IS THE NEWFOUNDLAND REDFISH FISHERY SUSTAINABLE? MODELLING RECOVERY STRATEGIES FOR TWO REDFISH STOCKS

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IS THE NEWFOUNDLAND REDFISH FISHERY SUSTAINABLE?

MODELLING RECOVERY STRATEGIES FOR TWO REDFISH STOCKS

by

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ABSTRACT

Marine resources have supported the economy and culture of Newfoundland and Labrador (NL) for over 500 years. Stock abundance has fluctuated in most species due to increased pressure to fulfill new markets, the development of new gear, and survive in a competitive industry. In some cases, declines in resource abundance led to closures or moratoriums. The redfish (*Sebastes* species) fishery in NL has stocks that have remained opened but have experienced declines in total allowable catch (TAC), while others have been closed in hopes of recovery.

This thesis models the recovery strategies of two Newfoundland redfish stocks, Unit 1 (Gulf of St. Lawrence) and Unit 2 (Laurentian Channel), using the Schaefer model. This analysis examines the potential for these stocks to reach biologically sustainable biomass levels under different harvesting levels. Due to the slow growing nature of the *Sebastes* species, recovery is slower than in other groundfish species. Despite this obstacle, and other opposing factors, neither stock examined for this research has reached a critical point from which recovery is impossible. However, conservation and precaution are key components for the future of this fishery in this region.

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List of Abbreviations

CAFSAC	Canadian Atlantic Fisheries Scientific Advisory Committee
CSAS	Canadian Science Advisory Secretariat
DFO	Department of Fisheries and Oceans
EEZ	Exclusive Economic Zone
FAO	Food and Agriculture Organization
FRCC	Fisheries Resource Conservation Council
MSY	Maximum Sustainable Yield
NAFO	Northwest Atlantic Fisheries Organization
TAC	Total Allowable Catch
YPR	Yield Per Recruit

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Chapter 1: Introduction

1.1 Introduction to the Study

The management of fisheries stocks is a dynamic endeavour, with necessity to consider biological, social, and economic consequences. Establishing appropriate methods for each species or stock is not easy, but combining a variety of management philosophies and modelling approaches can help decrease uncertainties concerning the effects that implementing different assessments may have on the condition of a resource.

Like most fisheries, the redfish (*Sebastes* species) fishery in Newfoundland and Labrador has experienced fluctuations in biomass and landings since it was first targeted in the 1930s. Innovative harvesting, refrigeration, and transportation technologies, in addition to emerging markets, have increased pressure on these resources. Presently, three redfish stocks in the region are closed to commercial exploitation and the majority of the remaining stocks have had total allowable catches (TACs) reduced within the last 20 years. Declines in abundance have obvious effects on industry participants, but the biological and ecological consequences of decreases in diversity of species within ecosystems are more often speculated upon rather than proven. However, policies that include cultural, biological, and economic factors are complex and can define a method that respects a variety of perspectives (DFO 1993).

The purpose of the research described in this thesis is to examine the prospects of redfish exploitation in the context of fisheries diversification in Newfoundland. The focus is on the biological sustainability of continued harvesting of stocks that are in various states of depletion, and the possibility for these stocks to recover from these depleted states. To accomplish this, I will examine the recovery strategies of those redfish stocks in close proximity to Newfoundland using the widely used Schaefer (1954) model. Comparisons will be made between stocks that are already closed due to low biomass estimates and stocks that have remained opened but that are very likely in a depleted state.

The significance of this study is twofold. Firstly, although considerable work has been done on redfish, no previous attempts have yet been made to assess the feasibility or projections of recovery strategies for this species. It needs to be determined whether redfish can be rendered meaningful for fisheries diversification. I raised this issue in my Master of Marine Studies Major Report (Goetting 2008). Secondly, this new research will follow up on some of the strategies recommended in that research, although the economic issues are not considered here as they are the subject of future research. Nonetheless, quantitative biological analysis is a necessary precursor to a full bio-economic analysis. Moreover, a biological analysis is necessary from a policy standpoint to provide guidance as to whether changes in exploitation and management of the resource should be pursued.

1.2 Historical Context

The settlement of Newfoundland and Labrador, Canada's tenth Province, was prompted by the region's abundant marine resources (Lear 1998; Wright 2001; Rose 2007). The fishing industry influenced the formation of cultural, social, and political institutions throughout the Province and has provided significant employment opportunities through harvesting, processing, and management (Hanrahan 1993). Particularly significant was Atlantic cod (*Gadus morhua*), which has fed millions of people in Europe and the Americas over five centuries. While regional stock fluctuations and periodic declines were quite common prior to the twentieth century, the idea that cod stocks throughout Newfoundland could decline to the point of commercial extinction seemed unfathomable given the harvesting technologies of the day. The industrial technologies that would eventually contribute to the collapses of marine resources had not yet been imagined (Wright 2001). Although the lobster, salmon, and seal fisheries in Newfoundland have made significant contributions to the industry, Atlantic cod was harvested in larger numbers than other species in most of Newfoundland and Labrador (Rose 2007) and there was little reason or need to diversify.

Prior to the late 1800s, there was very little change in harvesting methods for cod or most other species. Longlines, unbaited jiggers, and single handlines with bait were the primary fishing gear from the 1500s to the mid-1800s (Rose 2007). Towards the end of the 19th century, the cod trap was developed. With this new invention came controversy, mostly concerning the connection between the cod trap and fisheries declines. Despite the concerns, the cod trap remained the dominant harvesting gear used in Newfoundland fisheries in the late 1800s to the early 1900s (DFO 1956; Rose 2007). Eventually gas powered engines came along, and emerging advances in refrigeration and land transportation opened up markets for other species during World War II (DFO 1956). Newfoundland saw its first commercial trawler in 1935 (Lear 1998). Naval technologies developed during the war, in combination with the increasing availability of fossil fuels, contributed to the rise of oil powered vessels, including trawlers that were capable of harvesting fish at much higher rates than ever before (White 1954; DFO 1956; Wright 2001).

Species that had been previously discarded or underutilized, such as redfish, were exploited at higher rates with the genesis of a new generation of vessels. In addition, due to more advanced harvesting and transportation technology, species like Atlantic cod were exploited much more efficiently and by more people at rates never seen before. Some harvesters, both commercial and subsistence inshore fishers, argued that the large trawlers would reduce the number of people employed in the fishery and negatively affect the migratory stocks, although no real action was taken to address these concerns (Wright 2001).

Observers noticed declines and fluctuations in the cod fishery and raised concern about the situation as early as the late 1800s. By the 1940s and 1950s, groundfish stocks, including cod, were considered abundant, decreasing many previous anxieties concerning the state and future of these fisheries. These profusions of stocks were catalysts for the expanding international fleet presence in the Newfoundland area (Rose 2007). When Newfoundland and Labrador confederated with Canada in 1949, apprehensions arose regarding the impacts that foreign fishing would have on the cod stocks in waters around Newfoundland. In 1977, the declaration of the 200 mile exclusive economic zone (EEZ) extended Canada's rights over exploiting and discovering marine resources in the region (Grafton et al. 2000). Many felt that foreign overfishing prior to 1977 significantly affected the status of cod stocks and there was hope that the EEZ would now help regulate the situation (Lear and Parsons 1993; Rose 2007).

Unfortunately it seems that damage done prior to 1977, and possibly even before confederation, had impacted the stocks more than was initially understood. Groundfish species in the northwest Atlantic had sustained exhaustive exploitation for centuries. Although there were declines and recoveries throughout this time, the situation never seemed to reach a state severe enough to warrant drastic action. Between the 1950s and 1992, many commercial fisheries, including grenadier, haddock, American plaice, and northwest Atlantic redfish stocks (*Sebastes* sp.) began to show alarming declines (Rose 2007). Appeals to re-evaluate and assess the situation were largely ignored and little changed until 1992, when John Crosbie, the Minister of Fisheries at the time, announced a two year moratorium for the northwest Atlantic cod stocks.

With the collapse of the cod stocks, much attention turned to targeting other species and finding ways to manage stocks sustainably. Fishers, politicians, and other interested parties searched for alternatives and inventive ways to move forward (DFO 1993). A popular and seemingly practical solution involved harvesting other species to enable people to continue fishing while providing time for the cod stocks to replenish. This was a goal most thought would be achieved in a few years; few realized the severity of the problem (Lear and Parsons 1993).

Many new species were targeted in an attempt to lessen the consequences of the cod collapse on incomes and livelihoods. A suitable species for diversification would meet a variety of needs and conditions. To start, exploiting a species that is harvested and processed in a similar manner to cod, with comparable gear and harvesting techniques, would eliminate costs associated with new equipment. Additionally, remaining in the same genre of fish species (i.e. groundfish) could prevent conflicts in the licensing of vessels. It was also important to select a species that can provide a reasonable livelihood for fishers. Finally, choosing a species whose life history is clearly understood, and healthy enough to survive increased exploitation, are two of the most important factors in fisheries diversification. In order to determine redfish potential for diversification and increased exploitation, it is important to understand how the fishery evolved over the years and what the motivations were for targeting it in the first place.

The redfish fishery in the northwest Atlantic began in the Gulf of Maine in the 1930s, and was mostly driven in the beginning by the need to replace collapsed stocks, rather than demand or new markets (White 1954; Kelly et al. 1972). Originally caught as bycatch and subsequently discarded due to lack of markets, increased exploitation and targeting of the species occurred when there was an increase in demand for frozen fish from the United

States (Kelly et al. 1972; Dawe 1976). Yellow perch from the Great Lakes region were the staple of the frozen fish industry and the landed amounts from those fisheries began to decline. Redfish were found to be comparable to yellow perch in freezing ability. Increased demand, decline of the yellow perch, advancements in packaging, refrigeration, and transportation technologies, and the discovery of new stocks throughout the northwest Atlantic all helped expand the fishery with little promotional effort from the industry (White 1954; Sandeman 1973). By 1956, Newfoundland had captured nearly 50 percent of the burgeoning frozen fish markets for fish sticks. Lower quality and lower price fish tends to supply this market and redfish meets both of these criteria (Rose 2007). Redfish were often sold as ocean perch (Kelly et al. 1972), but as markets elsewhere grew, demand in Atlantic Canada remained low, primarily because of the perception of the species as a 'poor man's meal' (Dawe 1976). Local markets for redfish have never fully developed and the primary redfish markets for Canadian harvesters are in the United States, Europe, and Asia (Kelly et al. 1972).

The first noteworthy amounts of redfish were not landed until 1953 (Sandeman 1973). The Canadian redfish fishery peaked in 1959, with total landings reaching almost 400,000 metric tonnes. By 1975, landings had decreased to 103,000 metric tonnes, and further declined to 82,000 metric tonnes by 1979 (McKone and LeGrow 1990). In the 1970s, calls for conservation were made regarding the Gulf of St. Lawrence redfish stocks (Fisheries and Environment Canada 1977), which supplied most of Canada's redfish at this time (Sandeman 1973). This redfish stock showed a biomass resurgence in the early 1990s, which led to high catches (FRCC 2003) and possibly contributed to a false sense of security that did little to consider conservation measures. If anything, actions should have been more attentive to the concerns voiced in the 1970s. Instead, there was a steady decrease following this peak and the stock was closed in 1995 (FRCC 2003).

