RESIDENT FISH PRODUCTION, ECOSYSTEM CARRYING CAPACITY AND POPULATION DYNAMICS OF ATLANTIC COD (GADUS MORHUA) IN GILBERT BAY, LABRADOR: A MARINE PROTECTED AREA

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Resident fish production, ecosystem carrying capacity and population dynamics of Atlantic cod (*Gadus morhua*) in Gilbert Bay, Labrador: a Marine Protected Area

by

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Abstract

The Marine Protected Area in Gilbert Bay, Labrador was created mainly to protect its resident Atlantic cod (*Gadus morhua*) population, which is genetically distinguishable from other northern Atlantic cod populations. In order to effectively manage this population in the future, basic information regarding production, ecosystem carrying capacity, and population dynamics is needed. In this research, a bottom-up food chain dynamics approach was used to calculate the resident fish production in Gilbert Bay (340 tons per year) and the ecosystem carrying capacity for Atlantic cod (286 tons) based on a primary production rate of 190 g C $m^{-2}y^{-1}$. The availability of suitable habitat for juvenile cod as well as food availability may limit the production of Atlantic cod (109 tons per year). The age-structured Leslie matrix population model was used to simulate the rebuilding of the Atlantic cod population in Gilbert Bay. The elasticity analysis suggests that protecting juveniles and their habitat is most important to the population growth.

Key words: Gilbert Bay, Marine Protected Area, Atlantic cod, fish production, ecosystem carrying capacity, Leslie matrix, population projection

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Lastly, but most importantly, I wish to thank my mother, my daughter, my sisters, and especially my husband, upon whose constant encouragement, understanding, and love I have relied throughout my studies.

I dedicate this thesis to my father who will always live in my heart.

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Chapter 1 Introduction

Intensive exploitation has led to a rapid decline of fish stocks worldwide (Hiborn *et al.*, 2003). Our development of fisheries is unsustainable. Countries are taking action to protect their fish resources from overexploitation. The traditional management measures such as setting fishing quotas, restricting fishing gear and mesh size, reducing fishing effort, and seasonal closures have had limited success. Marine Protected Areas (MPAs) have been gaining attention as a potential tool for conservation and fishery management (Roberts et al., 2001). In 2005 Gilbert Bay was announced as a Marine Protected Area (MPA) under Canada's *Oceans Act* to protect its resident population of Atlantic cod (*Gadus morhua*) that is genetically distinguishable from the offshore northern Atlantic cod population (Ruzzante *et al*, 2000; Beacham *et al*, 2002). The subpopulation of cod in Gilbert Bay is part of the northern cod metapopulation which is considered in danger of extinction by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2003). The purpose of this research is to understand the population dynamics of the Atlantic cod in Gilbert Bay to determine whether the management plan for the MPA protects the cod population.

1.1 The Gilbert Bay MPA

Gilbert Bay is a narrow inlet located on the southeast coast of Labrador (Figure 1.1). The bay is 25 km long and 1-3 km wide with a total area of approximately 60 km^2. The inner part of Gilbert Bay is generally shallower than the outer part. According to the bathymetry map (Figure 1.2) generated from a multibeam survey of Gilbert Bay conducted by the Canadian Hydrographic Survey in 2002, about 56% of the area is

