50,000 per tonne to NZ$200,000–300,000 per tonne (Figure 1.3). Not only did the stock rebuild, but the profitability and asset value of the quota holders did too.

Another example of the potential gains from stewardship is that of Atlantic sea scallop, where Canadian and U.S. stocks on the Georges Bank were separated by the "Hague Line" after a 1984 court decision (Repetto 2001). On the U.S. side, open access was replaced by limited entry in 1994, the same year that three areas were closed to dredging. Allowable days at sea were decreased from 200 to 120, and a maximum crew size of seven was legislated in 2000. All of these measures were intended to restrict fishing effort to restore stocks to a level that would produce maximum sustainable yield. There has generally been opposition to these effort reductions in the U.S. fishery. On the Canadian side of the Hague Line, companies were allocated Enterprise Allocations, and the resulting stakeholders decided to take a conservative approach to catch limits in order to increase future catch rates and stabilize the harvest despite fluctuations in recruitment. The results were dramatic. In the U.S., fishing mortality outside the closed areas remained high, the number of vessels increased to take advantage of a recruitment peak and then remained in the fishery when recruitment declined, and revenue per sea-day remained constant. In contrast, in Canada the biomass of larger scallops doubled, fishing mortality declined, the number of vessels halved, and revenue per sea day increased by a factor of 3-5 (Figure 1.4).

It would be tempting to end the sea scallop story at that point and conclude that ITQs are the way forward for scallop management. However, subsequent events have shown that the U.S. regulations were also successful in returning the fishery to a sustainable and profitable state. Closed areas and fishing restrictions reduced overall fishing mortality to 0.14 in 1999 in the U.S. sea scallop fishery (Hart 2001). Inside the U.S. closed areas, scallop abundance rose 10-fold from 1994 to 2001, and the U.S. fishery currently operates on a rotational system where different areas are opened for scallop fishing each year (Brodziak et al. 2004). Scallop yields, landings per unit effort and profits have dramatically increased. Nevertheless, overcapacity still remains the key problem for New England fisheries (Brodziak et al. 2004).

*Quota busting and data fouling*

The biological gains from stewardship under ITQs may be dissipated if monitoring and enforcement are insufficient. For example, in Chile, illegal catches have amounted to up to 100% of the TAC for the Chilean sea bass fishery (Bernal et al. 1999) and Copes (1986) argued that “There is no reason to assume that fishermen, where confronted with the rules of individual quota management, will lose either their ingenuity of circumvention or their incentive to promote individual self-interest at the expense of collective interest.” In ITQs, these incentives are expressed as quota busting (illegally exceeding ITQ share), data fouling (misreporting catches), and discarding and high-grading (Copes 1986). Several of the early Canadian ITQ fisheries were plagued by misreporting such as the Atlantic herring and western Newfoundland groundfish fisheries (Crowley and Palsson 1992). In the New Zealand fisheries for red rock lobster, paua (abalone), snapper, and orange roughy, quota busting was known to occur from the outset of the fishery. These problems have been reduced by prosecutions levying penalties including the loss of quota and vessels, and by more active industry participation (Boyd and Dewees 1992, Annala 1996). In the Gisborne red rock lobster fishery, shifting to a winter season substantially reduced illegal catches by non-quota holders (Annala 1996).

*High-grading*

High-grading is one of the most frequently mentioned problems associated with ITQs (e.g., Copes 1986). High-grading occurs when lower-valued fish are discarded to land a higher proportion of high-valued fish. Theoretical studies have suggested that in comparison to open access systems, ITQs increase the incentives to high-grade when the cost of catching fish to replace those that are discarded is outweighed by price differences between fish of different grades and the costs of discarding, including any legal penalties (Anderson 1994, Arnason 1994, Vestergaard 1996, Kingsley 2002). High-grading has been reported for the New Zealand red snapper fishery where some fish meet the criteria for a lucrative Japanese market, while others can only be sold locally for much less (Dewees 1989, Boyd and Dewees 1992). Increased enforcement and severe penalties reduced the level of high-grading in this fishery, and fishing practices changed to increase the proportion of landings that were suitable for the Japanese market (Boyd and Dewees 1992). In most fisheries, however, price differentials are not great and it is not economically worthwhile to high-grade, as has been shown for Pacific halibut and Icelandic cod (Arnason 1994, NRC 1999). In addition, if there is an incentive to high-grade, there will also be an incentive to change fishing patterns or fishing gear to avoid catching the lower grade fish, which may be easier with the greater flexibility afforded under ITQs (Arnason 1996a). For example, after changes in the Alaska longline sablefish fishery, the fraction of mature fish in the catches (sampled before any discarding) increased from 65% to 82% for females and from 78% to 89% for males, whereas survey fractions remained the same (Sigler and Lunsford 2001).

*Discarding*

Discarding may occur under ITQs even in the absence of incentives for high-grading because the fisher may lack sufficient quota for the species that has just been caught (e.g., Annala et al. 1991). This is particularly problematic for multispecies fisheries, where TACs based on biological productivity may not match the ratio of species caught on the grounds, which may in turn be different from the quota holdings of an individual vessel. In the multispecies trawl fisheries of inshore New Zealand, South-East Australia, and Nova Scotia, discarding is known to be problematic (Annala et al. 1991, Dupont and Grafton 2001, Grieve and Richardson 2001), but in Iceland and British Columbia there were no increases in discards after ITQs were introduced (Arnason 1993, Turris 2000). Discard problems may dwindle over time as fishers learn to adjust their fishing patterns to avoid constraining species, and acquire quota to cover bycatch species (Dewees 1998). A more direct solution, implemented in the British Columbia groundfish fishery, is to place observers on board every vessel, and deduct discard mortality from quota holdings, thus providing incentives to change fishing practices (Turris 2000).

Experience shows that the impact of ITQs on discard levels depends on the management system in place before ITQs. In derby-style fisheries with very short seasons, the frantic pace of fishing may result in high discard levels compared to the more relaxed pace and flexibility of ITQs. For example, when ITQs were introduced in Alaska, the discards of sablefish in the halibut fishery decreased by 83%, and mortality from lost gear (ghost fishing) in the halibut fishery decreased by 77% (NRC 1999). Similarly, in the Chilean squat lobster fishery, discards decreased from >100 t to negligible quantities when ITQs were put in place (Bernal et al. 1999).

*Fishing for history*

ITQ allocations are usually based on catch history. This provides incentives to the individual to ensure that their catch history is as high as possible, and may lead to excessive fishing effort in the years before an ITQ system is implemented, a process termed "fishing for history" (e.g., NRC 1999, Macinko and Bromley 2002). It is therefore important to establish a control date, after which no fishing effort will be considered when establishing catch histories for ITQ allocations. Even with a control date in place, if the process takes too long, there may be some speculative fishing just in case the control date is moved (NRC 1999). In the B.C. groundfish fishery the incentives to fish for history were circumvented when new species (big skate, longnose skate) were added to the ITQ system, because allocations were made proportional to the participants' ITQ holdings in other species (weighted by ex-vessel value), and not the catches of those two species.

*Spillover effects*

ITQs may cause undesirable effects for non-ITQ fisheries in the same region. In general, fleet size decreases under ITQs, which may lead to a displacement of vessels and fishing effort to alternative fisheries or onto non-ITQ species (Squires et al. 1998, Baelde 2001, Dupont and Grafton 2001). In countries like Australia, Iceland and New Zealand where ITQs are the preferred management tool, the few remaining unregulated fisheries may face greater fishing effort, especially when combined with the incentives for catching for history (e.g., Copes 1986). To minimize these effects in New Zealand, entry to all non-quota fisheries is limited (Batstone and Sharp 1999).

*Ecosystem impacts*

Little has been written about the ecosystem impacts of ITQs. ITQs provide more choice about when and where to fish and encourage low cost fishing practices, but this does not necessarily translate into positive changes in ecosystem impacts. In ITQ fisheries, the race to maximize the quantity of fish caught is replaced by a desire to maximize income by improving product quality, which may lead to fishing practices that reduce or increase damage to bottom habitats. In general, however, there is still no consensus on the overall ecosystem impacts of ITQs: they could be negative, neutral or positive.

*Effects of absentee ownership on stewardship*

One note of caution regarding long-term impacts of ITQ systems on biological stocks is the trend toward "absentee ownership" or "armchair fishers" (e.g., Connor and Alden 2001). Over time, the original fishers leave the fishery, but many retain their ITQ holdings and lease them to other fishers and become "quota landlords" (Connor and Alden 2001). In addition, private investors, processors, and large companies may buy up ITQs to form vertically integrated conglomerates that control fishing, processing and marketing. Investments in ITQs may be lucrative, providing not only a capital investment but also a steady stream of income from leasing. However, this practice leads to fishing being conducted by non-quota owners who have little long-term incentive to protect the resource by engaging in environmentally sound practices. This may increase the incentives to engage in discarding and misreporting (Phillips et al. 2002, Bradshaw 2004).

**Economic impacts**

ITQs are designed primarily to alleviate the fisheries' economic and not biological problems (Hannesson 1996). But do they actually improve the economic performance of fisheries? While biological impacts of ITQs have been well- documented, economic impacts are less well publicized. Theoretical studies suggest substantial gains: for the reef fish fishery in the northern Gulf of Mexico, it was estimated that moving to ITQs would raise revenues by $3.2 million by eliminating market gluts, and additionally reduce costs by $8.1 million by eliminating red snapper trip limits and seasonal closures (Weninger and Waters 2003). In practice, the economic benefits from ITQs come primarily from: (1) increased flexibility in choosing when, where, and how to fish; (2) increased ex-vessel prices as landings are timed to accommodate market needs and product quality is improved; (3) a reduction in vessel numbers as more efficient vessels buy quota from less-efficient exiting vessels, thus increasing overall efficiency and allowing for economies of scale; and (4) increased security of catch privileges provides incentives to rebuild stocks to maximize the leasing and asset values of ITQs.

*Increased flexibility and reduced fishing costs*

In many non-ITQ fisheries, there is excessive expenditure on technology in order to catch fish as quickly as possible (the race for fish) before the fleet-wide TAC is exceeded and the fishery is closed. Under ITQs, the emphasis is on catching the allowed amount of fish with minimum effort and costs, while maximizing prices (e.g., Dewees 1989). In the Alaska sablefish fishery, catch rates (compared to the surveys) improved by 80% while the costs for fuel, bait and gear declined from 8% to 5% of landed value—translating to annual savings of $3.1 million. In 1995, for example, only 50 million hooks and 4,800 vessel days were required to catch the TAC, compared with an estimated 80 million hooks and 7,800 vessel days under open access (Sigler and Lunsford 2001).

*Increased ex-vessel prices: market timing and product changes*

Early proponents did not consider the effects that ITQs might have on ex-vessel prices (Christy 1973, Moloney and Pearse 1979), but in practice increases in product prices have been a major source of increased profits. Market prices may increase because product can be caught when prices are highest ("market timing"), in contrast to derby-style or competitive fisheries where market gluts and depressed prices are common during short fishery openings. In the first year of ITQs, ex-vessel prices for sablefish increased from $0.90–1.53 to $1.56–2.37 per pound in Alaska (Hartley and Fina 2001b), and prices in the U.S. wreckfish fishery increased from $1.98–$3.41 per kg to around $4.07 per kg (Gauvin et al. 1994).

A common source of increased prices is a change to the product form. ITQs allow for more leisurely fishing methods instead of a race for fish. The British Columbia halibut fishery increased the proportion of fresh (instead of frozen) product from 42% to 94% when ITQs were introduced (Casey et al. 1995), increasing their revenue by

Can$23.2 million in 1991–94 (Herrmann 1996). When the Alaska halibut fishery moved to ITQs in 1995, a similar change occurred, and about half of the price advantages in the B.C. fishery were eroded (Figure 1.5), but the B.C. halibut fishery revenue was still an estimated Can$16.1 million higher in 1995–98 than under the pre-ITQ system (Herrmann 2000). In the New Zealand snapper fishery, there was a shift from trawling to long-lining or gill-netting to supply the *ike jime* (a method of rapid killing) market in Japan, and they subsequently started to export snapper live to Japan to obtain even higher prices (Boyd and Dewees 1992, Annala 1996). Similarly, more than 90% of New Zealand red rock lobster is exported live to Asian markets (Breen and Kendrick 1997). Perhaps the most spectacular example of changes in product form is that of the Australian southern bluefin tuna fishery. First, they moved from supplying low-value canneries to producing high-value sashimi, increasing prices from A$988 per tonne in 1983-84 to $2,000 per tonne in 1986-87, and generating an additional A$4.9 million in resource rents (Geen and Nayar 1988). Then in 1991, operators started capturing 3-4 yr old fish, towing them back to oceanic pens and rearing them to adulthood. When market prices for fresh sashimi peak, the reared fish are killed and flown directly to Japan.

An increase in the quality of product may also result in ex-vessel price increases, as operators move from maximizing quantity to maximizing quality. Under Enterprise Allocations in Nova Scotia, vertically integrated companies adopted ice boxes for storage on vessels instead of bulk storage (Binkley 1989). In the Australian South East Fishery, according to some fishers, quality was improved by increasing mesh sizes (from 13.5 to

22.5–30 cm), decreasing trawl duration (from 6–8 hours to 3–4 hours), and training deckhands on how to sort, wash and prepare different species (Waitt and Hartig 2000).

A final method for increasing prices under ITQs lies in value-added processing, for example adding sauces, crumbing, or otherwise packaging the final product in a more appealing manner. It is hard to estimate the additional revenue obtained from this source, but in New Zealand from 1990 to 1995, employment in the catching sector increased by 9% (and catches by 13%), while employment in the processing sector increased by 44%, and the total value of the fishery increased by 54%, suggesting that changes in the processing sector generated substantial increases in revenue (Batstone and Sharp 1999). In the Canadian Enterprise Allocation system, one company alone was able to increase the proportion of upgraded packs from 22.2% to 45.4%, adding $3 million to the gross value of their products (Gardner 1988).

It should be noted that in some instances under ITQs, increased ex-vessel prices are not reflected in increased ex-processor costs, but are merely transfers of wealth from processors to harvesters. This can happen when ITQs are allocated solely to vessel owners, companies are not vertically integrated, and there is an excess of processing capacity. In such cases, and perhaps under less stringent conditions, competition among processors for product leads to harvesters appropriating most of the economic rents of the fishery (Matulich et al. 1996, Matulich and Sever 1999, Matulich and Clark 2003).

*Reduction in overcapitalization*

In nearly every ITQ fishery, the number of vessels has decreased over time (e.g., Grafton 1996b, Dupont and Grafton 2001, Ford 2001). The pace of vessel exit depends on alternative employment, quota prices, and market prices for old vessels. More efficient fishers are prepared to pay higher prices for ITQs, and thus tend to buy ITQs from less efficient vessels, which then exit. This results in improvements in economic efficiency, and a reduction in overall costs associated with redundant vessels. In the U.S. surfclam and ocean quahog fishery, the number of vessels declined by 74% and 40% respectively, while catches per trip increased 2-3-fold (McCay et al. 1995, Wertheimer and Swanson 2000). In the Icelandic summer-spawning herring fishery, the stock gradually rebuilt after a collapse in the late 1960s, and the fishery was reopened in 1975 under an IQ system, which converted to ITQs in 1990 (Jakobsson and Stefánsson 1999). Despite substantial increases in stock size and catches, the number of vessels in the fishery declined from a peak of 144 in 1980 to less than 40 in 1994-96, while the catch per vessel increased by more than an order of magnitude, greatly improving the profitability of this fishery (Jakobsson and Stefánsson 1999).

*Value of ITQ shares*

The present value of an ITQ fishery is capitalized in the value of ITQ shares. Owning ITQ shares allows an entity (individual or company) to make money from the fishery, and therefore ITQ share prices will rise until the expected returns are equivalent to those which can be obtained from alternative investment opportunities. ITQ share prices may change in complicated ways depending on the security of ITQs and the perceived future of the fishery. All other things being equal, their value will increase when TACs increase, and decrease when TACs decline. However, if TACs are reduced to rebuild the stock, ITQ share prices will tend to increase, anticipating increased future profits (e.g., Breen and Kendrick 1997). Also, if TACs increase too much and depress market prices, then ITQ share prices will decline. In the Gisborne rock lobster fishery discussed previously, ITQ share prices remained low from 1990–93 until the TAC was halved in 1993, and then ITQ share prices increased by almost an order of magnitude (Figure 1.3). In contrast, when ITQs were implemented in the U.S. wreckfish fishery, only 590 t of the 910 t TAC was caught in the first year, and permanent harvest shares could be bought for just $1.10 per kg compared to ex-vessel prices of $4.07 per kg (Gauvin et al. 1994). Subsequent events suggest that the fishery was no longer profitable at that time (perhaps because the high effort during the exploratory phase had collapsed the stock), and recent catches have languished at around 10% of the TAC despite increases in ex-vessel prices to $5.00 per kg (Wertheimer and Swanson 2000).

The value of ITQ shares is high in many fisheries and generally increases in the initial years of the fishery. In the Tasmanian rock lobster fishery, pot license prices (unadjusted for inflation) were AU$1,000 in 1980, and AU$4,000 in 1990. Prices rose just before ITQs were implemented to AU$10,000 in 1997, and to AU$50,000 in 2002 (Bradshaw 2004). Some increases in quota values may be due to irrational exuberance—speculative investments in ITQ shares in anticipation of further price increases. In New

Zealand, quota share prices increased by 2.1 to 83 times (median 4.6 times) for 12 species from 1986 to 1996, but then decreased for 11 out of 14 species (median decrease 24%) from 1996 to 2000 as the quota market matured (Stewart and Callagher 2003). The total value of all New Zealand ITQs was estimated to be nearly NZ$1 billion in 1992 (Johnson 1995). In Iceland, the estimated total value of quota shares in the demersal fisheries increased steadily from $36–57 million in 1984 to $222–267 million in 1990, suggesting that significant economic benefits were being generated by the quota system (Arnason 1993).

While permanent sale prices reflect the present value of the resource, leases are a reflection of the annual income obtainable from ITQ shares. Many ITQ fisheries have moved to leasing arrangements where fishers lease quota from retired fishers, private investors or vertically integrated companies (Eythórsson 2000, Bradshaw 2004). For those that do not own quota, lease prices need to be factored into their costs. In multispecies fisheries, lease prices may be a reflection of the scarcity of quota for a particular species, rather than the economic return that can be obtained from fishing for that species. For example, lease prices for Icelandic cod have sometimes increased to 70–80% of ex-vessel prices because cod quota is needed to cover bycatch while fishing for other species (Pálsson and Helgason 1995). In single-species fisheries, the relationship between lease prices ($L$) and sale prices ($P$) of quota provides an indication of the discount rates ($r$) of fishers (Asche 2001):

$$(1.1)\ r = \frac{L}{P - L}$$

Discount rates calculated in this way for a variety of species in Iceland ranged from 12% to 40% in 1995, but decreased over time for some species. Similarly, discount rates for New Zealand fisheries were 20–33% in the early 1990s but decreased to 11–14% in 1997 (Asche 2001). In contrast, the estimated discount rate for U.S. wreckfish in the first year of ITQs was 150% (Gauvin et al. 1994), suggesting that the fishers (correctly) placed near-zero value on future earnings from the resource. Estimates of discount rates provide a measure of how secure ITQ users feel about their harvesting rights. Additionally, perpetual ITQ rights may not be necessary if discount rates are high, because the present value of actions far in the future would be greatly discounted (Asche 2001).

**Social impacts**

While biological impacts of ITQs are mixed but generally positive, and economic impacts are positive, social impacts are often considered to be negative. To some extent, this is because ITQs may cause a change in the balance of power from a more egalitarian enterprise to one where some players are able to dominate at the expense of others. Even if the overall profitability of the fishery is improved, it is unlikely that all initial participants will be better off under ITQs.

*Concentration of quota*

The transferability of ITQs allows quota to become concentrated in the hands of fewer people, which is considered a problem in many countries. Some fisheries have strict ownership caps to prevent concentration (e.g. U.S. halibut), others rely only on anti-monopoly limits (e.g. U.S. surfclam and ocean quahog). In New Zealand, the percentage of fishers and company managers that were worried about company control increased from 26% in 1987 to 46% in 1995 (Dewees 1998). During that period, the holdings of the top three companies increased from 28% to 44%, although the holdings of the top ten companies remained stable at 67% and 68% respectively (Dewees 1998). In general, concentration has increased in New Zealand and in Iceland, with large companies controlling more of the quota than small companies (Eythórsson 2000, Stewart and Callagher 2003). Concentration as measured by Gini coefficients (0 = evenly distributed, 1 = monopoly) in the Icelandic cod fishery increased from 0.677 in 1984 to 0.799 in 1994, although vessels that left the fishery were still included in these calculations (Pálsson and Helgason 1995). Concentration estimates are difficult to interpret, especially when the fleet is initially overcapitalized and one of the goals of ITQ systems is to reduce the fleet size to an efficient level. Fleet reduction logically implies an increase in quota concentration. In some countries, such as Iceland, New Zealand, and South Africa, large vertically integrated companies which controlled fishing, processing and marketing were already dominating some fisheries. Allocating ITQs to those companies changes little in the structure of the fishery.

*Quota landlords and leasing arrangements*

One of the most contentious consequences of ITQs has been the rise of a new way of profiting from fisheries: leasing quota instead of fishing it. Ownership of ITQs ensures a steady stream of income without any risks, and has spawned terms like “armchair fishermen”, “quota landlords”, and “quota profiteering”. In the Australian South East Fishery, “stock landlords” were defined as those who leased out their entire quota for some species (Connor and Alden 2001). The percentage of the TAC leased by stock landlords increased from 22% in 1992 to 42% in 1998, of which 11% and 24% respectively was leased out by entities who never fished quota for any species. In Iceland there has been outrage at the feudal system (termed “fishing for others”) that has arisen where large processors sign contracts with vessel owners who are obliged to deliver their landings to the same processors for a fixed price, usually 50–60% (for cod) of those obtainable at auctions (Eythórsson 1996). ITQs have effectively facilitated the transfer of ownership of the fishery from the public to fishers and from fishers to outside investors and companies, a situation that is anathema to many.

*Fairness and equity*

The windfall gains from ITQ allocations accrue only to the generation of fishers who happen to be fishing when ITQs are implemented. This has broad implications for inter-generational fairness and equity, and may breed resentment. A favorable view of ITQs may also be affected by the size of initial allocations. In the Alaska halibut fishery, participants who received less than 4.5 t had more negative responses than positive responses, while only 4-5% of those who were allocated more than 9 t had negative impressions of the ITQ system (Knapp 1997).

*Changes in employment and impacts on crew members*

In general, under ITQs employment decreases (but may be better paid) in the catching sector as overcapitalization is reduced, although employment in the processing sector may increase. One hard-line viewpoint is that if employment adds nothing to production then it is of "dubious value" (Hannesson 1996). However, this ignores the fact that there may be little alternative employment for displaced fishers, and that increased unemployment may cause social problems in fishing communities. In the Lake Erie multispecies freshwater fishery, crew numbers fell from 915 to 714 (Crowley and Palsson 1992), and in the Canadian offshore scallop fishery, crew employment declined by about 70 people per year (Repetto 2001). In New Zealand fisheries, total employment in the catching sector increased from 4,425 in 1990 to 4,845 in 1995, but employment in the processing sector increased even more, from 3,560 to 5,110 over the same period (Batstone and Sharp 1999). In the Enterprise Allocation system in Canada, processing employment also increased with the introduction of more labor-intensive value-added products, increasing labor required per tonne from 30 h in 1984 to 36 h in 1987 despite increased mechanization (Gardner 1988).

In nearly every ITQ system implemented so far, crew members did not receive any quota shares. As a result, they have not benefited to the same extent as quota recipients, and in some cases their overall welfare has declined. Crew members that are rendered unemployed by ITQs are obviously worse off, but the remaining crew tend to have more secure jobs and often receive increased wages under ITQs. In the early Canadian experience, crew incomes increased in all ITQ fisheries, for example, crew income in the Lake Erie fishery rose from $25,000 to $40,000 in one year (Crowley and Palsson 1992). In British Columbia, employment declined from 10,500 to 3,200 causing some frustration among the unemployed, but the remaining crew members worked a longer season and individual payouts increased from $1,095 to $2,512 per person for halibut and from $3,165 to $8,342 for sablefish (Hartley and Fina 2001b).

One of the biggest changes under ITQs is the trend towards the replacement of catch shares with salaries. In previous management systems, crew members were rewarded with increased pay when the boat caught more fish and were accordingly rewarded with a share of the catch, a tacit acknowledgment of some crew ownership of the TAC (Macinko 1993). Under ITQs, the vessel owner owns a fixed share of the TAC and larger catches become less important, thus crew are often paid a salary instead of a catch share (Grafton 1996b). In the U.S. surfclam fishery, employment decreased by one-third, the remaining crew members were required to work longer hours for lower pay, and often the cost of leasing was removed from catches before crew shares were calculated, reducing payouts (McCay et al. 1995). In the Nova Scotia groundfish fishery, the crew shares were reduced from 50-50 to 60-40 or even 65-35 (McCay et al. 1995). Furthermore, crew members in Nova Scotia reported reduced job satisfaction because their work was being completely controlled by companies (Binkley 1989). In Iceland, crew members have gone on several strikes in protest at their lower status and the "feudal system" of leasing by big companies which has reduced their status to that of "serfs" (Pálsson and Helgason 1995, Eythórsson 1996).

*Safety*

In many fisheries, one of the reasons ITQs are introduced is to improve safety by relieving the race for fish (e.g., Fina in press). The increased profitability associated with ITQ systems may also help to improve vessel maintenance, reducing the risk of vessel loss. In the Alaska halibut fishery 28% of fishers mentioned safety as one of the benefits of moving from a derby fishery to an ITQ fishery (Knapp 1997), and the number of search and rescue missions in that fishery declined from 83 in 1992–94 to 31 in 1995-97 (Wertheimer and Swanson 2000). In the B.C. halibut fishery, 72% of respondents agreed that "IVQs make the fishery safer" (Dewees 1998). However, under ITQs there is pressure to maximize catche value by fishing when prices are higher—often during bad weather or winter months. Thus, despite overall safety improvements, there was concern about going out in bad weather in the British Columbia halibut fishery (Casey et al. 1995). In the Nova Scotia groundfish fishery, crew tended to work longer hours and become more fatigued, there was an exodus of skilled crew members, and they changed to a storage system which required at-sea handling of 32–50 kg boxes of fish and ice (Binkley 1989, McCay et al. 1995). An examination of the Workers' Compensation Board revealed that accidents and injuries actually increased under ITQs in Nova Scotia (Binkley 1989).

*Balance of power between processors and harvesters*

While harvesters may be better off overall under ITQs, processors can be harmed. This is especially true if the previous system was a derby fishery that encouraged excessive investment by processors to handle a glut of product during the short openings. When ITQs are introduced and the season length increases, processors bid against each other for the right to purchase fish. Ex-vessel prices increase with the net result that most of the increased economic rents are appropriated by harvesters (Matulich et al. 1996). The Alaskan halibut and sablefish fisheries provide classic examples where the processing sector lost 56% and 76% (for halibut and sablefish respectively) of their prior economic rents and 82% and 96% of the existing processors were worse off under ITQs (Matulich and Clark 2003). It is not yet clear whether this result applies to derby fisheries only, or is generally applicable to all fisheries, but there are other cases where the existing processors have been bypassed altogether under ITQs, either through a change in product form, or by at-sea processing. One example is the Australian southern bluefin tuna fishery discussed previously, where the canning factories are now obsolete since tuna are mainly shipped whole to the lucrative sashimi market in Japan (Geen and Nayar 1988).

Two ways of mitigating against the impacts of ITQs on processors have been proposed: the “one-pie” and “two-pie” systems (Matulich and Sever 1999). In the one-pie system, some of the ITQs are allocated to the processors. In the U.S. West Coast groundfish fishery, processors are currently arguing that up to 50% of any future ITQs should be allocated to them. Under the two-pie system, harvesters are allocated ITQs as before, and processors are allocated individual processing quotas (IPQs), based on processing history. Fish can only be caught by ITQ holders and can only be processed by IPQ holders. This system was proposed for the Bering Sea and Aleutian Islands (BSAI) crab fisheries, and permission was obtained from U.S. Congress to implement this plan in 2005, circumventing an explicit ban on IPQs in U.S. fisheries (Fina in press). In the final system, 90% of landings must be processed by those holding IPQs, while the remaining 10% can be processed by non-IPQ holders. It remains to be seen whether either the one-pie or two-pie system will provide equitable outcomes in practice.

In many ITQ fisheries, processors have played an increasingly dominant role over time. There are obvious advantages for a processor in being able to coordinate catches with processing availability, resulting in a trend toward vertical integration in ITQ fisheries. In the surfclam and ocean quahog fishery, processors eventually owned a large percentage of the ITQs through prior vessel ownership, making it harder for some individual operators to continue in the fishery (McCay et al. 1995). Regardless of who eventually owns the ITQs, there is likely to be increased coordination between vessels and processors under ITQs.

*Impacts on communities*

The main fear in fishing communities is that quota owners will remove their ability to fish by selling their quota outside the community. In some countries, like Iceland, small fishing communities fear quota holders in the capital city buying up their quota, but in other countries, like New Zealand, there are few communities that depend largely on fishing (NRC 1999). One New Jersey community lost their clamming and processing ability for a year when the sole processor sold their surfclam and ocean quahog quota (McCay et al. 1995). In Iceland, there was a slight shift in quota ownership away from Reykjavik and toward the communities in the North, which would generally be considered a positive outcome (Arnason 1993). However, in later years, cutbacks in the cod TAC led to some communities losing their quotas, with marked negative impacts on the entire community (Skaptadóttir 2000), although it is not clear whether ITQs or TAC cutbacks should be blamed for their poorer circumstances. In British Columbia, the halibut fishery used to land 90% of their catches in two regions, but now landings are spread out over many more regions (Casey et al. 1995). ITQs may also change the dynamics in fishing communities because quota owners have increased power and wealth, and may strain the formerly egalitarian atmosphere of fishing communities (McCay et al. 1995, Pálsson 1998).

One method of protecting fishing communities is to allocate quota as community development quotas (CDQs) instead of ITQs (Wingard 2000). Instead of assigning the privilege of catching fish to vessel owners, quota would be assigned to entire communities, who could then decide who would catch it. Set up correctly, there could be greater fishery involvement from sectors of the community dependent on fishing. Currently, the only CDQ program in operation is for coastal villages bordering the Bering Sea that have substantial Native Alaskan populations (NRC 1999). In 1992, 55 communities were allocated 7.5% of the walleye pollock quota, with a requirement that the profits were to be used in improving fishery-related industries. The CDQs were leased, realizing $53 million in royalties in 1992–94, and increasing basic employment by 57% from 1989 to 1994 (Ginter 1995). The Alaskan CDQ program was subsequently extended to halibut, sablefish, other groundfish, and crab fisheries (NRC 1999).

Another alternative is to give communities the right of first refusal when quota will be transferred out of the community, as will happen in the BSAI crab fisheries (Fina in press), or to place restrictions on transferability of quotas.

*Future entrants*

The high price of ITQ shares is a major barrier to new entrants and young skippers in all ITQ fisheries (Casey et al. 1995, Grafton 1996a, Dewees 1998, Phillips et al. 2002). Under open access, it costs nothing to enter a new fishery except for the price of a boat, gear and bait. Limited entry fisheries increase the cost of entry by adding the price of a license, and ITQs further increase the cost of entry. Traditionally, fishers followed a career path, starting as a crew member before saving enough money to buy a boat and enter the fishery as a skipper, but under ITQs this is difficult. It has been suggested that capturing some or all of the economic rent of the fishery would reduce the price of entry (Grafton 1996a), although this option may be politically infeasible, and may shift the industry's preferred TAC to the level that would be taken in an open-access fishery (Johnson 1995). An alternative is to capture some of the economic rent of the fishery and channel it to low-interest loans for skippers and crew members to buy ITQ shares at market prices.

**Impacts on fisheries management**

In general, fisheries managers favor the change to ITQs. After six months of ITQs in New Zealand, 100% of interviewed fisheries managers felt that the fishing industry would be better off under ITQs and that the new system would be successful (Dewees 1989). The overall impression is that while ITQs may be more complicated to administer, stakeholders have more incentives to support managers than under alternative regimes.

*Complexity of the management system*

ITQs have increased complexity in some ways because cumulative catches for individual quota holders have to be tracked efficiently. This requires a complex paper trail and good database management, although this may be no greater than alternative output control management systems. On the other hand, the number of participants generally decreases over time, which tends to reduce the workload associated with administering the fishery.