Redfish have few of the characteristics that would make it a successful choice to help ease the burden of the cod collapse. Since redfish are a groundfish species, the same harvesting and processing equipment can be used as is used for cod, making the transition to increased redfish exploitation easier. Despite the areas in which redfish were lacking, they were still considered a promising form of diversification that could add income to struggling households that had relied primarily on one species (cod) for decades. A few years before the cod moratorium was announced, redfish were described as an underutilized species by the Atlantic Fisheries Adjustment Program (DFO 1990). The decision to target redfish more intensively appears to be a rather passive one, with no official pronouncement that redfish would help ease the burden associated with the cod moratorium. For instance, it seems that little research was conducted to ensure that this was a sound management choice. Regardless, redfish landings increased in the years following the closure of cod stocks. In 1995, however, just three years after the cod moratorium was issued, the Unit 1 redfish stock was closed to commercial fishing. It is possible that the increased exploitation of redfish immediately following the cod closures contributed substantially to this closure, suggesting that the choice of redfish to help ease the burden of the cod collapse was not justified.

The rise and fall of Newfoundland redfish stocks occurred within 60 years. Even though redfish suffered declines and closures in the past, recovery of stocks still seemed possible, given the low exploitation rate compared to other commercial stocks. If stocks can rebound, another question arises as to whether the fishery can provide meaningful financial contributions to Newfoundland. To answer this latter question requires analyses beyond the scope of this thesis. This thesis examines the projections made by the Schaefer (1954) model to assess the biological status of two Newfoundland redfish stocks.

1.3 Outline of the thesis

The second chapter of this thesis consists of a literature review. This review offers a full description of the species, including biology, distribution, habitat, and life history characteristics. In addition to the biological aspects of the species, information on the redfish stocks and the fishery as a whole are presented. Previous studies and research conducted on various aspects of redfish and the commercial fishery are offered, as well. It is the intention that the inclusion of different aspects of the redfish fishery in the analysis will help the reader understand the past and present states of the fishery, and the significance of this research.

Chapter 3 discusses what is meant by sustainability for the purpose of this research and explains the motives and guidelines for a precautionary approach to management, which appears to be an appropriate management scheme for this fishery. The purpose of this chapter is to introduce the reader to information that will be used after the model projections are performed.

The methodology used for this research is described in Chapter 4. The Schaefer (1954) model is explained and the equations used to carry out the model are outlined. Furthermore, I discuss how I estimated the parameters and data inputs necessary for the model.

Chapter 5 shows all of the results of the model under different scenarios. In order to address the uncertainties of the biological parameter estimations for redfish, a sensitivity analysis is included in Chapter 5. Additionally, implications surrounding the stock definitions revised in 1993 are discussed to clarify any inconsistencies and confusions found in research documents prior to that year.

The final chapter, Chapter 6, summarizes what has been learned from the model and discusses appropriate actions for two commercial redfish stocks in Newfoundland. It draws on information from all previous chapters to present conclusions and offer suggestions for future research.

Chapter 2: Review of Literature

2.1 Description of species

2.1.1 Species identification, distribution, and habitat

Fish from the *Sebastes* genus are found in both the Atlantic and Pacific Oceans. In the Atlantic, *Sebastes* species are commonly called redfish or ocean perch; in the Pacific, they are generally referred to as rockfish. Redfish harvested by Canada in the northwest Atlantic are primarily comprised of three species (Scott and Scott 1988): *Sebastes marinus* (Linnaeus 1758), *Sebastes fasciatus* (Storer 1854), and *Sebastes mentella* (Travin 1951). Unlike most other fisheries resources, redfish are managed by stocks instead of by species (DFO 1997) because of the difficulty in distinguishing between redfish species (Ni 1981 and 1984). Other groundfish stocks, like cod, are comprised of one species. In these cases, differences in life history would not be so severe, meaning that cod on the Grand Banks and cod in the Gulf of St. Lawrence are, for all intents and purposes, the same species, and any differences in growth would be attributable to water temperature or other environmental factors, rather than differences in inherent growth rates. For redfish, slight differences in growth rates and age of sexual maturity between different species are common. It is common for one redfish stock to be dominated by a particular species (Scott and Scott 1988), making it paramount to identify the composition of each stock and the differences between each species as accurately as possible. Indeed, the better understanding we have regarding the age structure and growth rates of all the species that are included in one stock, the more appropriate the management policies can be. Incorrect estimates of age, growth, and mortality of redfish can lead to acute declines in stock abundance caused by over exploitation (Saborido-Rey et al. 2004).

Redfish distribution is broad in the northwest Atlantic, ranging from the Gulf of Maine to the Davis Strait (Atkinson and Bowering 1987). Redfish are currently managed under nine management areas in the northwest Atlantic (DFO 2008) but there are six primary stocks that are or have been harvested and processed in Newfoundland and Labrador since the inception of the fishery in the 1930s: Unit 1 [Gulf of St. Lawrence], Unit 2 [Laurentian Channel], Unit 3 [Scotian Shelf], 3O [Grand Bank], Division 2+3K [Hamilton Bank], and 3M [Flemish Cap] (Figure 1).

Although the three redfish species are very similar, there are slight differences in range amongst species. For instance, *S. mentella* tend to inhabit deeper waters and be farther offshore and farther north than the other two species. In contrast, *S. fasciatus* dominates shallower water and is found in more southern regions than the other two (Scott and Scott 1988; Gascon 2003). Redfish, overall, are a deep water species, occurring at depths ranging from 100 to 750 meters (Scott and Scott 1988; Morin et al. 2004), with specimens being caught as deep as 1100 meters (Scott and Scott 1988). Although redfish typically dwell in deep waters, they do make diel vertical migrations at night, moving off the bottom of the ocean floor in search of food. This characteristic affects the strategies of commercial fish harvesters and researchers alike (Atkinson 1989; Morin et al. 2004).

2.1.2 Life history characteristics

Despite being classified as a groundfish species, redfish have a significantly different life history from most other groundfish species in the northwest Atlantic. Redfish are a long-lived, slow-growing, and late-maturing species (Scott and Scott 1988; Morin et al. 2004) with an average age of approximately 40 years (McKone and LeGrow 1990), but specimens 75

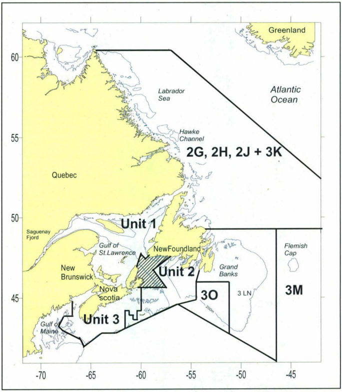

Figure 1. Map of six redfish management units in the northwest Atlantic: Unit 1; Unit 2; Unit 3; 3O; 3M; and Division 2+3K.

Source: NAFO. Adapted by the author.

years old have been found (Campana et al. 1990; Morin et al. 2004). Fertilization in redfish is internal and they give birth to live young (Scott and Scott 1988; Morin et al. 2004). The three redfish species in the northwest Atlantic differ slightly regarding larval development and spawning (Templeman 1980; Ni and Templeman 1985; Sévigny et al. 2000), but mating generally occurs in the fall months, with females carrying the embryos until the spring, and hatching occurring from late spring to early summer (Morin et al. 2004). In addition, redfish are less fecund than a species that releases eggs instead of larvae. Only 15,000 to 20,000 live young are born from approximately 50,000 fertilized eggs (Kelly et al. 1972).

As previously mentioned, the growth and maturity of redfish is a slow process. Each of the species has slightly different growth rates, with some differences in age and length at maturity. Generally, *S. fasciatus* mature 1-2 years earlier than *S. mentella*. Growth is typically faster in southern areas than northern areas and most differences in growth rates amongst species are obvious only after age 10. Males grow slower than females until approximately age 10, and males mature earlier (1-2 years) and at a smaller size (3-5 cm) than do females (Branton et al. 2003). On average, redfish are approximately 10 years old when they reach minimum harvestable size of 22 cm (DFO 2008). This characteristic can have important implications on recovery and management strategies, as will be discussed in detail below.

Recruitment of harvestable and mature redfish is essential to the sustainability of the commercial fishery. Recruitment levels in redfish vary significantly. Many redfish stocks have not experienced strong recruitment classes in decades, which has seriously compromised the sustainability of this resource. This has obvious implications for the commercial fishing industry. The Unit 1 redfish fishery experienced a strong 2003 year class. However, this group of fish had disappeared from the area by 2008 (DFO 2008), contributing virtually nothing to the depleted stock.

2.2 Spatial distribution

As previously mentioned, redfish are managed by stocks in various regions. Many redfish management units were redefined in 1993 to account for seasonal migrations. Unit 1 (see Figure 1) identifies redfish in the Gulf of St. Lawrence. Prior to 1993, the Unit 1 stock was managed as NAFO (Northwest Atlantic Fisheries Organization) Division 4RST. However, after examining the data, it was recommended that this management unit include the winter migration of redfish into the Cabot Strait area (Morin et al. 1995). Similar modifications were made to the Unit 2 (Laurentian Channel) redfish stock, which was once managed as two separate stocks (Power 1995). Likewise for Unit 3 (Scotian Shelf), which was previously contained in a much larger management unit (Branton 1996). The remaining primary redfish stocks fished from Newfoundland and Labrador are managed by NAFO. These include 3O (Grand Bank), 3M (Flemish Cap) and Division 2+3K (Hamilton Bank). These three stocks are under more intense exploitation by non-Canadian vessels in international waters than Units 1, 2, and 3.

The Unit 1 redfish stock was closed to commercial fishing in 1995. Prior to the closure, commercial catches were mostly comprised of fish from the early 1970s and the 1980 year classes and *S. mentella* was the dominant species in these catches (Morin et al. 2001). The 1988 year class for this stock was identified as *S. fasciatus*; however, this year class disappeared, creating concerns about the contribution of year classes from 1996, 1998, and 1999, since these were also composed primarily of *S. fasciatus*. In addition, the 2003 year class that disappeared from the area by 2008 was also found to belong to *S. fasciatus* (DFO 2008). *S. mentella* and *S. fasciatus* together make up the Unit 1 redfish stock. Although certain year classes may contain more of one species, it is believed that *S. mentella* numerically dominate this stock (Sandeman 1969; Ni 1984; Ni and Sandeman 1984; St. Pierre and de Lafontaine 1995). On-going analysis of historical samples (from the 1950s and 1960s) by the Department of Fisheries and Oceans (DFO) will attempt to determine the initial species composition of these stocks[1].

The species composition of redfish in Unit 2 is believed to contain all three species previously mentioned, although this stock is also considered to be dominated by *S. mentella*. However, there was an increase of *S. fasciatus* caught in the fishery in 2001, indicating a potential, but perhaps short-lived, increase of the available biomass resource (DFO 2004a).

The level of mixing between Units 1 and 2 has been a cause of concern over the years; it is uncertain how much mixing has been occurring. In addition, a hybrid of the two species has been found in both of these units (DFO 2004b). It has been recommended that these units be re-examined. Management strategies that assess and regulate the redfish stocks based on species rather than regions may be more appropriate than the current methods (DFO 2008).