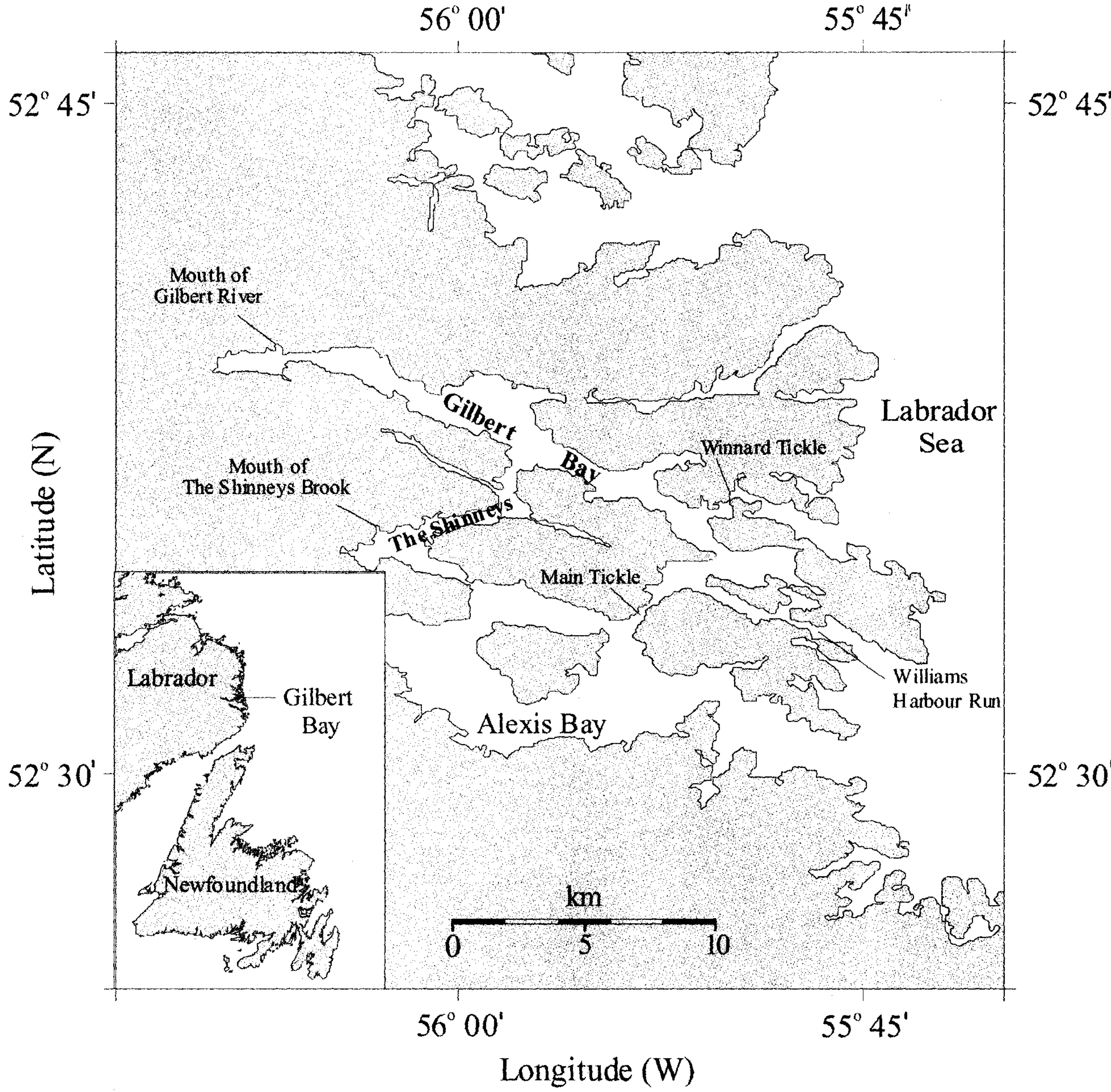


Figure 1.1 Map of Gilbert Bay. The waters of Gilbert Bay connect with the Labrador Sea at Winnard Tickle and Williams Harbour Run. Gilbert Bay connects with Alexis Bay through Main Tickle.

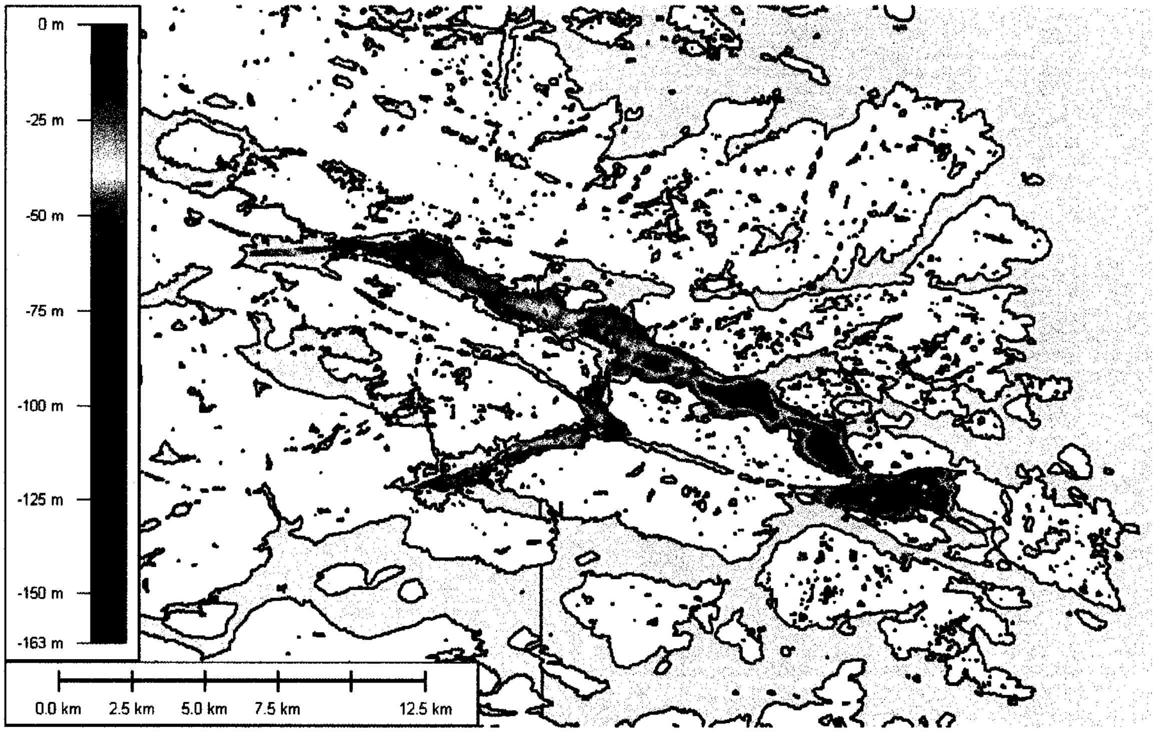


Figure 1.2 Gilbert Bay bathymetry.

shallower than 30 m; only about 6% of the surveyed area is deeper than 100 m (Copeland *et al.*, 2006). A number of sills separate basins along the main axis of the bay (Figure 1.2). These sills are thought to prevent the water from the Labrador Sea from circulating through the bay, which may enhance in the retention of the cod eggs and larvae in the bay (Morris 2000; Morris and Green, 2002). The archipelago at the mouth of Gilbert Bay plays an important role by nearly blocking the wind-driven surface water and its plankton from leaving the bay (Wroblewski et. al., 2005).