*Cost recovery and rent extraction*

In many ITQ fisheries, management costs are recovered from quota holders, which can lead to innovative ways of reducing management costs (Squires et al. 1995). In Nova Scotia, a cheaper monitoring system was developed by industry to reduce their costs (McCay et al. 1998). In the Australian South East Fishery, where industry paid 60–70% of management costs from 1995-96 to 1998-99, management costs remained stable despite an increase in the workload and complexity of management (Grieve and Richardson 2001). In New Zealand, the government collected NZ$60 million in the first three years from levies on catches and quotas, about two-thirds of the budget for fisheries research, management, and enforcement (Sissenwine and Mace 1992). Total management costs in New Zealand did not change much from 1991 to 1997, but from 1997 onwards research services were made available for open tender (Batstone and Sharp 1999). New Zealand quota holders have also formed companies (usually focused on single species) that have increasingly begun to contract directly with non-governmental researchers to perform additional stock assessments and surveys (Starr et al. 1998, Maunder and Starr 2002). Similarly, the British Columbia sablefish fishery funds stock assessments, biological sampling, tagging programs, and other research activities on top of their contributions to government research, because it is in their interest to know more about the status of the stock (Hilborn et al. 2004). Cost recovery has certainly increased the interest of quota holders in management and research (Dewees 1998), even to the point of forming commercial stakeholder organizations to represent the collective interests of quota holders in New Zealand and British Columbia (Yandle 2003).

*Compliance and enforcement*

ITQs might increase the incentives of individuals to try to circumvent quota-related restrictions on their landings, but they also increase their incentives to make sure that others are in compliance with management regulations. The balance between these incentives makes for interesting dynamics. For example, the British Columbia halibut fishery developed a fully funded system for tagging every fish with an individual vessel code to reduce the incidence of illegal fishing (Grafton et al. 1996), and British Columbia groundfish fishers have strongly supported the continuation of 100% observer coverage on the groundfish fleet, even though this program is fully funded by industry.

*Multi-sector allocation issues*

In many fisheries, ITQs affect only the commercial sector, or only one part of the commercial sector, while recreational fishers and other sectors remain outside the ITQ system. This can lead to problems in allocating TACs between ITQ and non-ITQ sectors. The snapper fishery is one of the most valuable coastal fisheries in New Zealand, but the recreational sector has gradually increased their catches from 22% of the commercial catch in 1984 to 57% in 1994 (Batstone and Sharp 1999). Increasing concern over the fishery led to a proposed reduction of 40% in the commercial TAC in 1996, but this was hindered by legal action from industry who successfully argued that it was unfair to only restrict commercial catches and not limit recreational catches (Batstone and Sharp 1999). Similar problems with recreational fishery allocations were experienced in the British Columbia groundfish fishery (Turris 2000). In the Australian South East Fishery, ITQs were implemented in Commonwealth waters (beyond three nautical miles), but fishing within the state waters of New South Wales remained unregulated (Pascoe 1993). Not surprisingly, reported catches of quota species in state waters increased, either because of displaced effort or deliberate misreporting of Commonwealth catches (Pascoe 1993, Waitt and Hartig 2000). While other Australian states have ceded authority to the

Commonwealth in similar instances, fishing is still separately regulated in New South Wales (Waitt and Hartig 2000, A.D.M. Smith, pers. comm.). The Icelandic demersal fisheries provide another example of the problems that can arise when inter-sector allocations are not fixed. In 1984, Icelandic demersal fisheries were placed under ITQs, but fishers were also given the option of fishing under a limited effort fishery. The latter sector grew from a minor to a substantial component of the fishery, increasing the total fishing capital and effort in the fishery (Arnason 1996b). The limited effort option was consequently removed in 1990.

**Implications for multispecies fisheries**

Multispecies fisheries face special problems under ITQs, but ITQs also provide particular incentives toward sustainable fishing that other management systems are unable to provide. If it is possible to perfectly target each species, then a multispecies fishery can be managed as a collection of single species fisheries. This section therefore deals with the real-world situation where multiple species are caught together and there is imperfect control over the proportion of each species in catches.

*Matching catches to quota*

For biological reasons, each species' optimum yield differs, and this is in turn different from the catch ratios of each species. If the relative fishing mortalities are fixed, it is not possible to catch the optimum yield for each species in a multispecies fishery simultaneously: either some species will be fished to extinction, or the total yield will be below the maximum possible yield (Paulik et al. 1967, Hilborn 1976, Hilborn et al.

2004). Economists call this the “Le Chatelier” effect, when producing many types of products reduces overall production below the levels that would be optimal for any given product. This problem affects all types of fisheries management, not just ITQs. Any system based upon input controls (or no controls) will fail to address this issue, but systems based on output controls are forced to confront this problem head-on.

Under ITQs, it is typical to place a biologically-based TAC on individual species, and let the fishers try to match catches to the TACs. When the TACs are constraining for some species, this will tend to reduce catches of other species, thus creating strong incentives to misreport or discard catches of the constraining species. ITQs will thus typically require stronger monitoring in multispecies fisheries than in single-species fisheries, especially if there are strongly constraining species. Where there is little monitoring, ITQs will be hardly better than pre-existing management systems, and some species will likely be over-caught. When monitoring is stringent, the TACs of many species will likely be under-caught, and fishers will use all possible mechanisms to avoid catching the constraining species. In the Australian South East trawl fishery, even though on-board observer coverage is poor, a variety of mechanisms are still used to avoid catching large bags of any particular species. These include fishing across different depths, avoiding areas of large single-species catches, changing the trawl duration, time of day or season, relying more heavily on GPS, plotters and sounders, and many other factors (Baelde 2001). As a result of these behavioral changes, catches of many species are increasingly well paired with individual quota holdings (Connor and Alden 2001). In the British Columbia groundfish fishery, which has observers on every vessel and 100% dockside coverage of catches, vessels are stopped from bottom fishing if they do not obtain quota to cover their catches (Turris 2000). There are thus very strong incentives to avoid some species and target others, and fishers are remarkably capable of matching their catches to their quotas.

Several solutions to the catch-quota mismatch problem have been used in ITQ fisheries, with varying degrees of success. The most obvious is to allow a period of time for the fisher to purchase or lease quota to cover any over-catches. The lease price may reflect not only the value of the over-caught species, but also the value of the other species that can be caught by remaining within the TAC for that species. In the B.C. fishery, lease prices for constraining species may exceed the ex-vessel value of those species. In most fisheries, some allowance is made for carrying forward a certain percentage of the over- or under-catch of quota to the following year. As fishers become better at targeting species, and buy and sell quota so that their holdings match their usual catches, the carry forward percentage may be reduced. For overfished species that are in need of rebuilding, over-catches may be forbidden to protect the stock. In New Zealand, over-catches may be landed provided a deemed value (penalty charge) is paid, which reduces incentives to dump over-catches at sea. The main problem is determining what the deemed value should be: if it is too high, fishers will discard catches, and if it is too low, there may be incentives to target that species. In some cases, even if the deemed value is 100% of the ex-vessel value, vertically integrated companies may still target that species because value can be added during processing (Sissenwine and Mace 1992). In the New Zealand hoki fishery, there is a minor (<1%) bycatch of silver warehou, but the silver warehou TAC is so small that it was exceeded by 62% in 1987-88. In this case it was worthwhile to pay the deemed value for silver warehou to continue fishing for hoki (Annala et al. 1991). Concerns over silver warehou led industry to develop a code of conduct that substantially reduced bycatches and enabled sustainable fishing (Annala et al. 1991, Annala 1996).

While ITQ systems can be modified in several sensible ways to reduce discards, improve compliance and add flexibility, there are other methods that have been implemented or suggested which may be biologically unacceptable. For example, Sissenwine and Mace (1992) suggested that some minor species could be excluded from ITQs or "sacrificed" in order to optimize fishing on more valuable species. In most countries this solution would be contrary to environmental laws. Another poor idea is to implement "basket quotas", where an ITQ is placed on a group of species. In New Zealand, three species of oreo dories (black, smooth and spiky) are managed by a combined TAC, resulting in potential targeting (and overfishing) of more valuable species within the group (Sissenwine and Mace 1992). A recent assessment within one management area concluded that the maximum constant yield for smooth oreo dories was 1,500 t (actual catch 371 t), and for black oreo dories was 1,700 t (actual catch 4,481 t) (Annala et al. 2002), suggesting that this system may cause problems for the sustainability of black oreo dories.

Another solution that may be unacceptable for biological reasons is to trade over-catches of one species for under-caught quota of another species, as used in New Zealand (Annala et al. 1991). Again, this method may lead to legalized overfishing of constraining species.

The potential benefits of ITQs may be limited by constraints on multiple species (Squires and Kirkley 1991, 1995, 1996), although most theoretical studies have assumed for simplicity that fishing technology is inflexible and that fishers are unable to change their operations in such a manner so as to alter the ratios of the species in their catches. In reality, behavioral changes may result in substantial economic rent in multispecies fisheries.

One important aspect of multispecies ITQ fisheries is how to add new species to an established ITQ fishery. Relying on catch history for the new species may seem attractive, but tends to encourage excessive speculative fishing effort on all non-ITQ species in case they are added to the system. In New Zealand, a 1996 law established a statutory catch history period comprising the best consecutive 12 months of fishing in 1991/92 and 1992/93. This period is used when new species are added to the ITQ system (Bess in press). Of course, as time passes, this period of years will bear little resemblance to current catches in the fishery. An alternative used in the British Columbia groundfish fishery is to allocate initial quota shares based on percentage ownership of all existing quota species (weighted by value), which would tend to discourage fishers from developing new markets for non-ITQ species.

**Discussion**

Are ITQs good or bad? The biggest benefits of ITQs are in the realm of economics, and to a lesser extent biology; the greatest problems are in the realm of social science, which also largely explains the divide between proponents and opponents of ITQs. Clearly, ITQs do not solve *all* the problems of fisheries management. On the other hand, problems with ITQs should not be compared with some imaginary fishery that is sustainably managed at high profitability with no negative social consequences. Instead, ITQs should be evaluated in comparison with existing management systems. In this sense it is important to note that the main problem with fisheries is not overfishing, which in the U.S. results in a loss of $0.5 billion annually, but overcapitalization, which wastes $2.9 billion annually (Hilborn et al. 2004). ITQs address the overcapitalization problem, and are generally better than the existing alternatives, even if they are not problem-free.

It is clear that there are substantial benefits to ITQ systems: remaining within the TAC, increasing the profitability and efficiency of the fishery, introducing stewardship into the equation, and aligning the incentives of fishers with the desired outcomes of fisheries. On balance, most conclude that ITQs are an improvement over open access and limited entry systems (Annala 1996, Grafton et al. 1996).

However, ITQs do not bring a utopian world. It is very difficult to design a system where all of the previous participants are winners—there will be some losers. In Iceland, crew members have expressed discontent, culminating in two strikes to protect their rights (Eythórsson 2000), and in many other fisheries the losers have not been content with the changes wrought by ITQs. This discontent stems from the increased power and control that ITQ holders have over the fishery. Some newer ITQ systems have restricted transferability and spread ITQ allocation to include processors and crew members to retain the existing balance of power in pre-ITQ fisheries. Some people object to the giveaway of public resources, arguing that fisheries belong to the public and that ITQs should therefore not be given away but auctioned or taxed to return benefits to the public (Macinko and Bromley 2002).

It is important to realize that ITQs cannot by themselves bring about sustainability in fisheries. They are merely a mechanism for dividing the TAC. Thus if stock assessments are highly uncertain, and the TAC is incorrectly specified, then a fishery may be overfished under ITQs. This problem is not limited to ITQs since incorrect or uncertain assessments would have equivalent impacts on fisheries managed by other systems like effort controls or closed areas.

Unintended consequences of ITQs include the incentives for fishers to circumvent ITQ regulations by misreporting, data fouling, and high-grading (Copes 1986), prevention of which requires more stringent enforcement and monitoring. It is an open question whether these incentives will be outweighed by the incentives under ITQs to increase conservation (McCay 1995). ITQs will therefore be difficult to implement in fisheries that have many vessels, multiple landing points, or are not very valuable. Other fisheries in which it will be more difficult to implement ITQs include those with unstable stocks, fisheries managed by escapement and not catches, short-lived species, flash fisheries, and fisheries that require in-season management (Copes 1986). In such fisheries it is either difficult to define an appropriate TAC, leaving an ITQ as a share of an uncertain quantity, or the privilege of fishing could be revoked during the season, increasing incentives for a race for fish at the start of the season just in case the season is closed prematurely (Copes 1986).

Problems may also arise in fisheries where a portion is managed under ITQs while the remaining fishing remains uncontrolled. The non-ITQ sector may erode the security of ITQ holdings. Examples discussed in this chapter include illegal poaching in the Gisborne rock lobster fishery (Breen and Kendrick 1997), recreational catches in the New Zealand red snapper fishery (Batstone and Sharp 1999), and increased catches in Icelandic limited effort demersal fisheries (Arnason 1996b). It is therefore important to decide on a fixed inter-sector TAC allocation before implementing ITQs in one sector of a multi-sector fishery.

Since ITQs are not perfect, we should not consider ITQs a panacea for all fisheries' problems. ITQs focus on providing very individual-specific incentives for conservation and stewardship, with collective action arising only peripherally, but future management systems might emphasize cooperation as their central goal (Squires et al. 1995). Some of the current alternatives to ITQs include CDQs, cooperatives and territorial fishing rights. CDQs (discussed previously) encourage entire communities to benefit from the fishing resources by redistributing the wealth of the fishery throughout the community (e.g., Wingard 2000). Cooperatives are groups of fishers who pool their quota and decide how they can harvest their joint quota most efficiently while sharing the profits (e.g., Kitts and Edwards 2003). They have proven as successful as ITQs for single-species fisheries like pollock off Alaska, Pacific whiting off the U.S. West Coast, and the Lake Chignik salmon fishery (Kitts and Edwards 2003). One of the chief benefits of cooperatives in U.S. fisheries is that they are much easier to implement than ITQs because permission can be obtained for them directly from Congress (Criddle and Macinko 2000). In addition, there is some evidence that cooperatives may be more successful at reducing under-harvest of ITQs, and should therefore be encouraged in addition to ITQs (Fina in press). Territorial fishing rights have been implemented in the Chilean loco fishery, where villages ("caletas") have been granted the right to manage their own loco fisheries and protect them against outsiders, after first assessing the status of their stocks and presenting a management plan to the fisheries authorities (e.g., Bernal et al. 1999). They have yielded substantial benefits compared to remaining open access areas (Hilborn et al. 2004).

In summary, while ITQs provide substantial benefits in terms of flexibility, improved economic performance and the ability to fish sustainably, they are not perfect. Mechanisms to reduce social disruption and the balance of power in fisheries stakeholders need to be included, and monitoring and enforcement will probably need to be strengthened. Managers considering ITQs should also ponder whether CDQs, cooperatives, territorial fishing rights, or other systems including marine tenure might better address the problems arising from open-access and competitive fisheries. In fisheries management, one size rarely fits all.

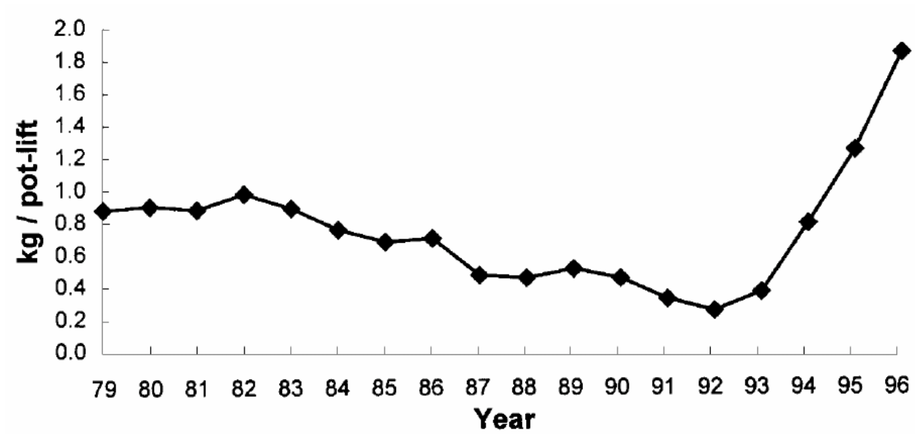


**Figure 1.1**. Commercial CPUE (kg per pot lift) for the Gisborne red rock lobster fishery. ITQs were introduced in 1990, and the proposal by the ITQ-holders was implemented in 1993. Reproduced from Breen and Kendrick (1997), with permission.

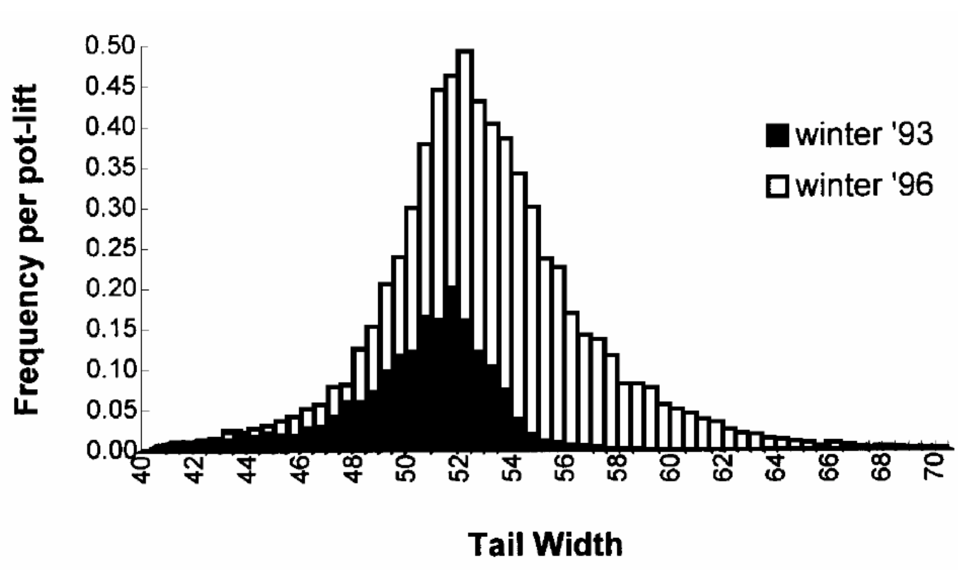


**Figure 1.2**. Size distribution of male lobsters in the all-male Gisborne red rock lobster fishery during June–August before (winter 1993) and after (winter 1996) the implementation of the management plan developed by the ITQ holders. Reproduced from Breen and Kendrick (1997), with permission.

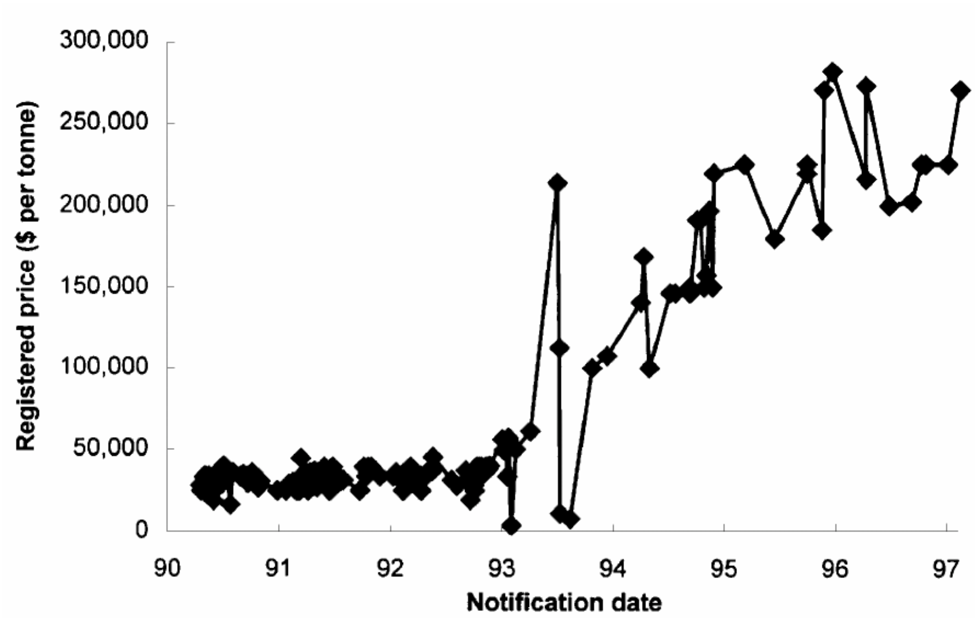


**Figure 1.3**. Mean monthly trading price (NZ$ per tonne) of Gisborne red rock lobster quota. The management plan proposed by the ITQ-holders was implemented in 1993. Reproduced from Breen and Kendrick (1997), with permission.

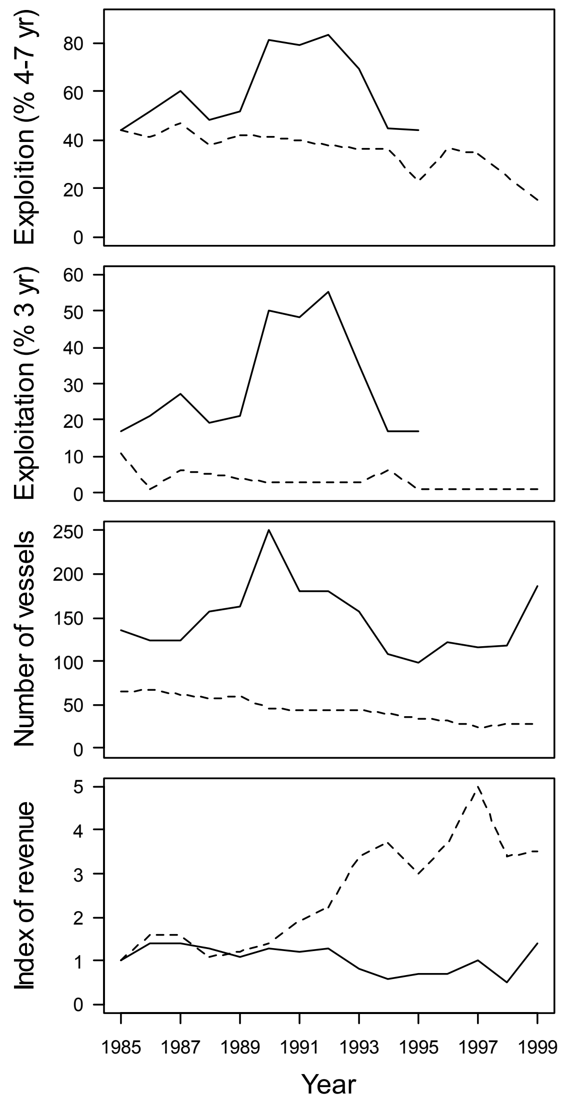


**Figure 1.4**. Changes in the U.S. (solid line) and Canadian (dashed line) Atlantic sea scallop fisheries on either side of the Hague Line on the Georges Bank. Enterprise Allocations, whereby ITQs are granted to companies, were introduced in the Canadian fishery in 1985. The exploitation rates for 4-7 yr old and 3 yr old scallops are shown, together with the number of vessels, and the relative index of revenue per sea-day (normalized to 1985) for the two fisheries. Redrawn and modified from Repetto (2001).

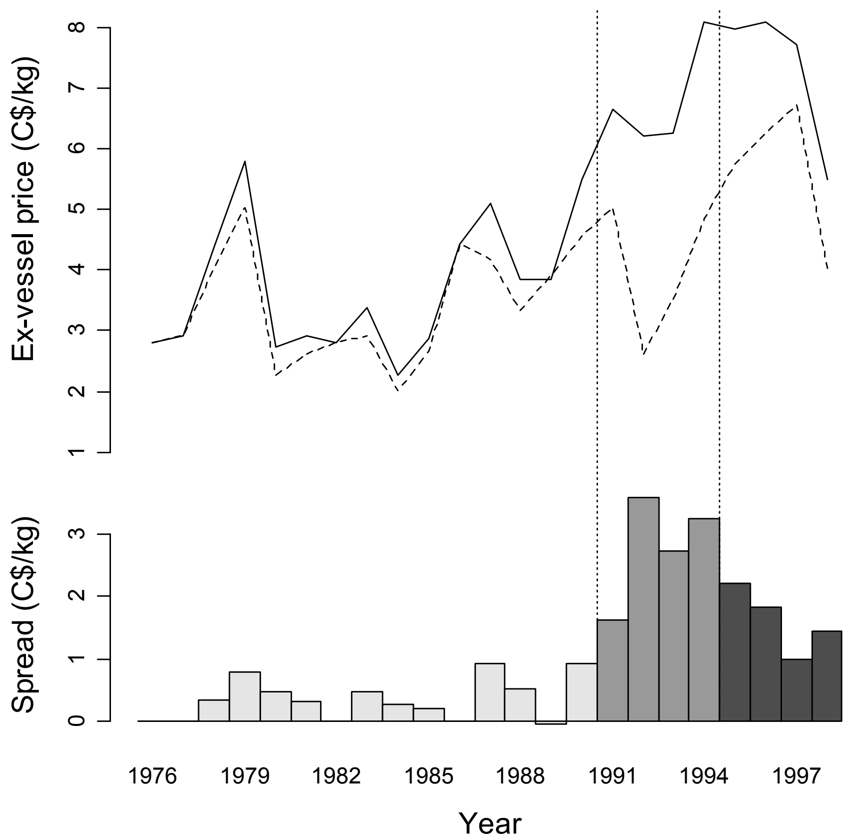


Figure 1.5. Ex-vessel prices for halibut in the British Columbia fishery (solid line) and the Alaska fishery (dashed line). The difference in prices ("spread") is indicated by solid bars in the bottom panel. Bar colors and dotted lines indicate the introduction of ITQs in B.C. (in 1991) and in Alaska (in 1995). Redrawn and modified from Herrmann (2000).

# CHAPTER 2

# REPLACING TRIP LIMITS WITH ITQS:

# IMPLICATIONS FOR DISCARDING

## Introduction

Individual Transferable Quotas (ITQs) are being considered for many fisheries in the United States since the federal moratorium on individual quota systems expired in October 2002. The basic idea of ITQs is well-established: divide the total allowable catch among a specified set of recipients and allow them to choose when and how to fish, and whether to buy additional quota share or to sell or lease their own quota share. By ending the “race for fish”, ITQs offer substantial advantages: increased economic rent, reduced overcapitalization, improved safety, and better product quality (e.g., NRC 1999). Potential problems with ITQs include numerous social issues—how they are assigned, changes in the balance of bargaining power of quota holders compared to processors, and the loss of employment as fleets are reduced (e.g., NRC 1999).

Some authors (e.g., Copes 1986) argue that implementation of ITQ’s will increase discarding. In this paper, I define “discards” as caught fish that are returned to the sea, “landings” as retained catch, “catch” as the sum of discards and landings, “discard fraction” as the ratio of discards to catch, “marketable discard fraction” as the ratio of marketable discards to catch, and “high-grading” as the practice of preferentially discarding less valuable (generally smaller) fish in order to land a higher proportion of more valuable fish.

Theoretical incentives for high-grading and discarding in ITQ fisheries are often cited (Copes 1986, Annala et al. 1991, Squires et al. 1998). In theory, ITQs offer more incentives to high-grade compared to open access fisheries if limits are imposed on landings and not on catches (Anderson 1994, Arnason 1994). Conditions leading to high-grading include relatively low costs of discarding, a large price differential between classes of fish, and low costs of catching fish to replace those that were discarded (e.g., Kingsley 2002). For example, high-grading was problematic in the northern New Zealand snapper fishery because of a US$3 / kg differential between large and small fish. This problem only diminished after the imposition of a high-profile at-sea enforcement program and extensive discussions with industry (Boyd and Dewees 1992). ITQs may also induce discarding when some species in a multispecies fishery have constraining quotas and the mix of quota does not match the mix of species that are caught. Discarding the quota-constrained species gives the skipper the chance to continue fishing for the remaining species. This would encourage illegal discarding at sea if full retention of quota species is required by law.

Theoretical incentives to high-grade and discard fish are countered by incentives to reduce discards. For example, the more relaxed pace of fishing in ITQ fisheries and increased security of harvesting rights, gives operators incentives to use more selective fishing gear, to target or avoid particular fishing locations, share information about which areas to avoid, increase self-enforcement, and lease or buy quota to reduce mismatches between quota and catch mixtures (Squires et al. 1995, Squires et al. 1998, Baelde 2001, Dupont and Grafton 2001). In a multispecies fishery, quota leasing prices will be highest for constraining species because quota holdings of those species allows continued fishing on the remaining species. Lease prices for constraining species may even exceed their ex-vessel value, thus there are incentives not only to discard such species if they are caught, but also to change fishing practices to avoid catching them in the first place.

In practice, the evidence for increased discarding in ITQ fisheries is mixed (Squires et al. 1995, Squires et al. 1998). In Iceland, there was no evidence of increased discarding (Arnason 1994, 1996), but fishers in the Australian south-east fishery maintain that discards have increased (Baelde 2001). In Nova Scotia, at-sea observers suggest that discarding and high-grading have increased, but dockside monitors indicate that the level of cheating has probably declined (McCay et al. 1995). In New Zealand, discarding was initially considered a problem in the deepwater trawl fleet (Annala et al. 1991), but the proportion of interviewed fishers and managers concerned about discards decreased from 66% in 1987 to 25% in 1995 (Dewees 1998). When ITQs replaced frenetic derby-style fishing in the Alaska halibut and sablefish fishery the discards of halibut in the sablefish fishery were reduced by 83%, and mortality from lost gear in the halibut fishery decreased by 77% (NRC 1999, pp. 74-75). A similar outcome was obtained in the Chilean squat lobster fishery, where discards decreased from >100 t per year to negligible quantities when ITQs were introduced (Bernal et al. 1999).

Discarding can be problematic for several reasons. First, while discards of unmarketable fish are to be expected in most fisheries, discards of marketable fish may represent a substantial loss in income to individual fishers[1]. Second, accurate stock assessments and management regulations require estimates of total fishing mortality from both landed fish and discarded fish. Biased estimates of discard fractions may therefore lead to the setting of total allowable catches that are overly optimistic or pessimistic.

On-board monitoring of catches and discards is one solution to the discard problem (Arnason 1994). On-board observers would prevent unreported discarding when quotas are exceeded, and allow accurate estimates of discards to be gathered. Many authors have considered this solution to be too costly (Anderson 1994, Arnason 1994, Squires et al. 1995, Turner 1997, Squires et al. 1998, NRC 1999). However, the costs of observer coverage may be outweighed by their benefits. In many ITQ fisheries, increased profitability enables on-board observers to be funded from cost-recovery programs, increased retention of marketable fish would usually increase the profits of fishers, and there may be considerable economic value attached to more accurate and reliable stock assessments and resultant total allowable catches.

The U.S. West Coast groundfish fishery (West Coast fishery), and the British Columbia groundfish fishery (B.C. fishery) offer interesting insights into the effects of different management schemes (landing limits and ITQs) on discarding. These fisheries catch more than 70 commercially valuable species common to both fisheries, they use a similar mix of vessels, and their main markets are the U.S. and Japan. Until 1995, both

[1] High-grading may be economically profitable to individual skippers (although not necessarily to society as a whole), but when discarding is required or induced by regulations, marketable discards reduce the income available to fishers.

fisheries were managed by cumulative landing limits (described below). This system continues to date in the West Coast fishery, but in 1996, the B.C. fishery added 100% on-board observer coverage and full mortality accounting (whereby discard mortality of marketable fish was deducted from landing limits), and in 1997 moved to ITQs. In recent years, many West Coast species were declared overfished, resulting in order of magnitude reductions in TACs and highly restrictive landing limits for those species, whereas landings in the B.C. fishery have generally remained at levels similar to those in 1996. In this chapter I compare discards between the two fisheries and between the pre- and post-ITQ years in the B.C. fishery.

**Background**

*Management regulations in the West Coast fishery*

Trip limit regulations were introduced to the West Coast fishery in the 1980s to limit total catches and to spread landings throughout the year to provide fish year round to the markets. Under trip limits, individual vessel catches in excess of trip limits had to be discarded. As the fishing capacity in the fishery increased and total allowable catches were reduced, limited entry was introduced in 1994 (although a small open-access fishery remains), and trip limits were progressively lowered for many species. Since both observer programs (Pikitch et al. 1988) and theoretical studies (Sampson 1994, Gillis et al. 1995a, Gillis et al. 1995b) concluded that discards would increase if trip limits were reduced, trip limits were replaced by monthly, and finally two-monthly cumulative landing limits. Nevertheless, discarding continued because when limits were exceeded for some species, fishers were required to discard additional catches of those species while continuing to fish for other species.