Unit 3 redfish does not have the same uncertainty issues as Units 1 and 2 and there is not as much concern regarding migrations and mixing with other nearby stocks. It is believed that Unit 3 redfish on the Scotian Shelf are almost exclusively *S. fasciatus*. Furthermore, this species is a separate stock from the *S. fasciatus* found in Units 1 and 2 (FRCC 2003).

For this research, Units 1 and 2 will be examined and analyzed for potential recovery strategies. These two stocks were chosen for a variety of reasons. To begin, this research was designed to focus on stocks that are in close proximity to the province of Newfoundland and Labrador. Secondly, comparing two stocks that differ in commercial

[1] Dr. Martin Castonguay, Department of Fisheries and Oceans, Quebec. Personal communication. 30 March 2009.

harvesting status (i.e. open to commercial fishing and under moratorium) will likely shed light on challenges associated with facilitating the recovery of the species, even under moratorium conditions, and suggest some possible pre-emptive actions that might have helped to avoid collapse. Furthermore, the relationship between these two stocks has been studied intensely and suggestions have been made regarding the management structure of Units 1 and 2 that go beyond the merging of the two stocks. It has been proposed that these two redfish stocks would benefit by being managed as separate species rather than by area. This could be beneficial due to the variety of differences in biology, distribution, and population structure of the individual species (i.e. *S. mentella* and *S. fasciatus*) that comprise both Units 1 and 2 (DFO 2008). New research has shown that redfish from Unit 1 are moving into the Laurentian Channel during the winter and mixing more extensively with Unit 2 redfish than first believed. This could mean that Unit 1 redfish is fished as part of the Unit 2 quota, contributing to the slow recovery of the Unit 1 stock (Campana et al. 2007). Since these two stocks share a management area for part of the year, mixing and migrating between the areas could greatly affect recovery of the Unit 1 stock and the overall stock conditions in Unit 2. For this reason, it seems logical to assess them conjunctively rather than as two stocks that have little or no influence on each other.

2.3 Stock status, harvesting, and TACs

Redfish were caught and subsequently discarded in other groundfish fisheries before they became a target species in the 1930s. Since the 1950s, they have been caught almost exclusively by bottom trawlers. Initially, because redfish were known to be a deep water species, trawler nets were used to harvest them during the daytime. As noted above, it has since been discovered that redfish make diel[2] vertical migrations, meaning that they rise off the ocean floor at night in search of food (Pikanowski et al. 1999). This discovery allowed harvesters to target redfish 24 hours a day, using mid-water trawlers (Kelly et al. 1972; Dawe 1976). The use of mid-water trawlers excluded smaller vessels from fishing for redfish as intensely since it was not economically feasible or physically possible for these vessels to safely accommodate the required type of gear (Hearn 1993).

Another issue regarding gear and harvesting in the redfish fishery concerned cod bycatch. In 1993, the DFO conducted research to study and address the cod bycatch problem in the redfish fishery. A primary objective at this time was the rebuilding of cod stocks. Cod bycatch in other fisheries, even in minimal amounts, posed an additional challenge in what was already an uphill battle. To help avoid and minimize cod in redfish nets, semi-pelagic trawling was suggested at times when cod were known to be present in large numbers. To avoid the costs of purchasing an entire mid-water trawling system, harvesters were still permitted to fish for redfish just off the ocean floor using bottom trawling gear already outfitted on the boat. In addition, the use of a net monitor could further reduce the juvenile cod bycatch problem while still allowing for high levels of redfish to be harvested (Hearn 1993).

A primary component of the management scheme for redfish in the northwest Atlantic is the total allowable catch. A variety of factors are analyzed in determining a TAC, including, but not limited to, previous catch rates, life history characteristics, and biomass estimates. TACs are just one component of fisheries management that aid in establishing exploitation levels for a prolonged period of time. But they are not a guaranteed route to sustainability. This is evident from analyzing the TACs set for various redfish stocks.

[2] Alternatively, the term diurnal is used in literature to describe the same behaviour.

The Unit 1 (Gulf of St. Lawrence) redfish stock supplied the bulk of Canada's redfish in the 1970s (Sandeman 1973) and redfish were historically the most abundant species in this area, at least in the northern Gulf of St. Lawrence (see footnote 1). Nevertheless, by 1977, the redfish biomass in this region was believed to be only one fifth of what it was in 1970 (Fisheries and Environment Canada 1977). After this significant decline and predicted low recruitment, calls for conservation were made, yet once again little action was taken. This was perhaps due to a harvesting peak in the early 1990s (FRCC 2003), which may have caused participants and managers to become complacent and overly confident that the problem was not significant. The catch in 1992 for Unit 1 redfish was recorded as 77,400 tonnes, more than double what was caught in the same area in 1985 (FRCC 2003). However, shortly thereafter, in 1995, a moratorium was issued for the Unit 1 stock. The primary cause of the collapse of this stock is believed to be declines in the adult population caused by overfishing (Morin et al. 2004). Pressure from the targeted fishery (Fisheries and Environment Canada 1977), declines in small, immature redfish due to bycatch incidents in the shrimp fishery (Fisheries and Environment Canada 1977; Morin et al. 2004), predation, and natural mortality due to changing environmental conditions (Gascon 2003) all contributed to the decrease in biomass and the resulting moratorium. Yet, it seems clear that management procedures are likely partially to blame for the present state of Unit 1 redfish. Figure 2 shows the TAC levels and landed amounts for Unit 1 redfish for an eighteen year period (1985 – 2002). From 1985 to 1989, landed amounts fell below what was deemed suitable for removal, by substantial amounts in some cases (20,000 metric tonnes in 1986) to small amounts in others (2,000 metric tonnes in 1989). After 1987, landed amounts began to rise and even exceeded TAC levels three years in a row (1990 – 1992). In the two years prior to the Unit 1 closure, both TACs and landed amounts dropped drastically, raising questions

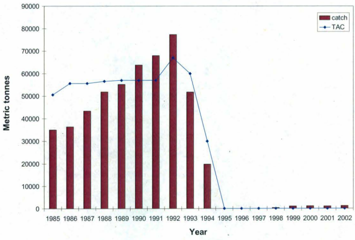

Figure 2. TAC levels and landed amounts of Unit 1 (Gulf of St. Lawrence) redfish from 1985 to 2002.

Source: Data compiled by author, from FRCC (2003).

about inaction and inadequate policy that most likely contributed to the acute decline. The Unit 1 stock has remained closed for the past 14 years and it is now widely believed that the fish were virtually gone by the time the moratorium was issued (see footnote 1). A 2,000 tonne index fishery quota has been in place for Unit 1 since 1995, but this amount is rarely caught in its entirety.

The Unit 2 (Laurentian Channel) redfish stock has remained open to commercial fishing, but it has not been immune to management problems, poor recruitment, and overfishing. The TAC for this stock has decreased by 20,000 metric tonnes in ten years (Figure 3). In 1990, 1991, and 1999, the landed amounts of redfish in Unit 2 exceeded the TAC levels by approximately 5,000 metric tonnes in each year (FRCC 2003). These may not seem significant but when the TAC is only 10,000 to 15,000 metric tonnes, removing one third to one half more than what is recommended can have serious consequences. This is a factor that needs to be considered when adjusting TAC levels from year to year. Fortunately, the Unit 2 stock has been managed at a relatively low exploitation level of 8,000 tonnes since 2000 (FRCC 2003).

The current state of these stocks was not caused solely by overfishing the TAC. However, many contributing factors are related to management and the effects of decisions on the TAC level. For instance, setting TAC levels that considered the unknowns surrounding life history may have been a more appropriate method. In addition, the science behind the TACs must be as accurate and up-to-date as possible. Finally, enforcement of TAC levels is crucial to their effectiveness. After all, setting a limit is of no use if that limit is continuously ignored at no consequence.

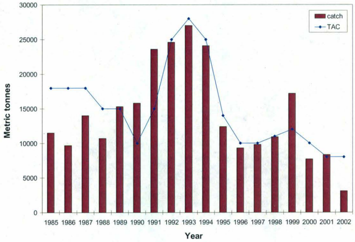

Figure 3. TAC levels and landed amounts for Unit 2 (Laurentian Channel) redfish from 1985 to 2002.

Source: Data complied by author, from FRCC (2003).

2.4 Previous studies

A great deal of research has been conducted on various aspects of the redfish fishery since the 1980s. Initially, finding ways to harvest redfish more efficiently and developing methods through which to increase the market for the species were sought (O'Leary et al. 1985; O'Leary and Clarke 1987; Fisheries Diversification Program 2001). Although these studies can help the fishery in economic terms, they contribute little to understanding the prerequisites for sustainability and appropriate management of the species. Examining the fishery from a biological perspective can contribute to the development of more appropriate policies and exploitation regulations with stable economic contributions, if the information is utilized and considered properly.

One document of particular interest is Morin et al. (2004). This compilation of data analyzes redfish from a species-at-risk viewpoint. The authors review the structure, abundance, and distribution of redfish in order to: determine a suitable level of exploitation; predict recovery potential for closed stocks; and suggest conservation protocols to aid in the protection of redfish stocks in Atlantic Canada. General biological information regarding life history characteristics, habitat preferences, and reproduction is offered in addition to descriptions of seven different redfish stocks of the northwest Atlantic. Morin et al (2004) also discuss the level of decline, whether the decline has ceased or is reversible, and probable time scales for recovery. An update was also released on the work by Sévigny et al. (2008) on the same aspects.

In 2007, Ávila de Melo et al. provided an ASPIC[3] based (Prager 1994) assessment of redfish in NAFO Divisions 3LN. Their research presents catch and effort data, and length and weight data collected from research surveys and commercial fishery sampling. The

[3] The computer program ASPIC is often used to fit Schaefer's (1954) surplus production model.

ASPIC analysis projects a variety of parameters for this particular stock, including intrinsic growth rate, carrying capacity, maximum sustainable yield (MSY), and biomass estimates. Exploitation levels and management protocols are set according to these values, stressing the importance of accurate data and projections. Although the stock analyzed by Ávila de Melo et al. (2007) is not the same as the stocks being analyzed for this thesis, it emphasizes the importance of determining these parameters for as many redfish stocks as possible if we are to find the most appropriate conservation policies possible.

In 2003, the Fisheries Resource Conservation Council (FRCC) released a document stating the conservation requirements for a variety of redfish stocks in the waters around Newfoundland, in addition to other groundfish stocks on the Scotian Shelf, the Bay of Fundy, and in Newfoundland waters. This report offers advice on these stocks based on the most recent scientific evidence from the Department of Fisheries and Oceans at that time, and examines five redfish stocks in this region, including Unit 1 and Unit 2. Some characteristics found in this description include the overall condition of the stock, qualitative assessments of the spawning biomass and total biomass, distribution, recent exploitation levels, and TACs and landed amounts, when applicable, from 1985 to 2002. The FRCC, as a Conservation Council, is mandated to offer advice rooted in sustainability, conservation, and recovery.