Gilbert Bay connects to the Labrador Sea through Williams Harbour Run and Winnard Tickle. The Main Tickle links the bay to neighbouring Alexis Bay (Figure 1.1). Freshwater from the Gilbert River and the Shinneys Brook flows into Gilbert Bay. The Gilbert River is derived from a watershed area of 642 km^2; the Shinneys Brook watershed covers an area of 313 km^2 (Anderson, 1985). Linking the two rivers (Gilbert River and

The Shinneys Brook) to the Labrador Sea, Gilbert Bay has estuarine oceanographic conditions. The surface water salinity increases near the mouth of Gilbert Bay (Wroblewski *et al.*, 2007).

1.2 Finfish in Gilbert Bay

Wroblewski *et al.* (2007) collected 25 fish species in Gilbert Bay. They categorized these 25 species into five groups: (1) estuarine and marine fishes resident in the bay throughout the year, (2) anadromous species transiting the bay, (3) marine species which migrate into the bay to spawn, (4) offshore-spawning marine fishes for which the bay is a nursery area, and (5) marine species which migrate into the bay to feed (Wroblewski, *et al.*, 2007). The four species considered year-round residents of Gilbert Bay are Atlantic cod (*Gadus morhua*), Greenland cod (*Gadus ogac*), short horn sculpin (*Myoxocephalus scorpius*), and winter flounder (*Pseudopleuronectes americanus*). Species which may complete their entire life cycle within the bay as well include: rock gunnel (*Pholis gunnellus*), ocean pout (*Zoarces americanus*), daubed shanny (*Lumpenus maculatus*), threespine stickleback (*Gasterosteus aculeatus*), blackspotted stickleback (*Gaterosteus wheatlandi*), fourspine stickleback (*Apeltes quadracus*), and ninespine stickleback (*Pungitius pungitius*). Anadromous species include Atlantic salmon (*Salmo salar*), Arctic char (*Salvelinus alpinus*), rainbow smelt (*Osmerus mordax*), Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*), and brook trout (*Salvelinus fontinalis*). Migratory species that spawn in Gilbert Bay include: capelin (*Mallotus villosus*), American sand lance (*Ammodytes americanus*), and lumpfish (*Cyclopterus lumpus*). Offshore spawning white hake (*Urophycis tenuis*) and offshore spawning Atlantic cod may use Gilbert Bay as a nursery area. Species which migrate into Gilbert Bay to feed include: Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), and Atlantic cod migrating inshore from the continental shelf (Wroblewski *et al.*, 2007).

Sonic tracking experiments indicate that Atlantic cod in Gilbert Bay have a strong homing tendency and remain in the bay all year round despite unrestrained access to the open ocean (Green and Wroblewski, 2000). Atlantic cod in Gilbert Bay have a relatively slow growth rate (Smedbol, 1999; Ruzzante *et al.*, 2000; Morris and Green, 2002) and, as a result, relatively lower reproductive potential compared with the Atlantic cod found on the Labrador continental shelf (Smedbol, 1999; Ruzzante *et al.*, 2000; Morris and Green, 2002). Unlike grayish offshore Atlantic cod, Gilbert Bay cod are reddish brown to golden in coloration, likely due to a carotenoid-rich diet of invertebrates (Gosse and Wroblewski, 2004). Examination of the stomach contents of Gilbert Bay cod indicates that their diet is mostly invertebrates (scallops, mussels, brittle stars, crab, shrimp, sea urchins, etc.) rather than fish (Morris and Green, 2002).

1.3 The Gilbert Bay MPA management zones

In 2005, the Gilbert Bay MPA was created to protect the local cod population and its habitat. The MPA has a management plan where the bay is divided into three management zones (Figure 1.3). Zone 1 has the highest level of protection because it is considered to be the spawning and overwintering ground of the cod (Green and Wroblewski, 2000; Morris and Green, 2002). Zone 2 is an important feeding ground and secondary spawning area, and has the second highest level of protection. Zone 3 is an important feeding area for cod during the summer and fall. Based on MPA regulations, no commercial fishing for Atlantic cod is allowed within the MPA. However, the

Regulations allow for the possibility of a recreational/food fishery for cod in Zone 3. Based on the tag-recapture method, Morris *et al.* (2003) estimated the abundance of resident Atlantic cod in Gilbert Bay to be $\leq$ 70 tons. To manage a recreational/food fishery in Gilbert Bay, it is essential to know the sustainable level of cod harvest. This requires information on the annual production of cod and the ecosystem carrying capacity for cod. Although the biology and movement of cod in Gilbert Bay have been well studied (Green and Wroblewski, 2000; Ruzzante *et al.*, 2000; Morris and Green, 2002), the annual production of Atlantic cod and the ecosystem carrying capacity for Atlantic cod in the bay have not been investigated.