A major management concern in the West Coast fishery is the number of species that have been declared overfished. Overfished species require stringent rebuilding plans. These rebuilding plans generally include highly restrictive two-monthly limits on the overfished species and on co-occurring non-overfished species (to reduce bycatch of the overfished species). For example, canary rockfish were initially managed under a 40,000 lb trip limit in 1983 as part of the Sebastes (rockfish) complex and were managed individually under a 6,000 lb per month limit in 1995. After being declared overfished in 2000, landings were restricted to two-monthly limits of 100–600 lbs. As intended, total canary rockfish trawl landings were reduced by two orders of magnitude from 1991 to 2001. Although total mortality of the overfished species has been dramatically reduced, discard fractions of these species have increased. Ongoing concern about overfished species has led to the introduction of footrope rules limiting trawling in prime rockfish habitat (Hannah 2003), and a $46 million vessel buyback program in December 2003 which reduced the limited-entry trawl fleet from 263 to 171 vessels. In addition, Groundfish Conservation Areas (trawl closures), covering much of the shelf region, were declared in late 2002, further reducing landings of many rockfish species. At present, the fishery targets primarily flatfish species and the deeper water DTS species (Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish). The Pacific Fisheries Management Council is currently considering an ITQ system for this fishery in the hope that it will solve some of the problems described above.

*Management regulations in the B.C. fishery*

The B.C. fishery followed a similar pattern to the West Coast fishery, with dramatic growth in fishing capacity, increasingly restrictive trip limits, and major concerns about discarding (Turris 2000). By 1995, a complicated system of trip limits and quarterly fleet-wide TAC caps had proved insufficient to prevent TAC overages for several species, and in September of that year the fishery was closed. When it reopened in February 1996, some dramatic changes had been enacted: near-100% on-board observer coverage[2] was added to the existing 100% shoreside coverage of landings, and individual vessel limits were placed on catches (not landings) for four-monthly or annual periods. Discards were allowed, but if the discarded fish were marketable (greater than size limits set in conjunction with processors), then the assumed mortality of the marketable discards would be subtracted from quota limits. Assumed discard mortality varies by species, e.g., it is 100% for all rockfish species, but for sablefish it is 10% for the first two trawl hours and 10% for each additional hour. After a transition period at the start of 1997 this system was then transformed into ITQs in April 1997. All ITQs are annual catch limits which can be bought or sold and include discard mortality of marketable fish. Some ITQs are coast-wide, others are subdivided among smaller management areas. While no leasing is formally allowed, *de facto* leasing arrangements are commonplace, especially to cover

[2] Trips targeting Pacific hake using midwater gear do not need to carry an observer, unless they bottom trawled during the trip. In addition, observer coverage has been 10% or lower for the small “B-option” trawl fishery in the Straits of Georgia. Finally, because of the round-the-clock nature of the fishery, some trawls are not observed even if an observer is on the vessel.

overages. Quota holders have been allowed to carry underages and overages up to 37.5% (less for some species and in some years) forward to the following year, although in practice fishers tend to under-catch their quota. As in 1996, if the skipper held insufficient quota to cover catches, that vessel would be restricted to midwater trawling for the remainder of the year. The ITQ system initially included 22 species and one species group, but big skate and longnose skate were added in 2002, and more species may be added in the future.

## Methods

### *Comparison of discards between the West Coast and B.C. fisheries*

Discard fractions were obtained from the West Coast Groundfish Observer Program (NWFSC 2004). Observer coverage of the limited-entry trawl sector was 13% of the landed tonnage in 2001–02 (1 September–31 August) and 16% in 2002–03. Observed vessels were chosen to be representative of the fishery, and were observed for two-month periods corresponding to those used for cumulative landing limits.

I restricted my comparison to discard fractions presented in the observer report (NWFSC 2004), i.e., excluding midwater trawls and Pacific hake trips. Although some components of the Pacific hake fishery have observers on the vessels, the shoreside whiting fishery, which requires full retention of all fish, does not have observers. It is unknown whether any illegal discarding of bycatch species occurs in the shoreside fishery. Observer-recorded discards for bottom trawling trips had been matched to the corresponding fish tickets (recorded landings). Species identification was not always consistent between observer records and fish tickets, and therefore discard estimates were not available for all species; less easily identified species were grouped into categories. Catches and discards identified as unspecified "thornyheads" were assigned to longspine thornyheads (73%) and shortspine thornyheads (27%) in proportion to their identified ratio in the remaining landings. Two species (cowcod and California halibut) did not occur in the B.C. fishery, and were therefore excluded from the comparisons.

For the B.C. fishery, total catches and total discards for each species were extracted from the PacHarv observer database. This database includes all bottom, midwater, and Pacific hake trawls. However, only bottom trawls were extracted for the comparison with the West Coast fishery. Fish species (or species categories) were extracted for 2001–02 (1 April–31 March) and 2002–03, and grouped into categories that corresponded to the West Coast categories. Catches and discards identified as "thornyheads" were assigned to longspine thornyhead (65%) and shortspine thornyhead (35%) according to the identified ratio in the B.C. catches.

*Ex-vessel value of discarded fish in West Coast fishery*

Three elements were used to estimate the ex-vessel value of discarded West Coast fish: total discard weight, the proportion of discards that would have been marketable, and the price obtained for landings. For most species and species groups, total discard weight ($D$) was obtained by combining the landed weight ($L$) from the PacFIN database with the observer estimates of discard fractions ($F$):

$$(2.1)\quad D = \frac{F}{1-F} L$$

This method was considered less reliable for species or groups where the discard fraction exceeded 90% in either year. In such cases, I assumed that the percentage observer coverage (*O*) was representative of the whole fishery, and therefore that the weight of discarded fish on observed trips ($D_o$) could be expanded as follows:

$$(2.2)\ D = \frac{D_o}{O}$$

Equations 2.1 and 2.2 give similar results: the correlation between total discard weights for species or groups with discard fractions < 90% was 0.994 in 2001-02 and 0.995 in 2002-03.

It was not possible to obtain a direct estimate of the value of discarded marketable fish in the West Coast fishery for the 2001–02 and 2002–03 seasons. Although the skipper’s reasons for discarding were recorded during the West Coast observer program (classified into ‘prohibited’, ‘size’, ‘market’, ‘regulation’, and other), these data have not yet been validated and released. I therefore used an indirect method, assuming that the same proportion of catches by species would be marketable in both the West Coast and B.C. fisheries, and that marketable discards in the B.C. fishery were negligible. If these assumptions hold, the estimated ex-vessel value (*V*) of the discarded fish in the West Coast fishery is given by:

$$(2.3)\ V = P\left(L + D\right)\left(F_{BC} - F_{WC}\right)$$

Where $P$ is the West Coast ex-vessel price, $L$ is the West Coast landed weight, $D$ is the West Coast discard weight, $F_{WC}$ is the discard fraction in the West Coast fishery and $F_{BC}$ is the discard fraction in the B.C. fishery.

The estimated value was calculated only for lingcod and shortspine thornyhead, because available data suggested that the assumptions above were met for those species. Ex-vessel values for lingcod and shortspine thornyhead were \$1.48 and \$1.50 per kg respectively[3].

*Pre-ITQ and post-ITQ discard fractions in the B.C. fishery*

To examine changes in discard fractions over time in the B.C. fishery, discard fractions were obtained for the pre-ITQ 1996 season (12 February–31 December), and for each of the post-ITQ seasons (1997 to 2002, 1 April–31 March). An interim management period from 1 January–31 March 1997 was omitted. To obtain a full representation of this fishery, midwater and Pacific hake trawls were included in this portion of the analysis. I included all species under ITQ management, and all non-ITQ species with average annual catches greater than 50 t over the period, selecting 35 species.

The reasons for discarding are recorded in the B.C. database; from this I calculated the marketable discard fraction (the proportion of catches that were “marketable” but

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[3] Price data for the West Coast fishery were obtained from PACFIN on 20 April 2004 from report #058Wtwl available at http://www.psmfc.org/pacfin/data/r058Wtwl.p03.

were discarded). For most commercially important species, and for all rockfish species, marketability was defined by size after consultation with processing companies. For other species there were no size divisions, and discards were always recorded as unmarketable. This was the case for arrowtooth flounder, flathead sole, Pacific hake, rex sole, sand sole, shortspine thornyhead (in 1996), longspine thornyhead (1996), spiny dogfish (1996), big skate (1996–2001), and longnose skate (1996–2001). Discards of prohibited Pacific halibut were classified as “dead” or “alive”, not according to marketability. For those species where marketable size limits were defined in all years, the median of their discard fractions was calculated for 1996 (pre-ITQ), 1997–98 (quota transfer and adjustment period), and for 1997–98 to 2002–03 (post-ITQ).

**Results**

*Comparison of discards between the West Coast and B.C. fisheries*

Bottom trawl discard fractions were consistently greater in the West Coast fishery than in the B.C. fishery in both 2001–02 and in 2002–03 (Figure 2.1). In 2001–02, discard fractions were greater in the West Coast fishery for every species or category examined, but after the declaration of the Groundfish Conservation Areas in 2002–03, discard fractions for black rockfish, Pacific hake, petrale sole, sablefish, nearshore rockfish, and other roundfish were greater in the B.C. fishery. However, catches of black rockfish and nearshore rockfish were very small in both fisheries (Table 2.1), and although Pacific hake is caught in relatively large quantities by bottom trawlers, these vessels typically lack the specialized equipment that is needed to process and deliver Pacific hake (unlike midwater trawlers). The discard fraction across all species was 43%

in 2001–02 and 31% in 2002–03 for the West Coast fishery and 14% and 19% for the B.C. fishery (Table 2.1).

Although the same suite of species was generally caught in both fisheries, the tonnage caught for each individual species varied considerably between the two fisheries (Table 2.1). Catches of some groups were much higher in the B.C. fishery, especially for most of the overfished West Coast species, and groups that were more abundant further north (e.g., arrowtooth flounder, yellowtail rockfish, other shelf rockfish, and other slope rockfish). Catches of other groups were higher in the West Coast fishery, particularly for the DTS species, petrale sole, and other flatfish. Some groups were minor components (black rockfish, and nearshore rockfish), or were prohibited (yelloweye rockfish, Pacific halibut, and salmon species) in both fisheries.

In the West Coast fishery, the declaration of the Groundfish Conservation Areas increased fishing effort on the deep-water DTS species and decreased effort on the remaining species in 2002–03. Landings of the DTS species increased from 8,500 t to 11,400 t, but landings of other species decreased from 9,900 t to 8,600 t, and landings of the overfished species (excluding Pacific hake) declined by 48% from 498 t to 258 t.

*Ex-vessel value of discarded fish in West Coast fishery*

Although the weight discarded was great for Pacific hake, arrowtooth flounder, and other flatfish (Table 2.1), these species have low ex-vessel prices, unlike the higher-value species like rockfish, thornyheads, sablefish, and Dover sole. A combination of ex-vessel price and discard weight suggests that the total ex-vessel value of discards would likely be dominated by sablefish and Dover sole, although it was not possible to estimate the marketable discard fraction for those species. The estimated value of discarded lingcod and shortspine thornyhead in the West Coast fishery was $0.7 million in 2001–02 and $0.8 million in 2002–03, split fairly evenly between the two species.

*Pre-ITQ and post-ITQ discard fractions in the B.C. fishery*

There were low discard fractions (< 15%) for almost all B.C. species under catch limits in 1996 and ITQ management thereafter (Figure 2.2). Note that the B.C. system in 1996 already differed from that in the West Coast (full observer coverage, deduction of discards from catch limits). There were few dramatic changes in discarding when ITQs were introduced in the 1997–98 season, except for increased discards of yelloweye rockfish which could be landed and sold in 1996 (near zero discard fraction) but was required to be relinquished after 1997–98.

Compared to species discard fractions in 1996, there was an initial increase in 1997–98 for many species, but decreases for many species in subsequent years (Figure 2.3). In 1997–98, discard fractions were greater than in 1996 for 19 of the 35 species, but in 1998–99 there were increases in only 15 species, and in only 8–10 species from 1999–00 to 2002–03. Discard fractions for ITQ species in 1998–99 to 2002–03 were generally similar or less than in 1996, except for lingcod; discard fractions for many non-ITQ species were much lower, notably for splitnose rockfish, greenstriped rockfish, big skate, rex sole, and sharpchin rockfish.

Marketable discard fractions were low for most B.C. species, except for yelloweye rockfish (9.8%–45.9%) and spiny dogfish (9.5–32.5%) in 1997–2002 (Figure 2.2). Of the remaining species, marketable discard fractions were greater than 1% only for sablefish

(13.3% in 1996, 1.2–2.8% after 1997–98), Dover sole (1.1%–3.0%, all years), and for big skate (4.8%) and longnose skate (2.6%) when marketable sizes were first defined in 2002–03. Marketable sizes were defined in all years for 24 species. The median marketable discard fraction for these species was 0.20% in 1996, 0.16% in 1997–98 and 0.10% in 1998–99 to 2002–03. Marketable discard fractions decreased from 1996 to the later period for 18 species, and increased for six species.

**Discussion**

*Comparison of discards between the West Coast fishery and the B.C. fishery*

Discard fractions were higher in the West Coast fishery than in the B.C. fishery for every species in 2001–02 and most species and groups in 2002–03. The imposition of Groundfish Conservation Areas in 2002–03, which reduced West Coast landings for many species, is the most likely explanation for the change in 2002–03. Of the species and groups with lower discards in the West Coast fishery in 2002–03, some were minor components in both fisheries (black rockfish, nearshore rockfish, other roundfish), were primarily caught in midwater trawl gear (Pacific hake) or were not substantially different (petrale sole, 6% vs. 9%). The large fraction of sablefish discarded (69% in B.C. vs. 32% in West Coast) may be due to an exceptionally large 2000 sablefish year class in B.C. and northern Washington. B.C. trawlers complained that it was difficult to avoid the abundant under-sized sablefish in that year[4]. Alternatively, skippers may have decided to discard

[4] E-mail correspondence with Vivian Haist, 9 May 2004. 1262 Marina Way, Nanoose, B.C. V9P9C1, Canada.

some marketable sablefish to fully catch their quotas of Dover sole and thornyheads (estimated mortality is deducted from quota holdings but the discard mortality for sablefish is assumed to be just 10% for the first two hours). This explanation seems less likely because the marketable discard fraction for B.C. sablefish was only 2.4% in 2002–03.

The greater discards overall in the West Coast fishery are partly due to differing circumstances in the two fisheries. Priorities in the West Coast fishery included reducing the total mortality of the overfished species as required in the rebuilding plans (by 1–2 orders of magnitude in some cases), and maintaining a year-round fishery. The resulting landing constraints on some species have resulted in situations where a single trawl could catch the entire two-monthly landing limit. An observer study showed that when trip limits were decreased, discard fractions increased (Pikitch et al. 1988). For example, only 5.7% of widow rockfish was discarded under 30,000 lb weekly limits, but 52.3% was discarded under 3,000 lb weekly limits.

In the B.C. fishery total catches of most species have remained at similar levels to past catches, although catches of some species (lingcod, yelloweye rockfish, rougheye rockfish and shortraker rockfish) have decreased by more than 50%, and Pacific cod catches are more than an order of magnitude lower than their peak. While the different circumstances in the two fisheries partially explain the higher West Coast discard fractions, it should be noted that discards of species and groups not listed as overfished were also higher in the West Coast fishery, especially in 2001–02.

Differences in individual incentives between the two fisheries may also account for greater discards in the West Coast fishery. When two-monthly limits are exceeded in the West Coast fishery, all subsequent catches of that species must be discarded, but the fisher can continue fishing for other species. At the end of the year, the estimated fleetwide discard mortality is applied in determining future fleetwide allowable catches. In the B.C. fishery, if any individual quota is exceeded, that vessel is restricted to midwater trawling for the remainder of the year, unless quota can be obtained from others to cover overages in excess of allowed levels. Furthermore, quota for constraining species is more expensive to buy or lease, further increasing the individual incentives for skippers to avoid catching such species. Although both fisheries take total mortality into account when setting total allowable catches, individual incentives help avoid discards in the B.C. fishery, compared to fleetwide incentives in the West Coast fishery.

Finally, discard fractions may differ between the two fisheries for a number of other reasons, ranging from different market acceptance, to different patterns of distribution of unmarketable sizes of fish, to vessel technology and fleet size. Such factors may be able to explain differences in discard fractions for particular species, but are unlikely to be the main reason for the overall pattern of higher discards for most species in the West Coast fishery.

*Estimated ex-vessel value of discards in the West Coast fishery*

It is difficult to estimate the income lost to fishers because of regulatory-induced discards in the West Coast fishery. The lost income will be a combination of the total discard amount, the ex-vessel value of the fish, and the proportion of the catches that were marketable but were discarded because of regulations. Estimates of total discard amount and ex-vessel value are relatively easy to obtain, but the proportion of discards attributable to regulations is more difficult to estimate. Previous West Coast observer studies have reported on the percentage of discards that skippers attributed to “markets”, “size”, “high-grading” and “regulations”. These studies suggested that a substantial proportion of discards were induced by West Coast landing limit regulations, including the majority of discards of Pacific ocean perch, sablefish, widow rockfish, yellowtail rockfish, lingcod, and shortspine thornyhead (Table 2.2). For some of these species (but not sablefish), the contrast between near-zero discards in the B.C. fishery and high discard fraction in the West Coast fishery in 2001–02 and 2002–03 suggests that the majority of West Coast discards are marketable. However, the reasons given by skippers for discarding fish should be viewed with caution as they are difficult to validate and may be misreported for strategic reasons.

By assuming that the percentage of marketable discarded West Coast lingcod and shortspine thornyhead was the same in both fisheries, I estimated that the West Coast ex-vessel value for these species was \$0.7 million in 2001–02 and \$0.8 million in 2002–03. Although market acceptance, fishing patterns, recruitment events and the geographic distribution of most species probably differ between the fisheries, this was not an unreasonable assumption for these two species. Discard fractions were substantially higher in the West Coast fishery (lingcod: 74–77% vs. 8–11%; shortspine thornyhead 31–34% vs. 4–5%), the 1995–99 observer program implicated regulations as the primary reason for their discards in the West Coast fishery (93% of lingcod discards, 54% of shortspine thornyhead discards, Table 2.2), and marketable discards of these species comprise only a small fraction of catches in the B.C. fishery (0.0–0.1% for lingcod, 0.3–0.6% for shortspine thornyhead). I did not estimate the ex-vessel value of West Coast discards of all species. The total value is likely to be dominated by discards of Dover sole and sablefish, which had large discard weights, because the 1995–99 observer study suggested that a large percentage of their discards were caused by trip limit regulations (Table 2.2). Sablefish additionally has high ex-vessel prices. Although discard fractions were high for many overfished West Coast species, their absolute discard amounts were generally low, and the ex-vessel value of discards of overfished species is probably also relatively small.

Other studies have also suggested that West Coast regulations result in some loss of income to fishers. Theoretical models suggested that trip limit management could result in high levels of discarding and highgrading (Sampson 1994, Gillis et al. 1995a, Gillis et al. 1995b), and potentially reduce average profits per trip by 66% (Babcock and Pikitch 2000). An observer study from 1985–87 concluded that the ex-vessel value of discarded widow rockfish and sablefish averaged \$1.8 million per year (Pikitch et al. 1988).

*Pre-ITQ and post-ITQ discard fractions in the B.C. fishery*

Discard fractions were low for most species in the B.C. fishery in 1996, and remained low after the introduction of ITQs. It is therefore likely that the system of near-100% observer coverage, in combination with fishing limits that included the assumed mortality of discarded marketable fish, resulted in these low discard levels. Fish will be discarded if they are too small or no market exists in any fishery, so it is not surprising that discarding continued for some species. Of greater importance is the level of marketable discards. In the B.C. fishery, marketable discard fractions were negligible for most species, with the exceptions of yelloweye rockfish (which was required to be relinquished) and spiny dogfish (which has low value and is difficult to handle). Marketable discard fractions were less than 1% for the remaining species except for sablefish (< 3% except in 1996), Dover sole (< 3%), and for big skate (4.8%) and longnose skate (2.6%) in 2002–03, suggesting that occasional catches of those species were unwanted. All four species have low assumed discard mortalities—10% for the first two hours and 10% for each hour thereafter (sablefish, Dover sole); 5% for the first two hours and 5% for each hour thereafter (skate species). Since discard mortalities (and not total discards) are deducted from quota holdings, it is possible that skippers may have engaged in high-grading or discarding of these species for strategic reasons.

What influence did ITQs have on discards? The main reasons for low discard fractions in the B.C. fishery were 100% observer coverage and individually specified catch limits that included the mortality of marketable discards. Discards increased for the majority of species when ITQs were introduced in 1997–98, but in subsequent years, discard fractions were generally lower than in 1996. The initially higher discards in 1997–98 were probably due to the method of initial allocation of ITQs: each fisher was allocated a percentage of ITQ holdings, based on the total value of their catches (measured in “groundfish equivalents”), and this percentage was then applied to the ITQs for each individual species to obtain their holdings. Not surprisingly, the quotas held by fishers did not match the mix of species in their historical catches. The 1997–98 season was therefore a time of rapid ITQ readjustments as fishers bought and sold quota so that they held sufficient quota for species-area combinations that they normally fished.

From 1998–99 onwards, several factors were probably responsible for lower discards than in 1996, all interlinked with the more relaxed and flexible fishing strategies allowed under ITQs. The large decreases in discards in non-ITQ species may have resulted from markets development for species that had not formerly been targeted, such as big skate and longnose skate. Fishers also had more flexibility to choose when, where, and how to fish so that small and unmarketable fish were caught less and they could now lease quota if they caught over their quota holdings. Marketable discards decreased after 1996 for 18 out of 24 species and median marketable discards for those species declined by 51%, perhaps because trading of quotas allowed fishers that specialized on some species and areas to legally increase their catches of those species.

Under the B.C. system of management, long-term decreases in discard fractions are likely because the total catch is capped, and profits can be improved only by minimizing costs, improving product quality, cheating (unlikely given 100% observer coverage), or targeting non-ITQ species.

*Potential effects of implementing the B.C. system in the West Coast fishery*

The Pacific Fisheries Management Council is currently considering ITQs for the West Coast fishery. If the 1996 B.C. system were implemented in the West Coast fishery (i.e., 100% observer coverage, limits on total fishing mortality), the very low allowable catches of the overfished species would be problematic. The 1996 B.C. system, which lacks quota transferability, would likely result in individual fishers rapidly exceeding allowable catches of a few overfished species, and then being prevented from fishing for the rest of the year, resulting in low utilization of the remaining species. Transferability is therefore crucial since it allows fishers to cover overages, in addition to being able to specialize in particular species or areas. Quota trading is now a crucial part of the B.C. fishery: in 2003–04 there were 2,700 trades among just 65 active vessels[5].

Assuming that the full B.C. system was implemented in the West Coast fishery, there are several reasons to believe that discards might be reduced: (1) discarding marketable fish would reduce the total possible income available to fishers, (2) individual incentives would reduce marketable discards, (3) annual quotas present fewer occasions to exceed quotas compared with two-monthly limits, (4) quota transferability allows quota mix to be matched with the target mix of species, and (5) the fleet size would likely decrease under ITQs as less efficient operators sell their quota. However, given the constraints of the overfished species, discards may not necessarily be reduced to the same extent seen in the B.C. fishery.

A necessary feature of the B.C. system is 100% observer coverage that enables the accounting of total fishing mortality, including discards. Without observers, limits can only be placed on landings, and any attempts to restrict landing limits will induce greater discard fractions of highly constrained species. The cost of observers may be prohibitively expensive for many fisheries, especially those with many small boats and numerous landing sites. In the B.C. fishery, many smaller operators had to sell their

[5] E-mail correspondence with Bruce Turris, 3 August 2004. 333 Third Street, New Westminster, B.C. V3L 2R8, Canada.

quotas and leave the fishery because of high observer costs. However, ITQ fisheries in general produce considerable economic rent, and in many ITQ fisheries quota holders are able to pay for observer and enforcement costs out of their increased profits (Annala 1996, Turris 2000, Dupont et al. 2002). The B.C. at-sea observer program is likely to cost $1.7–1.8 million in 2004–05, including administrative costs, overhead, training and supplies[6]. If the B.C. system was applied in the West Coast, observer costs would depend on the number of days at sea, the level of fleet consolidation under ITQs, and many other factors, and may be quite different to the B.C. costs. Estimated costs of full West Coast observer coverage would need to be weighed against the estimated lost value of discarded marketable fish under the current West Coast system ($0.7–0.8 million for lingcod and shortspine thornyhead alone, total likely to be dominated by Dover sole and sablefish discards).

**Conclusions**

In the B.C. fishery, discards were reduced to low levels by implementing near-100% observer coverage and deducting the assumed mortality of marketable discards from catch limits. The introduction of ITQs (while continuing full observer coverage) further reduced both total discards and marketable discards for most species, contrary to some previous studies that suggested that ITQs would tend to increase discards.

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[6] Email correspondence with Sue Bunten, 25 August 2004. Fisheries & Oceans Canada, Suite 200–401, Burred Street, Vancouver, B.C., V6C 3S4, Canada.

Discards were higher in the West Coast fishery, at least in part because of highly restrictive two-monthly landing limits on overfished species, resulting in some loss of income to fishers. Implementing the B.C. system in the West Coast fishery would increase observer costs and probably result in reduced marketable discard levels. However, reductions to the levels seen in the B.C. fishery would not necessarily be expected because of the overfished West Coast species.

**Table 2.1**. Estimated total discards (t), total landings (t), and discard fractions (discards/discards+landings) for the bottom trawl component of the British Columbia and U.S. West Coast groundfish fisheries in 2001-02 and 2002-03. For the B.C. fishery, these are the total discards and landings, but for the West Coast fishery, landings were obtained from the PacFIN database, and discard weight was obtained by applying the observer discard fractions to the landings, except where noted. Overfished species are indicated by (O) and prohibited species by (R). Landings of some overfished species were also occasionally prohibited.

| | W.C. discards | | W.C. landings | | B.C. discards | | B.C. landings | | W.C. discard fraction | | B.C. discard fraction | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species / category | 2001-02 | 2002-03 | 2001-02 | 2002-03 | 2001-02 | 2002-03 | 2001-02 | 2002-03 | 2001-02 | 2002-03 | 2001-02 | 2002-03 |
| Bocaccio rockfish (O)[a] | 41.6 | 7.5 | 26.7 | 7.0 | 0.5 | 0.8 | 195.1 | 196.5 | 79% | 100% | 0% | 0% |
| Canary rockfish (O) | 30.6 | 23.0 | 36.7 | 13.6 | 4.0 | 2.1 | 772.0 | 793.6 | 45% | 63% | 1% | 0% |
| Darkblotched rockfish (O) | 136.7 | 62.2 | 140.8 | 41.6 | 9.0 | 13.8 | 72.6 | 76.4 | 49% | 60% | 11% | 15% |
| Lingcod (O) | 286.3 | 272.1 | 99.6 | 82.3 | 102.1 | 203.1 | 1,205.0 | 1,700.7 | 74% | 77% | 8% | 11% |
| Pacific hake (O)[a] | 2,480.6 | 1,227.8 | 43.4 | 26.6 | 108.2 | 83.3 | 26.4 | 3.9 | 99% | 95% | 80% | 96% |
| Pacific ocean perch (O) | 23.7 | 19.9 | 169.1 | 108.8 | 41.2 | 45.0 | 5,461.0 | 5,485.7 | 12% | 15% | 1% | 1% |
| Widow rockfish (O) | 0.9 | 7.7 | 23.9 | 3.9 | 0.4 | 0.9 | 550.4 | 364.4 | 4% | 66% | 0% | 0% |
| Yelloweye rockfish (O) | 2.6 | 1.4 | 0.9 | 0.5 | 4.9 | 6.8 | 4.9 | 3.8 | 74% | 74% | 50% | 64% |
| Pacific halibut (R)[a] | 507.7 | 169.2 | 0.0 | 0.0 | 340.7 | 466.0 | 0.1 | 0.1 | 100% | 100% | 100% | 100% |
| Salmon species (R)[a] | 22.0 | 31.4 | 0.0 | 0.0 | 2.8 | 5.0 | 0.2 | 0.3 | 100% | 100% | 95% | 94% |
| Arrowtooth flounder | 2,776.6 | 1,387.8 | 2,659.0 | 2,098.8 | 2,280.2 | 2,952.2 | 7,391.0 | 4,455.9 | 51% | 40% | 24% | 40% |
| Black rockfish | 0.6 | 0.0 | 0.8 | 0.1 | 0.1 | 0.1 | 10.1 | 9.0 | 44% | 0% | 1% | 1% |
| Dover sole | 999.6 | 776.9 | 4,984.4 | 6,839.5 | 288.3 | 353.8 | 2,925.5 | 3,037.9 | 17% | 10% | 9% | 10% |
| Longspine thornyhead | 345.8 | 478.9 | 1,445.2 | 1,916.5 | 64.3 | 73.1 | 605.7 | 673.1 | 19% | 20% | 10% | 10% |
| Petrale sole | 172.0 | 115.7 | 1,959.5 | 1,709.6 | 20.5 | 38.9 | 438.4 | 392.6 | 8% | 6% | 4% | 9% |
| Sablefish | 2,044.6 | 905.3 | 1,519.4 | 1,906.3 | 346.9 | 556.6 | 297.9 | 249.3 | 57% | 32% | 54% | 69% |
| Shortspine thornyhead | 275.7 | 324.9 | 526.0 | 715.0 | 29.3 | 33.8 | 527.2 | 763.7 | 34% | 31% | 5% | 4% |
| Yellowtail rockfish | 83.3 | 3.6 | 297.6 | 147.9 | 3.2 | 4.2 | 1,998.7 | 2,185.7 | 22% | 2% | 0% | 0% |
| Other flatfish | 2,093.3 | 1,552.9 | 3,340.8 | 2,926.1 | 744.6 | 955.1 | 2,063.2 | 2,635.5 | 39% | 35% | 27% | 27% |
| Other nearshore rockfish[a] | 16.1 | 0.2 | 2.3 | 0.8 | 4.4 | 5.8 | 1.5 | 1.9 | 100% | 45% | 75% | 76% |
| Other shelf rockfish[a] | 240.6 | 99.7 | 36.8 | 14.1 | 144.4 | 135.9 | 1,813.0 | 1,799.7 | 66% | 98% | 7% | 7% |
| Other slope rockfish | 141.3 | 286.6 | 256.6 | 189.6 | 174.2 | 171.0 | 3,360.7 | 3,219.0 | 36% | 60% | 5% | 5% |
| Other roundfish | 952.7 | 1,203.3 | 809.9 | 1,273.4 | 390.7 | 525.9 | 633.4 | 518.3 | 54% | 49% | 38% | 50% |
| Total | 13,674.9 | 8,958.1 | 18,379.4 | 20,022.0 | 5,104.8 | 6,633.2 | 30,354.2 | 28,566.7 | 43% | 31% | 14% | 19% |

[a]Estimated West Coast discard weights for these species and groups were obtained by dividing the discarded weight on observed trips by the percentage observer coverage (13% in 2001-02 and 16% in 2002-03).