Further recent advice on redfish in Units 1 and 2 was published in a DFO Canadian Science Advisory Secretariat (CSAS) Science Advisory Report in 2008. This report discusses the stock definition of redfish (*Sebastes fasciatus* and *S. mentella*) in Unit 1 and Unit 2, and offers advice based on two primary data sources: otolith elemental fingerprints and microsatellite DNA markers. Discovering more information on the species composition of these stocks is paramount to evaluating the best exploitation and recovery strategies of the stock. The CSAS paper provides useful recommendations and models for further studies and discussions.

The primary data for the CSAS paper is provided by Campana et al. (2007). This document outlines studies conducted to track the seasonal migrations of redfish in and around the Gulf of St. Lawrence (i.e. Unit 1 and Unit 2) in order to aid the management of redfish, as well as to contribute to research and discussion about the migrations of deep water species.

Finally, prior to the new stock definitions for Units 1, 2, and 3 that were implemented in 1993, reports and papers were published to discuss the need for new definitions and boundaries in these areas (Atkinson and Power 1991; Power 1992). These publications are helpful in understanding the changes being made to redfish management at the time. They show that managers and policy makers were continuously searching for information on the migration and distribution of redfish to ensure the most appropriate management unit delineations.

The thorough review of the literature that I have undertaken for this thesis suggests that these stocks have not been ignored, and that attempts are made to better understand the species in order to implement appropriate management protocols. Despite all this research, however, recovery strategies for Unit 1 and Unit 2 redfish such as those proposed in this thesis have not been previously examined.

Chapter 3: Sustainability and the Precautionary Approach

3.1 Sustainability

The question posed in this research concerns the biological sustainability and recovery potential of the redfish fishery in Newfoundland and Labrador. The model is used to estimate the status of the stocks given initial parameters (intrinsic growth rate and carrying capacity) when subjected to a variety of harvesting scenarios. Through the output from the model, more informed predictions can hopefully be made about the sustainability and recovery potentials for redfish in this region.

In order to examine the sustainability of a fisheries resource, there are a variety of aspects within sustainability itself that must be considered. Biological sustainability speaks for the exploited species and its purpose is to avoid depletion to the point of irreparable harm or extinction. This point of view is not concerned with human gains. Economic sustainability is measured by yield per unit effort, and considers economic contributions, while social sustainability involves the cultural and shared aspect of being a member of a certain industry. The latter notion brings along with it a sense of community, with both positive and negative consequences. Sometimes it manifests itself as competition, while other times it can allow for collaborations and help from other members in the same industry. Others have argued that sustainability of fish stocks can not be examined without also considering the sustainability of fishing communities (Ommer 1995). Often social and economic factors are considered as part of one (socio-economic) complex. All of these types of sustainability are measured in a certain time period, and must be reanalyzed on a regular basis. For instance, what is sustainable this year, under given circumstances (i.e. biological, economical or social), can change next year for a variety of reasons. For the purpose of this research, sustainability will encompass biological features, and aspects that will remain relevant to any socio-economic analysis. That is, biological sustainability is a necessary but not a sufficient condition for socio-economic analysis.

Since the cod moratorium was implemented in 1993, the actions of DFO were influenced by the need "to create an Atlantic groundfish fishery that is ecologically and commercially sustainable" (DFO 1993). Identifying conservation-minded exploitation is difficult for a lot of reasons. To begin, even with all the different models that can be used to predict responses to exploitation, the reality is that they produce estimates only. Nothing can remove uncertainties. Estimating biological parameters is difficult, potentially delaying management actions as estimates are improved (Mace and Reynolds 2001). Secondly, the type of management plan designed for a particular resource will vary depending on the objectives/motivation. For example, political pressures can greatly affect policy and usually only consider the next few years (Mace and Reynolds 2001).

In addition to the overall challenges to sustainability, redfish are more vulnerable to overexploitation than other groundfish species, such as cod or haddock. Fish species with shorter life spans (i.e. earlier age of maturity and faster growth rates) can be expected to better handle and sustain populations under higher harvest rates than fish with longer life spans such as redfish (Reynolds et al. 2001). In terms of recovery, evidence indicates that recovery is slower in demersal and late-maturing species (Hutchings and Reynolds 2004), suggesting that compromised stocks, such as the Unit 1 redfish stock, may require long closures. Secondly, the redfish fishery is relatively young compared to many other fisheries in the northwest Atlantic. People have been fishing for cod for over 500 years, adapting harvest levels and harvesting techniques according to new information and understanding of the species in terms of habitat, distribution, and life history traits. Even though the cod fishery in Newfoundland waters collapsed, it took approximately 500 years for this to happen. The Unit 1 redfish stock, on the other hand, has been under moratorium only 60 years after it became a targeted fishery. This is shorter than the lifespan of some redfish.

Another reason that redfish need to be given unique consideration relates to the uncertainties associated with the life history characteristics of the species and the mixing of the different stocks. Because redfish inhabit such deep waters, it is difficult to study them. They also suffer 100% mortality when brought to the surface from these depths (Fisheries Diversification Program 2001), which means that sampling allows for few, if any, retained specimens on which further studies can be conducted. In addition, discards do not get counted in the TAC but have still been removed from the biomass. If these occur in large amounts, it could have significant impacts on the recovery and sustainability of the stock.

Decades passed before many of the characteristics of redfish were discovered, which possibly allowed for harvesting practices that were not sustainable. Harvesting techniques changed when it was learned that redfish make diurnal vertical migrations at night (Pikanowski et al. 1999), but no concern was given to whether or not the stocks could handle increased harvesting because most thought that redfish were similar to other groundfish species, like cod, haddock, and pollock. Yet, from year to year, there is always an element of uncertainty. That is, there is no way to be sure how much of the resource will be harvested compared to the previous year, how much is available to be harvested, and how today's harvesting techniques will affect future harvesting (Charles 1994).

As mentioned above, the different redfish species that comprise the stocks discussed in this research are difficult to distinguish from one another without dissection. This issue gives rise to uncertainties regarding stock dynamics, decreasing the chances that the resource will be managed sustainably (Hilborn et al. 2005). Indeed, continuously studying species to decrease doubts regarding the impacts of exploitation and the environment on mortality and abundance is a prerequisite for responsible management (Frost 1938).

Achieving biological sustainability is clearly not a straightforward endeavour, especially when initial recovery is required. In addition, labelling a fishery as sustainable is not something that will apply in perpetuity. Because the stock needs to be assessed periodically to adapt to any unforeseen changes, so must the guidelines of sustainability. In the case of the Unit 1 and Unit 2 redfish stocks, I will consider the life history parameters and the model projections to determine the potential for conservation and exploitation based on the precautionary approach.

3.2 The Precautionary Approach

A major obstacle to achieving sustainability involves the development and implementation of proper management plans. As previously mentioned, an effective strategy for conservation must consider the best available biological information, as well as the political and social motivations behind the management objectives.

Understanding what sustainability means and the obstacles faced in achieving sustainability allows managers to develop appropriate regulations and policies. A suitable guideline is that the policy be based on the precautionary approach. Gaining momentum in the 1990s, precautionary management encompasses values and standards that render it suitable for regulating the redfish fishery in the northwest Atlantic. This method, as defined by the Food and Agriculture Association (FAO 1995), is based on a variety of principles, many of which make it especially applicable to the redfish fishery. The principle asserts that it is necessary to be cautious when data and information about the species is uncertain, but it is important to continue to develop and implement policies even when information is lacking. This means that the monitoring and collection of data should be ongoing, and management scenarios should be adapted accordingly as new information becomes available. This principle helps define the roles of scientists and managers as it considers both socio-economic conditions and biological aspects (Atkinson 2000).

The precautionary approach is a policy approach rooted in conservation and another factor in sustainable management involves being clear about the overall goals of the conservation. With many people involved for different reasons, discussing the objectives and the methods required to achieve them is necessary to ensure that everyone is aware of others' motivations (Mace and Reynolds 2001). Fisheries management governed by politics will become crisis management if people do not collaborate and discuss issues and concerns. As well, successes need to be presented to see if these approaches can be used in another fishery or in another community that is experiencing obstacles to sustainability.

Many of these guidelines for establishing clear objectives relate to the precautionary approach. In order to determine if regulations are working towards sustainability, monitoring needs to be ongoing. This applies to both the monitoring of the resource (i.e. abundance, distribution, etc.) as well as observing the harvesters (Mace and Reynolds 2001) for changes in effort or gear that may impact the stocks. Furthermore, even though information about redfish biology is lacking, it is imperative to use whatever is available and to constantly be searching for and applying the most current data (Mace and Reynolds 2001). Only in this way can uncertainties and unknowns be incorporated in regulations and policies (Wade 2001).

Clearly, implementation of the precautionary approach needs to take into account whether the fishery is open or closed. For instance, since Unit 1 is currently closed to a targeted fishery, the precautionary approach applies in a different way compared to the Unit 2 stock, which remains open. For Unit 1, the goal is recovery. Recovery in most fish populations rarely occurs rapidly. In fact, most fish populations show little or no change in total biomass up to 15 years after collapse (Hutchings and Reynolds 2004). Thus, it is believed that long-term closures are necessary for the recovery of depleted stocks, especially for long-lived species (Caddy and Seijo 2005). Therefore, despite the closure of the Unit 1 redfish fishery, the monitoring is still required, as is the use of the best biological information available. While the goals of management may vary, a cautious, conservative system is suitable for many fisheries, including both of the stocks examined in this thesis.

Chapter 4: Methodology

4.1 The Model

The approach taken here follows that of Haedrich and Hamilton (2000) who considered paths to the renewal of cod stocks after the 1992 moratorium using the Schaefer (1954) model. It is understood that the Schaefer model represents a rather drastic simplification of the biological growth process and the environment in which the species exist. Nevertheless, the model has been extensively used and shown to yield robust predictions given the assumptions on which it rests. Haedrich and Hamilton's analysis involves a range of policy scenarios, including a total fishing ban, making it appropriate for the redfish fishery as well. A recent paper that uses the Schaefer model in the context of the redfish fishery is Ávila de Melo et al. (2007). Here, they examine redfish in NAFO Divisions 3LN to assess appropriate regulations, but recovery strategies were not considered. These studies are two recent relevant examples of countless studies that validate the use of the surplus production model in assessing different fisheries stocks[4].

This approach uses the Schaefer model, according to which certain parameters for redfish need to be determined. Specifically, an intrinsic growth rate (*r*) and a carrying capacity (*K*) for each unit are needed to estimate impacts of exploitation and rates of recovery. Following Rose (2004), I use the Solver minimization algorithm in Microsoft Excel to estimate these parameters.

Once the parameters have been estimated, the model can be used to simulate population growth under a variety of conditions. The first equation measures population growth rate and is expressed by the following differential equation:

[4] A standard reference to the Schaefer model is found in Haddon 2001.

$$\frac{dB_t}{dt} = rB_t\left(1 - \frac{B_t}{K}\right) \tag{1}$$

where $\frac{dB_t}{dt}$ is the instantaneous growth of biomass; B_t is the biomass in period t; K is the carrying capacity; and r is the intrinsic growth rate. B_t is determined from:

$$B_t = \frac{K}{(1 + \frac{(K - B_o)}{B_o})e^{-rt}} \tag{2}$$

where B_o is the initial biomass.