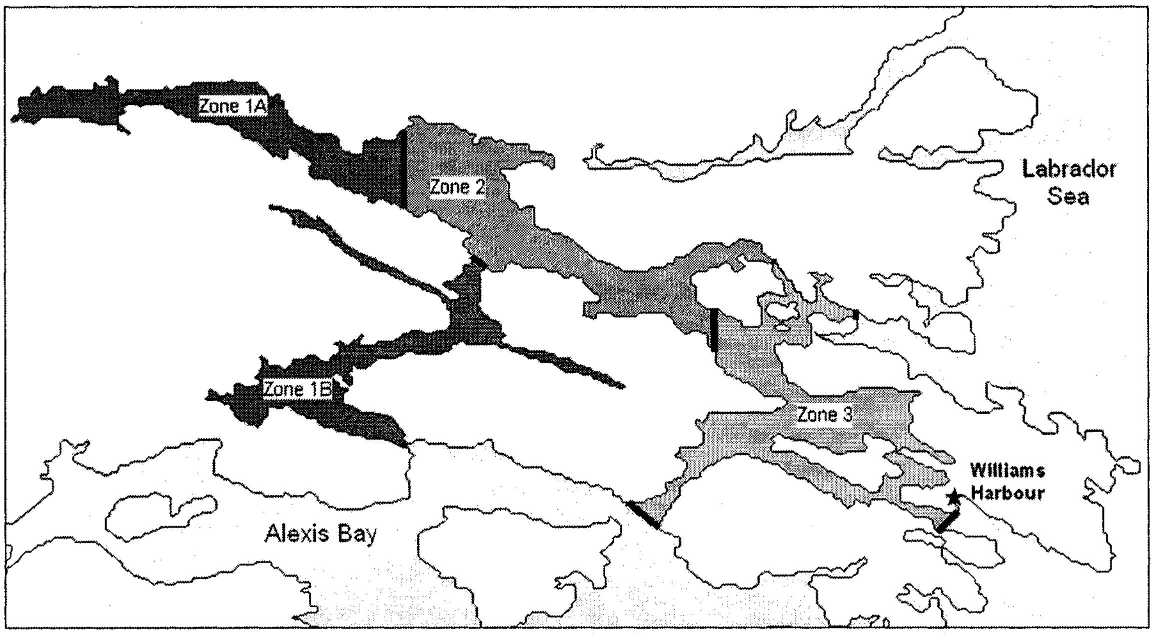


Figure 1.3 Map of the three management zones of Gilbert Bay Marine Protected Area.

It is well known that fish production in the sea is related to primary production (Ryther, 1969; Pauly and Christensen, 1995; Ware, 2000; Harrison and Parsons, 2000; Ware and Thompson, 2005). In Chapter 2, I estimate the annual resident fish production and the ecosystem carrying capacity for Gilbert Bay cod by examining a range of possible primary production values for the bay. Although food limitation is an important factor determining the ecosystem carrying capacity for the cod population, habitat availability is also considered. In Chapter 3, I explore the habitat availability for juvenile cod in Gilbert Bay by examining the bottom substrate at three sites in the main arm of the bay and in The Shinneys (Figure 1.1). In Chapter 4, I use the age-structured Leslie matrix model (Leslie, 1945) to investigate the population dynamics for Atlantic cod in Gilbert Bay and to project its rebuilding time.

Chapter 2 Resident Fish Production and Ecosystem Carrying Capacity for Atlantic Cod in Gilbert Bay

2.1 Introduction

Knowledge of the annual fish production and the ecosystem carrying capacity in a marine area is essential to fisheries resource conservation. Research has shown that fish production is related to the primary production in the sea through food chain dynamics (Ryther, 1969; Pauly and Christensen, 1995; Ware, 2000; Harrison and Parsons, 2000; Ware and Thompson, 2005). Ware and Thompson (2005) found that for the Northeast Pacific the alongshore variation in retained primary production is highly correlated with the alongshore variation in long term annual catch of resident fish (tons km^{-2} yr^{-1}).

In this chapter, I will use a bottom-up approach (Ware and Thompson, 2005) to estimate the resident fish production and the ecosystem carrying capacity for Atlantic cod in Gilbert Bay.

2.1.1 Primary production and fish production

The bottom-up approach is based on the fact that the long-term fish production and ecosystem carrying capacity are mainly controlled by primary production. Primary production is the amount of organic material produced by the process of photosynthesis, which converts sunlight energy into energy stored in chemical bonds within plant tissue. Other than production by marine macrophytes, the base of the marine food chain is phytoplankton. The feeding position of an organism in a food chain is called its trophic level. In the marine ecosystem, phytoplankton is the first trophic level, followed by herbivorous zooplankton and carnivorous fish. Only a small fraction of the primary production is transferred to the next higher trophic level due to incomplete utilization and metabolic losses. The fraction of the production transferred from one trophic level to the next is called the transfer efficiency. Figure 2.1 shows the simple food chain pyramid in the sea.