**Table 2.2**. The percentage of discards attributed to "regulations" by skippers in the West Coast fishery, from previous observer studies of the fishery. Data are presented from Pikitch et al. (1988) and from the Enhanced Data Collection Program (EDCP), based on observer coverage in 1995–99. Discards attributed to "high-grading" in Pikitch et al. (1988) are not included, although such discards were also a result of trip limit regulations according to Pikitch et al. (1988). Species from the EDCP program were only included if there were more than 40 discard records. EDCP data source: Table 4.1.0b, Groundfish Bycatch Draft Programmatic Environmental Impact Statement, available at http://www.nwr.noaa.gov/1sustfsh/groundfish/eis_efh/pseis/DPEIS/.

| Species | Pikitch et al. | EDCP |
|---|---:|---:|
| Pacific ocean perch | 75% | - |
| Sablefish | 50% | 83% |
| Widow rockfish | 100% | 63% |
| Yellowtail rockfish | 99% | 71% |
| Lingcod | - | 93% |
| Arrowtooth flounder | - | 0% |
| English sole | - | 0% |
| Dover sole | - | 25% |
| Shortspine thornyhead | - | 54% |
| Longspine thornyhead | - | 7% |
| Pacific whiting | - | 2% |

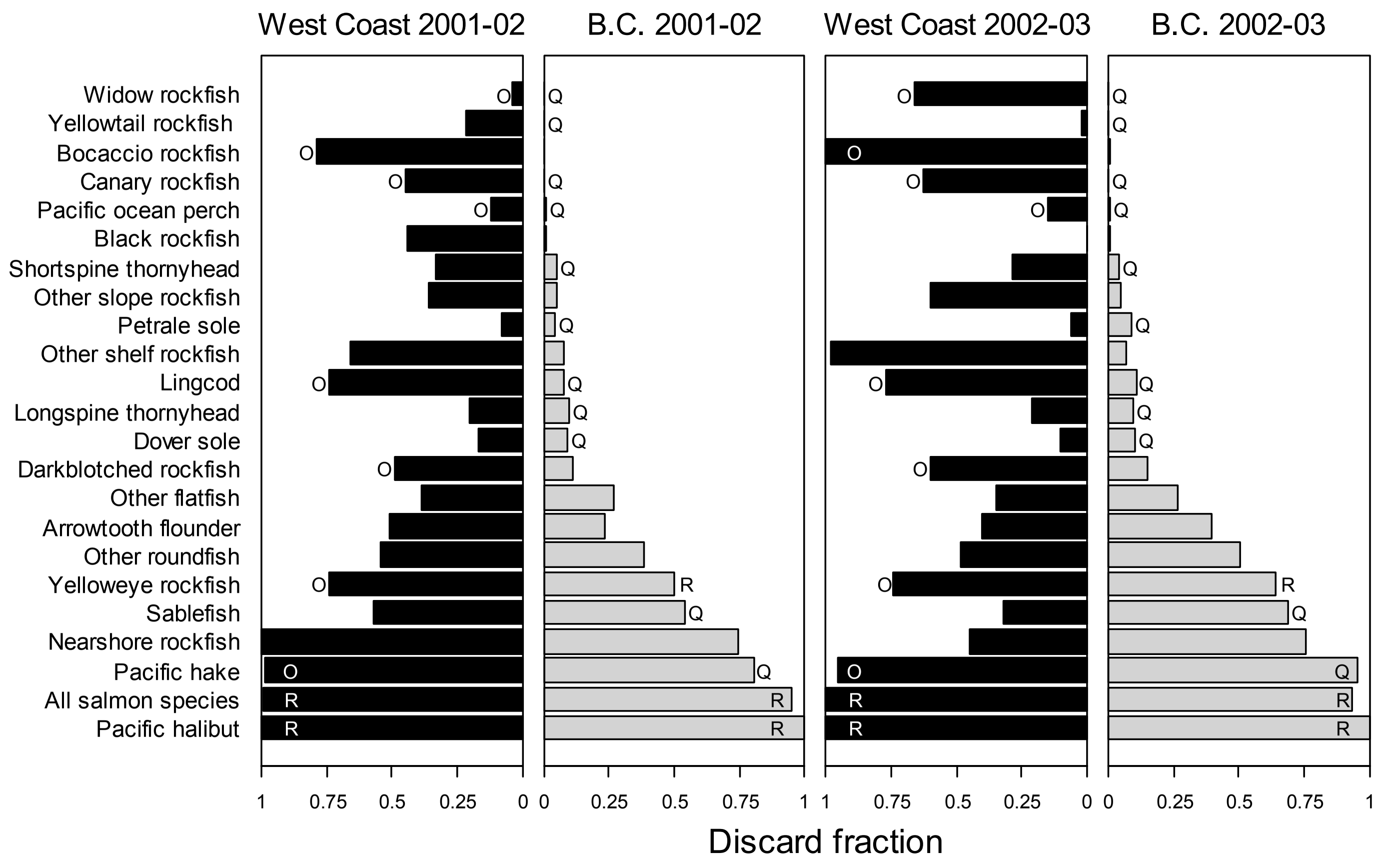


**Figure 2.1**. Comparison of the fraction of fish caught during bottom trawling that were discarded in the West Coast fishery and in the B.C. fishery in 2001–02 and 2002–03 for available species or species categories. Letters indicate West Coast overfished species with restrictive allowable catches (O), species that must be relinquished (R) and species under ITQ management (Q). Some overfished species were also required to be relinquished. The x-axes are reversed for the West Coast fishery data to aid comparisons.

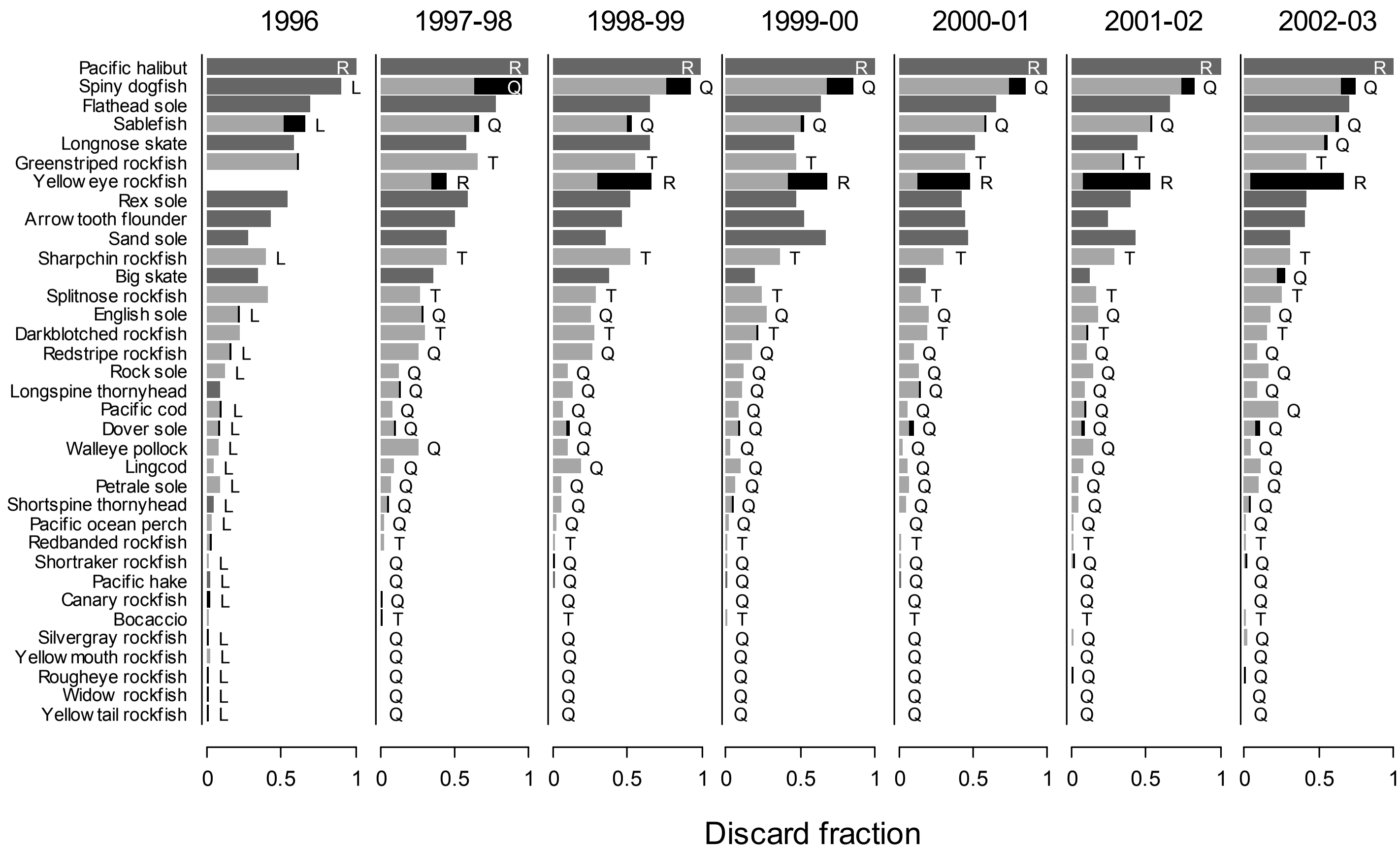


**Figure 2.2**. The fraction of fish that were discarded in the 1996 to 2002–03 seasons for the most important species in the B.C. fishery. Discards were classified into marketable (black) and unmarketable (light gray) based on size, although in some cases (dark gray) no marketable sizes were in place because all discards were assumed to be unmarketable. Most species were under four-monthly or annual limits in 1996 (L) and under ITQ management thereafter (Q), although a few were required to be relinquished (R), and there was a combined trip limit for minor rockfish species (T). Data are for bottom and midwater trawls, including Pacific hake trawls.

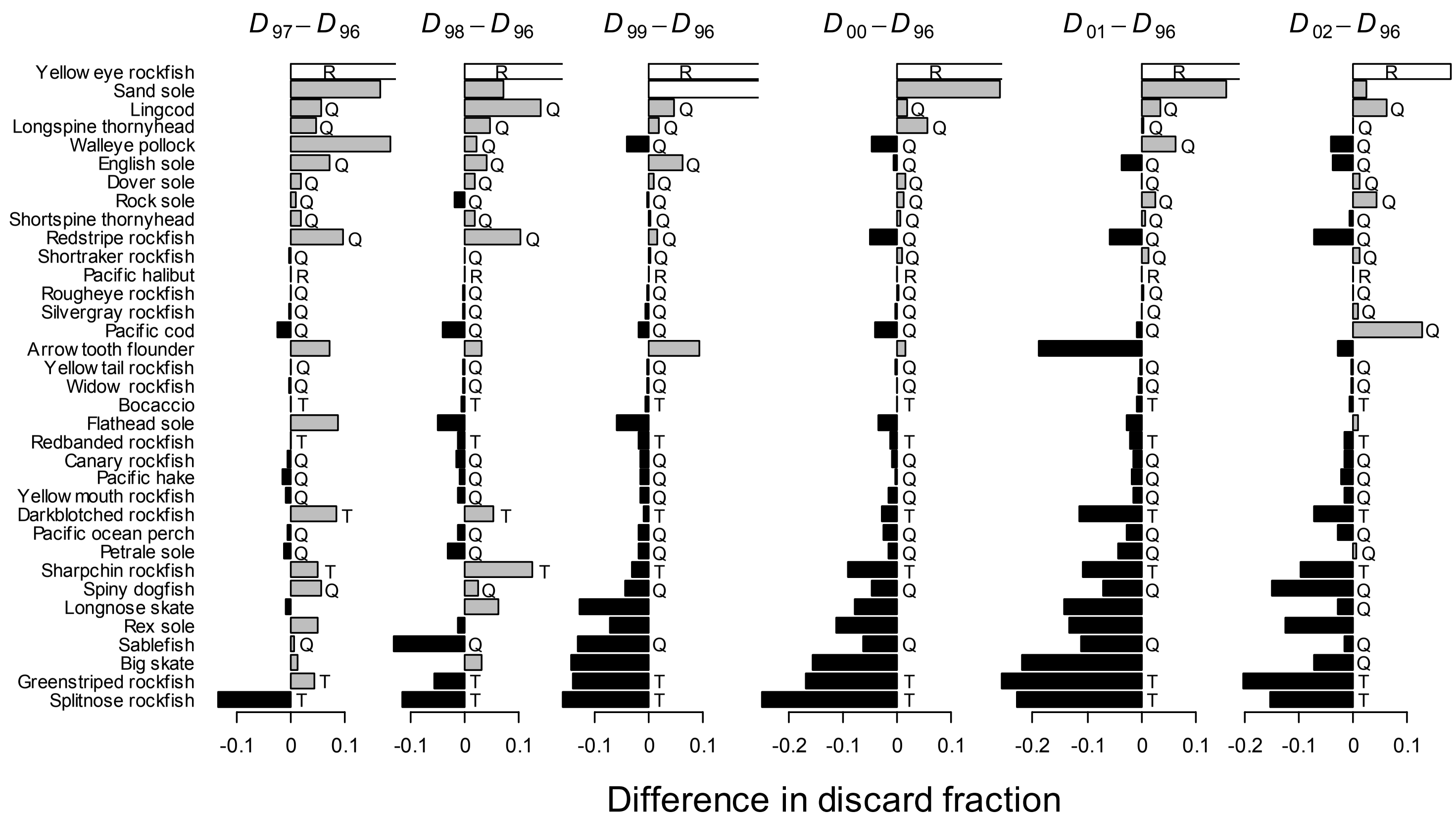


**Figure 2.3**. Changes in the discard fraction in the B.C. fishery compared to the pre-ITQ discard fraction in 1996, e.g., $D_{97} - D_{96}$ is the difference between the discard fraction in 1997–98 and that in 1996. Negative (black) values indicate that the discard fraction was lower than in 1996, positive (grey) values indicate a higher discard fraction in the later year. White bars indicate where discard fractions increased by more than 0.25 compared to 1996. Many species were managed under ITQs (Q) in the later season, although a few were required to be relinquished (R), and there was a combined trip limit for minor rockfish species (T). Data are for bottom and midwater trawls, and include Pacific hake trips.

# CHAPTER 3

# ESCAPING THE TYRANNY OF THE GRID: A MORE REALISTIC WAY OF DEFINING FISHING OPPORTUNITIES

## Introduction

Understanding the behavior of fishers is essential if we wish to examine the impact of management regimes like Individual Transferable Quotas (ITQs) and Marine Protected Areas (MPAs) on fisheries. One of the most basic elements of fishing behavior is the choice of when and where to deploy fishing gear: a skipper chooses between conducting exploratory fishing and fishing at competing “fishing opportunities”. I define “fishing opportunities” to be regions over which the skipper of a vessel repeatedly trawls, i.e., groups of trawls that are consistently placed over the same geographic area (Figure 3.1). These trawls should have a tight cluster of start positions and a tight cluster of end positions. Trawls that are in opposite directions can still belong to the same fishing opportunity if they cover the same ground (i.e., the start and end positions are switched). However, trawls starting in the same position, but conducted in opposite directions, would belong to different fishing opportunities. Some fishing opportunities could therefore be long and thin (for long trawls), others could be small and round (e.g., short trawls, or “circular” trawls that involve a midway 180° turn). For ease of presentation, I describe the method of defining fishing opportunities as if it only applied to trawlers. However, with minor modifications, this method could be applied to vessels using long-lines, pots, gillnets, and other types of fishing gear.

As defined above, fishing opportunities are similar to what might be called "fishing grounds". However, I consider fishing grounds to be larger regions that are fished by many vessels, whereas fishing opportunities represent vessel-specific methods of catching fish within these fishing grounds. Thus, for each fishing opportunity, a skipper will have previous knowledge gained through fishing (or from other skippers) about likely catch rates, species mix, optimal fishing months, appropriate gear, and the probable costs of fishing. Depending on historical knowledge, one skipper might only conduct short trawls in summer in the northern part of a fishing ground to target a skate species, while another vessel fishing in the same fishing ground may always conduct long winter trawls that traverse most of fishing ground and catch a wide mix of species. In this paper I therefore define fishing opportunities to be vessel specific, so that they can be related directly to fisher behavior. In reality, fishing grounds often include areas that are "untrawlable" (i.e., too steep or rough), limiting the number of available fishing opportunities. It is therefore likely that multiple vessels will frequent some fishing opportunities.

Little research has been conducted on fisher behavior at the level of fishing opportunities; most published studies simply divide the available space into statistical areas (e.g., Gillis et al. 1993, Mistiaen and Strand 2000, Cabrera and Defeo 2001) or into grid cells based on lines of latitude or longitude (e.g., Campbell and Hand 1999, Dorn 2001, Hannah 2003). Grid cells may be a reasonable approximation in a randomly spread out fishery that uses traps or pots to catch a sedentary resource (e.g., Swain and Wade

2003), but work poorly for trawlers since long trawls do not fit conveniently into rectangular cells. True fishing opportunities may be split over several grid cells because the cells are defined independently of geographical features. Grid cells are either too big and include multiple fishing opportunities such as the $5° \times 5°$ cells used by Campbell and Hand (1999), or too small, resulting in trawls that extend across many grid cells, like the 0.5 km × 0.5 km cells in Zimmerman (2003). Cells that are too small require an algorithm to assign effort and catches from each trawl across several grid cells. Statistical areas (data reporting regions) can be an improvement over grid cells since they are often based on fishing effort, but are usually too vast to be anything but broad indicators of fishing behavior: some statistical areas encompass 25,000 $km^2$ (Holland and Sutinen 2000).

Two published papers have offered reasonable approaches to defining fishing opportunities. Walters and Bonfil (1999) analyzed catch data from the British Columbia groundfish trawl fishery (B.C. fishery). Trawls were first assigned to one nautical mile square grid cells (using start positions), then catches were smoothed over adjacent cells, and finally grid cells with similar multispecies catches were manually grouped into 19 irregularly-shaped “fishing grounds”. However, the grouping procedure was subjective and presumably time consuming, and produced fishing grounds that were much larger than typical trawl lengths in the fishery. The resultant fishing grounds probably included multiple fishing opportunities, each fished by different skippers and containing different mixtures of species.

Pelletier and Ferraris (2000) took an alternative approach in their study of a small-scale marine fishery off Senegal. They censused canoe owners and produced a map of 28 known fishing locations, named by local fishers according to either geography or fishing direction. By reflecting local knowledge and fishing patterns they provided a realistic definition of fishing opportunities, but their approach would be time consuming to apply to most fisheries.

In this paper, I present a simple clustering method for allocating trawls to different fishing opportunities. I show how easily this approach scales to trawl length by analyzing data from a groundfish trawl fishery with long trawls, and a scallop fishery with short trawls. I provide recommendations on the appropriate spatial scale of fishing opportunities, based on the characteristics of the fishery. I apply this method to the B.C. fishery to show how the species composition differs among fishing opportunities; and to the Patagonian scallop fishery to discriminate between exploratory trawls and regular fishing trawls. The defined fishing opportunities for the B.C. fishery are used in Chapter 4 to show how fishers changed their behavior when regulated under Individual Transferable Quotas (ITQs). I also note that this method allows for the easy identification of positional errors in fisheries databases.

## Methods

### *Fishing opportunities specific to each vessel*

Each skipper has knowledge about a specific set of fishing opportunities, although fishing opportunities from many skippers may overlap in a variety of ways. For each vessel, their set of fishing opportunities was defined using the method outlined below. The total number of fishing opportunities in this dissertation is therefore the sum of the number of fishing opportunities for each vessel.

*Clustering individual trawls*

Both start and end positions of trawls are important when defining fishing opportunities. Euclidean distance was used to measure the geographical closeness of individual trawls. The Euclidean distance for a given pair of trawls was defined as the combination of the distance between the two start positions, and the distance between the two end positions, using as inputs the start and end latitudes, and start and end longitudes (all in decimal degrees) of each trawl. Before calculating Euclidean distance, two adjustments were made to the input data: (1) because lines of longitude are closer together than lines of latitude except at the equator, longitudes were multiplied by the cosine of the latitude to ensure that latitudes and longitudes were both in the same distance units:

$$
\begin{aligned}
\text{lon}^{start} &= \text{lon}^{start} \cdot \cos\left(\frac{\text{lat}^{start}}{360} 2\pi\right) \\
\text{lon}^{end} &= \text{lon}^{end} \cdot \cos\left(\frac{\text{lat}^{end}}{360} 2\pi\right)
\end{aligned} \tag{3.1}
$$

(2) trawls were "re-oriented" by swapping the start and end positions of trawls that pointed southwards, to ensure that trawls that were conducted in opposite directions over

the same ground would be clustered together. Trawls in the eastward and westward direction may occasionally be incorrectly reoriented using this method. However, this is a relatively minor issue since this problem would only arise if there were a group of eastward (or westward) facing trawls, some of which pointed slightly northwards, and some slightly southward. If most trawls in a fishery were in the eastward (or westward) direction it would be sensible to re-orient trawls by swapping the start and end positions of trawls that point eastwards.

The Euclidean distance ( $D_{i,j}$ ) between the *i*th trawl, and the *j*th trawl is therefore given by:

$$(3.2)\ D_{ij} = \sqrt{\left(\mathrm{lon}_i^{start} - \mathrm{lon}_j^{start}\right)^2 + \left(\mathrm{lon}_i^{end} - \mathrm{lon}_j^{end}\right)^2 + \left(\mathrm{lat}_i^{start} - \mathrm{lat}_j^{start}\right)^2 + \left(\mathrm{lat}_i^{end} - \mathrm{lat}_j^{end}\right)^2}$$

I clustered trawls using hierarchical agglomerative clustering, based on the Euclidean distances between each pair of trawls (see Appendix B). In this method, all trawls are initially assigned to single-trawl clusters, and then clusters are progressively joined by minimizing the average dissimilarity between members of clusters (Venables and Ripley 1999, pp. 336-8), until all clusters have been combined into a cluster tree (Figure 3.2).

*Obtaining fishing opportunities using a cut point*

Once the cluster tree was obtained, I chose a particular Euclidean distance "cut point" to divide the cluster tree into individual clusters of trawls (Figure 3.2). Each cluster of trawls has similar start and end positions, thus matching the definition of a fishing opportunity. Not all resulting clusters will contain multiple trawls. A trawl that was conducted far from other trawls will be classified into a cluster by itself, i.e., it is a "solitary trawl". Solitary trawls are the result of either exploratory fishing or database error.

The choice of cut point determines the balance between fishing opportunities and solitary trawls. A cut point that is too small will subdivide the real fishing opportunities and produce many apparent fishing opportunities and many solitary trawls; conversely, a cut point that is too large will group even distant trawls into a few fishing opportunities. I developed a "rule of thumb" cut point leading to the clustering of groups of trawls that are closer together than the median trawl length in the fishery. First the median trawl length in the fishery ($\bar{d}$ , in km) was converted to latitudinal degrees (*d*) using the constants 360 (degrees around the earth) and 40,075 (circumference of the earth in km). If two trawls have start points that are *d* distance apart, and end points that are *d* distance apart, then Equation 1 implies that the Euclidean distance between the two trawls will be $\sqrt{2}d$ , giving finally:

$$(3.3)\quad \begin{aligned} d &= \frac{360}{40\,075}\bar{d} \\ \text{cut point} &= \sqrt{2}d \end{aligned}$$

For fisheries with very short trawl lengths, the mean distance between successive starting positions for the same vessel may be a better estimate of $\bar{d}$ than trawl length itself. In other fisheries, the spatial autocorrelation in the resource may provide a good estimate for $\bar{d}$; methods to estimate this distance are provided by Vignaux (1996) and Dorn (1997). Another method would be to interview fishers to estimate the fraction of their trawls that were exploratory, and then find the cut point that produces that fraction of solitary trawls.

*The effect of different cut point values on simulated trawl data*

To illustrate the effect of different cut point values, I simulated trawls and applied the clustering method to assign trawls to fishing opportunities. The simulated trawls were generated using the following method: (1) For each fishing opportunity, the mean start position ($lat^{start}$, $lon^{start}$) within the bounds of the fishing area, mean trawl direction ($\theta$), and mean trawl distance ($r$, in km) was generated. (2) The mean end position ($lat^{end}$, $lon^{end}$) of that fishing opportunity was calculated:

$$\text{(3.4)} \quad \begin{aligned} \mathrm{lat}^{end} &= \frac{360}{40\,075} r \sin\theta + \mathrm{lat}^{start} \\ \mathrm{lon}^{end} &= \frac{360}{40\,075} r \cos\theta \cos\left(\frac{\mathrm{lat}^{start} + \mathrm{lat}^{end}}{2}\right) + \mathrm{lon}^{start} \end{aligned}$$

3. For each trawl within a fishing opportunity, a start position from a bivariate normal distribution (with variance-covariance matrix $\Sigma$) around the mean start position. was generated 4. An end position for each trawl around the mean end position was generated in the same way as step 3. This procedure ignores the curvature of the earth, but the bias is slight.

The parameter values used for the simulated trawls were drawn from the following distributions:

$$\text{(3.5)} \quad \begin{aligned} &\mathrm{lat}^{start} \sim U(41^\circ, 43^\circ) \\ &\mathrm{lat}^{start} \sim U(124.1^\circ, 124.3^\circ) \\ &\theta \sim U(60^\circ, 120^\circ) \\ &r \sim \text{randomly drawn from actual trawl distances in B.C. groundfish fishery} \\ &\Sigma = \begin{bmatrix} 0.002 & 0 \\ 0 & 0.0004 \end{bmatrix} \end{aligned}$$

These parameters implied that the simulated fishery was off the coast of Oregon, and conducted within a narrow longitudinal band typical of a fishery confined to a particular depth range. I simulated four fishing opportunities containing 30, 40, 50, and

60 trawls each and 40 solitary trawls (which could overlap with the fishing opportunities), for a total of 220 trawls. The simulated trawls were assigned to fishing opportunities using cut points of 0.01, 0.15, 0.2, 0.5, and 2.

*Multispecies catches in fishing opportunities in the British Columbia groundfish fishery*

The clustering method was applied to observer data from the British Columbia groundfish trawl fishery ("B.C. fishery"), to illustrate the species composition and number of fishing opportunities for a multispecies fishery. This fishery comprises 80–120 active vessels in a given year fishing for more than 70 commercially valuable species, governed by ITQs (Turris 2000).

I extracted trawl start and end positions, and species catches from the observer database PacHarv for the 1996–2001 fishing years. Pacific hake fishing trips (> 50% Pacific hake caught during the trip) were eliminated because Pacific hake schools are not consistently found in the same location, although non-hake midwater trawls were retained. Trawls that lacked start or end positions were also deleted. The resulting database included 105,375 trawls, although no vessel conducted more than 3,500 trawls. I obtained vessel-specific fishing opportunities for the 70 vessels that conducted the greatest number of trawls during 1996–2001. Based on speed and trawl duration, the median trawl distance in the fishery was 10.8 km, suggesting a cut point of 0.14 from Equation 3.2. I rounded this value upward to 0.15 for the analyses. Five of the resulting fishing opportunities were randomly selected for graphical display. From each of these fishing opportunities I randomly selected 15 trawls, and plotted catch proportions in each trawl for those species that cumulatively represented > 95% of the catch.

*Classifying trawls as exploratory or regular fishing in the Patagonian scallop fishery*

The Patagonian scallop commercial fishery started in 1996 and is now one of the most important scallop fisheries in the world, with annual landings of 6,000 metric tonnes of muscle meat. The fleet is small: four vessels operated by two companies. The main fishing area is on the Argentine continental shelf (39°S–45°S) at depths of 80–195 m. Each trip lasts 20–40 days, and vessels can complete 40–60 trawls per day alternately deploying two otter trawl nets. Nearly all trawls were 6–14 min long in the analyzed data.

I used observer data from a single trip (737 trawls) in 1995, during an experimental fishing program instigated by one of the vessels in the fishery. Observers on board recorded trawl positions, and speed and duration of trawls in addition to recorded catches. Trawls with missing start or end positions were eliminated, leaving 614 trawls. Catch data at the individual trawl level were not available for 357 trawls, leaving 257 trawls from which catch-per-unit-effort (CPUE) could be calculated. Trawls in this fishery are typically very short compared to the time taken for the gear to be deployed and hauled, and so the median distance between start positions of successive trawls (1.2 km) was used to suggest a cut point of 0.014. I used a higher cut point of 0.02 in the analyses because some trawls had been excluded, and because skippers space out their trawls on the scallop grounds to avoid trawling over the same area twice. Solitary trawls were assumed to be exploratory; fishing opportunities with 2–4 trawls were “likely exploratory", and opportunities with ≥ 5 trawls were classified as "regular fishing". Relatively few trawls were classified as "likely exploratory", so these trawls were grouped with the exploratory trawls. For the trawls with catch data, the average CPUE ($t \cdot km^{-2}$) was calculated for exploratory and for regular fishing trawls. I used a randomization test to test whether the mean CPUE in regular fishing trawls was higher than in exploratory trawls. Assuming $x$ exploratory trawls and $y$ regular fishing trawls, I repeated the following procedure 1 million times: (1) randomly select with replacement one set of $x$ and one set of $y$ CPUE values from the 257 trawls, (2) calculate the mean CPUE for these two sets, (3) test whether the difference in mean CPUE is greater than the observed difference in CPUE.

*Finding positional errors*

The clustering method outlined above is intended to find groups of trawls that have start and end positions that are geographically close together. For a given trawl, if there is an error in either the start or the end position, that trawl is likely not to be clustered together with any other trawls. The larger the error, the greater will be the Euclidean distance (Equation 3.1) between that trawl and all other trawls. Therefore, once a cluster tree based on Euclidean distance has been obtained, solitary trawls are likely to be those with positional errors, especially if a high cut point (relative to the recommended cut point) is used to divide the cluster tree into fishing opportunities. To test whether a high cut point would uncover positional errors, I carefully examined the solitary trawls resulting from cut points of 1.0 in the B.C. fishery and 0.5 in the Patagonian scallop fishery, i.e., cut points around an order of magnitude greater than recommended.

**Results**

*Applying different cut point values to simulated trawl data*

Only one set of simulated trawls is shown for this illustration, but when the simulations were repeated, the recommended cut points ranged from 0.10–0.17. The cluster tree (Figure 3.3) and fishing opportunities obtained for different cut point values (Figure 3.4) are presented for a single set of simulated trawls. When the cut point was too small (0.01), almost all the trawls were classified as solitary; for a slightly higher cut point (0.05), the four simulated fishing opportunities were subdivided into multiple small fishing opportunities. Values near the recommended cut point (0.15 and 0.20) best recreated the simulated fishing opportunities, although some of the simulated solitary trawls were grouped together into fishing opportunities. When the cut point was larger (0.5), the four simulated fishing opportunities were joined into two groups, and at a cut point of 2, all simulated trawls were considered to belong to a single fishing opportunity.

*Consistent multispecies catches from fishing opportunities in the B.C. fishery*

A representative cluster tree from a single vessel in the B.C. fishery shows the typically large number of fishing opportunities (32 for this vessel) with ≥ 15 trawls at a cut point of 0.15 (Figure 3.5). The number of fishing opportunities per vessel (for the top 70 vessels) ranged from 2–69 (mean 26, standard deviation 16). A total of 1804 fishing opportunities were identified. Species composition differed greatly among the randomly selected fishing opportunities. In some, one or two species dominated the catches, with longspine and shortspine thornyheads always caught in one opportunity (Figure 3.6, opportunity A), rock sole in another (Figure 3.6, opportunity C), and arrowtooth flounder and yellowtail rockfish in a third (Figure 3.6, opportunity E). In contrast, ≥ 10 species were caught in each of the other two opportunities, where only abundant species like spiny dogfish and arrowtooth flounder were caught often (Figure 3.6, opportunities B and D).

These five fishing opportunities typified the 1804 fishing opportunities obtained from all vessels. It should be noted that both bottom and mid-water trawls were included in this analysis, so that it is not surprising that the occasional trawl caught mid-water species like yellowtail (e.g., Figure 3.6 opportunity E), in amongst trawls catching mainly demersal species. Some fishing opportunities (not represented in Figure 3.6) also included occasional trawls from closely adjacent shallower (or deeper) waters. In addition, the tonnage caught in each trawl also varied considerably, although this is masked somewhat by plotting proportions in Figure 3.6.

*Classifying trawls as exploratory or regular fishing in the Patagonian scallop fishery*

In the Patagonian scallop fishery, there was an obvious distinction between exploratory (1–4 trawls per fishing opportunity) and regular fishing (≥ 5 trawls per opportunity) trawls. Regular fishing trawls clustered together at small cut point values, whereas exploratory trawls were quite dissimilar from other trawls (Figure 3.7). At a cut point of 0.02, 13 fishing opportunities (with ≥ 5 trawls each) were identified, but 12 of these were grouped into a southern fishing ground containing 75% of the total trawls (Figure 3.8). The 13th fishing opportunity contained only five trawls and may have been an area that initially seemed promising but proved not to be commercially viable. Overall, 24% of the trawls were classified as exploratory (19% were solitary trawls), and 76% were classified as regular fishing trawls. For the trawls with CPUE information, 30% (77 trawls) were classified as exploratory and 70% (180 trawls) as regular fishing. The mean trawl duration was similar between exploratory (9.7 min, standard deviation = 2.6 min) and regular fishing trawls (9.8 min, standard deviation = 2.4 min), but CPUE was almost four times higher for the regular fishing trawls: 39.1 $t \cdot km^{-2}$ (standard deviation = 23.4) versus 10.6 $t \cdot km^{-2}$ (standard deviation = 13.8). This difference in CPUE was highly significant ($p < 10^{-6}$, randomization test).

*Finding positional errors*

Positional errors were identified in both fisheries. In the B.C. fishery, trawls had already been carefully screened for implausible distances between the start and end position, and so only 30 possible errors were flagged (0.03% of the total). Of these, five were definite errors, being located on land (n = 4) or traversing multiple depth contours (1), 17 were possible errors, being found in very shallow waters close to land (n = 13), or far offshore (n = 4), and the remaining eight trawls did not contain any obvious errors and may have been exploratory trawls. In the Patagonian scallop fishery, four trawls were classified as possible errors (0.6% of the total); in each case, the errors were obvious, with distances of around 0.5° (2 trawls), 1° and 2° between the start and end latitudes, far further than the vessels would have steamed during a single trawl.