The biomass that sustains the maximum physical yield is readily obtained from Equation 1 as:

$$B_{msy} = \frac{K}{2} \tag{3}$$

Upon substitution of Equation 3 into Equation 1 we obtain the maximum sustainable yield as:

$$MSY = \frac{rK}{4} \tag{4}$$

The maximum sustainable yield is the maximum amount of biomass that can be removed per period from the stock in a sustainable manner, i.e., without changing the stock level.

4.2 Data and Parameter Estimation

When considering different management strategies, the outcomes of the model are dependent on the data and parameter estimations used. Changes in *r* or *K* values will alter the growth of the population biomass over time under different harvest rates. Ávila de Melo et al. (2007) estimated an *r* value for redfish in NAFO Divisions 3LN between 0.38 and 0.42. Haedrich and Hamilton (2000) estimated an *r* value for cod in the northwest Atlantic of 0.185. Because of the slow growth and long lifespan of redfish, especially compared to cod, Ávila de Melo et al.'s *r* value appears optimistic. After consulting fisheries scientists[5], I determined that an appropriate *r* value for redfish in the waters around Newfoundland and Labrador would range between 0.04 and 0.10. Using the Excel Solver minimization algorithm yielded an *r* value of 0.05.

To obtain a starting biomass required for the minimization algorithm, I examined catch and survey biomass data for each Unit. An average of the various types of survey biomass data was used to obtain a representative level that made use of all data. For Unit 1, catch data is available from 1953 to 2000. Biomass surveys for this stock started in 1990 (Morin et al. 2001). Unit 2 catch results are available for 1960 to 2000. The biomass surveys for Unit 2 begin in 1973 (Power and Mowbray 2000). Data for both Units are found in Appendix A.

Fitting Equation 2 to the biomass survey data, assuming no difference in the intrinsic growth rate between management units, resulted in $r = 0.05$ for Units 1 and 2. $K_1 = 7.6$ million tonnes, and $K_2 = 5.6$ million tonnes for Units 1 and 2 respectively.

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[5] Dr. George Rose (Fisheries Conservation Chair, Memorial University of Newfoundland) and Dr. Joseph Wroblewski (Research Professor, Memorial University of Newfoundland).

Having estimated the parameters of the model, various recovery strategies are simulated for Units 1 and 2. Given the discrete nature of the data, the scenarios are modelled using the following difference equation describing the stock dynamics:

$$B_{t+1} = B_t + rB_t(1 - \frac{B_t}{K}) - (B_t F_t) \qquad (5)$$

where F_t is the fishing rate in year *t*. In this case, the fishing rate F is measured as a percentage of fish harvested each year. Yield-per-recruit (YPR) analysis is often used to help determine appropriate F values. However, it is important to acknowledge that YPR analysis does not necessarily reflect sustainability of optimal F values. Using a harvest rate that produces maximum yield, F_{max}, might seem like a logical choice. However, it has been shown that, due to uncertainties in YPR analysis, F_{max} is usually too high and can lead to stock declines (Haddon 2001). An alternative strategy that still uses YPR analysis is $F_{0.1}$. The $F_{0.1}$ value is calculated by finding the harvest rate where the slope of the YPR curve is 10% of the slope at the origin of the YPR curve. That is, an $F_{0.1}$ value does not mean that 10% of the estimated total biomass is being harvested in a given year (i.e. $F = 0.10$). Although $F_{0.1}$ policies are *ad hoc*, they are still widely accepted and preferable to F_{max} due to their conservative nature (Haddon 2001). Having accurate catch amounts and estimates of population size are important aspects when determining F values. In the case of this research, no YPR analysis is available or undertaken. Instead, I use past fishing rates to help determine how risky certain scenarios might be. For instance, for Unit 2 redfish in 1997, a TAC of 10,000 tonnes was deemed lower than the $F_{0.1}$ value (Power and Orr 1997). In 1996, a harvest rate of $F = 0.10$ would equal approximately 10,000 tonnes, suggesting a total biomass of 100,000 tonnes

(Power et al. 1996). In both of these years, the TAC was set at 10,000 tonnes for Unit 2 and the harvest rate was believed to be no higher than $F = 0.10$. This assumes that the estimated biomass was approximately 100,000 tonnes and that the TAC was set lower than the $F_{0.1}$ value for both years. It thus appears that Unit 2 redfish have been fished in a conservative manner in the past, staying within what is believed to be a cautious level of exploitation.

Chapter 5: Modelling Recovery Strategies

5.1 Biological Characteristics of Unit 1 and Unit 2 redfish

The first step to understanding the biology and growth of each stock is to assess how each stock grows in the absence of fishing. Using the parameter estimates reported earlier, the growth for Unit 1 is as shown in Figure 4. This graph shows the logistic growth of the population (Equation 2). Initially, there is a rapid increase in population as food is abundant relative to the weight of the biomass. However, these conditions change and as the stock grows, growth slows. Left undisturbed, the asymptotic population size (carrying capacity) is eventually reached. For Unit 1, this takes approximately 210 years in the absence of fishing with a starting biomass of 38,833 tonnes.

Unit 2 growth is seen in Figure 5. For this projection, the starting biomass is equal to 98,000 tonnes, the estimated total biomass for Unit 2 in 2007 (McClintock and Teasdale 2009). In 200 years, the total biomass of Unit 2 is within 15,000 tonnes of carrying capacity.

For Unit 1, the MSY is equal to 95,000 tonnes, with a B_{msy} of 3.8 million tonnes (Figure 6). The Unit 2 MSY is 70,000 tonnes and the B_{msy} is 2.8 million tonnes (Figure 7).

The shortcomings of MSY as a management objective are well-known, and it is not advocated as such here. Yet, it is a major prediction of the model, and serves the present purpose as a useful reference level. From a biological point of view, determining MSY depends on population size and growth rates. Lack of accurate data leads to uncertainties regarding these parameters, leading to imprecise MSY levels. These calculations are static, not considering the effects changing natural phenomena can have on growth and mortality. From another perspective, MSY calculations do not make reference to economic characteristics, in particular harvesting costs. Despite these weaknesses, there is still value in estimating MSY

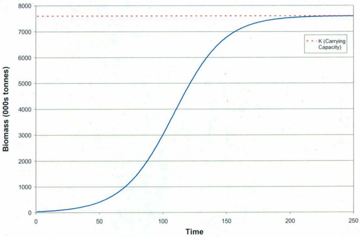

Figure 4. Logistic growth, Unit 1 redfish biomass.

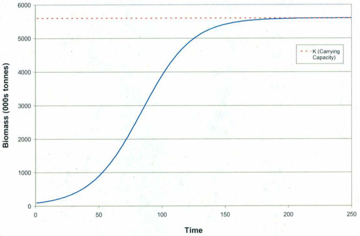

Figure 5. Logistic growth, Unit 2 redfish biomass.

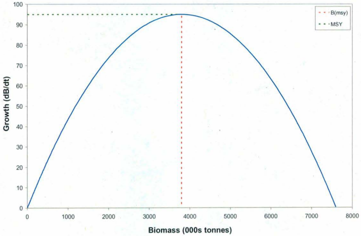

Figure 6. MSY and B_{msy} for Unit 1 redfish.

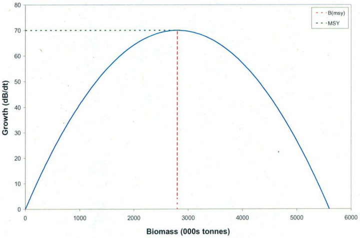

Figure 7. MSY and B_{msy} for Unit 2 redfish.

levels, as long as these values do not, by themselves, result in a definitive management prescription. In other words, MSY estimations can provide a starting point for exploitation levels and can be useful in conjunction with other models to achieve a better understanding of the factors associated with managing fisheries.

The next step for this research is to see how each stock responds when subjected to harvest.

5.2 Simulation Results: Unit 2

The fishing scenarios for Unit 2 are examined first, since this stock is not under moratorium. The goal here is to find a fishing rate that is sustainable. All scenarios depict arbitrary 150 year trajectories of biomass under different fishing rates. Due to the degree of separation between projected biomass and B_{msy} levels in some scenarios, all predictions for both Units are graphed on a logarithmic scale to depict the conditions for each stock.

The starting biomass for the Unit 2 scenarios is 103,919 tonnes in 2009. The biomass estimate in 2007 is 98,000 tonnes (McClintock and Teasdale 2009). The model was used to grow the stock from 2007, with reported catches removed for 2008[6]. The catch data has not yet been finalized for 2009. In the scenarios, fishing starts in 2009, and the 150 year projections begin in that year. The B_{msy} level is also included in the graphs to give a threshold for biologically feasible exploitation.

Three different fishing rates are shown for Unit 2 in Figure 8. To start, a conservative fishing rate of 0.02 is implemented, meaning that 2% of the weight of the total biomass is removed in each year. The main purpose of this harvest level is to show how long it takes for the stock to reach B_{msy} under a low-intensity fishing scenario. Under this harvest rate, the stock

[6] The catches were taken from the Redfish Historical Catches All Areas document by the DFO.

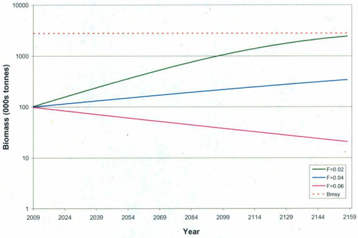

Figure 8. Predicted Unit 2 redfish biomass under three different harvest levels, with an estimated starting biomass in 2009 of 103,919 tonnes.

reaches nearly 2.4 million tonnes in 150 years. Although this fishing rate can basically guarantee sustainability, it seems that the stock can handle a higher rate of exploitation. If the revenues and costs of fishing warrant, fishing at $F = 0.02$ thus appears biologically sustainable in that the stock continues to grow under this scenario.

The next scenario also depicts a conservative, albeit somewhat higher, harvest rate of 0.04. This rate is just below the intrinsic growth rate for redfish so net growth is guaranteed under this assumption. In addition, although the harvest rate is cautious, it is on par with landed amounts in 2007 and 2008 (see footnote 6). The landed amounts are larger under this scenario than under $F = 0.02$. Given the slow growth of redfish, any scenario that has the biomass growing is desirable, all else being equal.

When a harvest value of $F = 0.06$ is applied, net growth does not occur. The stock is slowly heading for collapse/extinction. Within 150 years, the stock is at 21% of the original starting biomass. The Schaefer model estimated here does not exhibit depensation of any kind. Hence, the stock will head to extinction only gradually. Nevertheless, the landed amounts will continue to fall, and in all likelihood, render exploitation economically unsustainable in rather short order.

Comparing the three different harvest levels for Unit 2 shows that the stock grows under two conditions ($F = 0.02$ and $F = 0.04$) but decreases under the $F = 0.06$ rate. It appears that a harvest rate of $F = 0.02$ is consistent with a sustainable fishery. A rate of $F =$ 0.02 allows the stock to grow more quickly, but it tolerates an unrealistically low level of participation, and can therefore not be expected to contribute in an economically significant way to commercial fishing in Newfoundland and Labrador. Even removing 4% (i.e. $F = 0.04$) of the biomass on a yearly basis would allow for growth but as the fishing rate nears the intrinsic growth rate, net stock growth slows down. It appears that a harvest rate of approximately $F = 0.04$ results in a fishery that is at least biologically (if perhaps not economically) sustainable at the present time. However, this situation leaves a narrower margin of error if changes in environmental factors over time have a negative impact on stock growth.