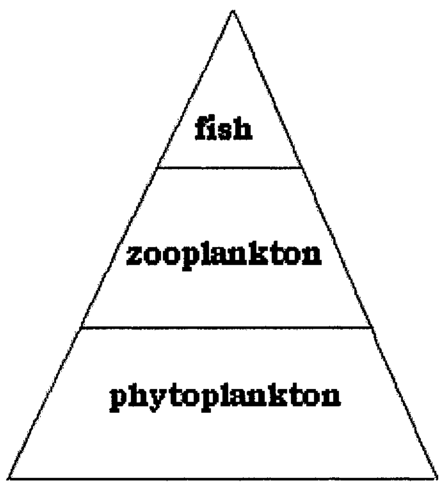


Figure 2.1 The simple food chain pyramid in the sea. As the trophic level increases, the biomass of the organisms in the trophic level decreases.

Annual fish production is the total fish biomass produced in a specific area every year. Numerous attempts have been made to relate fish production to the primary production in the sea (Ryther, 1969; Pauly and Christensen, 1995; Ware, 2000; Ware and Thompson, 2005). Besides the amount of primary production, there are other important factors that can affect the annual fish production, e.g. mean trophic level of fish within the area and efficiency of the production transfer from one trophic level to another (Mills and Fournier, 1979; Pauly and Christenson, 1995; Ware, 2000). The trophic level for a fish species may vary from region to region depending on its prey items (Pauly *et al.*, 2001; 2002). Mills and Fournier (1979) demonstrated that the structure of the ecosystem must be taken into account when estimating fish production in different ocean regions. Pauly and Christenson (1995) also considered ecosystem trophic levels while estimating the primary production required to sustain global fisheries. Here I followed the methodology of Harrison and Parsons (2000) in using primary production and trophic level to get a first order calculation of the potential resident fish production in Gilbert Bay.

2.1.2 Ecosystem carrying capacity

A population cannot grow infinitely since resources are finite. As a population grows the per capita share of resources will decrease. Eventually there is a limit to the number of individuals (and their total biomass) that an ecosystem can support, which we call the ecosystem carrying capacity. Marine ecosystem carrying capacity for fish refers to the maximum fish biomass that a specific area can support over a relatively long period of time. It plays an important role in fishery management by providing the theoretical upper limit of fish biomass in a particular marine area. The carrying capacity varies for different fish species and can change over time. Waters (1977) found that the ratio of annual production of a fish species to its biomass (P/B) is approximately constant. In general, the P/B ratios are higher for small organisms than large ones (Ware, 2000). Given the maximum annual fish production (P) an ecosystem can produce, we can estimate the carrying capacity for the specific species (B).

2.2 Materials and methods

2.2.1 Data source

To date, four species are considered to be year-round residents of Gilbert Bay: Atlantic cod, Greenland cod, short horn sculpin, and winter flounder (Wroblewski *et al.*, 2007). The data from the fish fauna survey at Site 1, Site 2, and Site 3 conducted by Wroblewski *et al.* (2007) during the ice-free season of 2004 were analyzed to estimate the proportion (by weight) of each resident fish species. The three sites are chosen based on suitability for seining, and location in the three management zones of the MPA (Figure 2.2). Three different sampling gears used at each standardized sampling site in the 2004 survey are: 10 m by 1.5 m beach seine, 25 m by 1.5 m beach seine (both with 10 mm stretch mesh) and 30 m by 3.7 m gillnet (with 7.6 cm stretch mesh). The 10 m by 1.5 m seine was hauled parallel to the shoreline by two people to sample water <1.5 m deep. The 25 m by 1.5 m seine was deployed 30 to 60 m from the shoreline to sample water depths of 0-5 m. The gillnet was set during the day, fished overnight, and retrieved the following day to sample water depths 3-15 m (Wroblewski *et al.*, 2007).

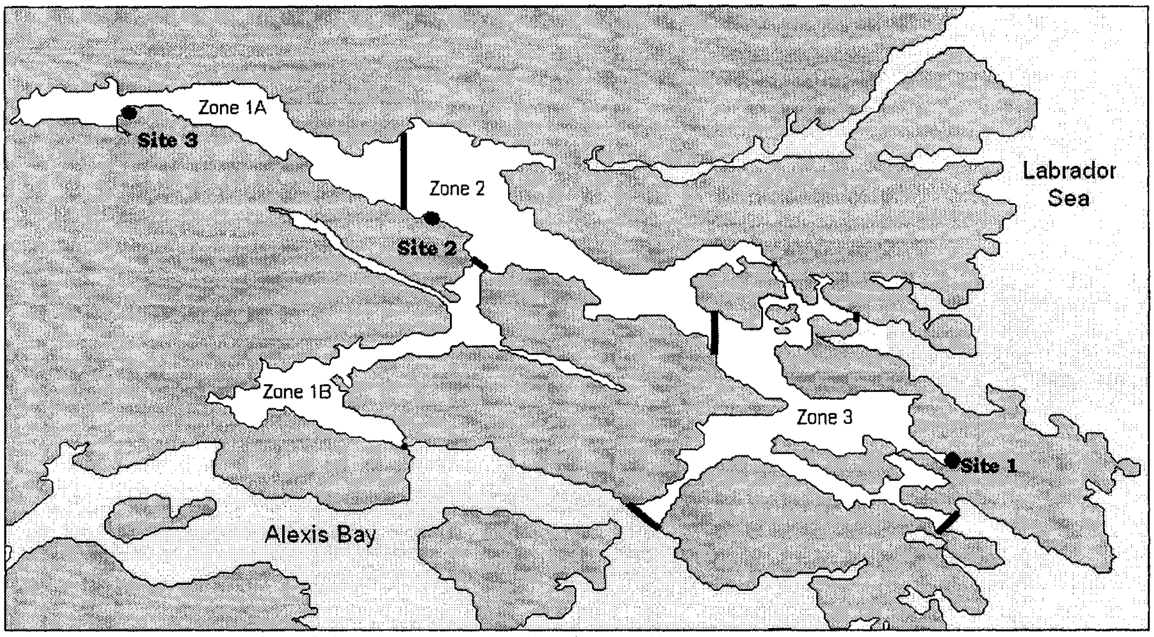


Figure 2.2 The location of the three standardized sampling sites.