**Discussion**

How do skippers choose where to fish? The answer depends on the scale of the fishing areas that are considered and how they are defined. In most fisheries, skippers can name their favorite fishing locations, places where they return to year after year because they know catch rates of their target species will be high there, herein called "fishing opportunities". At each fishing opportunity, the mix of species caught depends on the bottom topography (steep or flat) and the substrate type (e.g. rocky or muddy) of that location. Since skippers learn which gear to use and what time of the year to fish at each fishing opportunity, fishing opportunities are best defined as vessel-specific. Furthermore, since learning is a function of historical search patterns and exploratory behavior, each skipper will have information about a specific set of fishing opportunities, although information sharing among skippers may broaden the range of available fishing opportunities.

I defined fishing opportunities using a clustering algorithm which groups trawls that all start in a similar position and end in a similar position. According to this operational definition, fishing opportunities may also be termed "fishing grounds" (if defined with a large cut point), "hot spots" or "track lines", except that these terms imply that the time of year and choice of gear type is irrelevant. My use of "opportunities" carries the connotation that fishing opportunities play an integral role in location choice, although I recognize that location choice also depends on a wide range of other factors. This clustering method is simple enough to implement using three commands in R (itself a freely available software package). I show that fishing opportunities can be identified from simulated data, the British Columbia groundfish trawl fishery (which has relatively long trawls), and the Patagonian scallop fishery (characterized by very short trawls).

Fishing opportunities are a finer-scale grouping than “métiers” or “fishing tactics”, which are groupings of vessels or trips (not trawls), defined using fishing location, gear, time of the year, and target species (Biseau and Gondeaux 1988, Biseau 1998, Pelletier and Ferraris 2000). These methods rely on multivariate statistics that can be complicated and produce impractical results (Biseau 1998). Métiers correspond to much larger regions than true fishing opportunities, although the fishing locations for the Senegalese fishery in Pelletier and Ferraris (2000) are realistic. Métiers may be useful for the classification of vessels or trips, especially when detailed trawl-by-trawl data are unavailable, but are less useful when trying to analyze why a skipper chose to fish at a particular location.

An alternative to grouping trawls into fishing opportunities is to extract and use individual trawls directly. For example, Vignaux et al. (1998) outlined how to produce fine-scale (i.e., at a resolution finer than individual trawls) mapping of fish biomass, using a Bayesian maximum entropy method, and Rijnsdorp et al. (1998) used automatic position recorders (data recorded every six min), to estimate the proportion of fishing grounds that have been disturbed multiple times by trawls. These methods could be usefully linked with fishing opportunities: once groups of trawls within each fishing opportunity have been identified, these trawls could be analyzed to produce maps of species distribution and habitat disturbance within the most heavily fished areas.

A key feature of this definition of fishing opportunities is the cut point. A small cut point will produce many fishing opportunities each containing few trawls; a large cut point will group many trawls into just a few fishing opportunities. Recommended cut points can be obtained from the mean trawl length, inter-trawl distance, or the extent of spatial autocorrelation in the underlying fish populations or habitat types. Although recommended cut points provided reasonable characterizations of fishing opportunities for the examples in this paper, these values should only be seen as recommendations, and may not be appropriate for all fisheries. Cut points at or slightly above the recommended value provide reasonable characterizations of fishing opportunities, while cut points below the recommended value tend to induce splitting.

This method of determining fishing opportunities has straightforward data requirements: the start and end position of individual trawls. Many fisheries record these data in the form of logbooks or observer data. However, some fisheries record only the start position of each trawl. Fishing opportunities could be defined using just the start position using this method, but a number of additional issues arise when interpreting the results: (1) trawls which start in the same position but travel in opposite directions would be grouped together, (2) trawls which cover the same ground but are conducted in opposite directions (start and end positions swapped) would be separated into two opportunities, (3) circular trawls that end near their starting positions (Vignaux 1996, Gillis 1999) would be classified together with linear trawls, and (4) an algorithm would be needed to map fishing effort from the starting position to adjacent areas—many grid-based studies have distributed effort in circles around the starting points (e.g., Walters and Bonfil 1999, Hannah 2003), even though the actual effort is typically linearly distributed because of bottom topography. These problems plague grid-based analyses of fishing data, and it is preferable to analyze data that include both start and end positions when available.

In the B.C. fishery, quotas under the ITQ program limit total catches. Vessel owners should therefore seek to maximize their profits by exactly catching their quota holdings, reducing costs, and landing species when market prices peak. Knowledge about species distribution and abundance in different fishing opportunities accordingly gains great value. The analysis of the B.C. fishery shows that the average skipper trawled in 26 different fishing opportunities (≥ 15 trawls in each), although this varied greatly (2–69) among the top 70 vessels. Skippers in this fishery visit substantially more locations than were reported for Icelandic skippers fishing cod, who generally visited only a few locations, and were not considered to be very innovative (Durrenberger and Pálsson 1986). Their study focused on locations that were 225 $km^2$ in size, but noted that each location might contain a number of small "fishing spots"—perhaps similar to the fishing opportunities described here.

The great number of target species in the B.C. fishery probably also motivates skippers to fish in a wide variety of fishing opportunities. Although 1804 total fishing opportunities were identified in this paper, many were likely duplicated among the vessels, so that the effective total was probably substantially lower.

Trawls within each fishing opportunity in the B.C. fishery caught fairly predictable mixes of species. However, huge quantities of one species were occasionally landed, demonstrating the highly variable returns even within a fishing opportunity. It was possible to identify fishing opportunities dominated by (for example) thornyheads, rock sole and arrowtooth flounder, while in other fishing opportunities a wide range of species were caught. Sometimes midwater and bottom trawls were included in the same fishing opportunity if they were co-located; if trawl gear data are available these types of trawls could be analyzed separately, or separated *a posteriori* based on catch composition. More problematic was the occasional inclusion of shallow-water and deepwater trawls in the same fishing opportunity, especially where the topography was steep and these habitats were close together. Including depth as an additional clustering variable made the method complicated since despite careful scaling, distant trawls at the same depth sometimes clustered together. The majority of trawls in a fishing opportunity were at similar depths even when only latitude and longitude was used in the clustering process.

Like most sedentary species, Patagonian scallop is a spatially structured resource because of larval drift and settlement. At the outset of this fishery, trawling was characterized by random search (“exploratory fishing”) alternated with systematic trawling (“regular fishing”, like a sewing pattern) once high-density areas were encountered. This pattern of exploitation on sedentary resources can lead to serial depletion, with the densest patches being exploited first, resulting in hyperstability in CPUE (catch per unit effort) indices (Hilborn and Walters 1992, pp. 187-91). When calculating CPUE, and modeling local profitability and depletion in this fishery, it is therefore important to distinguish between exploratory trawls and regular fishing trawls. Using the method outlined in this paper, it was easy to separate out exploratory and regular fishing trawls in the Patagonian scallop fishery. As expected, regular fishing trawls were characterized by far greater catch rates—four times higher—than exploratory trawls. Any measure of overall CPUE in the fishery would therefore be skewed if the proportion of trawls that are exploratory changed over time (as might be expected in a maturing fishery). Furthermore, sequential depletion of the resource could be masked unless CPUE from each fishing opportunity was calculated separately.

Fishing opportunities therefore provide a natural way to incorporate geography in the calculation of CPUE. Within each fishing opportunity, CPUE could be monitored over time to detect depletion at small scales. Outside the fishing opportunities, CPUE could be calculated for large areas from the exploratory trawls, and any CPUE declines would suggest the contraction of fish into favorable habitat. The fishery-wide CPUE could be calculated from an area-weighted average of the CPUE indices from fishing opportunities and exploratory regions.

An unexpected benefit of this method of determining fishing opportunities was that positional errors in the database were easy to detect. The trawls that were flagged usually included obvious positional errors, such as being on land or having an estimated speed beyond the capabilities of the vessels. I did not investigate this method further, as it was not the central focus of this study, but it would be instructive to measure the usefulness of this method by comparing the error rate in a randomly selected set of trawls (acting as a control), with a set of trawls that have been flagged by this method.

Although I have applied my method for defining fishing opportunities to bottom trawlers that catch fish reliably found at given locations, this method would also be useful for other types of fisheries. For example, fishing opportunities might also be useful in mobile pelagic fisheries, where this method could separate exploratory trawls from regular fishing trawls, provided data from different time periods are analyzed separately. The number of trawls within each fishing opportunity would then be an indicator of the overall size of the fish aggregation that was targeted. When calculating CPUE for pelagic species, the total time spent searching for aggregations could be inferred from the total time and the time devoted to trawls on aggregations.

There are many uses of fishing opportunities in addition to those that have been outlined in this paper. Models of Marine Protected Areas (MPAs) currently make very general assumptions about displaced fishing effort, which could be avoided by basing MPA models on fishing opportunities. For example, assume a skipper fishes in $n$ fishing opportunities, with $n_i$ trawls in each fishing opportunity $i$. A proposed MPA would close some of these fishing opportunities to fishing. It would be relatively simple to redistribute the trawls formerly conducted inside the MPAs to those remaining outside the MPAs, with some adjustment for increased costs. When applied to all vessels, the resulting redistribution of effort could be used as a starting point for future predictions of the effects of MPAs. Actual changes, however, are likely to be more complicated than this simple starting point might suggest.

Fishing opportunities could also be applied to multispecies fisheries that are constrained by small allowable catches on some species. This situation is currently responsible for the closure of large swathes of the U.S. West Coast groundfish fishery due to overfishing of a few species. Classical models predict that when sustained catches are taken from a multi-stock (or multispecies) fishery, those species with low growth rates will diminish toward commercial extinction (Ricker 1958, Paulik et al. 1967). However, these models assume spatial homogeneity in abundance, and constant catchability for each stock (or species). In reality, each fishing opportunity has a particular mix of species, and placing catch limits on one species will merely shift fishing effort from fishing opportunities where that species is likely to be caught, to fishing opportunities where it is less abundant. There is evidence for these shifts in the B.C. fishery, where total allowable catches (TACs) were reduced for a few species (generally those with low productivity) when ITQs were introduced. Catches of those species declined to match TACs, but catches of other species in the fishery remained constant, suggesting that skippers were able to shift their fishing effort to alternative fishing opportunities where other species dominated.

In conclusion, fishing opportunities provide an intuitively natural way of defining where fishers choose to fish, and can be easily determined from positional data. Many useful patterns of behavior can be inferred from fishing opportunities, but examples have been limited here to two fisheries. The analysis of the B.C. fishery demonstrates how catch information from a multispecies fishery can be partitioned into fishing opportunities to provide a useful basis to predict changes in fishing effort resulting from reductions in TACs for some species. Data from the Patagonian scallop fishery indicates that exploratory and regular fishing can be separated, and that such separation is necessary to avoid biases in CPUE trends and estimates. I also show that database errors in positions can be isolated using fishing opportunities.

Fishing opportunities will be most useful where predictive models need to include fisher behavior in order to be realistic. MPAs and other types of management will induce changes in fishing behavior as skippers reallocate their fishing effort to previously less desirable places from areas rendered less profitable by the regulations. Perhaps a focus on fisher behavior will address Hilborn's (1985b) comments regarding fisheries management: "This sad litany of fisheries disasters can be ascribed to poor understanding of the dynamics of fishermen, how they fish, and how they invest." Fisheries scientists still largely concentrate on fish and less on fishers. Fishing opportunities can provide a way for scientists to model fisher behavior, hopefully ensuring that the right numbers of fishers are allowed to pursue the right number of fish in the right places.

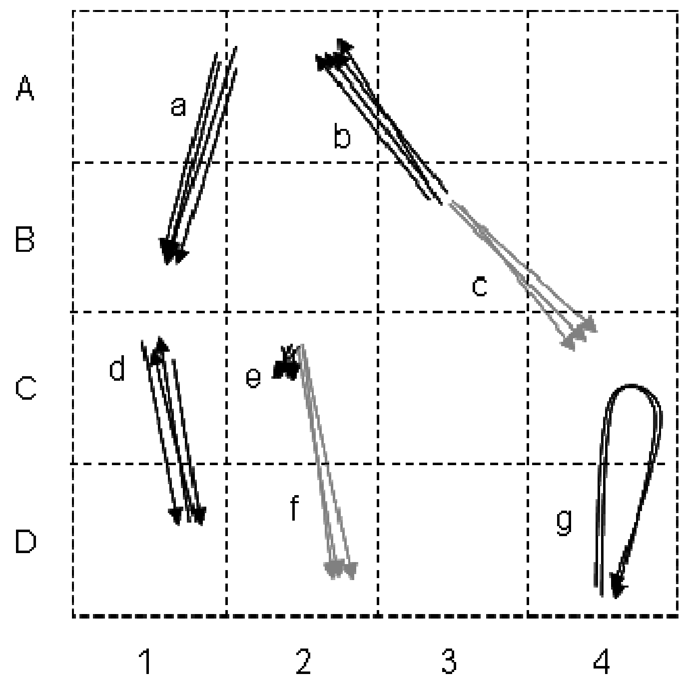


**Figure 3.1**. Trawls comprising types of fishing opportunities (a to g), overlaid by a regular grid. (a) Fishing opportunity with a tight cluster of start positions and end positions, but with start positions in grid cells A1 and A2. (b, c) Two fishing opportunities with similar start positions, but conducted in opposite directions. (d) Fishing opportunity comprised of trawls covering the same ground but conducted in opposite directions. (e, f) Two fishing opportunities with the same start positions, but different trawl lengths. (g) Fishing opportunity comprised of "circular" trawls.

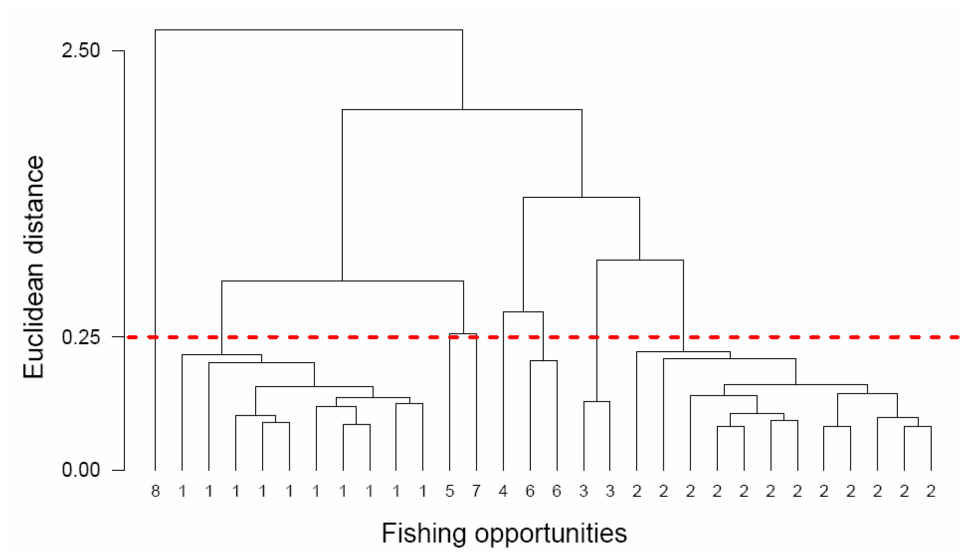


**Figure 3.2**. Example cluster tree obtained from 30 simulated trawls, illustrating the fishing opportunities obtained with a cut point of 0.25. The numbers underneath each individual trawl indicate the fishing opportunity to which the trawl was assigned. For example, those labeled “8”, “5”, and “7” are solitary trawls, whereas the 10 trawls labeled “1” all belong to the same fishing opportunity.

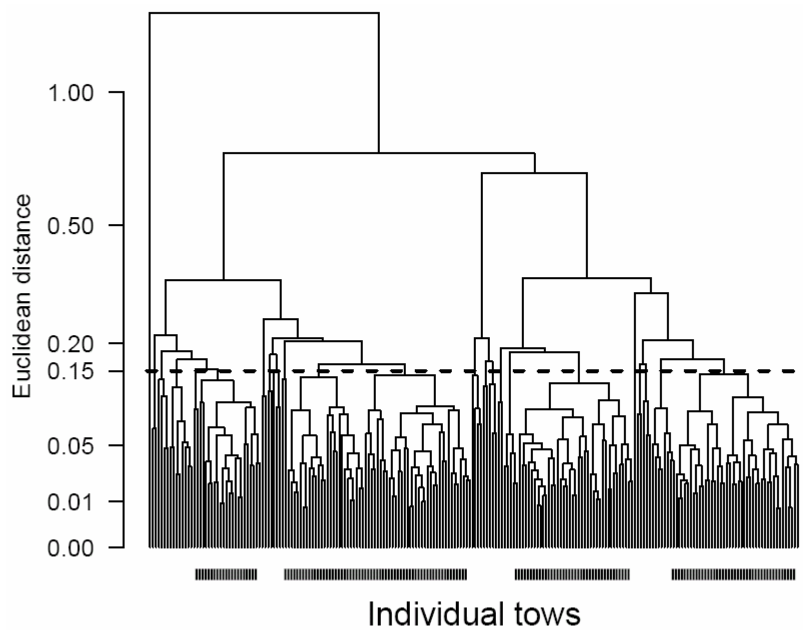


**Figure 3.3**. Cluster tree obtained from start and end positions of simulated trawls. Trawls which are contained in fishing opportunities (containing ≥ 10 trawls at a cut point of 0.15), are identified by a "|" just below the x-axis. The y-axis is plotted on a square-root scale to better show the detail of relationships between clusters at small Euclidean distances (in degrees).

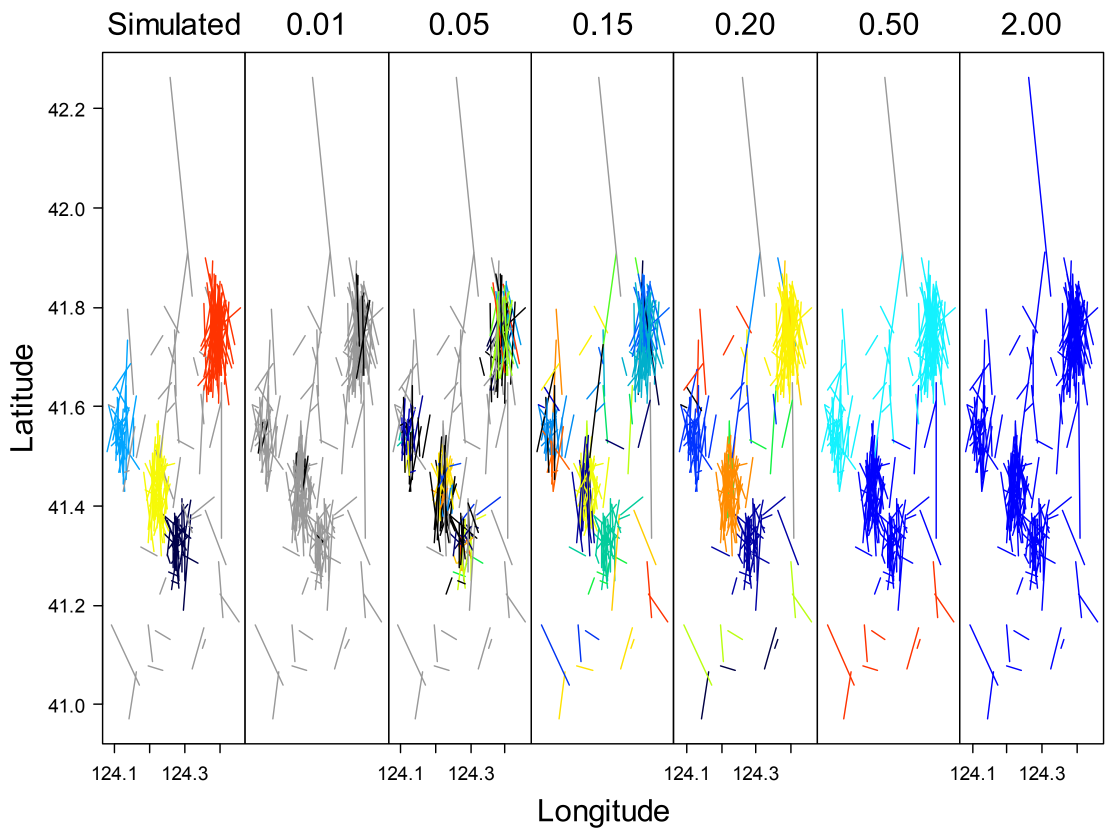


**Figure 3.4**. Fishing opportunities obtained using different cut point values from the cluster tree in **Figure 3.3**. The simulated trawl data is shown in the leftmost panel; light gray trawls represent randomly distributed solitary trawls; trawls in simulated fishing opportunities are displayed in different shades, with a distinctive shade for each opportunity. The other six panels represent fishing opportunities obtained from the simulated data for different cut points (0.01°–2°). Again, light gray trawls are solitary trawls, and each fishing opportunity is represented by a different, randomly allocated, shade.

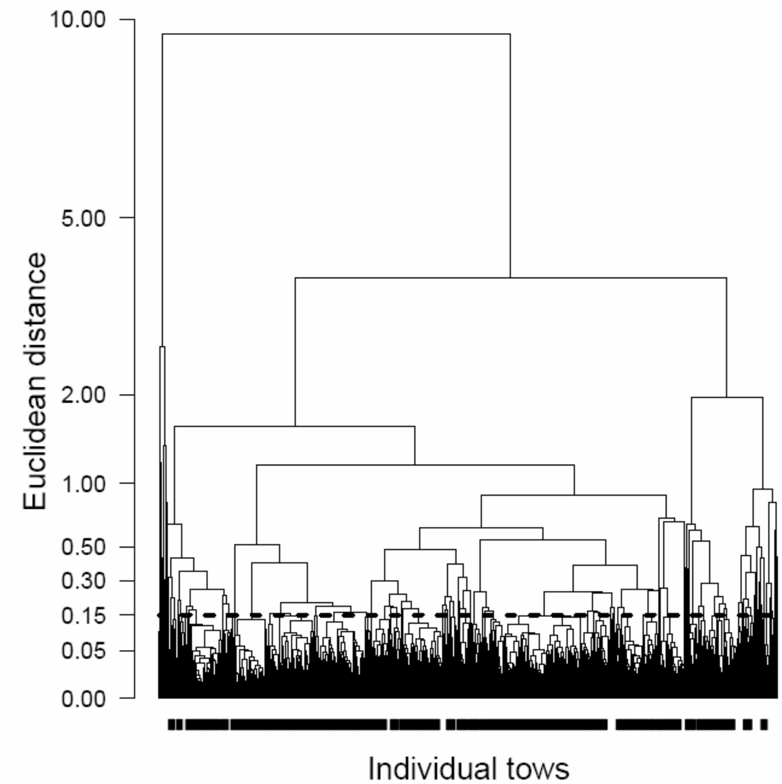


**Figure 3.5**. Cluster tree obtained from start and end positions of a single vessel (not the entire fleet) in the British Columbia groundfish trawl fishery, based on trawls from 1996–2001. Fishing opportunities with ≥ 15 trawls at a cut point of 0.15, are identified by a "|" just below the x-axis. The y-axis is plotted on a square-root scale.

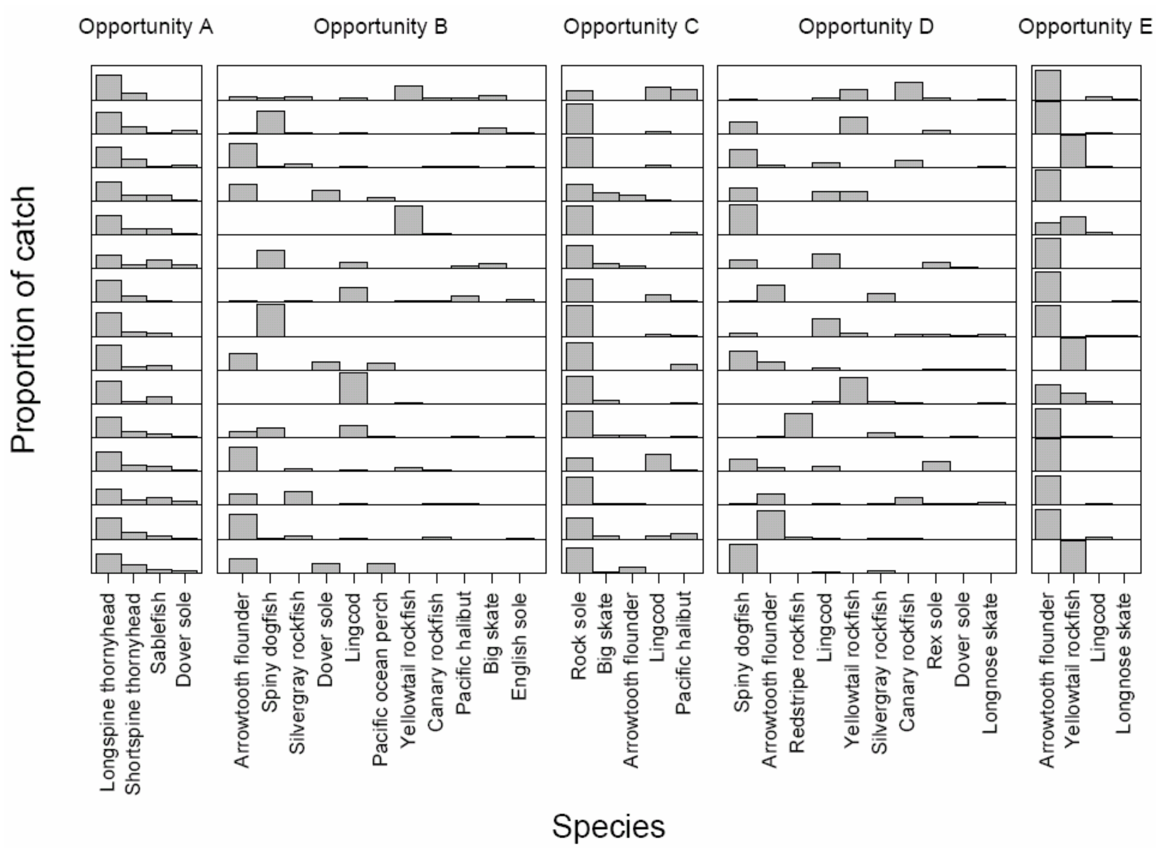


**Figure 3.6**. Species compositions recorded in individual trawls in five randomly selected fishing opportunities in the British Columbia groundfish trawl fishery. For each opportunity, 15 trawls were selected at random, and the most important species (summing to > 95% of the total catch) in those trawls were plotted. Fishing opportunities are vessel-specific: in this illustration, each fishing opportunity was defined for a different vessel.

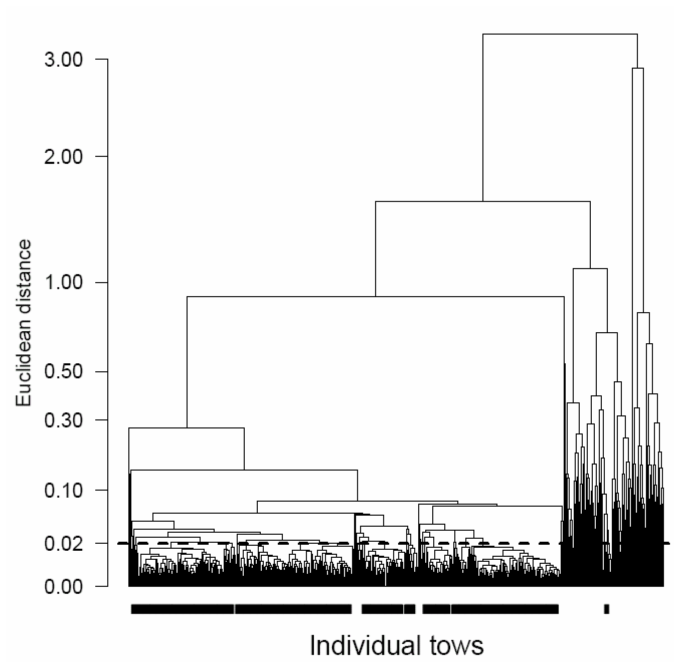


**Figure 3.7**. Cluster tree obtained from a single trip by one vessel in the Patagonian scallop (*Zygochlamys patagonica*) fishery. Regular fishing trawls, those in opportunities with ≥ 5 trawls at a cut point of 0.02, are identified by a “|” just below the x-axis. The y-axis is plotted on a square-root scale.

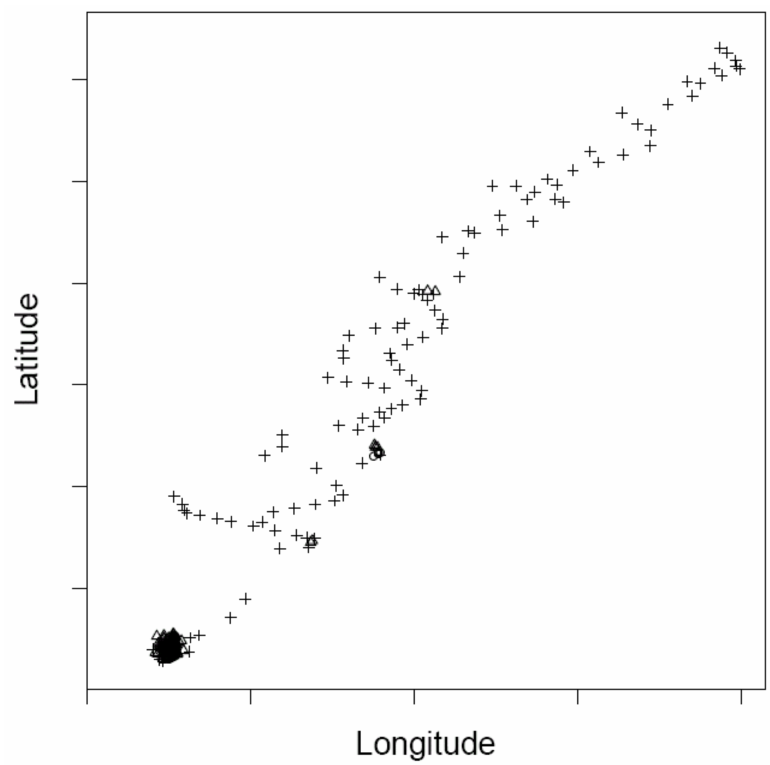


**Figure 3.8**. Distribution of start locations of trawls from a single trip in the Patagonian scallop fishery. Distinctions are made between trawls that are classified as exploratory (one trawl per fishing opportunity, + symbol), probable exploratory (2–4 trawls per opportunity, triangles) and regular fishing (≥ 5 trawls per opportunity, circles). Latitude and longitude have been omitted for confidentiality reasons, but the tick mark labels are placed 0.5° apart.

# CHAPTER 4

# MATCHING CATCHES TO QUOTAS IN A MULTISPECIES FISHERY: INCENTIVE-DRIVEN BEHAVIOR UNDER ITQS

## Introduction

The maximization of yield from multispecies (or mixed stock) fisheries has been the subject of a number of papers (Ricker 1958, Paulik et al. 1967, Ricker 1973, Hilborn 1976, 1985a, Hilborn et al. 2004), which have generally concluded that the total yield is maximized when some species are overfished and others are underfished. Mixed-species fisheries therefore pose particular problems for two fisheries management objectives: optimizing yield, and preventing overfishing. For example, Hilborn et al. (2004) modeled 12 species in the West Coast fishery and showed that maximizing the overall yield from all of these stocks combined would always result in some stocks being overfished, but that preventing overfishing of any stock would result in about 90% of potential yield being lost.

These conclusions are based on the assumption that the catchabilities of the species are fixed. If it is possible to independently target each species, then no species need be overfished, and the mixed-species maximum yield would increase to the sum of the maximum yields of the individual species (Ricker 1958, Paulik et al. 1967). In most fisheries there is at least an imperfect ability to target or avoid individual species (Beverton and Holt 1957, p. 164). For example, the B.C. fishery, which targets more than 70 commercially valuable species, is highly spatially heterogeneous. Different species are found at different depths, in different habitats and at different latitudes. Furthermore, even when fishing at the same location, changes in trawling gear and trawling duration, season, and even time of day can produce different mixes of species. In this fishery, it is to be expected that skippers have the ability to vary their mix of species by changing when, where, and how they fish.