Higher harvest rates than those proposed here do not appear consistent with rebuilding of the redfish biomass in Unit 2. More specifically, higher harvest rates may cause collapse or extinction in the near future given that the stock is being fished at biomass levels well below B_{msy}. This means that if the stock exhibits depensation (critical or non-critical), collapse could occur in the foreseeable future at higher rates of harvest.

5.3 Simulation Results: Unit 1

Because Unit 1 is under moratorium, the approach to examining exploitation strategies is slightly different. To start, a moratorium was implemented in 1995 and is still in effect. The redfish stock in this Unit is analyzed under two different assumptions regarding the moratorium. The first assumes that the fishery is opened in 2010, following a 15 year closure. The other moratorium scenario extends the closure another fifteen years, for a total of 30 years, reopening the stock to fishing in 2024. As with Unit 2, the B_{msy} for Unit 1 (3.8 million tonnes) is included to provide a minimum biomass threshold.

The starting biomass for Unit 1 is derived from data from the existing surveys, occurring from 1984 to 2000 (Atkinson and Power 1990; Morin et al. 1995; Morin et al. 2001). Figure 9 shows the biomass estimates for eight different survey types for Unit 1 redfish. The 4RST Summer Survey is used here for the biomass estimate for this redfish stock for a couple of reasons. Firstly, this survey is the longest one, occurring in each of the seventeen years.

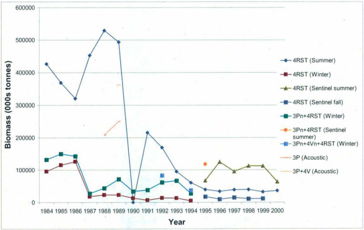

Figure 9. Unit 1 redfish survey data for 1984 to 2000.

Sources: DFO Research Documents (90/57; 95/109; 2001/001).

Secondly, the biomass estimates derived from this survey type show the crash of the stock in 1989 to 1990. I have used the biomass estimate from 1995 (38,833 tonnes) as the starting biomass since this is the year the fishery was closed.

The first scenarios for Unit 1 follow a 15 year moratorium. Fishing begins in 2010 at a biomass of roughly 76,000 tonnes and three different harvest rates are applied (Figure 10). The first scenario shows fishing at $F = 0.02$ in 2010. Fishing at such a cautious level guarantees growth and the moratorium allows the starting biomass to grow nearly 40,000 tonnes from the original starting point to approximately 76,500 tonnes. Once fishing begins at $F = 0.02$, the net biomass growth in the next 15 years is still approximately 40,000 tonnes, showing that such a low fishing rate has a rather insignificant impact on the stock status and such low landed amounts would in all likelihood contribute little to the commercial fishing industry in Newfoundland and Labrador.

Increasing the fishing rate to $F = 0.04$ still allows for growth in the stock. As with the Unit 2 stock, Unit 1 redfish grow slowly in this scenario. However, fishing at this level can not be expected to contribute notably to jobs in the commercial fishing industry.

Fishing at $F = 0.06$ has the opposite effect on the Unit 1 stock, leaving no net growth once fishing begins. It does not seem that a fifteen year closure is enough time for the biomass to reach a level that can sustain any considerable exploitation. In fact, the biomass of this stock decreases to what appears to be a precariously low 13,000 tonnes in the 150 year projection.

It is evident that a moratorium is necessary for this stock to increase to a level that could sustain commercial fishing. However, closing a fishery has economic and social consequences so it is important to find an appropriate combination of moratorium length and harvest rate that will allow for a worthwhile fishery in Unit 1. The next set of scenarios projects the

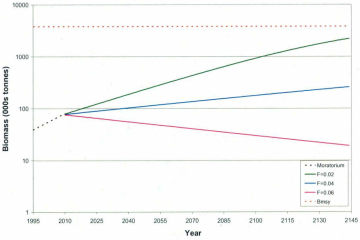

Figure 10. Predicted Unit 1 redfish biomass under three different harvest rates after a fifteen year moratorium ending in 2010. Starting biomass in 1995 is 38,833 tonnes.

biomass amount in Unit 1 with a 30 year closure, with fishing commencing in 2024. The same three harvest rates that were used for the other scenarios are applied here (Figure 11).

When $F = 0.02$, the biomass grows with each passing year. However, comparing the biomass in any given year between the fifteen year moratorium and the 30 year moratorium when $F = 0.02$ reveals that the moratorium length influences the sustainability of the stock less than the fishing rate once the closure is lifted. In other words, fishing at such a low level will guarantee net growth of the stock regardless of how long the fishery remains closed. It is still possible to bring a stock back to its pre-moratorium state if the harvest rate is too high once fishing resumes.

Finally, harvest levels of $F = 0.04$ and $F = 0.06$ are applied after the 30 year closure in Unit 1. These scenarios have similar results after a 30 year closure as they do after a fifteen year moratorium, with the $F = 0.04$ resulting in slow growth over time. Under the harvest rate $F = 0.06$ the stock does not grow at all.

Because the starting biomass (38,833 tonnes) is so low and redfish grow so slowly, a longer moratorium period would be preferred. I could, for the sake of comparison, use the model to estimate the biomass after a 50 year moratorium. This is, however, an unrealistic scenario. It serves little purpose to see how big the Unit 1 redfish stock could get in absence of fishing if it will not benefit industry participants for half of a century.

5.4 Sensitivity Analysis

Because of the uncertainties surrounding estimates for biological parameters, subjecting the redfish stocks to a sensitivity analysis is necessary to better understand how easily the growth rate can change the stock recovery potential. The analytical question posed in this section is:

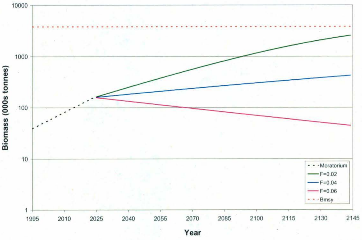

Figure 11. Predicted Unit 1 redfish biomass under three different harvest rates after a thirty year moratorium ending in 2025.

how sensitive is the recovery strategy to assumptions about the natural growth rate, and the policy-determined harvest rate? To address this issue, I have structured the analysis so as to answer the following question. Given a set cautious harvest rate and a hypothetical target biomass level, what would the (assumed) growth rate have to be for the biomass to reach the target stock level within 10, 15, and 20 years, respectively, when fishing resumes after the existing 15 year moratorium is lifted?

The analysis is performed by applying two different types of harvest rates. The first uses a constant F value to model the harvest as in the previous scenarios[7]. As explained above, this means that the actual harvested volume is increasing when the biomass increases, and vice versa. In the Schaefer framework, this implies that fishing effort remains constant. The second part of the sensitivity analysis models harvesting using instead a constant harvest rate (a total allowable catch), which assumes that the effort level is variable.

The sensitivity analysis is performed based on a hypothetical target biomass equal to the B_{msy} of Unit 1 (3.8 million tonnes). In each case, intrinsic growth rates (r) are determined so as to just allow the biomass to reach the target level within ten ($r10$), fifteen ($r15$), and twenty ($r20$) years after fishing recommences. All scenarios use the Unit 1 stock assuming that the 15 year old moratorium is lifted and fishing resumes.

5.4.1 Constant effort

An F value determines the percentage of the stock biomass that is removed every year. This means that the allotted catch will fluctuate from year to year, depending on the current biomass. Figure 12 shows the three different r values when fishing resumes at $F = 0.04$. Even with such a low harvest rate, the growth rate must be significantly higher than what would be

[7] This is the same type of harvest rate used by Haedrich and Hamilton (2000).

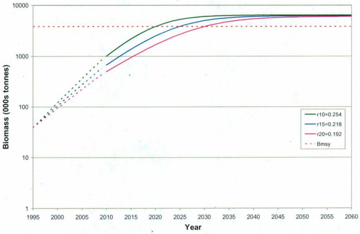

Figure 12. Three intrinsic growth rates (*r*) for Unit 1 redfish stock after a 15 year moratorium under a harvest rate of $F = 0.04$.

expected for a slow growing species like redfish. The lowest r value, 0.192, which allows the stock to reach the target biomass 20 years after fishing begins, is greater than the estimated growth rate of cod by Haedrich and Hamilton (2000).

As expected, when the harvest rate is increased to $F = 0.10$, the three growth rates increase (Figure 13). The r_{10} value when the harvest rate is $F = 0.04$ is equivalent to the r_{20} value when $F = 0.10$. The target biomass of 3.8 million tonnes significantly dictates the high growth rates. Furthermore, when the same harvest rate was applied with a target biomass of 1.9 million tonnes ($B_{msy}/2$), the lowest projected r value was still above 0.10. Although expecting the biomass to reach such levels in a relatively short amount of time may be overly optimistic, it does illustrate that (1) the assumed growth rate is relatively more important to the likelihood of recovery than the harvest rate, and (2) if fishing in Unit 1 were to resume, the harvest levels consistent with continued stock recovery are so low as to call into question the economic viability of the fishery. These point to the importance of accurate biological parameter estimations and cautious management policies. The bottom line is that the manager is hostage to the low growth rate of the species (and the current low stock level).

5.4.2 Constant harvest

In this part of the analysis, a constant harvest rate in the form of a total allowable catch (TAC) is applied. This means that an amount is set each year that can be removed from the stock. Fishing effort can fluctuate but the amount of fish that is landed is set. TACs are divided amongst participants in different ways and they usually remain the same for a few years in a row.

The TAC for Unit 2 redfish in 2005 was 8,000 tonnes. Given the biomass estimate for

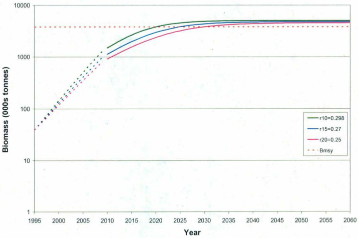

Figure 13. Three intrinsic growth rates for Unit 1 redfish stock after a 15 year moratorium with a harvest rate of $F = 0.10$.

that year, it was concluded that this TAC represented approximately 11.5% of the total biomass. This percentage was used to estimate an appropriate TAC level for Unit 1 after a 15 year moratorium. With a growth rate of $r = 0.05$, the biomass grows to approximately 76,000 tonnes after a 15 year closure, resulting in a TAC of 6,600 tonnes. This estimation was performed simply to get an idea of a logical starting point when implementing a TAC for Unit 1 redfish.

Figure 14 shows the Unit 1 redfish stock with a TAC of 6,000 tonnes following a 15 year moratorium. Although the projected r values are lower than with the $F = 0.04$ and $F = 0.10$ scenarios, they are still above what would be expected for such a long-lived species like redfish. A TAC of 20,000 tonnes (Figure 15) changes the respective r values very little. Lowering the TAC to 4,000 tonnes and decreasing the target biomass to 1.9 million tonnes still did not yield an intrinsic growth rate below $r = 0.10$. It is clear that it is difficult for the biomass to grow to a high target level within a 15 year period even when subjected to low harvest rates. Growth rates that fall within the range suggested by some fisheries scientists for this species could possibly be achieved with these fishing rates and biomass targets if the time period was extended. For instance, if I assessed growth rates according to if targets were met within 20, 25 and 30 years, instead of within 10, 15, and 20 years, the possibility of meeting the target with growth rates under $r = 0.10$ is much greater. However, allowing more time for growth is not a realistic option. It is important to see what can be done in a period of time that is relevant to the harvesters that are benefiting from the resource.