2.2.2 Fish production estimation for resident fish species

According to the bottom-up approach, fish production in an ecosystem is controlled largely by the primary production within the ecosystem. Gilbert Bay is nearly isolated from the Labrador Sea and Alexis Bay (Figure 1.1). In this study, I considered Gilbert Bay to be essentially a closed system. Local primary production and fish production are not significantly influenced by fluxes across the boundaries of the bay.

A relationship between the total annual primary production (P_P, ton year^{-1}) and annual fish production (F_P, ton year^{-1}) is:

$$F_p = F_a \times P_p \times TE^{(TL-1)} \quad (1)$$

where F_a= 0.4 is the fraction of the total primary production available to the food chain, TE is transfer efficiency, and TL is fractional trophic level of the fish species (Ware, 2000). Phytoplankton represents the first trophic level, TL=1. Ware (2000) assumed a 25% transfer efficiency (TE) in the North Sea for the transfer from trophic level 1 to trophic level 2. The TE among the rest of the trophic levels varies among different ecosystems. Therefore, equation (1) can be rewritten as:

$$F_p = 0.4 \times P_p \times 0.25 \times TE^{(TL-2)} \qquad (2)$$

While Slobodkin (1961) states that TE may be 10%, Ryther (1969) assigned 15% to the coastal province. Pauly and Christensen (1995) re-estimated the mean transfer efficiency between trophic levels and suggested a value of 10%. I used 10% transfer efficiency in my calculations.

Prasad and Haedrich (1994) report a primary production rate of 194 g C m^{-2} $year^{-1}$ on the Grand Banks off Newfoundland. Cardoso (2004) estimated that the primary production rate of the Labrador Shelf varied from 212 g C m^{-2} $year^{-1}$ in the 1970s to 200 g C m^{-2} $year^{-1}$ in the 1990s. Ware (2000) calculated a primary production rate for the North Sea as 200 g C m^{-2} $year^{-1}$. Since Gilbert Bay is ice covered for several months of the year, I assumed a primary production rate of 190 g C m^{-2} $year^{-1}$ in Gilbert Bay. Considering the uncertainty of primary production rate in the bay, I considered the range of 110 g C m^{-2} $year^{-1}$ to 250 g C m^{-2} $year^{-1}$ to explore a variation of fish production. A 9:1 ratio was set for the conversion of wet weight to carbon (Pauly and Christensen, 1995).

The mean trophic level of resident fish in Gilbert Bay was calculated from the trophic levels of the four residents in the bay by using:

$$TL = \sum_{i=1}^{k} (PF_i \times TL_i) \qquad (3)$$

where PF_i is the proportion of the fish species i, TL_i is the trophic level of fish species i, and k is the total number of the resident fish species.

The trophic level for Atlantic cod was calculated from the fish's diet in the bay. Stomach contents data (Morris, 2000; Morris and Green, 2002) during different time periods from different parts of the bay were averaged for this species. The equation from Pauly *et al.* (2001) was used to calculate the trophic level (TL_i) for Gilbert Bay cod:

$$TL_i = 1 + \sum_{j=1}^{n} D_{ij} TL_j \tag{4}$$

where D_{ij} is the proportion of diet occurrence j for resident fish species i, n is the number of diet components, TL_j is the trophic level for prey j. The trophic levels of the species found in Atlantic cod stomach in Gilbert Bay were taken from Pauly and Christensen (1995). The trophic levels for Greenland cod, short horn sculpin, and winter flounder are shown in Table 2.1.

Table 2.1 The trophic levels of Greenland cod, short horn sculpin, and winter flounder used in this calculation.

Species	Trophic level	Region	Reference
Greenland cod	3.5	Saqvaqjuac Inlet	Mikhail and Welch, 1989
short horn sculpin	3.9	Scotian Shelf	Bowman *et al.*, 2000
winter flounder	3.4	Scotian Shelf	Bowman *et al.*, 2000

The annual fish production calculated here includes all resident fishes in Gilbert Bay (Table 2.2). I partitioned the theoretical total fish production into the four most abundant (biomass) resident fish species. The overall proportions of each resident fish species were estimated mainly from the catch per unit effort (CPUE) data for gillnet sampling. The CPUE data from 10 m and 25 m beach seines were used to further refine the estimate of the proportion of winter flounder and sculpin. To convert the fish length to biomass, the weight (g)–length (cm) relationships for all four resident fish species are provided in Table 2.3.