While skippers may have the ability to target or avoid species in many multispecies fisheries, they usually lack strong incentives from management systems to do so. One exception is Individual Transferable Quotas (ITQs, reviewed in Chapter 1), where each vessel's annual catch is limited to a specified share of the Total Allowable Catch (TAC) for each species, and this share can be bought, sold and leased. ITQs allow fishers to choose when and where they catch their quotas, thus allowing for increased season length and improved safety compared to competitive fisheries (e.g., NRC 1999). ITQs may encourage increases in product quality and form, and allow for changes in the timing of catches, accordingly increasing ex-vessel prices (e.g., Geen and Nayar 1988, Gauvin et al. 1994). ITQs also reduce overcapitalization and increase economic efficiency as fishers minimize their costs to catch the same amount of fish, and less efficient vessels sell their ITQ shares and exit the fishery (e.g., Crowley and Palsson 1992, Grafton 1996). Improved economic performance allows for management costs and potentially economic rents to be extracted from the fishery (e.g., Annala 1996). The increased security of ITQ shares results in them becoming a valuable asset, which may encourage stewardship, reduce cheating and TAC overruns, and increase the involvement of fishers in management decisions and research (e.g., Annala 1996). However, not all effects of ITQs are positive: processors and crew members may be negatively impacted as the balance of power shifts to quota owners (Matulich et al. 1996, Matulich and Clark 2003), and fishing communities may lose the basis of their economy if quota is sold to outsiders (Eythórsson 2000, Skaptadóttir 2000). Except in strictly enforced fisheries (e.g., 100% observer coverage), ITQs may encourage high-grading (discarding low-value catches to increase the proportion of high-value catches in their landings) and discarding (Copes 1986, Anderson 1994, Arnason 1994). Discarding is particularly problematic for multispecies fisheries where it is difficult to match catches of multiple species to quota portfolio, and the skipper has incentives to discard catches in excess of quota instead of leasing quota to cover these overages (Annala 1996, Batstone and Sharp 1999). This discarding problem may become acute when there are very constraining TACs for some species in the fishery.

The B.C. fishery implemented a form of ITQ management in 1997 that provides strong incentives for targeting and avoiding species to match catches to quotas (Turris 2000). In this chapter I describe the management system implemented in the B.C. fishery, and examine the extent to which fishers were able to target and avoid species. Changes in TACs were compared with changes in total catches for the most important species to provide evidence that the species mixture could be altered. To examine the trawl data at a finer resolution, I defined the "fishing opportunities" where that vessel frequently fished (Chapter 3), and analyzed the total number of fishing opportunities associated with each vessel. There were substantial reductions from 1996 to 1997 in the TACs for three species: rougheye, shortraker and yelloweye rockfish, and I show that this resulted in less fishing in the fishing opportunities containing these three species. However, when this analysis was extended from these three species to the 32 most important species, there was only equivocal evidence for the avoidance or targeting of fishing opportunities based on the multispecies mixture in catches.

**Background**

Prior to 1996, the B.C. fishery was managed under a system of trip limits (maximum landing limits for each species or species complex). In 1995, 100% dockside monitoring of catches was introduced, but continued concerns over TAC overruns and problems with discarding led to the closure of the fishery in September 1995. When it reopened in February 1996, each vessel was required to carry an observer, except for Pacific whiting boats, and a small “Option B” sector of the fishery (which lands 0.3–1.7% of the total catch). Trip landing limits were replaced with four-monthly or annual limits on total catch mortality, i.e., landings plus the estimated mortality of marketable discards. Marketability was based on size limits developed in conjunction with processors; estimated mortality of discards varied by species and tow duration. Total mortality limits were imposed on either individual species or pairs of species. If a vessel exceeded the total mortality limit for any species or pair of species, that vessel would not be allowed to continue bottom trawling for the remainder of the catch period. In April 1997, after an interim January-March management period, the fishery additionally moved to individual transferable quotas (ITQs), comprising shares of the TAC that were allocated to vessel owners based partly on vessel length (30%) and partly on catch history (70%). ITQs could be bought or sold, and arrangements could be made which amounted to leasing. Vessels were allowed to carry forward overruns and underruns of up to 37.5%

(varying by species and year) to the following year. The 1996 requirements of full observer and dockside monitoring were retained, as was the focus on mortality limits instead of landing limits. These limits all became annual limits, and where they had been imposed on pairs of species, were now imposed only on individual species. TACs were imposed on 22 species, sometimes on an area-specific basis and sometimes coast-wide, totaling 55 species-area TAC restrictions in 1997-98 (Table 4.1), with only slight alterations in subsequent fishing seasons.

The combination of ITQs, full observer coverage, the counting of discard mortality against quota holdings, and a halt to bottom trawling when quota holdings are exceeded, strongly limits the catch that can be taken for any species. To maximize their profits, skippers therefore should attempt to catch their ITQ share for as many species as is profitable, while minimizing costs and maximizing ex-vessel prices. Species that are difficult to separately target may have catches that are lower than their TACs. There are thus strong incentives for skippers to change their fishing behavior to match their catches to their ITQ holdings. Where TACs have changed, it is possible to make predictions about avoidance and targeting of those species. If the TAC increased, skippers should increase trawls in areas where that species is abundant; if it decreased, the corresponding areas should be fished less.

## Methods

### *Catch ratios*

Individual trawl data were obtained from the British Columbia PacHarv database for these analyses. Extracted information included start and end positions, vessel identification numbers (coded for anonymity), and catches of the top 32 species. These species included all those under ITQ management, and all non-ITQ species with average annual catches greater than 50 t. I defined "catch" as the amount that would be subtracted from quotas, i.e., total landings plus discard mortality of marketable fish. For rockfish and thornyheads, assumed discard mortalities were 100%, but for other species, assumed discard mortalities were lower—for sablefish and sole species, for example, the assumed mortalities were 10% for the first two hours of trawling and 10% per hour thereafter. Annual catches (Table 4.2) were obtained for six fishing seasons: the pre-ITQ 1996 fishing season (12 February to 31 December), and five post-ITQ fishing seasons from 1997 to 2001 (1 April to 31 March), but I excluded the interim period between the management systems (1 January to 31 March 1997). For each species, I calculated the "catch ratio", $R_C$, which measures the change in actual catches between 1996 and 1997-2001:

$$(4.1)\quad R_C = \frac{2\overline{C}_{1997-2001}}{\overline{C}_{1997-2001} + C_{1996}} - 1$$

Where $C_{1996}$ is the catch in 1996, and $\overline{C}_{1997-2001}$ is the mean annual catch in the 1997 to 2001 seasons. The catch ratio is bounded between -1 and 1, is positive if mean catches increased compared to 1996, and is negative if mean catches decreased after 1996.

*TAC ratios*

The TAC ratio is a measure of the change in TACs from 1996 to 1997–2001, and is analogous to the catch ratio. For each species the TAC ratio, $R_T$, is defined by:

$$(4.2)\quad R_T = \frac{2\overline{T}_{1997-2001}}{\overline{T}_{1997-2001} + T_{1996}} - 1$$

Where $T_{1996}$ is the TAC in 1996, and $\overline{T}_{1997-2001}$ is the mean TAC in the 1997 to 2001 seasons. The TAC ratio is bounded by -1 and 1, and will be positive if the mean TAC increased after 1996, and negative otherwise.

For many species, TAC ratios could not be obtained directly. However, TAC ratios can be thought of as the relative incentive to target or avoid a species: positive values indicate increased incentives to target that species (relative to 1996), negative values indicate that the species should be avoided compared to 1996. Where regulations have changed, species can be classified into those that should be preferentially targeted ($R_T > 0$) and those that should be preferentially avoided ($R_T < 0$). Following this logic, TAC ratios were calculated or assigned as follows for each group of species (see Table 4.3):

1. Individual species TACs available in all years (4 species): TAC ratio calculated directly.

2. TACs available for pairs of rockfish species in 1996, and for individual species in 1997 to 2001 (9 species). Divided the 1996 TAC between the two species based on the 1996 catch proportions of those species before calculating the TAC ratios.
3. TAC available for a pair of species in 1996, but under trip limit for all minor rockfish species thereafter (sharpchin rockfish): since trip limit was less restrictive than TAC, there was an increased incentive to target this species, hence $R_T > 0$.
4. TAC in 1996 applied to a limited region, TAC in 1997 to 2001 was coastwide (3 species). For these species, total coastwide catches in 1996 were smaller than the TACs in 1997 to 2001, therefore $R_T > 0$.
5. Could be landed only as bycatch in 1996, but under TACs for 1997 to 2001 (2 species). Since restrictions were reduced, $R_T > 0$.
6. No TAC in any season (4 species), would expect the development of markets for these species since catches of other species were constrained, and hence increasing targeting, therefore $R_T > 0$.
7. Minor rockfish (4 species): no TAC restriction in any season, but under a combined species trip limit of 5,000 pound in 1997 and 15,000 pound in 1998-2001. Would expect increased avoidance, hence $R_T < 0$.
8. Catches less than 20% of TACs (spiny dogfish and walleye pollock). These species are low value, difficult to process and would generally be avoided, hence $R_T < 0$.

9. No TAC in 1996, TAC only imposed in 1997 to 2001 (longspine thornyhead): would expect avoidance, hence $R_T < 0$.

10. Pacific halibut was required to be discarded, but there were tradeable individual bycatch limits that were reduced after 1996; yelloweye rockfish was required to be relinquished from 1998 onwards with a target of at most 16 t after catches of 48 t in 1996. Would expect increasing avoidance of these species, hence $R_T < 0$.

*Relationship between TAC ratios and catch ratios*

TAC ratios reflect changes in the TACs from 1996 to 1997–2001. A positive TAC ratio indicates an increasing incentive to catch that species; a negative TAC ratio indicates greater incentive to avoid that species. Catch ratios reflect the actual change in catches: positive values indicate that catches increased, negative values indicate that catches decreased. If TAC ratios changed for some species but the corresponding catch ratios for those species remained near zero, that would indicate little ability to match catches to quotas at a fleet-wide level; but a perfect correspondence between TAC ratios and catch ratios would provide strong support for changes in fishing behavior to match catches to quotas.

The correlation between the TAC ratios and catch ratios was obtained for species in (1) and (2) above, where the TAC ratio could be obtained directly. A high correlation coefficient supports changes in fishing behavior; a low correlation suggests fishing behavior was little changed.

Species where TAC ratios could not be obtained directly, were divided into two groups: those with positive TAC ratios ($n_1 = 10$), and those with negative TAC ratios ($n_2$

= 9). The ability to match catches to quotas would be supported if species with positive TAC ratios had positive catch ratios, and species with negative TAC ratios had negative catch ratios. In addition, a randomization test was conducted to detect whether the mean catch ratios ($x_1$ and $x_2$) were significantly greater for species with positive TAC ratios than for those with negative TAC ratios with a null hypothesis that the true mean catch ratios for the two groups was identical. The following process was repeated $N$ = 100,000 times, starting with $m$ = 0: out of the pool of $n_1 + n_2$ catch ratios, select with replacement one set of size $n_1$ and one set of size $n_2$. Calculate the mean catch ratios for these two sets ($\mu_1$ and $\mu_2$). Increment $m$ if $\mu_1 - \mu_2 \geq x_1 - x_2$. The probability of obtaining the observed difference purely by chance, if the null hypothesis was true, is given by $m/N$.

*Defining fishing opportunities*

The choice of fishing location is an obvious way to alter the mix of species that are caught. Each skipper chooses whether to fish in a known “fishing opportunity”, or to go exploratory fishing; typically, skippers will use the same gear and fish in the same season whenever they fish at a given fishing opportunity. As defined in Chapter 3, a fishing opportunity is observed as a group of trawls that are clustered together over a portion of the same fishing ground. Each fishing opportunity is associated with one vessel. A brief summary of the method for obtaining fishing opportunities from individual trawl start and end positions is provided here, but more details can be found in Chapter 3.

(1) Longitudes were multiplied by the cosine of the latitude to ensure that latitudes and longitudes were in the same distance units.

(2) Trawls that were conducted in a southward direction were re-oriented to face north by swapping their start and end positions.

(3) The Euclidean distance ( $D_{i,j}$ ) between each pair of trawls $i$ and $j$ was obtained by:

$$(4.3)\ D_{ij} = \sqrt{\left(\mathrm{lon}_i^{start} - \mathrm{lon}_j^{start}\right)^2 + \left(\mathrm{lon}_i^{end} - \mathrm{lon}_j^{end}\right)^2 + \left(\mathrm{lat}_i^{start} - \mathrm{lat}_j^{start}\right)^2 + \left(\mathrm{lat}_i^{end} - \mathrm{lat}_j^{end}\right)^2}$$

(4) Trawls were grouped into a cluster tree by hierarchical agglomerative clustering (Venables and Ripley 1999, pp. 336-8).

(5) The cluster tree was cut into fishing opportunities using a "cut point" of 0.15, a rounded value of the recommended cut point for this fishery based on a mean trawl length of 10.8 km (Chapter 3).

Fishing opportunities were obtained separately for each of the 34 vessels that conducted at least 100 trawls per year in the fishery. All subsequent analyses in this paper used data from these vessels only. For each vessel, the number of fishing opportunities with ≥ 1, 5, 10, 15, and 20 trawls (in all years) were examined, but for further analyses, fishing opportunities were assumed to be those in which ≥ 15 tows were conducted. The number of fishing opportunities fished by each vessel gives an indication of the variety of places that are required to be fished to maximize economic yield from the fishery. If a vessel only fishes at a few fishing opportunities, it is likely specializing on a few species, but if a large number of fishing opportunities are utilized the vessel is probably targeting a wide variety of different species, each of which is most abundant in a few fishing opportunities.

*Targeting ratio*

I calculated whether each vessel increased or decreased the proportion of trawls at each of their associated fishing opportunities from 1996 to 1997–2001 using a "targeting ratio" (Equation 4.4). Targeting ratios are based on the proportion of trawls conducted at a fishing opportunity, and not the total number of trawls, because the number of trawls increased each year for the top 34 vessels from 1996 to 2001 (Figure 4.1). This change occurred as some vessels exited the fishery (reducing the number of active vessels from 108 in 1996 to 72–75 in 1997–2001), and the remaining vessels presumably acquired a greater proportion of each species' quota. The targeting ratio, $R_P$, for each fishing opportunity was calculated as follows:

$$\begin{aligned} p_{y,i} &= \frac{N_{y,i}}{\sum_i N_{y,i}} \\ R_{P,i} &= \frac{2\overline{p}_{1997-2001,i}}{p_{1996,i} + \overline{p}_{1997-2001,i}} - 1 \end{aligned} \qquad (4.4)$$

$N_{y,i}$ is the number of trawls in year *y* in fishing opportunity *i*

$\sum_i N_{y,i}$ is the total number of trawls conducted by that vessel in year *y*

$p_{y,i}$ is the proportion of trawls by a particular vessel conducted in fishing opportunity *i* and year *y*.

$\overline{p}_{1997-2001,i}$ is the mean proportion of trawls in fishing opportunity $i$ in 1997 to 2001

$p_{1996,i}$ is the proportion of trawls in fishing opportunity $i$ in 1996.

The targeting ratio measures whether a given vessel increased targeting (the proportion of trawls) on a particular fishing opportunity in 1997–2001 (positive $R_P$) or decreased targeting (negative $R_P$), compared to 1996. The highest targeting ratio ($R_P = 1$) is assigned to "new" fishing opportunities, where no trawls were conducted in 1996; the lowest possible targeting ratio ($R_P = -1$) is for "defunct" fishing opportunities, which were not trawled in 1997–2001. Targeting ratios were calculated for all fishing opportunities with ≥ 15 trawls over the 1996–2001 period.

*Evidence for avoidance of shortraker, rougheye and yelloweye rockfish*

Avoidance of species is most likely to be demonstrated when the TACs of those species have been sharply decreased. In the B.C. fishery, avoidance incentives should have been strongest for three species: shortraker rockfish, rougheye rockfish and yelloweye rockfish. TACs for shortraker and rougheye rockfish decreased by 60% and 38% respectively after 1996 (Table 4.3). These two species were treated separately even though they are probably closely related and can be difficult to identify separately at sea (Love et al. 2002). The third species, yelloweye rockfish, had no species-specific restrictions in 1996 (when 48 t were caught), but the TAC for 1997 was set at 16 t, and thereafter they were required to be relinquished with total catch targets ranging from 0 to 14 t.

To detect changes in fishing patterns corresponding to these more constraining TACs, trawls by the top 34 vessels were examined. Catch rates (catch per trawl) in each fishing season were calculated for each species, controlling for the increase in the number of trawls by these vessels (Figure 4.1). Admittedly, technology improvements may increase catch rates over time; alternatively, if fishing patterns changed to avoid catching these species, catch rates in 1997–2001 would be much lower than in 1996. Avoidance behavior could involve avoiding large catches of these species, or avoiding habitat where these species occur in any quantity. To determine which of these scenarios was most likely, the proportion of trawls that caught non-zero, medium, and large quantities of these species in each year were plotted, where “medium” and “large” were species-specific thresholds chosen so that the sum of catches greater than the thresholds corresponded to 75% and 25% of the total catch of those species.

To determine if it is possible to detect the avoidance of fishing opportunities where these three species were more abundant, the proportion of these three species was calculated for each fishing opportunity, as a percentage of the total catch at each fishing opportunity (summed over trawls and species). Targeting ratios (defined above) lower on average for fishing opportunities with higher proportions of these three species would imply avoidance behavior. Analyses were conducted both including and excluding new fishing opportunities. Randomization tests were conducted to see if targeting ratios were significantly lower in fishing opportunities where noticeable proportions (>1%) of these three species were caught.

*Multispecies TAC ratios*

The analyses on rougheye, shortraker and yelloweye rockfish were extended to all of the top 32 species. For each fishing opportunity I combined the proportions ( $p_i$ ) of each species *i* with the species-specific TAC ratios ( $R_T$ ), to obtain multispecies TAC ratios, $R_A$, for each fishing opportunity:

$$p_i = \frac{\sum_t C_{t,i}}{\sum_i \sum_t C_{t,i}} \tag{4.5}$$
$$R_A = \sum_i p_i R_{T_i}$$

Where $C_{t,i}$ is the catch of species *i* in trawl *t* at a fishing opportunity.

As discussed previously, it was not possible to calculate TAC ratios for many species, although they were classed as having either positive or negative TAC ratios. For those species, three scenarios were assumed for TAC ratios: (1) set TAC ratios to zero, (2) set TAC ratios to -0.14 for species with negative TAC ratios and 0.12 for species with positive TAC ratios, based on the mean catch ratios for each of these groups, and (3) delete those species from the calculations.

For each of these three scenarios, both including and excluding new fishing opportunities, the correlation between the multispecies TAC ratio and the targeting ratio was obtained. A randomization test was conducted to determine whether the mean targeting ratio differed significantly for fishing opportunities with positive and negative multispecies TAC ratios. The properties of the new fishing opportunities were examined to determine whether a greater proportion than expected had positive multispecies TAC ratios, using a chi-square contingency table and the Yates correction factor (Zar 1996, pp. 488-90).

**Results**

*TAC ratios and catch ratios*

TAC ratios and catch ratios were highly correlated ($r = 0.90$, $P < 0.001$, $n = 13$), indicating that when TACs were increased, catches of the corresponding species increased proportionately, and when TACs decreased, catches decreased accordingly (Figure 4.2).

A similar trend was apparent for those species where the TAC ratio could not be calculated directly (Figure 4.3). Nine out of ten species with positive TAC ratios had positive catch ratios (mean 0.12, range -0.03–0.46); and eight out of nine species with a negative TAC ratio had negative catch ratios (mean -0.14, range -0.49–0.15). The lowest catch ratio was for yelloweye rockfish (-0.49), and the highest catch ratio was for big skate (0.46). The mean catch ratio was significantly greater for species with positive TAC ratios than for species with negative TAC ratios ($n_1 = 10$, $n_2 = 9$, $\mu_1 = 0.12$, $\mu_2 = -0.14$, $P = 0.002$, randomization test).

*Fishing opportunities*

Each of the top 34 vessels conducted ≥ 1 trawl at a diverse range of fishing opportunities (mean 129, range 60-250, Figure 4.4), although this number includes exploratory fishing opportunities and those that may have been based on positional errors in the data (Chapter 3). As the threshold number of trawls increases to 15 trawls, the number of qualifying fishing opportunities decreased to 1,302, but each vessel still fished at a wide range of fishing opportunities (mean 38, range 20–69, Figure 4.4). Out of the 1,302 fishing opportunities, 585 (45%) were new fishing opportunities (not fished in 1996) and 11 (0.8%) were defunct fishing opportunities (not fished in 1997–2001).

*Avoidance of shortraker, rougheye and yelloweye rockfish*

Between 1996 and 1997-2001, catch rates (catch per tow) of the top 34 vessels of rougheye, shortraker and yelloweye rockfish were reduced by 56%, 59%, and 65% respectively (Figure 4.5). The percentage of trawls that caught non-zero quantities of these species was lower in 1997-2001 for rougheye and shortraker rockfish, but not for yelloweye rockfish, but there were large decreases in the percentages of trawls that caught medium and large quantities of all three species in 1997–2001 (Figure 4.6).

There was good evidence for the avoidance of fishing opportunities where rougheye, shortraker and yelloweye rockfish were likely to be caught. Fishing opportunities with noticeable proportions of these species (> 1% of the total catch) had lower targeting ratios, even when new fishing opportunities (not fished in 1996) were excluded from the analysis (Figure 4.7). Randomization tests indicated that when these species comprised ≥ 1% of the catches, the targeting ratios were significantly lower for rougheye rockfish ($n_1 = 1089$, $n_2 = 213$, $\mu_1 = 0.47$, $\mu_2 = 0.19$, $P < 0.00001$), and shortraker rockfish ($n_1 = 1207$, $n_2 = 95$, $\mu_1 = 0.44$, $\mu_2 = 0.15$, $P = 0.00001$), but these differences were not significant at the 5% level for yelloweye rockfish ($n_1 = 1292$, $n_2 = 10$, $\mu_1 = 0.43$, $\mu_2 = 0.13$, $P = 0.08$).

*Multispecies TAC ratios and targeting ratios among fishing opportunities*

For all three scenarios considered, there was a wide range of targeting ratios for all levels of multispecies TAC ratios (Figure 4.8), and no clear patterns emerged for different levels of the multispecies TAC ratio. When all fishing opportunities were included, there were significant correlations between the multispecies TAC ratio and the targeting ratio for scenarios 1 and 2 ($r = 0.085$, $r = 0.086$, $P < 0.005$ for both), but not for scenario 3 ($r = 0.041$, $P > 0.05$). The mean targeting ratio was greater when the multispecies TAC ratios were positive (0.44–0.50 vs. 0.36–0.39), and this difference was statistically significant for scenarios 1 and 3, but not for scenario 2 (Table 4.4).

When new fishing opportunities were excluded, there was a significant correlation between multispecies TAC ratios and targeting ratios only for scenario 2 ($r = 0.100$, $P < 0.005$). Mean targeting ratios were higher when the multispecies TAC ratio was positive (0.49–0.50 vs. 0.45–0.47) but this was only significant for scenario 2 (Table 4.4).

New fishing opportunities were more likely than expected to have positive multispecies TAC ratios under both scenarios 1 and 3 ($\chi^2 = 17.9–18.1$, $P < 0.001$), but this was not true under scenario 2 ($\chi^2 = 0.3$, $P > 0.1$).

**Discussion**

If skippers are unable to control the proportions of species in their catches, then multispecies fisheries cannot be managed to optimize economic benefits without overfishing some species (Ricker 1958, Paulik et al. 1967, Hilborn et al. 2004). Usually skippers do have some ability to control their catch mixture, thereby increasing yields with lower than predicted risks of overfishing, but most management systems provide neither the incentives nor the flexibility for fishing fleets to match catches of individual species to the corresponding TACs. For example, open-access and competitive fisheries encourage over-capitalization and a race for fish. This may lead to a shortened season and reduced fishing flexibility, while input controls, effort restrictions, and area closures reduce fishing effort by limiting flexibility. In contrast, ITQ systems generally increase fishing flexibility by allowing year-round fishing, reducing input controls, and allow leasing of quota to cover overages, while the quota constraints provide incentives to keep catches within TACs. However, ITQs also provide incentives to under-report, high-grade and discard catches of species with constraining TACs (Copes 1986, Anderson 1994, Arnason 1994).

The B.C. fishery is managed under an ITQ system that provides incentives for skippers to match their catches to individual-species quotas and also attempts to minimize misreporting, high-grading and discarding by placing observers on board each vessel and deducting discard mortality of marketable fish from quotas (Turris 2000). Under this system, fishers can maximize their profits by fully catching their quotas for as many species as possible (or leasing their quota to others) while minimizing their fishing costs. To the extent that it is possible, fishers should therefore avoid catching species with constraining TACs while targeting (valuable) species with non-constraining TACs.

TACs for many species in the B.C. fishery were changed in 1997–2001, compared to 1996 TACs. The change in TACs (measured by the TAC ratio) was highly correlated ($r = 0.90$) with corresponding changes in catches (measured by the catch ratio) for species where the TAC ratio could be measured directly. For species where the TAC ratio could not be measured directly, but “positive” or “negative” TAC ratios were inferred, catch ratios were also correlated with TAC ratios in a manner that was unlikely to be due to chance alone ($P = 0.002$). The correlation between TAC ratios and catch ratios provides evidence that the B.C. fishing fleet was able to alter their catch mix to increase catches of species with increasing TACs, while decreasing catches of species with decreasing TACs. Alternatively, changes in TACs may be due to underlying changes in abundance, which would be reflected in changes in catch mixtures. However, given that these changes applied to almost all species in the fishery, it seems more likely that changes in catch ratios were reflective of changes in fishing practice.

There are a variety of methods that skippers can use to adjust the species proportions in their catches, including fishing location, depth, gear type, time of day, month, trawl duration, and mesh size. This analysis has focused on changes in the proportion of trawls at “fishing opportunities”—collections of trawls by a single vessel over the same portion of fishing ground (defined in Chapter 3). Trawls within fishing opportunities are usually conducted at the same time of the year, with similar gear and trawl duration, and catch similar species mixtures, but do not fully encompass all possible fishing methods. In the B.C. fishery, the top vessels each conducted ≥ 15 trawls in a wide variety of fishing opportunities (mean 38, range 20–69) over the period of interest (1996–2001). Studies on location choice have tended to restrict analyses to a few (<15) large fishing areas (Hilborn and Ledbetter 1979, Eales and Wilen 1986, Dupont 1993, Gillis et al. 1993, Holland and Sutinen 2000, Mistiaen and Strand 2000, Smith 2002), although 28 fishing locations were reported for a Senegalese artisanal fishery (Pelletier and Ferraris

2000). One exception is a study by Durrenberger and Pálsson (1986), which examined fishing locations in Iceland that were 15×15 km in size. They found that only 50 out of 90 possible locations were visited by the entire fleet, and that most skippers fished only in a few locations (39% of all trips were in one location), although a few skippers fished in many locations. Although these grids may have been too broad to encompass the fine-scale fishing spots that skippers talked about (Durrenberger and Pálsson 1986), skippers likely fished at far fewer fishing opportunities than skippers in the B.C. fishery. Another study, by Rijnsdorp et al. (1998), analyzed continuous fishing positions in 5.6×5.6 km grids for the Dutch trawl fleet. The fleet fished in 5,493 of these grids in 1993–1996, and 25 sampled vessels fished in a mean of 957 locations (range 92–2,120), far more than the number of fishing opportunities fished in the B.C. fishery. However, Rijnsdorp et al.'s method could record a single trawl in a number of locations, thereby over-estimating the total number of fishing opportunities fished. The number of fishing opportunities is important because this is an indication of the range of possible options that a skipper can use to try to match multispecies catches to quota holdings. The relatively high number of fishing opportunities per vessel in the B.C. fishery is likely related to the large number (55) of species-area TAC combinations.

In the B.C. fishery, 45% of the fishing opportunities were classified as new (not fished in 1996), and only 0.8% were classified as defunct (not fished after 1996). The high proportion of new fishing opportunities may be due to an expansion of fishing in deeper waters on the DTS species (Dover sole, thornyhead, sablefish), but may also be due to ITQ implementation in 1997 encouraging fishers to find new fishing opportunities where constraining species would not be caught. The discrepancy between numbers of new and defunct fishing opportunities may also be due to the threshold of 15 trawls defining a fishing opportunity; this threshold is less likely to be reached if a fishing opportunity is only fished in one year (1996) than if it is fished in five years (1997–2001). There was also a greater probability that zero trawls would be conducted in 1996 (new fishing opportunity) than throughout 1997–2001 (defunct fishing opportunity), especially since the top vessels conducted fewer trawls in 1996 than in subsequent years under ITQ management.

When TACs for rougheye, shortraker, and yelloweye rockfish were reduced substantially skippers decreased catch rates of those species by more than 50% from 1996 to 1997–2001, mainly by reducing the percentage of trawls that caught medium and large quantities of these species. Analyzing targeting ratios showed that vessels reduced the proportion of trawls conducted in fishing opportunities where these three species were more abundant. Mean targeting ratios, including new fishing opportunities, were substantially lower (0.13–0.19 vs. 0.43–0.49) in fishing opportunities where more than 1% of the total catch comprised rougheye, shortraker, or yelloweye rockfish. These differences were significantly lower ($P < 0.0001$) for rougheye and shortraker rockfish, but not ($P = 0.08$) for yelloweye rockfish, perhaps because the catch proportion of yelloweye rockfish exceeded 1% in only 10 fishing opportunities.

Although there was evidence for the avoidance of fishing opportunities where shortraker, rougheye and yelloweye rockfish were caught, extending this idea to multiple species gave mixed results. The multispecies TAC ratio was used to measure the incentives to increasingly avoid (negative values) or target (positive values) fishing opportunities in 1997–2001 compared to 1996, and was based on a combination of catch proportions of each species, and the TAC ratios for those species. Results differed depending upon which of three scenarios for TAC ratios were assumed when TAC ratios could not be calculated directly. In general, there was a positive correlation between the multispecies TAC ratio and the targeting ratio, and the mean targeting ratio was higher for fishing opportunities with positive multispecies TAC ratios, but these results were only statistically significant for some scenarios. Results changed little when new fishing opportunities were excluded from the analysis: again, there were some trends, but these were statistically significant only for some scenarios. There was a wide scatter of targeting ratios regardless of the multispecies TAC ratios, suggesting that (1) this relationship has weak predictive power, or (2) other factors play a more important role in determining whether to increase or decrease the proportion of trawls at a particular fishing opportunity, for example, the expected size of the catch at a fishing opportunity, quota remaining for each species, current market prices, distance from the port, and weather conditions.

In conclusion, the ITQ system in the B.C. fishery provides incentives for the fleet to adjust their total catches when the TACs for individual species are altered. One mechanism for doing this is to change the proportion of trawls allocated to fishing opportunities that are known to each skipper. There is good evidence that this mechanism explains how catches of rougheye, shortraker, and yelloweye rockfish were reduced by more than 50% when more restrictive TACs were imposed on those species in 1997.

However, there is only weak evidence that skippers increased or decreased the proportion of trawls allocated to different fishing opportunities based on the proportions of all 32 of the most important species in those fishing opportunities. A variety of factors likely play a more important role in choosing where to fish than the species mixture, except when highly constraining species are likely to be caught in fishing opportunities.

**Table 4.1** Total allowable catches (TACs) by area and species in 1997-98 in the B.C. fishery. Area 3C/D is west of Vancouver Island, Area 4B is between Vancouver Island and mainland Canada, Area 5A/B is between Vancouver Island and the Queen Charlotte Islands, Area 5C/D is between the Queen Charlotte Islands and mainland Canada, and Area 5E is west of the Queen Charlotte Islands.