One last evaluation is made to illustrate the impact that biological parameter estimates can have on the sustainability of fisheries. Since a range of r values may be suitable for a particular species, it is useful to see the different outcomes that various growth rates can

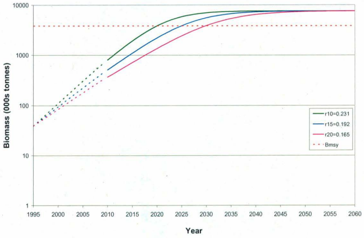

Figure 14. Three intrinsic growth rates for Unit 1 redfish stock after a 15 year moratorium with a TAC of 6,000 tonnes.

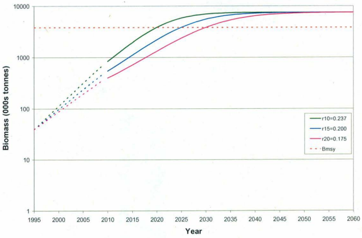

Figure 15. Three intrinsic growth rates for Unit 1 redfish stock after a 15 year moratorium with a TAC of 20,000 tonnes.

produce. Figure 16 compares three different growth rates for Unit 1 redfish with a 15 year moratorium and a TAC of 6,600 tonnes. The highest growth rate ($r = 0.40$) is from Ávila de Melo et al.'s (2007) paper assessing the redfish found in NAFO Divisions 3LN. The lowest growth rate ($r = 0.05$) is the one used for the scenarios in this research. The middle r value (0.10) represents the upper limit of the range assumed for redfish in waters off of Newfoundland and Labrador (see footnote 5). When $r = 0.40$, the biomass has almost reached the target of 3.8 million tonnes even when the moratorium is still in place. For this reason, only extremely high TAC levels will impact the net growth of the stock. In fact, the harvests would need to be over one million tonnes to see any sort of decline with a growth rate as high as this. Of course, the goal is not to see a decline but to try to find a sustainable harvest level. With a growth rate of 0.10 and a TAC of 6,600 tonnes, the stock still experiences net growth. When $r = 0.05$, however, the stock experiences no net growth at all when fishing resumes. In order for the stock to grow or at least remain level with a growth rate of 0.05, the TAC would need to be approximately 3,800 tonnes. This amount is only 1,800 tonnes higher than what is currently allowed to be harvested from the Unit 1 stock for the sentinel/index fishery.

Although it appears that the stock could handle high harvest rates under certain growth rates, the model and projections do not account for any sudden increases in mortality due to environmental or other natural changes. Therefore, it is advisable to use a precautionary approach when developing management policies, especially with a species such as redfish that experiences slower recovery potential due to its life history characteristics. In addition, it is important to look at the simulations realistically. Although a low harvest rate may allow for extreme net growth, it allows a limited number of participants. However, assuming a high r

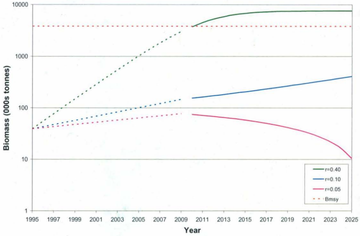

Figure 16. Unit 1 redfish with three different growth rates and a TAC of 6,600 tonnes after a fifteen year moratorium.

value can be dangerous if there is any amount of uncertainty. Finding a realistic balance for both F and r values is essential to a sustainable fishery.

5.5 Implications of the Revised Stock Definitions

One essential consideration regarding the management of both Unit 1 and Unit 2 redfish is that the stocks were redefined in 1993. This point is important for a variety of reasons, both for the purpose of this thesis as well as the overall management of the redfish fishery in these areas. To begin, the questioning of the appropriateness of the stock management boundaries by the Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) shows a willingness to adapt regulations when new or contradictory data emerges. The previous management units were defined in the early 1970s, but no efforts were made to re-examine the issue until 1989 (Atkinson and Power 1991). Consequently, although it was decided that the issue was going to be examined, stock assessments were postponed until the new units were established.

It was discovered, after analyzing trawling and acoustic survey data and the Observer Program commercial catch and effort data, that the redfish distribution was continuous over the 3P4V line and that redfish were migrating from the Gulf into the 3Pn and 4Vn areas during the winter. New management units were established to consider the winter migration out of the Gulf of St. Lawrence and redfish were managed in this region throughout the year as two different units (Unit 1 and 2). Under the new protocol, redfish in the Unit 1 Gulf of St. Lawrence stock consisted of 4RST all year long, and 3Pn and 4Vn from January to May. The new stock definition for the Unit 2 Laurentian Channel redfish covered 3Ps4Vs4Wfgj all year round, and 3Pn and 4Vn from June to December (Atkinson and Power 1991).

This research and subsequent reconsideration of boundaries occurred in the late 1980s, less than a decade before the Unit 1 redfish fishery closed. As previously mentioned, stock assessments were postponed in the years surrounding the evaluations but it was important to not waste time in instituting TACs for the new units. Accordingly, the total TAC for all three units combined was 102,000 tonnes in 1992. It was decided that this amount would be divided amongst Units 1, 2, and 3 based on the percentage of the average catches from 1981 to 1990. This resulted in Unit 1 receiving the majority of the TAC, at 67,000 tonnes and Unit 2 receiving a 25,000 tonnes limit. The remaining 10,000 tonnes were allocated to Unit 3 (Atkinson and Power 1991).

When this reapportioning occurred, the redfish in the area appeared to be in good condition (Atkinson and Power 1991). It is unfortunate that the stock reassessment and the appearance of stability coincided in time. If redfish had seemed to be in decline or at risk, more precautionary measures may have been implemented that could have either avoided the closure of Unit 1, or at least facilitated rebuilding of the stock. For instance, if there were suspicions of decline or instability, perhaps the overall TACs would have been lowered, or the TACs for areas of uncertainty would have decreased until new assessments on the new units could be conducted. In hindsight, it is hard not to consider these possibilities as Unit 1 was closed only two years after it was redefined.

In the context of this research, the new management units complicated the collection of data for the model, most especially for Unit 1. Since it was closed in 1995, stock assessments and biomass estimates are not presented. Instead, qualitative descriptions are used, where the stock is defined as having no significant recruitment (FRCC 2003), low biomass (FRCC 2003), or a poor prognosis for the foreseeable future (DFO 2004b). As previously explained, the survey data was examined to determine the best starting estimate for the closed Unit 1 redfish stock.

Managing Unit 2 is further complicated by the fact that it shares space with Unit 1 (see Figure 1). The new management units implemented in 1993 are only believed to be more appropriate than the previous ones. With new emerging data and information, it is possible that the current units will have to be re-examined and changed yet again. Currently, research by the DFO and collaborators is ongoing regarding the population structure of both Units 1 and 2. The implications of this research concern the interactions between the Units and aim to determine if redfish in this area should be managed by species rather than by the established stocks of mixed species (DFO 2008).

Chapter 6: Conclusions

A comprehensive analysis is needed when discussing the recovery potential for the two redfish stocks studied for this thesis. This means that the potential sustainability of the stocks needs to be examined from different perspectives, such as the model projections and the life history characteristics of the species, and with recognition of the chronic uncertainties that plague the enterprise of fisheries management in the open ocean.

In my Master of Marine Studies Major Report (Goetting 2008), I examined the diversification potential of redfish in the wake of the 1992 cod moratorium. That is, could redfish stocks around Newfoundland and Labrador handle increased exploitation and could the fishery provide adequate financial returns? I concluded that many of the examined redfish stocks were mismanaged, with little consideration given early on to the life history characteristics of the species, and a lack of enforcement of regulations. In addition, decreases in total allowable catches (TACs) in response to declines in biomass estimates were often implemented too late. Suggestions for future management policies were rooted in the precautionary approach and multi-species management. This research led to the current questions being examined in this thesis regarding the recovery and sustainability of two redfish stocks (Unit 1 and 2) in the northwest Atlantic. What is the recovery potential for the Unit 1 stock and what level of harvesting can it sustain if fishing resumes in 2010? What level of exploitation can the Unit 2 stock uphold over the next two decades? For both of these stocks, biomass levels have declined to dangerous levels following several decades of intense, industrial fishing. In order to attempt to answer these questions, past research relating to the stocks under consideration was first reviewed. Using secondary data, a growth function for redfish was then estimated. This function was used to project recovery trajectories for the two stocks under consideration. Finally, sensitivity analysis was used to assess the sensitivity of the recovery trajectories to alternative assumptions about growth rates, harvesting, and moratorium lengths. On the basis of this analysis, tentative recommendations are made regarding current management and policy strategies.

Redfish research, although not as extensive as that of cod in this region, has been broad. Some studies have examined ways to improve harvesting and processing, while many others have assessed the status of various redfish stocks off the coasts of Newfoundland and Labrador. As the life history characteristics of redfish were discovered, most studies acknowledged the challenges associated with the long-lived and slow growing nature of the species. Modifications were made to harvesting equipment, and strategies were developed to more efficiently exploit the resource. Redfish catches in the region increased, with landing peaks for many stocks seen in the 1970s. Around this time, however, concerns about the conservation of redfish in the Gulf of St. Lawrence (Unit 1), the major source of Canada's redfish in the 1970s, were raised. Eventually, it was understood that redfish required a unique management protocol.

The methodology used in this research applies the Schaefer (1954) model to estimate the biological status of two Canadian redfish stocks: Unit 1 (Gulf of St. Lawrence) and Unit 2 (Laurentian Channel). The model is then used to generate projections concerning the future of each of these stocks under different fishing scenarios. In the case of Unit 1, which has been closed to directed fishing since 1995, it looks more directly at the potential recovery of the stock. The scenarios for Unit 2 address the possibility of increased exploitation. These stocks were chosen for a few reasons. First, it was constructive to analyze two stocks that were in different states of depletion. Unit 1 stock has been closed to commercial exploitation since 1995. The Unit 2 stock, however, is still open to commercial fishing, although the TAC has been reduced significantly since 1993 and is now only 8,500 tonnes. Second, both of these stocks were redefined in 1993 and currently share an area (see Figure 1) to consider seasonal migrations. Ongoing research is also being conducted to attempt to establish species composition of each stock that may lead to new management definitions. These stocks influence one another and the Unit 1 stock's recovery could be substantially impacted by the harvesting that occurs in Unit 2.

In order to obtain outputs from the Schaefer model, biological parameters are required. The most critical of these is the intrinsic growth rate (r) of redfish. Growth rates, or r values, have been estimated by different researchers using a variety of methods. However, growth rate estimates for redfish are sparse. Since redfish are a slow-growing, long-lived species, growth rates can be expected to be substantially lower than those of other species with different life histories, such as cod or herring. For example, the growth rate for cod used by Haedrich and Hamilton (2000) is 0.185. It is assumed that the redfish growth rate is lower than this and, after consulting with fisheries scientists (see footnote 5), I have determined that based on the information available to me, an appropriate range would be 0.04 to 0.10. I used the Solver minimization algorithm in Microsoft Excel to estimate an intrinsic growth rate using data for the redfish stocks in question, which yielded an r of 0.05.