Table 2.2 Mean catch per unit effort for each species using a 30 m by 3.7 m gillnet (7.6 cm stretch mesh) set overnight, a 10 m by 1.5 m seine (10 mm stretch mesh), and a 25 m by 1.5 m seine (10 mm stretch mesh) during the daytime. Data source: Wroblewski *et al.* (2007)

Species	30 m by 3.7 m gillnet (number caught per hour)	10 m by 1.5 m seine (number caught per 100 m towed)	25 m by 1.5 m seine (number caught per haul)
C. harengus	0.026	0	0
S. salar	0.004	0	0.023
S. alpinus	0.024	0	0.091
S. fontinalis	0	0.023	0
O. mordax	0	0.365	0
M. villosus	0.026	152.1	1023
G. morhua	0.13	0	0.023
G. ogac	0.12	0.064	2.159
G. aculeatus	0	1.846	0.069
G. wheatlandi	0	0.126	0.023
A. quadracus	0	0.037	0.023
Z. americanus	0.005	0.339	0
L. maculates	0	0.023	0
P. gunnellus	0	0.951	0.227
A. americanus	0	0.854	58.39
H. americanus	0	0.023	0
M. scorpius	0.066	1.788	0.477
C. lumpus	0	1.112	0.568
P. americanus	0.002	0.392	0.182

Table 2.3 List of parameters used in standard length-total length and weight-length relationships for the resident fish species. (total length) = a + b * (standard length), weight = c * (total length)^d.

Common Name	a	b	c	d	Reference
Atlantic cod	0	1.07	0.0059	3.11	Morris and Green, 2002
Greenland cod	0	1.18	0.0117	3	Mikhail and Welch, 1989
short horn sculpin	0	1.19	0.0126	3.12	Bowman *et al.*, 2000
winter flounder	0	1.28	0.0213	3	Bowman *et al.*, 2000

2.2.3 Ecosystem carrying capacity calculation

Described by Ware (2000), in a steady state ecosystem the fish production to biomass ratio (F_P / B) decreases with body size (W, g):

$$F_p / B = qW^{-0.25} \quad (5)$$

where q, the species-specific parameter, is equal to 2.2 for Atlantic cod (Ware, 2000). Given the maximum annual fish production the ecosystem can produce (F_P), one can get the maximum fish biomass (B) or carrying capacity from equation (5). Gilbert Bay cod has a smaller length-at-age than offshore cod (Smedbol, 1999; Ruzzante *et al.*, 2000; Morris and Green, 2002), and consequently a lower average weight-at-age. The average weight for Gilbert Bay cod was calculated from Atlantic cod caught in Gilbert Bay in 1996 and 1997 (Appendix A and B in Smedbol, 1999), which is 1128 gram.

2.2.4 Parameter sensitivity analysis

This study used bottom-up ecosystem trophic dynamics to determine the fish production. There are many factors that can influence this calculation, such as trophic level, transfer efficiency, and primary production. The values of these factors vary from one ecosystem to another. A change of $\pm$10% was placed on initial parameter values (trophic level = 3.48, transfer efficiency = 10%, primary production rate= 190 g C m^{-2} $year^{-1}$) to compare the sensitivity of the calculation to the factors: trophic level, transfer efficiency, and primary production.

2.3 Results

2.3.1 Mean trophic level of resident fish in Gilbert Bay

The 2004 standardized survey with gillnet found that Greenland cod accounted for 46.1% of the total fish biomass caught. Atlantic cod contributed 36.8% of the biomass. Short horn sculpin and winter flounder have the proportions of 16.6% and 0.5%, respectively (Table 2.4).

Table 2.4 The CPUE (by number and weight), mean standard length (SL), mean weight, and proportions by weight of the main resident fish species caught during the 2004 standard survey with a gillnet (7.6 cm stretch mesh) in Gilbert Bay. Data sources: Kryger (2004); Wroblewski *et al.* (2007).

Species	Number of fish caught per hour	Mean SL (cm)	Mean weight (g)	Gram of fish caught per hour	Proportion by weight (%)
Atlantic cod	0.13	36.6	530.5	69.0	36.6
Greenland cod	0.12	33.7	735.7	88.3	46.9
short horn sculpin	0.066	24.3	456.2	30.1	16.0
winter flounder	0.002	21.0	413.7	0.8	0.4

However, gillnets are not efficient at catching fish species living on the bottom, such as winter flounder. The survey with 10 m and 25 m beach seines suggest that winter flounder is at least as abundant as sculpin (Table 2.5 and 2.6). So, I adjusted the catch of winter flounder to the same weight as sculpin caught by gillnet and re-calculated the potential proportion of the four major resident species. The results show that Atlantic cod and Greenland cod accounted for most of the fish biomass in Gilbert Bay (72%), short horn sculpin and winter flounder evenly shared the rest of the 28% (Table 2.7).

Table 2.5 The CPUE (by number and weight), mean standard length (SL), mean weight, and proportions by weight of the main resident fish species caught during the 2004 standard survey with a 10 m beach seine (10 mm stretch mesh) in Gilbert Bay. Data sources: Kryger (2004); Wroblewski *et al.* (2007).