<table>
<tr><th>Species</th><th>3C</th><th>3D</th><th>5A</th><th>5B</th><th>5C</th><th>5D</th><th>5E</th><th>4B</th><th>Gulf</th><th>Coastwide</th></tr>
<tr><td>Yellowtail rockfish</td><td>719</td><td colspan="6">4,514</td><td>–</td><td>–</td><td>5,233</td></tr>
<tr><td>Widow rockfish</td><td colspan="7">2,358</td><td>–</td><td>–</td><td>2,358</td></tr>
<tr><td>Canary rockfish</td><td colspan="2">503</td><td colspan="2">345</td><td colspan="3">81</td><td>–</td><td>–</td><td>929</td></tr>
<tr><td>Silvergrey rockfish</td><td colspan="2">331</td><td colspan="2">604</td><td colspan="2">302</td><td>273</td><td>–</td><td>–</td><td>1,510</td></tr>
<tr><td>Pacific ocean perch</td><td>431</td><td>230</td><td colspan="2">2,358</td><td colspan="2">2,818</td><td>644</td><td>–</td><td>–</td><td>6,481</td></tr>
<tr><td>Yellowmouth rockfish</td><td>100</td><td colspan="3">1,866</td><td colspan="2">360</td><td>104</td><td>–</td><td>–</td><td>2,430</td></tr>
<tr><td>Rougheye rockfish</td><td colspan="7">380</td><td>–</td><td>–</td><td>380</td></tr>
<tr><td>Shortraker rockfish</td><td colspan="7">77</td><td>–</td><td>–</td><td>77</td></tr>
<tr><td>Redstripe rockfish</td><td>150</td><td colspan="3">1,198</td><td colspan="2">49</td><td>226</td><td>–</td><td>–</td><td>1,623</td></tr>
<tr><td>Shortspine thornyheads</td><td colspan="7">748</td><td>–</td><td>–</td><td>748</td></tr>
<tr><td>Longspine thornyheads</td><td colspan="7">860</td><td>–</td><td>–</td><td>860</td></tr>
<tr><td>Yelloweye rockfish</td><td colspan="7">16</td><td>–</td><td>–</td><td>16</td></tr>
<tr><td>Quillback, copper, china and tiger rockfish</td><td colspan="7">14</td><td>–</td><td>–</td><td>14</td></tr>
<tr><td>Pacific cod</td><td colspan="2">694</td><td colspan="2">260</td><td colspan="3">1,620</td><td>–</td><td>–</td><td>2,574</td></tr>
<tr><td>Dover sole</td><td colspan="2">1,375</td><td colspan="2">598</td><td colspan="3">1,100</td><td>–</td><td>–</td><td>3,073</td></tr>
<tr><td>Rock sole</td><td colspan="2">102</td><td colspan="2">935</td><td colspan="2">1,045</td><td>–</td><td>–</td><td>–</td><td>2,082</td></tr>
<tr><td>English sole</td><td colspan="4">186</td><td colspan="3">605</td><td>–</td><td>–</td><td>791</td></tr>
<tr><td>Petrale sole</td><td colspan="7">479</td><td>–</td><td>–</td><td>479</td></tr>
<tr><td>Lingcod</td><td>1,225</td><td>220</td><td colspan="2">862</td><td colspan="3">580</td><td>–</td><td>–</td><td>2,887</td></tr>
<tr><td>Spiny dogfish</td><td colspan="7">3,840</td><td>1,600</td><td>–</td><td>5,440</td></tr>
<tr><td>Walleye pollock</td><td colspan="2">270</td><td colspan="2">1,790</td><td colspan="3">825</td><td>–</td><td>1,115</td><td>4,000</td></tr>
<tr><td>Pacific whiting</td><td colspan="7">99,400</td><td>–</td><td>15,200</td><td>114,600</td></tr>
</table>

**Table 4.2**. Yearly coast-wide catch and catch ratio for each species in the B.C. groundfish fishery.

| Species | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | Catch ratio |
|---|---|---|---|---|---|---|---|
| Arrowtooth flounder | 4,293 | 2,573 | 3,720 | 3,626 | 4,391 | 7,381 | 0.00 |
| Big skate | 274 | 482 | 456 | 892 | 624 | 1,201 | 0.46 |
| Bocaccio | 240 | 236 | 194 | 217 | 239 | 234 | -0.04 |
| Canary rockfish | 539 | 761 | 755 | 920 | 800 | 823 | 0.20 |
| Darkblotched rockfish | 108 | 71 | 55 | 82 | 84 | 77 | -0.18 |
| Dover sole | 2,791 | 2,454 | 2,647 | 2,984 | 3,054 | 3,173 | 0.02 |
| English sole | 635 | 674 | 669 | 749 | 676 | 608 | 0.04 |
| Lingcod | 1,764 | 1,160 | 802 | 1,095 | 1,756 | 1,257 | -0.18 |
| Longnose skate | 143 | 149 | 110 | 203 | 114 | 172 | 0.02 |
| Longspine thornyhead | 811 | 518 | 755 | 871 | 801 | 624 | -0.06 |
| Pacific cod | 598 | 1,249 | 926 | 669 | 620 | 544 | 0.14 |
| Pacific hake | 29,667 | 50,243 | 50,930 | 68,229 | 10,383 | 35,341 | 0.18 |
| Pacific halibut | 357 | 276 | 234 | 214 | 272 | 205 | -0.20 |
| Pacific ocean perch | 6,173 | 5,645 | 5,572 | 6,034 | 5,812 | 5,675 | -0.04 |
| Petrale sole | 280 | 354 | 339 | 347 | 423 | 452 | 0.16 |
| Redbanded rockfish | 332 | 237 | 191 | 288 | 268 | 271 | -0.14 |
| Redstripe rockfish | 924 | 895 | 866 | 1,097 | 1,104 | 1,025 | 0.04 |
| Rex sole | 210 | 204 | 257 | 308 | 322 | 325 | 0.14 |
| Rock sole | 1,091 | 959 | 898 | 1,068 | 1,155 | 1,091 | -0.02 |
| Rougheye rockfish | 1,068 | 489 | 597 | 494 | 448 | 464 | -0.36 |
| Sablefish | 227 | 246 | 333 | 392 | 330 | 315 | 0.18 |
| Sharpchin rockfish | 140 | 123 | 112 | 233 | 325 | 370 | 0.24 |
| Shortraker rockfish | 144 | 59 | 41 | 62 | 64 | 76 | -0.40 |
| Shortspine thornyhead | 731 | 515 | 518 | 798 | 682 | 569 | -0.08 |
| Silvergray rockfish | 1,164 | 1,167 | 1,226 | 1,510 | 1,192 | 916 | 0.02 |
| Spiny dogfish | 196 | 97 | 157 | 185 | 215 | 173 | -0.08 |
| Splitnose rockfish | 44 | 64 | 51 | 60 | 71 | 54 | 0.16 |
| Walleye pollock | 1,274 | 523 | 750 | 1,122 | 894 | 379 | -0.26 |
| Widow rockfish | 1,712 | 1,595 | 1,653 | 1,846 | 1,891 | 2,215 | 0.04 |
| Yelloweye rockfish | 48 | 13 | 15 | 17 | 24 | 15 | -0.48 |
| Yellowmouth rockfish | 1,649 | 2,206 | 2,090 | 2,368 | 2,120 | 2,209 | 0.14 |
| Yellowtail rockfish | 5,181 | 3,409 | 3,797 | 4,807 | 3,670 | 3,638 | -0.14 |

**Table 4.3**. Coast-wide Total Allowable Catches (TAC) and TAC ratios for species in the B.C. groundfish fishery in 1996-2001. TAC ratios could not be estimated for some species, which were indicated by "Positive" if regulations increased incentives to target them, and "Negative" if regulations decreased the incentives to target them. "Relinq." = required to be relinquished, "Trip" = combined trip limit for minor rockfish, "None" = no TAC limit.

| Species | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | TAC ratio |
|---|---|---|---|---|---|---|---|
| Arrowtooth flounder | None | None | None | None | None | None | Positive |
| Big skate | None | None | None | None | None | None | Positive |
| Bocaccio | None | Trip | Trip | Trip | Trip | Trip | Negative |
| Canary rockfish[3] | 660 | 929 | 929 | 921 | 1,097 | 1,046 | 0.20 |
| Darkblotched rockfish | None | Trip | Trip | Trip | Trip | Trip | Negative |
| Dover sole[1] | 2,913 | 3,073 | 3,073 | 3,073 | 3,073 | 3,073 | Positive |
| English sole[1] | 493 | 791 | 791 | 771 | 771 | 730 | Positive |
| Lingcod | 5,115 | 2,887 | 2,500 | 2,462 | 2,462 | 2,462 | -0.34 |
| Longnose skate | None | None | None | None | None | None | Positive |
| Longspine thornyhead | None | 860 | 861 | 855 | 404 | 405 | Negative |
| Pacific cod | Bycatch | 2,574 | 1,954 | 1,954 | 1,954 | 1,154 | Positive |
| Pacific hake | 53,000 | 114,600 | 94,687 | 90,300 | 90,300 | 81,600 | 0.28 |
| Pacific halibut | Relinq. | Relinq. | Relinq. | Relinq. | Relinq. | Relinq. | Negative |
| Pacific ocean perch[3] | 5,433 | 6,481 | 6,147 | 6,147 | 6,147 | 6,147 | 0.06 |
| Petrale sole | Bycatch | 479 | 479 | 479 | 479 | 479 | Positive |
| Redbanded rockfish | None | Trip | Trip | Trip | Trip | Trip | Negative |
| Redstripe rockfish[3] | 1,757 | 1,623 | 1,564 | 1,562 | 1,562 | 1,521 | -0.06 |
| Rex sole | None | None | None | None | None | None | Positive |
| Rock sole[1] | 1,553 | 2,082 | 2,082 | 2,022 | 2,022 | 1,650 | Positive |
| Rougheye rockfish[3] | 1,156 | 380 | 549 | 433 | 431 | 530 | -0.42 |
| Sablefish | 304 | 386 | 386 | 386 | 339 | 339 | 0.10 |
| Sharpchin rockfish[3] | 267 | Trip | Trip | Trip | Trip | Trip | Positive |
| Shortraker rockfish[3] | 155 | 77 | 117 | 92 | 94 | 105 | -0.24 |
| Shortspine thornyhead | 752 | 748 | 749 | 732 | 733 | 736 | 0.00 |
| Silvergray rockfish[3] | 1,425 | 1,510 | 1,510 | 1,498 | 1,373 | 1,240 | 0.00 |
| Spiny dogfish[2] | 17,000 | 5,440 | 5,440 | 5,440 | 5,440 | 5,440 | Negative |
| Splitnose rockfish | None | Trip | Trip | Trip | Trip | Trip | Negative |
| Walleye pollock[2] | 6,578 | 4,000 | 3,730 | 4,225 | 4,225 | 4,225 | Negative |
| Widow rockfish[3] | 1,921 | 2,358 | 2,157 | 2,157 | 2,358 | 2,316 | 0.08 |
| Yelloweye rockfish | None | 16 | Relinq. | Relinq. | Relinq. | Relinq. | Negative |
| Yellowmouth rockfish[3] | 1,451 | 2,430 | 2,385 | 2,407 | 2,408 | 2,365 | 0.24 |
| Yellowtail rockfish[3] | 5,813 | 5,233 | 4,464 | 4,464 | 4,464 | 4,422 | -0.12 |

[1]TAC for 1996 only applied to part of coast
[2]Catches <20% of TAC, TAC not constraining
[3]1996 TAC combined with another species

**Table 4.4**. Relationship between the targeting ratios ($R_P$) and multispecies TAC ratios ($R_A$), for three scenarios when all fishing opportunities are considered, and when new fishing opportunities are excluded. The correlation between $R_P$ and $R_A$ is indicated by *r*. For each scenario, $n_1$ is the number of fishing opportunities with positive $R_A$ values and $n_2$ is the number with negative $R_A$ values. Randomizations tests were used to obtain the probability (*P*) that the mean targeting ratio is the same when $R_A$ is positive as when $R_A$ is negative.

| Fishing opportunities | Scenario | $r$ | Mean $R_P$ ($R_A < 0$) | Mean $R_P$ ($R_A \geq 0$) | $n_1$ | $n_2$ | $P$ |
|---|---|---|---|---|---|---|---|
| All | 1 | 0.085* | 0.36 | 0.50 | 698 | 604 | <0.0001 |
| All | 2 | 0.086* | 0.39 | 0.44 | 521 | 781 | 0.09 |
| All | 3 | 0.041 | 0.36 | 0.50 | 698 | 603 | <0.0001 |
| Excl. new | 1 | 0.022 | -0.06 | -0.03 | 423 | 294 | 0.22 |
| Excl. new | 2 | 0.100* | -0.08 | -0.02 | 292 | 425 | 0.06 |
| Excl. new | 3 | -0.011 | -0.06 | -0.03 | 423 | 294 | 0.22 |

* $P < 0.005$

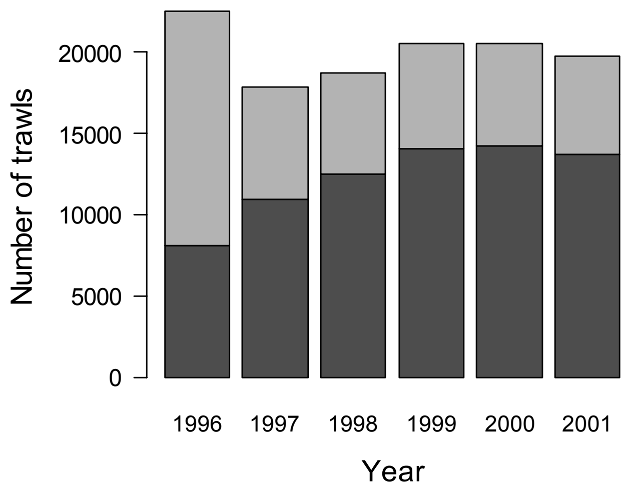


**Figure 4.1**. Number of trawls conducted in each year by the top 34 vessels (dark gray), and by the remaining vessels (light gray) in the B.C. fishery.

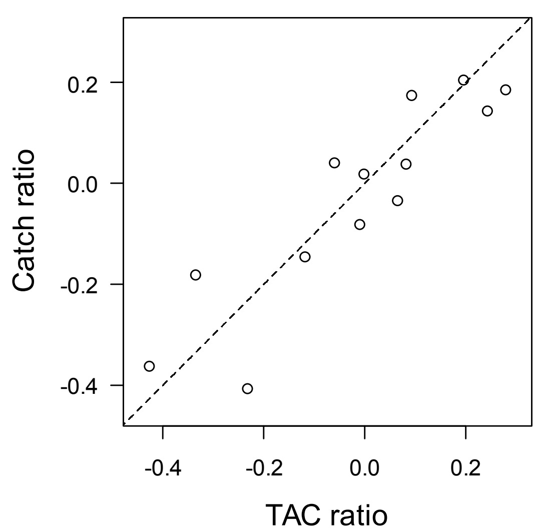


**Figure 4.2**. Relationship between the TAC ratio and the catch ratio for the 13 species for which the TAC ratio could be calculated. The 1:1 line is shown.

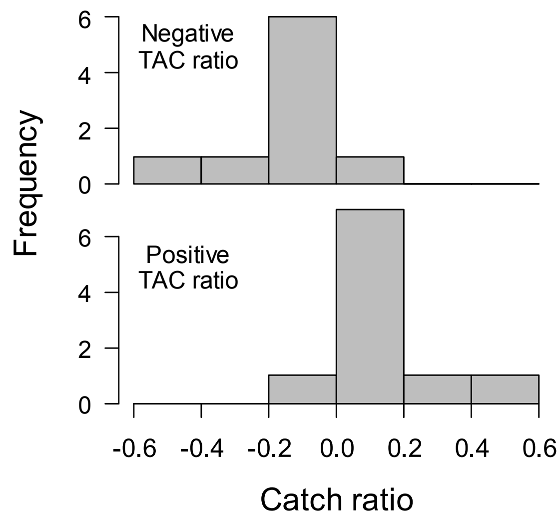


**Figure 4.3**. Distribution of catch ratios among species for which TAC ratios could not be calculated but which are presumed to fall into two groups: those with positive TAC ratios (top panel) and those with negative TAC ratios (bottom panel).

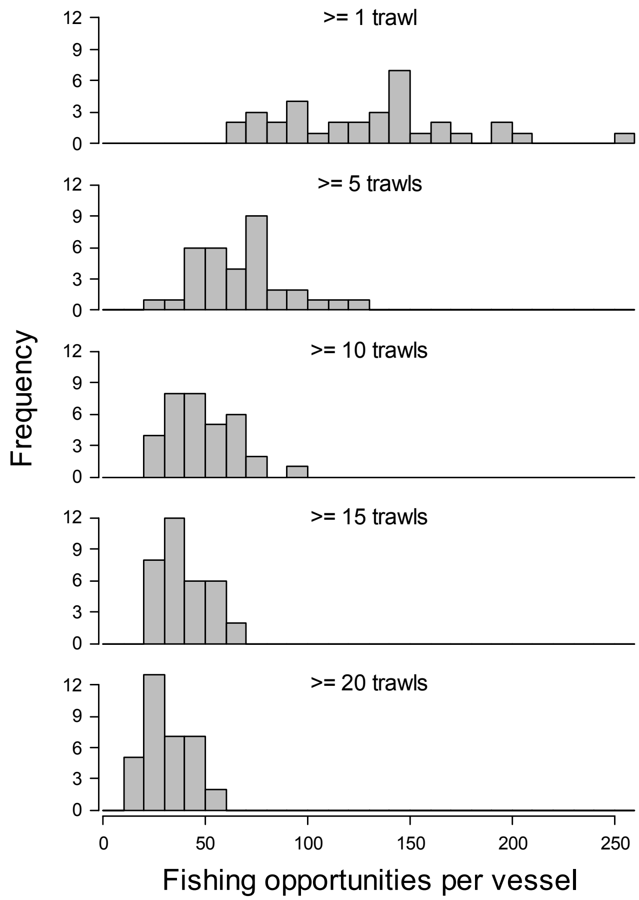


**Figure 4.4**. The frequency distribution of the number of fishing opportunities visited by each of the top 34 vessels in 1996–2001, with ≥ 1, 5, 10, 15, and 20 trawls in each fishing opportunity.

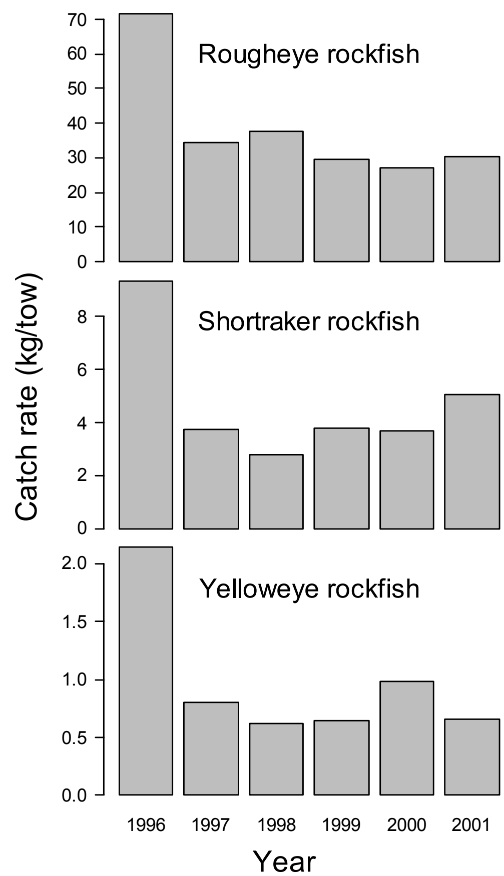


**Figure 4.5**. Catch rates (kg per trawl) of rougheye rockfish, shortraker rockfish, and yelloweye rockfish for the top 34 vessels in the B.C. fishery. Allowable catches were substantially reduced for all three species in 1997–2001.

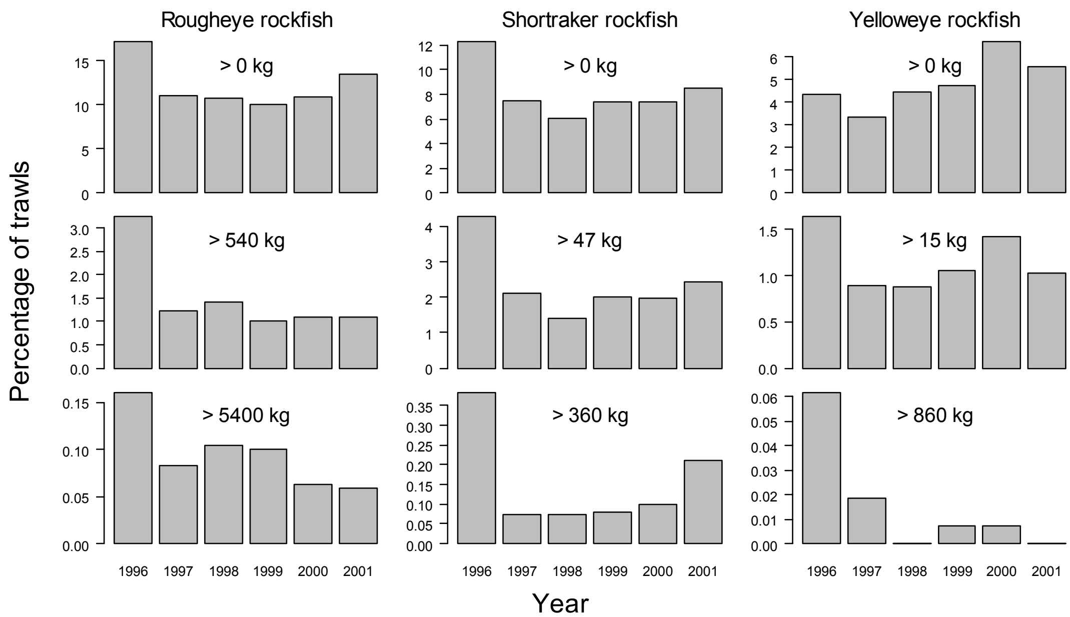


**Figure 4.6**. The proportion of tows by the top 34 vessels in 1996-2001 that caught small (>0 kg), medium, and large quantities of rougheye, shortraker, and yelloweye rockfish. The chosen catch levels for “medium” and “large” quantities cumulatively summed to 75% and 25% of the total catches of each species. Note that the scales on the y-axes are different for each individual graph.

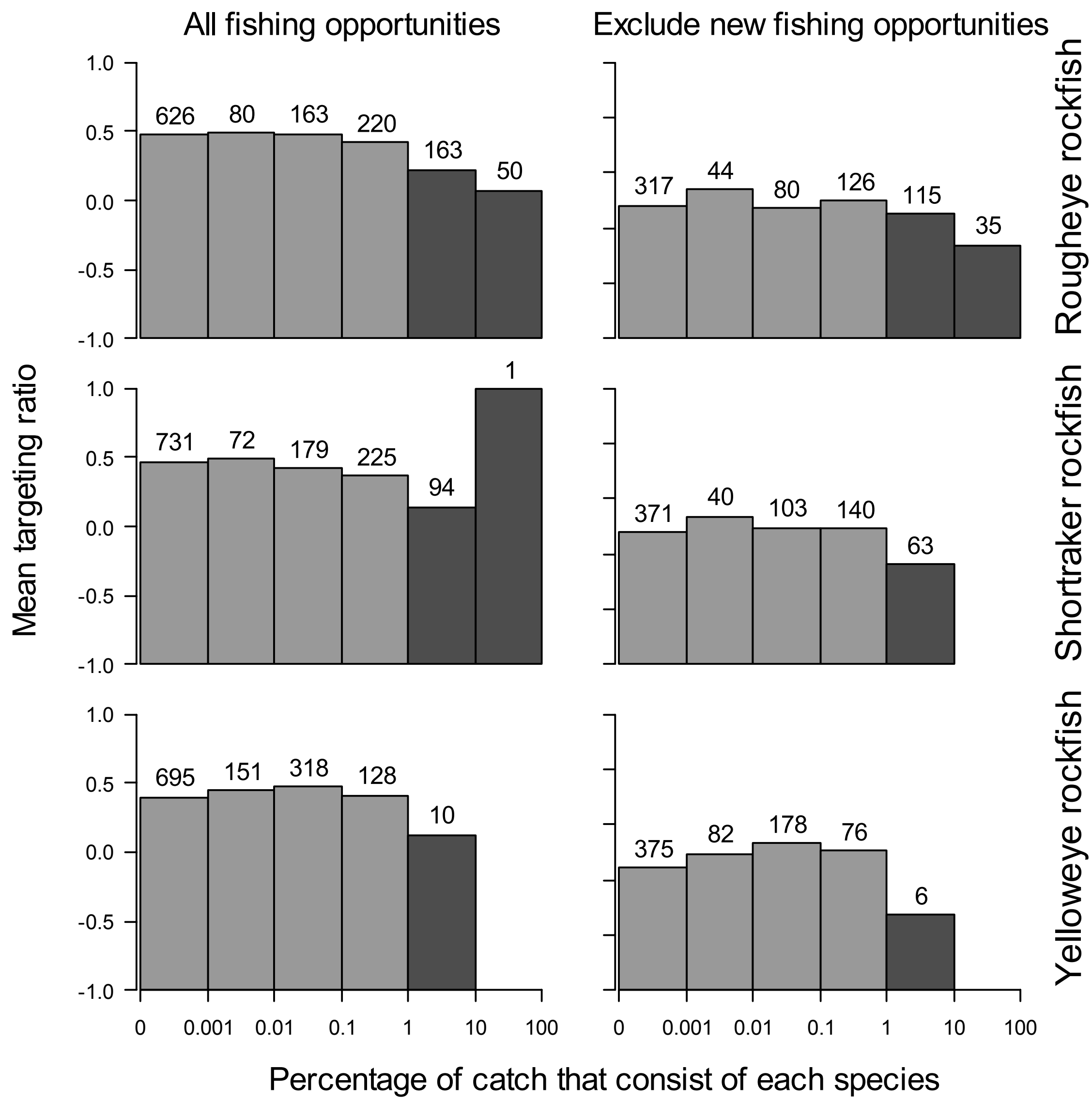


**Figure 4.7**. The mean targeting ratio in fishing opportunities with varying percentages of rougheye, shortraker and yelloweye rockfish. Light grey bars denoted fishing opportunities with where the catch of these species was < 1%, dark gray those where ≥ 1% of the catches was these species. The left column of graphs include all fishing opportunities, the right column of graphs exclude new fishing opportunities (where no trawls were conducted in 1996). For example, in 626 fishing opportunities the catch of rougheye rockfish was < 0.001% of the total catch, and the mean targeting ratio (including new fishing opportunities) in those fishing opportunities was 0.48. Note that only one fishing opportunity had more than 10% shortraker rockfish.

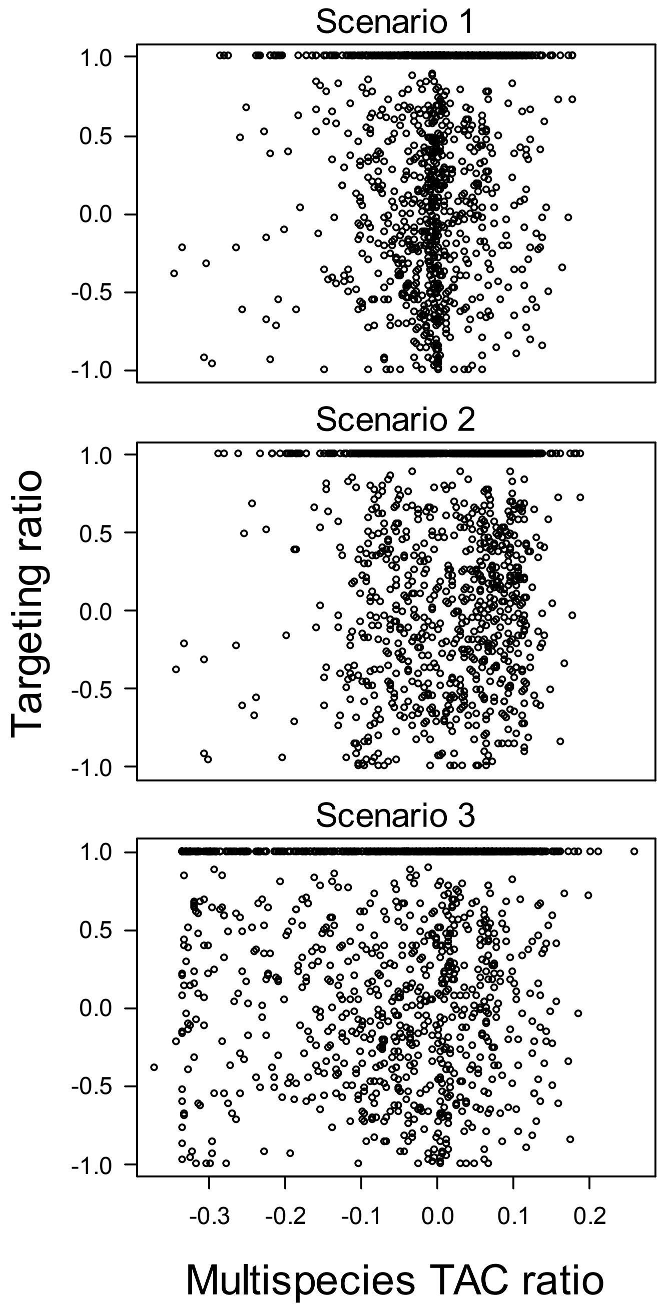


**Figure 4.8**. Relationship between the multispecies TAC ratios and targeting ratios for the fishing opportunities. New fishing opportunities are those with targeting ratios of 1. In Scenario 1, the TAC ratio was assumed to be 0.5 for all species where it could not be calculated directly; in Scenario 2, the TAC ratio was assumed to be -0.14 for species with presumed negative TAC ratios and 0.12 for those with presumed positive TAC ratios; in Scenario 3, species were only included if their TAC ratios could be calculated directly.

# OVERALL DISSERTATION DISCUSSION

There is no easy solution to managing multispecies fisheries. The problem remains that individual species vary in productivity and catchability and it is therefore difficult to maximize yields without overfishing some stocks in a multispecies fishery. ITQs may provide incentives for fishers to change their fishing behavior, but they also provide incentives for fishers to circumvent catch limits by misreporting, and to high-grade and discard (Chapter 1). These problems are magnified when enforcement is lacking or difficult, and when the TACs for some species are small relative to expected catches.

To minimize these problems, the British Columbia groundfish fishery (B.C. fishery) implemented ITQs with 100% observer coverage (to make misreporting difficult), the deduction of marketable discard mortality from quotas (to remove the incentives to discard and high-grade), and a halt to bottom trawling when the quota is exceeded for any species (to prevent TAC overruns). These regulations have been able to maintain catches within TACs while reducing discarding of marketable fish to less than 1% for most species (Chapter 2). However, the regulations impose strong constraints on profitable fishing behavior, despite provisions for leasing and for carrying forward quota underages or overages to the following year. Fishers would be predicted to change their fishing patterns to avoid catching species with more constraining TACs, while targeting species with undercaught (or no) TACs. The fishing fleet as a whole was able to match catches to TACs despite increases and decreases in the TACs of some species after 1996. In Chapter 3, a method for defining fishing opportunities was developed and applied to the B.C. fishery, and evidence was presented in Chapter 4 that fishers decreased the proportion of trawls in fishing opportunities where rougheye, shortraker, and yelloweye rockfish were likely to be caught when the TACs and regulations reduced allowable catches for these species. This change in fishing behavior was at least partially responsible for the reduction in catch rates of these species by more than 50%—without reducing catches of other species. The B.C. system appeared to offer substantial flexibility for fishers to decide when and where to fish in order to match catches to quotas. This does not mean that quotas were never exceeded. Quotas often were exceeded—there were more than 2,700 trades per year among just 65 active vessels in the fishery—but the ability to lease quota from other operators to cover overages gave skippers the ability to continue fishing without the overall TAC being exceeded.

In contrast, the U.S. West Coast groundfish trawl fishery (West Coast fishery) is currently managed by non-tradable two-monthly landing limits, and catches in excess of these species-specific limits are required to be discarded (Chapter 2). In comparison to the B.C. fishery, discard fractions for most species were much higher in the West Coast fishery, resulting in a loss of income to West Coast fishers. When comparing these results, it is important to take into account the very small two-monthly limits placed on many overfished species in the West Coast system in order to rebuild their populations.

ITQs are currently being considered for the West Coast fishery. It is likely that several aspects of a B.C.-style ITQ system would help to reduce discarding in the West Coast fishery: (1) A move from two-monthly limits to annual limits might reduce the number of occasions on which discarding would be induced by regulations; (2) Leasing of quotas among participants would allow participants that exceeded quotas to legally land their catches instead of discarding, and (3) The fleet size may be reduced under ITQs as some participants sell their quota share and leave the fishery, resulting in increased quotas for the remaining vessels and a reduced likelihood of discarding. At present, 168 active West Coast trawl vessels catch 18% less than 60–70 active B.C. trawl vessels (Chapter 2). However, there are a number of factors other than discarding to consider before implementing ITQs in the West Coast fishery. Most importantly, the cost of implementing full observer coverage may be prohibitive in the West Coast fishery, the low TACs for overfished species may seriously constrain the fishery under ITQs, and crew members, processors, and fishing communities may be negatively impacted under ITQs. Realistic predictions of the effects of ITQs on the West Coast and B.C. fisheries would require the inclusion of aspects of fisheries biology, economics and social sciences, knitted together by a realistic depiction of how fisher behavior would change in response to incentives created by regulations.

## BIBLIOGRAPHY


Alverson, D. L., M. K. Freeberg, S. A. Murawski, and J. G. Pope. 1994. A global assessment of fisheries bycatch and discards. FAO Fisheries Technical Paper **339**.

Anderson, L. G. 1994. An economic analysis of highgrading in ITQ fisheries regulation programs. Marine Resource Economics **9**:209-226.

Annala, J. H. 1996. New Zealand's ITQ system: have the first eight years been a success or a failure? Reviews in Fish Biology and Fisheries **6**:43-62.

Annala, J. H., K. J. Sullivan, and A. J. Hore. 1991. Management of multispecies fisheries in New Zealand by individual transferable quotas. ICES Marine Science Symposium **193**:321-329.