The lack of estimations for important biological parameters is indicative of the uncertainties that plague the redfish fishery. Redfish are found in deep waters ranging from 100 to 750 meters, rendering research difficult and resulting in 100% mortality when brought to the surface from such depths. In addition, redfish stocks are comprised of more than one redfish species, whereas a fishery like that of cod consists of only one species. Because the different redfish species are virtually indistinguishable from one another without dissection, attempting to determine the composition of each stock can result in more appropriate regulations.

The results of the projections presented in this research show that neither Unit 1 nor Unit 2 redfish are in danger of imminent extinction, or even exploitation that would take the biomass to collapse (that is, to a point of depensation on the growth curve). Unit 2 is not currently under moratorium, and the current biomass is at a stable level, meaning that it can likely sustain a higher harvest rate than Unit 1. The simulation results suggest that even when the Unit 1 fishery reopens, the harvest level should be very conservative in the first few years in order to prevent a return to a crisis situation. It would be a relatively small fishery because it can only support low harvest levels. That is, it could not sustainably maintain catch amounts that are anywhere near historical levels. If the harvest rate (F) for either stock remains below the r value, the net biomass grows towards B_{msy} in the model and the sustainability of the stock is almost assured under these circumstances, all else equal. If the F value is higher than the intrinsic growth rate, the net biomass declines. In the case of the Unit 1 stock, which examines the effects of two different moratorium lengths (15 and 30 year), the closures do help delay significant declines when the fishery is reopened at $F = 0.06$. However, the starting biomass remains under 80,000 tonnes when the fishery reopens after 15 years. Following a 30 year closure, the biomass reaches over 150,000 tonnes, allowing harvesting to occur at a higher rate without significant declines. Once fishing commences at $F = 0.06$, it still takes over 150 years for the stock to decline to the original starting biomass before the moratorium of 38,833 tonnes. The life history characteristics of commercially exploited fish species not only influence the results of harvesting scenarios but also the recovery rates of depleted stocks. Since redfish is a long-lived demersal species, closure lengths, although necessary, will most likely have to be longer than what would be required for species like cod and herring.

It is clear from the sensitivity analysis that recovery for redfish in Unit 1 is slow with reasonable growth rates and that the assumption of r is extremely important in assessing recovery. Of course, many circumstances influence harvest and recovery rates. Because of the effects of unknowns on the estimates of biological parameters, evaluations of policies and regulations should be continuous. This type of analysis also addresses the uncertainties that plague the fishery. For this purpose, I designate a 'target stock level' as a hypothetical policy objective. The level at which the target biomass level is set then largely determines the timeline for potential growth and recovery of the stocks. Considering a range of parameters to measure the effects is a good way to establish upper and lower limits when the true values of the parameters are unknown. From the sensitivity analysis, it appears that the growth rates are not particularly sensitive to either type of harvest rate, whether it is a constant proportion removed each year (F), or if it is a fixed quantity per unit time (TAC).

Time is an important factor in developing management decisions. The most striking feature of the model results, even those exploring higher growth rates, is the every slow pace of recovery, and the limited payoff from these fisheries along the way. Although these redfish stocks can experience substantial growth in the absence of fishing, or under very low harvest rates, this takes a considerable amount of time. Indeed, the projections for Unit 2 with an r value of 0.05 under three different harvest rates and no moratorium period show that the stock can experience net growth while being harvested (see Figure 8). However, the amount of time it takes for the biomass to reach a level in which it can tolerate harvesting that offers considerable financial gains renders it a rather unrealistic option. Slow-growing species like redfish will not, in the lifetimes of those now fishing, recover from overexploitation. It is not entirely clear if the fishery for Unit 1 is commercially viable at its present state. Regardless of the projections in this research, the reality is that the fishery still remains closed except to a sentinel/index fishery. Because of the uncertainty surrounding the estimates of the intrinsic growth rate *r* of redfish, it was important to see how fluctuations in the growth rate would change the projections under the same harvesting scenarios. Of course, the higher the growth rate, the faster the biomass will grow, all else equal.

Research involving the economic impact and viability of the redfish fisheries in Units 1 and 2 would be one way to build upon the research presented in this thesis. The projections presented in this thesis can be expanded to evaluate the fishing capacity in terms of vessels that can be supported by a certain amount of tonnage in landings. Research such as this could better inform participants in the industry of possible income in the future. It is important to analyze the economic impacts and attempt to maximize benefits over time. Currently, the redfish stocks studied in this thesis can not be said to be managed unsustainably. However, this does not mean that the fishery is as well-regulated as it could be, or that it is allowing an adequate financial return. Management tools, such as moratoria or reduced TACs, although beneficial in the long-term, should not be presented as steps that can bring near-term improvement, even if they save what's left of the stock. One key feature that is contributing to the conservation of this fishery in this region is that redfish have a relatively low economic value. The outcome would be less optimistic if there were pressure from harvesters to reopen Unit 1, or to increase TAC levels in Unit 2 due to increased demand. Fortunately, landed amounts of redfish per year seem to be satisfactory according to current market conditions. Assessing how many vessels could be sustained by a certain quota from a stock would help better understand the impacts of a collapse and help evaluate the contributions these fisheries can make to the economies of the communities which rely on them.

As is evident from the model projections and sensitivity analysis, one of the most important components of fisheries management involves appropriate estimations of biological parameters. The scientific literature on growth rates for redfish is lacking. Further research to determine upper and lower limits for redfish growth in the northwest Atlantic can help make projections more reliable and possibly decrease some uncertainty, leading to regulations that further support the precautionary principle. This method of management already takes into account aspects of the redfish fishery (i.e. the uncertainties) that will not be solved in the near term. For instance, the unknowns concerning the life history of redfish and the ability of recovery for the species will probably always be present at some level. Furthermore, harvesting technology and a whole host of economic conditions tend to be in a constant state of flux. This would necessitate a careful re-evaluation of what harvest levels are sustainable.

The projections, sensitivity analysis, and uncertainties of the redfish fishery reinforce the need for precautionary management. It is essential to use the best available information so as to not delay in implementing regulations. An important lesson that should be learned from the state of these redfish stocks is the need for caution when exploiting species whose biology is not well understood. Recovery is possible for these redfish stocks, but not in the near term. It will take decades, perhaps centuries, to restore the biomass to levels that can sustain historical and financially meaningful catches. Biological sustainability and economic sustainability are not the same thing. These fisheries may one day prove to be biologically sustainable, but not necessarily economically sustainable. Managing fisheries for the future should be a primary goal. Unfortunately, much time is spent on fixing problems and managing recovery. By adhering to precautionary principles, uncertainties are acknowledged but progress is still made. We can not change the biology and life history of the species. Instead, we need to adapt and change what we can, which is our involvement and our contribution by means of appropriate management protocols.

6.1 Recommendations

Suggestions derived from this research include:

1. economic analysis to establish the commercial viability of these fisheries
2. biological analysis to refine the estimates of the growth parameter and the carrying capacity. This analysis should include an estimation of a depensation parameter in the Schaefer model so that risks of stock collapse can be more reliably assessed.
3. examination of a quota system to determine vessel capacity of these two redfish stocks
4. based on the above, develop policies and regulations rooted in the precautionary approach

Using the Schaefer model to evaluate the recovery and harvest projections is just one method to assess the potential for these redfish stocks. However, because this model considers only one species and does not take into account environmental effects, it is best used in conjunction with other methods and information in order to decrease uncertainties.

Redfish in this region require a balanced management plan that considers the biological and socio-economic sustainability of the species. Currently, Unit 2 redfish are not considered to be over-exploited, given the low TAC level. The Unit 1 redfish stock remains closed after 15 years due to evidence of very weak recruitment and a low biomass level (FRCC 2003). These regulations seem appropriate for these stocks at the present time. However, it is necessary to be aware of changing markets and biomass levels in order to assess the suitability of the policies and estimate the possible responses to any changes that may occur. Constant monitoring and evaluation of stock status are essential components to the conservation of fish stocks. In short, achieving sustainability of redfish in the northwest Atlantic requires a cautious and adaptive approach.

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Appendix A. Survey data used for the Solver minimization algorithm.

Table 1. Catch and survey biomass data for Unit 1 redfish from 1953 to 2000 (Morin et al. 2001).

Year	Catch	DFO Research Survey Biomass	Sentinel Survey (summer) Biomass	Sentinel Survey (fall) Biomass
1953	8366			
1954	32768			
1955	49857			
1956	46834			
1957	34331			
1958	22570			
1959	17113			
1960	12830			
1961	11062			
1962	7151			
1963	20817			
1964	30524			
1965	52829			
1966	67962			
1967	71905			
1968	95264			
1969	92320			
1970	90503			
1971	82189			
1972	82592			
1973	136101			
1974	67081			
1975	70052			
1976	44378			
1977	17072			
1978	14934			
1979	16425			
1980	15539			
1981	22045			
1982	26704			
1983	24974			
1984	25521			
1985	35077			
1986	36414			
1987	43446			
1988	51892			
1989	52482			
1990	61934	324700		
1991	67527	208500		

1992	77753	160800		
1993	51091	95300		
1994	19392	60300		
1995	65	38700	67300	17300
1996	74	33300	124800	9400
1997	39	38400	94700	14700
1998	339	39300	112300	10700
1999	991	31600	112400	11200
2000	764	35900	63200	

Table 2. Catch and survey biomass data for Unit 2 redfish from 1960 to 2000 (Power and Mowbray 2000; FRCC 2003).

Year	Catch	3Ps Spring Research Survey Biomass	4VW Summer Survey Biomass	4VW Cod directed Spring Survey Biomass	DFO Research Survey Biomass
1960	23359				
1961	18841				
1962	26206				
1963	34886				
1964	29134				
1965	25883				
1966	42240				
1967	45866				
1968	23509				
1969	49320				
1970	59321				
1971	71191				
1972	54002				
1973	38837	72952	24106		
1974	40955	58800	33238		
1975	43311	92910	19391		
1976	24150	102343	39336		
1977	29057	52193	41583		
1978	27564	65903	55381		
1979	20413	48801	33623		
1980	18269	111141	17709		
1981	23172	33130	14865		
1982	19353	26401	33605		
1983	14774	27099	18070		
1984	8805	14304	60874		
1985	12250	31721	60060		
1986	11427	36472	58843	7232	
1987	15896	44002	44514	61671	
1988	11309	109193	67017	2400	

1989	16592	66325	126325	11530	
1990	15179	51820	43035	8562	
1991	25431	79423	81669	10600	
1992	20188	34006	50954	7156	
1993	33111	34290; 42180	47578	27349	
1994	25821	33994	17817	12357	258981
1995	12242	86210	48290	12511	225622
1996	9412	52853	43420	52946	213039
1997	9943	35547	42205	25459	232696
1998	10638	33280	23833	no survey	
1999	11345	65948	37300	29901	
2000	4368 (7700)	50827	15274	34430	258341