Annala, J. H., K. J. Sullivan, C. J. O'Brien, N. W. M. Smith, and S. J. A. C. Varian. 2002. Report from The Fishery Assessment Plenary, May 2002. Unpublished report held in NIWA library, Wellington, Wellington, New Zealand.

Arnason, R. 1993. The Icelandic individual transferable quota system: a descriptive account. Marine Resource Economics **8**:201-218.

Arnason, R. 1994. On catch discarding in fisheries. Marine Resource Economics **9**:189-207.

Arnason, R. 1996a. On selectivity and discarding in an ITQ fishery. Discarding of catch at sea. Working Paper #1. Research project available from ragnara@rhi.hi.is.

Arnason, R. 1996b. On the ITQ fisheries management system in Iceland. Reviews in Fish Biology and Fisheries **6**:63-90.

Asche, F. 2001. Fishermen's discount rates in ITQ systems. Environmental and resource economics **19**:403-410.

Babcock, E. A., and E. K. Pikitch. 2000. A dynamic programming model of fishing strategy choice in a multispecies trawl fishery with trip limits. Canadian Journal of Fisheries and Aquatic Sciences **57**:357-370.

Baelde, P. 2001. Fishers' description of changes in fishing gear and fishing practices in the Australian South East Trawl Fishery. Marine and Freshwater Research **52**:411-417.

Batstone, C. J., and B. M. H. Sharp. 1999. New Zealand's quota management system: the first ten years. Marine Policy **23**:177-190.

Bernal, P. A., D. Oliva, B. Aliaga, and C. Morales. 1999. New regulations in Chilean fisheries and aquaculture: ITQ's and territorial users rights. Ocean and Coastal Management **42**:119-142.

Bess, R. in press. Expanding New Zealand's quota management system. Marine Policy **00**:000-000.

Beverton, R. J. H., and S. J. Holt. 1957. On the dynamics of exploited fish populations. Fish. Investig. Ser. II. Mar. Fish. G.B. Minist. Agric. Fish. Food **19**:1-533.

Binkley, M. E. 1989. Nova Scotian offshore groundfish fishermen: effects of the enterprise allocation and the drive for quality. Marine Policy **13**:274-284.

Biseau, A. 1998. Definition of a directed fishing effort in a mixed-species trawl fishery, and its impact on stock assessments. Aquatic Living Resources **11**:119-136.

Biseau, A., and E. Gondeaux. 1988. Apport des méthodes d'ordination en typologie des flottilles. Journal du Conseil / Conseil International Pour L'exploration de la Mer **44**:286-296.

Boyd, R. O., and C. M. Dewees. 1992. Putting theory into practice: individual transferable quotas in New Zealand's fisheries. Society and Natural Resources **5**:179-198.

Bradshaw, M. 2004. A combination of state and market through ITQs in the Tasmanian commercial rock lobster fishery: the tail wagging the dog? Fisheries Research **67**:99-109.

Bradshaw, M., S. Williamson, and L. Wood. 2000. From input controls to quota management in the Tasmanian rock lobster fishery. New Zealand Geographer **56(2)**:32-41.

Breen, P. A., and T. H. Kendrick. 1997. A fisheries management success story: the Gisborne, New Zealand, fishery for red rock lobsters (*Jasus edwardsii*). Marine and Freshwater Research **48**:1103-1110.

Brodziak, J. K. T., P. M. Mace, W. J. Overholtz, and P. J. Rago. 2004. Ecosystem trade-offs in managing New England fisheries. Bulletin of Marine Science **74**:529-548.

Cabrera, J. L., and O. Defeo. 2001. Daily bioeconomic analysis in a multispecific artisanal fishery in Yucatan, Mexico. Aquatic Living Resources **14**:19-28.

Campbell, H. F., and A. J. Hand. 1999. Modeling the spatial dynamics of the US purse-seine fleet operating in the western Pacific tuna fishery. Canadian Journal of Fisheries and Aquatic Sciences **56**:1266-1277.

Casey, K. E., C. M. Dewees, B. R. Turris, and J. E. Wilen. 1995. The effects of individual vessel quotas in the British Columbia halibut fishery. Marine Resource Economics **10**:211-230.

Christy, F. T. 1973. Fisherman quotas: a tentative suggestion for domestic management. Occasional Paper Series Law of the Sea Institute University of Rhode Island **19**:1-7.

Clark, C. W., and G. R. Munro. 2002. The problem of overcapacity. Bulletin of Marine Science **70**:473-483.

Connor, R., and D. Alden. 2001. Indicators of the effectiveness of quota markets: the South East Trawl fishery of Australia. Marine and Freshwater Research **52**:387-397.

Copes, P. 1986. A critical review of the Individual Quota as a device in fisheries management. Land Economics **62**:278-291.

Criddle, K. R., and S. Macinko. 2000. A requiem for the ITQ in US fisheries? Marine Policy **24**:461-469.

Crowley, R. W., and H. Palsson. 1992. Rights-based fisheries management in Canada. Marine Resource Economics **7(2)**:1-21.

Davidse, W. P., L. V. McEwan, and N. Vestergaard. 1999. Property rights in fishing: from state property towards private property? Marine Policy **23**:537-547.

Dewees, C. M. 1989. Assessment of the implementation of individual transferable quotas in New Zealand’s inshore fishery. North American Journal of Fisheries Management **9**:131-139.

Dorn, M. W. 1997. Mesoscale fishing patterns of factory trawlers in the Pacific hake (*Merluccius productus*) fishery. California Cooperative Oceanic Fisheries Investigation Reports **38**:77-89.

Dorn, M. W. 2001. Fishing behavior of factory trawlers: a hierarchical model of information processing and decision-making. ICES Journal of Marine Science **58**:238-252.

Dupont, D. P. 1993. Price uncertainty, expectations formation and fishers' location choices. Marine Resource Economics **8**:219-247.

Dupont, D. P., and R. Q. Grafton. 2001. Multi-species Individual Transferable Quotas: the Scotia-Fundy mobile gear groundfishery. Marine Resource Economics **15**:205-220.

Dupont, D. P., R. Q. Grafton, J. Kirkley, and D. Squires. 2002. Capacity utilization measures and excess capacity in multi-product privatized fisheries. Resource and Energy Economics **24**:193-210.

Durrenberger, P., and G. Pálsson. 1986. Finding fish: the tactics of Icelandic skippers. American Ethnologist **13**:213-229.

Eales, J., and J. E. Wilen. 1986. An examination of fishing location choice in the pink shrimp fishery. Marine Resource Economics **2**:331-351.

Eikeland, S., and L. Riabova. 2002. Transition in a cold climate: management regimes and rural marginalisation in northwest Russia. Sociologia Ruralis **42**:250-266.

Eythórsson, E. 1996. Theory and practice of ITQs in Iceland: Privatization of common fishing rights. Marine Policy **20**:269-281.

Eythórsson, E. 2000. A decade of ITQ-management in Iceland fisheries: consolidation without consensus. Marine Policy **24**:483-492.

Fina, M. in press. Rationalization of the Bering Sea and Aleutian Islands crab fisheries. Marine Policy **000**:000-000.

Ford, W. 2001. Restructuring the Tasmanian rock-lobster fishery—the effect of two years of management under individual transferable quotas. Marine and Freshwater Research **52**:1641-1648.

Gardner, M. 1988. The enterprise allocation system in the offshore groundfish sector in Atlantic Canada. Marine Resource Economics **5**:389-454.

Gauvin, J. R., J. M. Ward, and E. E. Burgess. 1994. Description and evaluation of the wreckfish (*Polyprion americanus*) fishery under Individual Transferable Quotas. Marine Resource Economics **9**:99-118.

Geen, G., and M. Nayar. 1988. Individual Transferable Quotas in the southern bluefin tuna fishery: an economic appraisal. Marine Resource Economics **5**:365-387.

Gillis, D. M. 1999. Behavioral inferences from regulatory observer data: catch rate variation in the Scotian Shelf silver hake (*Merluccius bilinearis*) fishery. Canadian Journal of Fisheries and Aquatic Sciences **56**:288-296.

Gillis, D. M., R. M. Peterman, and E. K. Pikitch. 1995a. Implications of trip regulations for high-grading: a model of the behavior of fishermen. Canadian Journal of Fisheries and Aquatic Sciences **52**:402-415.

Gillis, D. M., R. M. Peterman, and A. V. Tyler. 1993. Movement dynamics in a fishery: application of the Ideal Free Distribution to spatial allocation of effort. Canadian Journal of Fisheries and Aquatic Sciences **50**:323-333.

Gillis, D. M., E. K. Pikitch, and R. M. Peterman. 1995b. Dynamic discarding decisions: foraging theory for high-grading in a trawl fishery. Behavioral Ecology **6**:146-154.

Ginter, J. J. C. 1995. The Alaska community development quota fisheries management program. Ocean and Coastal Management **28**:147-163.

González, E., R. Norambuena, and M. García. 2001. Initial allocation of harvesting rights in the Chilean fishery for Patagonian toothfish. Pages 305-321 *in* R. Shotton, editor. Case studies on the allocation of transferable quota rights in fisheries. FAO, Rome.

Gordon, H. S. 1954. The economic theory of a common-property resource: the fishery. Journal of Political Economy **62**:124-142.

Grafton, R. Q. 1992. Rent capture in an individual transferable quota fishery. Canadian Journal of Fisheries and Aquatic Sciences **49**:497-503.

Grafton, R. Q. 1994. A note on rent capture in an ITQ fishery. Journal of Environmental Economics and Management **27**:286-294.

Grafton, R. Q. 1995. Rent capture in a rights-based fishery. Journal of Environmental Economics and Management **28**:48-67.

Grafton, R. Q. 1996a. Implications of taxing quota value in an Individual Transferable Quota fishery: comment. Marine Resource Economics **11**:125-127.

Grafton, R. Q. 1996b. Individual transferable quotas: theory and practice. Reviews in Fish Biology and Fisheries **6**:5-20.

Grafton, R. Q., D. Squires, and J. Kirkley. 1996. Private property rights and crises in world fisheries: turning the tide? Contemporary Economic Policy **14(4)**:90-99.

Grieve, C., and G. Richardson. 2001. Recent history of Australia's South East Fishery; a manager's perspective. Marine and Freshwater Research **52**:377-386.

Hannah, R. W. 2003. Spatial changes in trawl fishing effort in response to footrope diameter restrictions in the U.S. West Coast groundfish trawl fishery. North American Journal of Fisheries Management **23**:693-702.

Hannesson, R. 1996. On ITQs: an essay for the Special Issue of Reviews in Fish Biology and Fisheries. Reviews in Fish Biology and Fisheries **6**:91-96.

Hardin, G. 1968. The tragedy of the commons. Science **162**:1243-1248.

Hart, D. 2001. Sea scallops. Available from http://www.nefsc.noaa.gov/sos/spsyn/iv/scallop/seascallop01.pdf.

Hartley, M., and M. Fina. 2001a. Allocation of individual vessel quota in the Alaskan Pacific halibut and sablefish fisheries. Pages 251-265 *in* R. Shotton, editor. Case studies on the allocation of transferable quota rights in fisheries. FAO Fisheries Technical Paper 411. FAO, Rome.

Hartley, M., and M. Fina. 2001b. Changes in fleet capacity following the introduction of individual vessel quotas in the Alaskan Pacific halibut and sablefish fishery. Pages 186-207 *in* R. Shotton, editor. Case studies on the effects of transferable fishing rights on fleet capacity and concentration of quota ownership. FAO Fisheries Technical Paper 412. FAO, Rome.

Herrmann, M. 1996. Estimating the induced price increase for Canadian Pacific halibut with the introduction of the individual vessel quota program. Canadian Journal of Agricultural Economics **44**:151-164.

Herrmann, M. 2000. Individual vessel quota price-induced effects for Canadian Pacific halibut: before and after Alaska IFQs. Canadian Journal of Agricultural Economics **48**:195-210.

Hersoug, B., and P. Holm. 2000. Change without redistribution: an institutional perspective on South Africa's new fisheries policy. Marine Policy **24**:221-231.

Hilborn, R. 1976. Optimal exploitation of multiple stocks by a common fishery: a new methodology. Journal of the Fisheries Research Board of Canada **33**:1-5.

Hilborn, R. 1985a. Apparent stock recruitment relationships in mixed stock fisheries. Canadian Journal of Fisheries and Aquatic Sciences **42**:718-723.

Hilborn, R. 1985b. Fleet dynamics and individual variation: why some people catch more fish than others. Canadian Journal of Fisheries and Aquatic Sciences **42**:2-13.

Hilborn, R., and M. Ledbetter. 1979. Analysis of the British Columbia salmon purse-seine fleet: dynamics of movement. Journal of the Fisheries Research Board of Canada **36**:384-391.

Hilborn, R., A. E. Punt, and J. Orensanz. 2004. Beyond band-aids in fisheries management: fixing world fisheries. Bulletin of Marine Science **74**:493-507.

Hilborn, R., and C. J. Walters. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman & Hall, New York.

Holland, D. S., and J. G. Sutinen. 2000. Location choice in New England trawl fisheries: Old habits die hard. Land Economics **76**:133-150.

Hutchings, J. A., and R. A. Myers. 1994. What can be learned from the collapse of a renewable resource—Atlantic cod, *Gadus morhua*, of Newfoundland and Labrador. Canadian Journal of Fisheries and Aquatic Sciences **51**:2126-2146.

Jackson, J. B. C., M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. H. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S.

Steneck, M. J. Tegner, and R. R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science **293**:629-638.

Jakobsson, J., and G. Stefánsson. 1999. Management of summer-spawning herring off Iceland. ICES Journal of Marine Science **56**:827-833.

Johnson, R. N. 1995. Implications of taxing quota value in an Individual Transferable Quota fishery. Marine Resource Economics **10**:327-340.

Kaufman, B., and G. Geen. 1998. Quota allocation and litigation: an economic perspective. Marine Resource Economics **13**:143-157.

Kingsley, M. C. S. 2002. Food for thought: ITQs and the economics of high-grading. ICES Journal of Marine Science **59**:649.

Kitts, A. W., and S. F. Edwards. 2003. Cooperatives in US fisheries: realizing the potential of the fishermen's collective marketing act. Marine Policy **27**:357-366.

Knapp, G. 1997. Initial effects of the Alaska halibut IFQ program: survey comments of Alaska fishermen. Marine Resource Economics **12**:239-248.

Love, M. S., M. Yoklavich, and L. Thorsteinson. 2002. The rockfishes of the Northeast Pacific. University of California Press, Berkeley, CA.

Macinko, S. 1993. Public or private? United States commercial fisheries management and the public trust doctrine, reciprocal challenges. Natural Resources Journal **33**:919-955.

Macinko, S., and D. W. Bromley. 2002. Who owns America's fisheries? Center for Resource Economics, Covelo, California.

Matulich, S. C., and M. L. Clark. 2003. North Pacific halibut and sablefish IFQ policy design: quantifying the impacts on processors. Marine Resource Economics **18**:149-166.

Matulich, S. C., R. C. Mittelhammer, and C. Reberte. 1996. Toward a more complete model of individual transferable quotas: implications of incorporating the processing sector. Journal of Environmental Economics and Management **31**:112-128.

Matulich, S. C., and S. Sever. 1999. Reconsidering the initial allocation of ITQs: the search for a Pareto-safe allocation between fishing and processing sectors. Land Economics **75**:203-219.

Maunder, M. N., and P. J. Starr. 2002. Industry participation in stock assessment: the New Zealand SNA1 snapper (*Pagrus auratus*) fishery. Marine Policy **26**:481-492.

McCay, B. J. 1995. Social and ecological implications of ITQs: an overview. Ocean and Coastal Management **28**:3-22.

McCay, B. J., R. Apostle, and C. F. Creed. 1998. Individual Transferable Quotas, comanagement, and community. Fisheries **23(4)**:20-23.

McCay, B. J., C. F. Creed, A. C. Finlayson, R. Apostle, and K. Mikalsen. 1995. Individual Transferable Quotas (ITQs) in Canadian and US fisheries. Ocean and Coastal Management **28**:85-115.

Mistiaen, J. A., and I. E. Strand. 2000. Location choice of commercial fishermen with heterogeneous risk preferences. American Journal of Agricultural Economics **82**:1184-1190.

Moloney, D. G., and P. H. Pearse. 1979. Quantitative rights as an instrument for regulating commercial fisheries. Journal of the Fisheries Research Board of Canada **36**:859-866.

Morgan, G. R. 1995. Optimal fisheries quota allocation under a transferable quota (TQ) management system. Marine Policy **19**:379-390.

Myers, R. A., and B. Worm. 2003. Rapid worldwide depletion of predatory fish communities. Nature **423**:280-283.

NRC. 1999. Sharing the fish: toward a national policy on individual fishing quotas. National Academy Press, Washington, D.C.

NWFSC. 2004. Northwest Fisheries Science Center West Coast groundfish observer program data report and summary analyses. Available from http://www.nwfsc.noaa.gov/research/divisions/fram/Observer/datareportjan2004.cfm.

Pálsson, G. 1998. The virtual aquarium: commodity fiction and cod fishing. Ecological Economics **24**:275-288.

Pálsson, G., and A. Helgason. 1995. Figuring fish and measuring men: the individual transferable quota system in the Icelandic cod fishery. Ocean and Coastal Management **28**:117-146.

Pascoe, S. 1993. ITQs in the Australian South East Fishery. Marine Resource Economics **8**:395-401.

Paulik, G. J., A. S. Hourston, and P. A. Larkin. 1967. Exploitation of multiple stocks by a common fishery. Journal of the Fisheries Research Board of Canada **24**:2527-2537.

Pelletier, D., and J. Ferraris. 2000. A multivariate approach for defining fishing tactics from commercial catch and effort data. Canadian Journal of Fisheries and Aquatic Sciences **57**:51-65.

Phillips, G., L. Kriwoken, and P. Hay. 2002. Private property and public interest in fisheries management: the Tasmanian rock lobster fishery. Marine Policy **26**:459-469.

Pikitch, E. K., D. L. Erikson, and J. R. Wallace. 1988. An evaluation of the effectiveness of trip limits as a management tool. NWAFC Processed Report 88-27, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, U.S. Department of Commerce.

Repetto, R. 2001. A natural experiment in fisheries management. Marine Policy **25**:251-264.

Ricker, W. E. 1958. Maximum sustained yields from fluctuating environments and mixed stocks. Journal of the Fisheries Research Board of Canada **15**:991-1006.

Ricker, W. E. 1973. Two mechanisms that make it impossible to maintain peak-period yields from stocks of Pacific salmon and other fishes. Journal of the Fisheries Research Board of Canada **30**:1275-1286.

Rijnsdorp, A. D., A. M. Buys, F. Storbeck, and E. G. Visser. 1998. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. ICES Journal of Marine Science **55**:403-419.

Sampson, D. B. 1994. Fishing tactics in a two-species fisheries model: the bioeconomics of bycatch and discarding. Canadian Journal of Fisheries and Aquatic Sciences **51**:2688-2694.

Sanchirico, J. N., and J. E. Wilen. 2001. A bioeconomic model of marine reserve creation. Journal of Environmental Economics and Management **42**:257-276.

Scott, A. 1955. The fishery: the objectives of sole ownership. Journal of Political Economy **63**:116-124.

Sigler, M. F., and C. R. Lunsford. 2001. Effects of individual quotas on catching efficiency and spawning potential in the Alaska sablefish fishery. Canadian Journal of Fisheries and Aquatic Sciences **58**:1300-1312.

Sissenwine, M. P., and P. M. Mace. 1992. ITQs in New Zealand: the era of fixed quota in perpetuity. Fishery Bulletin **90**:147-160.

Skaptadóttir, U. D. 2000. Women coping with change in an Icelandic fishing community: a case study. Women's Studies International Forum **23**:311-321.

Smith, M. D. 2002. Two econometric approaches for predicting the spatial behavior of renewable resource harvesters. Land Economics **78**:522-538.

Squires, D., H. Campbell, S. Cunningham, C. Dewees, R. Q. Grafton, S. F. J. Herrick, J. Kirkley, S. Pascoe, K. Salvanes, B. Shallard, B. Turris, and N. Vestergaard. 1998. Individual transferable quotas in multispecies fisheries. Marine Policy **22**:135-159.

Squires, D., and J. Kirkley. 1991. Production quota in multiproduct Pacific fisheries. Journal of Environmental Economics and Management **21**:109-126.

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

Squires, D., and J. Kirkley. 1996. Individual transferable quotas in a multiproduct common property industry. Canadian Journal of Economics **29**:318-342.

Squires, D., J. Kirkley, and C. A. Tisdell. 1995. Individual Transferable Quotas as a fisheries management tool. Reviews in Fisheries Science **3**:141-169.

Starr, P. J., J. H. Annala, and R. Hilborn. 1998. Contested stock assessments: two case studies. Canadian Journal of Fisheries and Aquatic Sciences **55**:529-537.

Stewart, J. M., and P. D. Callagher. 2003. New Zealand fisheries management: changes in property rights structure and implications for sustainability. Sustainable Development **11**:69-76.

Swain, D. P., and E. J. Wade. 2003. Spatial distribution of catch and effort in a fishery for snow crab (*Chionoectes opilio*): tests of predictions of the ideal free distribution. Canadian Journal of Fisheries and Aquatic Sciences **60**:897-909.

Turner, M. A. 1997. Quota-induced discarding in heterogeneous fisheries. Journal of Environmental Economics and Management **33**:186-195.

Turris, B. R. 2000. A comparison of British Columbia's ITQ fisheries for groundfish trawl and sablefish: similar results from programmes with differing objectives, designs and processes. Pages 254-261 *in* R. Shotton, editor. Use of Property Rights in Fisheries Management. FAO Fisheries Technical Paper 404/1. FishRights 99 Conference. FAO, Fremantle, Western Australia.

Venables, W. N., and B. D. Ripley. 1999. Modern Applied Statistics with S-PLUS, 3rd edition. Springer, New York.

Vestergaard, N. 1996. Discard behavior, high-grading and regulation: the case of the Greenland shrimp fishery. Marine Resource Economics **11**:247-266.

Vignaux, M. 1996. Analysis of spatial structure in fish distribution using commercial catch and effort data from the New Zealand hoki fishery. Canadian Journal of Fisheries and Aquatic Sciences **53**:963-973.

Vignaux, M., G. A. Vignaux, S. Lizamore, and D. Gresham. 1998. Fine-scale mapping of fish distribution from commercial catch and effort data using maximum entropy tomography. Canadian Journal of Fisheries and Aquatic Sciences **55**:1220-1227.

Waitt, G., and K. Hartig. 2000. Ecologically sustainable fishing in theory and practice: individual transferable quotas in Australia's South East fishery. Australian Geographer **31**:87-114.

Walters, C., and P. H. Pearse. 1996. Stock information requirements for quota management systems in commercial fisheries. Reviews in Fish Biology and Fisheries **6**:21-42.

Walters, C. J., and R. Bonfil. 1999. Multispecies spatial assessment models for the British Columbia groundfish trawl fishery. Canadian Journal of Fisheries and Aquatic Sciences **56**:601-628.

Watling, L., and E. A. Norse. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conservation Biology **12**:1180-1197.

Weitzman, M. L. 2002. Landing fees vs. harvest quotas with uncertain fish stocks. Journal of Environmental Economics and Management **43**:325-338.

Weninger, Q., and J. R. Waters. 2003. Economic benefits of management reform in the northern Gulf of Mexico reef fish fishery. Journal of Environmental Economics and Management **46**:207-230.

Wertheimer, A. C., and D. Swanson. 2000. The use of individual fishing quotas in the United States EEZ. Pages 127-136 *in* R. Shotton, editor. Use of property rights in fisheries management, FishRights99 conference. Rome, FAO, Fremantle, Western Australia.

Wingard, J. D. 2000. Community transferable quotas: internalizing externalities and minimizing social impacts of fisheries management. Human Organization **59**:48-57.

Yandle, T. 2003. The challenge of building successful stakeholder organizations: New Zealand’s experience in developing a fisheries co-management regime. Marine Policy **27**:179-192.

Young, M. D. 1999. The design of fishing-right systems—the NSW experience. Ecological Economics **31**:305-316.

Zar, J. H. 1996. Biostatistical analysis, 3rd edition. Prentice Hall International, London.

Zimmerman, M. 2003. Calculation of untrawlable areas within the boundaries of a bottom trawl survey. Canadian Journal of Fisheries and Aquatic Sciences **60**:657-669.

# APPENDIX A

## COMMON AND SCIENTIFIC NAMES OF SPECIES

Throughout the dissertation common names are used, and their scientific names are relegated to this appendix. The country the species occurs in is indicated in brackets after the common name for all species that do not occur in either the U.S. or in Canada.

| Common name | Species name |
|---|---|
| Arrowtooth flounder | *Atheresthes stomias* |
| Atlantic sea scallop | *Placopecten magellanicus* |
| Big skate | *Raja binoculata* |
| Black oreo dory (New Zealand) | *Allocyttus niger* |
| Bocaccio | *Sebastes paucispinis* |
| California halibut | *Paralichthys californicus* |
| Canary rockfish | *Sebastes pinniger* |
| Chilean sea bass = black hake | *Dissostichus eleginoides* |
| China rockfish | *Sebastes nebulosus* |
| Copper rockfish | *Sebastes caurinus* |
| Cowcod | *Sebastes levis* |
| Darkblotched rockfish | *Sebastes crameri* |
| Dover sole | *Microstomus pacificus* |
| English sole = lemon sole | *Parophrys* (*Pleuronectes*) *vetulus* |
| Flathead sole | *Hippoglossoides elassodon* |
| Geoduck | *Panopea abrupta* |
| Greenstriped rockfish | *Sebastes elongates* |
| Haddock (Iceland) | *Melanogrammus aeglefinus* |
| Herring (Iceland) | *Clupea harengus* |
| Hoki (New Zealand) | *Macruronus novaezelandiae* |
| Lingcod | *Ophiodon elongates* |
| Loco (Chile) | *Concholepas concholepas* |
| Longnose skate | *Raja rhina* |
| Longspine thornyhead | *Sebastolobus altivelis* |
| Ocean quahog | *Arctica islandica* |
| Orange roughy (New Zealand) | *Hoplostethus atlanticus* |
| Pacific cod | *Gadus macrocephalus* |
| Pacific hake = Pacific whiting | *Merluccius productus* |
| Pacific halibut | *Hippoglossus stenolepis* |
| Pacific ocean perch | *Sebastes alutus* |
| Patagonian scallop (Argentina) | *Zygochlamys patagonica* |
| Paua (New Zealand) | *Haliotis iris* |

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| Common name | Species name |
|---|---|
| Petrale sole | *Eopsetta jordani* |
| Quillback rockfish | *Sebastes maliger* |
| Red rock lobster (New Zealand) | *Jasus edwardsii* |
| Redbanded rockfish | *Sebastes babcocki* |
| Redstripe rockfish | *Sebastes proriger* |
| Rex sole | *Errex zachirus* |
| Rock sole | *Lepidopsetta bilineatus* |
| Rougheye rockfish | *Sebastes aleutianus* |
| Sablefish | *Anoplopoma fimbria* |
| Sand sole | *Psettichthys melanostictus* |
| Sharpchin rockfish | *Sebastes zacentrus* |
| Shortraker rockfish | *Sebastes borealis* |
| Shortspine thornyhead | *Sebastolobus alascanus* |
| Silvergray rockfish | *Sebastes brevispinis* |
| Silver warehou (New Zealand) | *Seriolella punctata* |
| Smooth oreo dory (New Zealand) | *Pseudocyttus maculatus* |
| Snapper (New Zealand) | *Chrysophrys auratus* |
| Southern bluefin tuna (Australia) | *Thunnus maccoyii* |
| Spiky oreo dory (New Zealand) | *Neocyttus rhomboidalis* |
| Spiny dogfish | *Squalus acanthias* |
| Splitnose rockfish | *Sebastes diploproa* |
| Squat lobster (Chile) | *Cervimunida johni* |
| Surfclam | *Spisula solidissima* |
| Tasmanian rock lobster | *Jasus edwardsii* |
| Tiger rockfish | *Sebastes nigrocinctus* |
| Walleye pollock | *Theragra chalcogramma* |
| Widow rockfish | *Sebastes entomelas* |
| Wreckfish | *Polyprion americanus* |
| Yelloweye rockfish | *Sebastes ruberrimus* |
| Yellowmouth rockfish | *Sebastes reedi* |
| Yellowtail rockfish | *Sebastes flavidus* |

# APPENDIX B

# COMPUTATIONAL ASPECTS OF DEFINING FISHING OPPORTUNITIES

A simple method for defining fishing opportunities is presented in Chapter 3. It is possible to assign trawls to fishing opportunities using just three lines of code from the public software program R (R Development Core Team 2003, available free from www.r-project.org). I assume that an array *X* has been produced which has rows representing individual trawls, and columns containing the start and end latitudes and longitudes in decimal degrees. I assume further that longitudes have already been multiplied by cos(latitude), and the trawls re-oriented to point northwards (these two steps can be conducted in Excel). Given *X*, the following R code will produce a vector *Y* that contains the number of the fishing opportunity that each trawl belongs to, at a cut point of 0.15.

```
distance <- dist(X, method="euclidean")
cluster.tree <- hclust(distance, method="average")
Y <- cutree(cluster.tree, h=0.15)
```

In R there is a limitation on the maximum number of trawls, *n*, that can be clustered ($n \approx 5{,}000$ for computers with 512 Mb RAM). This limitation arises because the Euclidean distances must be calculated between each pair of trawls, thus requiring an intermediate triangular matrix of about $n^2/2$ elements to be kept in memory, i.e., in computer science terminology, the algorithm has $O(n^2)$ memory requirements. In most fisheries, this factor will not limit analyses for single vessels, but can be a problem if the method is applied to the entire fleet. I suggest partitioning the trawls into groups before clustering. Partitioning algorithms exist that have $O(n)$ storage requirements, such as the *K*-means method (Hartigan and Wong 1979). This method was used by He et al. (1997) to partition 46,961 longline sets into groups, before conducting a hierarchical cluster analysis on each of the groups. In R, it took less than 20 seconds to partition the B.C. fishery data (115,060 trawls) into 200 clusters, each containing < 2,500 trawls. The centroids of these partitions can be specified beforehand to divide the fishery into geographic regions.

# VITA

Trevor Branch was born in Cape Town, South Africa, where he has lived for most of his life. All of his previous degrees were obtained from the University of Cape Town: a Bachelor of Science in Computer Science and Zoology (1994) with distinctions in both majors, Bachelor of Science Honours in Zoology (1995), first class, and Master of Science in Conservation Biology (1998) with distinction. He enrolled at the University of Washington in September 2000.

## Publications

Branch, T. A. 2001. A review of orange roughy (*Hoplostethus atlanticus*) fisheries, estimation methods, biology and stock structure. In: *A Decade of Namibian Fisheries Science*. Payne, A. I. L., S. C. Pillar and R. J. M. Crawford (Eds). South African Journal of Marine Science **23**:181-203.

Branch, T. A., and D. S. Butterworth. 2001a. Southern Hemisphere minke whales: standardised abundance estimates from the 1978/79 to 1997/98 IDCR-SOWER surveys. Journal of Cetacean Research and Management **3**:143-174.

Branch, T. A., and D. S. Butterworth. 2001b. Estimates of abundance south of 60ºS for cetacean species sighted frequently on the 1978/79 to 1997/98 IWC/IDCR-SOWER sighting surveys. Journal of Cetacean Research and Management **3**:251-270.

Branch, T. A., R. Hilborn, and E. Bogazzi. (accepted). Escaping the tyranny of the grid: a more realistic way of defining fishing opportunities. Canadian Journal of Fisheries and Aquatic Sciences **00**:000-000.

Branch, T. A., K. Matsuoka, T. Miyashita. 2004. Evidence for increases in Antarctic blue whales based on Bayesian modelling. Marine Mammal Science **20**:726-754.

Hilborn, R., T. A. Branch, B. Ernst, A. Magnusson, C. V. Minte-Vera, M. D. Scheuerell, and J. L. Valero. 2003. State of the world's fisheries. Annual Review of Environment and Resources **28**:359-399.

Minte-Vera, C. V., T. A. Branch, I. J. Stewart, and M. W. Dorn. (accepted). Practical presentation of meta-analysis results: avoiding the double use of data in future applications. Canadian Journal of Fisheries and Aquatic Sciences **00**:000-000.

Pulfrich, A. and T. A. Branch. 2002. Population dynamics and potential yield of three species of giant winkles in the Western Cape, South Africa. South African Journal of Marine Science **24**:161-183.

Spinks A.C., T. A. Branch, S. Croeser, N. C. Bennett, and J. U. M. Jarvis. 1999. Foraging in wild and captive colonies of the common mole-rat *Cryptomys hottentotus hottentotus* (Rodentia: Bathyergidae). Journal of Zoology **249**:143-152.