Species	Number of fish caught per 100 m towed	Mean SL (cm)	Mean weight (g)	Gram of fish caught per 100 m towed	Proportion by weight
Atlantic cod	0	0	0	0	0
Greenland cod	0.064	13	42.2	0.04	7.2
short horn sculpin	1.788	7.4	11.2	0.31	53.5
winter flounder	0.392	13.7	114.9	0.23	39.3

Table 2.6 The CPUE (by number and weight), mean standard length (SL), mean weight, and proportions by weight of the main resident fish species caught during the 2004 standard survey with a 25 m beach seine (10 mm stretch mesh) in Gilbert Bay. Data sources: Kryger (2004); Wroblewski *et al.* (2007).

Species	Number of fish caught per haul	Mean SL (cm)	Mean weight (g)	Gram of fish caught per haul	Proportion by weight
Atlantic cod	0.02	9.8	8.8	0.18	0.1
Greenland cod	2.16	7.3	7.5	16.15	9.5
short horn sculpin	0.48	12	50.5	24.23	14.2
winter flounder	0.18	25.3	723.4	130.21	76.2

Table 2.7 Proportions of the four resident fish species in Gilbert Bay assumed in this study based on the 2004 standardized survey.

Species	Proportion by weight (%)
Atlantic cod	32
Greenland cod	40
short horn sculpin	14
winter flounder	14

The Atlantic cod in the bay feed primarily on benthic invertebrates (Morris, 2000; Morris and Green, 2002). The Gilbert Bay cod stomachs sampled in 1998-2000 contained a very small portion of the diet as fish (Morris and Green, 2002). Morris and Green (2002) found that in The Shinneys the most frequently encountered food items of Atlantic cod were crab, shrimp, brittle stars, and amphipods. Fish accounted for 6% of all the foods found in stomachs sampled. In the main arm of the bay, scallop (36%) was the major food type. Crab, shrimp, brittle stars, and scallop made up 85% of the Atlantic cod food sources. Piscivorous prey accounted for only 7% of the stomach content. Gosse and Wroblewski (2004) concluded that the reddish brown to golden colouration of Gilbert Bay cod is due to a carotenoid-rich invertebrate diet. This suggests Gilbert Bay cod feed at low trophic levels.

From stomach content data (Morris and Green, 2002); the trophic level of Atlantic cod in The Shinneys and in the Gilbert Bay main arm were calculated to be 3.35 and 3.32 respectively (Table 2.8).

Table 2.8 The calculation of trophic level of Gilbert Bay cod in The Shinneys and Gilbert Bay main arm. The trophic levels of the major prey species found in Atlantic cod stomachs were based on Pauly and Christenson (1995).

Prey	Trophic level (TL)	The proportion of diet occurrence in Gilbert Bay cod stomachs (D)		D × TL	
		The Shinneys	Main arm	The Shinneys	Main arm
Crab	2.4	21%	17%	0.504	0.408
Shrimp and mysids	2.6	19%	20%	0.494	0.52
Brittle stars	2.1	14%	12%	0.294	0.252
Amphipods	2.4	16%	3%	0.384	0.072
Sea urchins	2.4	2%	2%	0.048	0.048
Sea cucumber	2.1	2%	2%	0.042	0.042
Fish	2.8	6%	7%	0.168	0.196
Gastropods	2.1	6%	0	0.126	0
Scallop	2.1	0	36%	0	0.756
Polychaetes	2.1	9%	1%	0.189	0.021
Bivalves	2.1	5%	0	0.105	0
Mean trophic level =1+Σ(D × TL)				**3.35**	**3.32**

As a result, the mean trophic level of Gilbert Bay cod was assigned as 3.3. This is lower than 4.1, the trophic level of Atlantic cod in the North Sea (Greenstreet, 1995), but agrees with the trophic level of Atlantic cod on the Newfoundland and Labrador continental shelf (Sherwood and Rose, 2004). A stable isotope analysis of the Newfoundland and Labrador continental shelf food web by Sherwood and Rose (2004) suggests that most Newfoundland and Labrador continental shelf fish feed mainly on low trophic level prey (e.g. shrimp and zooplankton), and they estimated a trophic level of 3.3 for shelf Atlantic cod.

Although the trophic level of short horn sculpin is as high as 3.9, it only accounted for 14% of the fish biomass. The mean trophic level of Gilbert Bay resident fish species mainly depends on the relative abundance of the species and their trophic level. In this case, the mean trophic level for resident fishes (all four species) in Gilbert Bay was calculated as 3.48 (Table 2.9).

Table 2.9 The calculation of mean trophic levels of Gilbert Bay resident fish.

Species	**Proportion by weight (%) (PF)**	**Trophic level (TL)**	**PF × TL**
Atlantic cod	32	3.3	1.06
Greenland cod	40	3.5	1.40
short horn sculpin	14	3.9	0.55
winter flounder	14	3.4	0.48
Mean trophic level = Σ (PF × TL)			**3.48**

2.3.2 Annual fish production and carrying capacity for Atlantic cod

Converted to wet weight, the primary production rate of 190 g C m^{-2} $year^{-1}$ is equivalent to a total primary production of 102,600 tons per year in Gilbert Bay:

wet weight =190 g C m^{-2} $year^{-1}$ ×60 km^2 × $(1000\ m/km)^2$ × 9 g/gC × 1 ton/10^6g

From equation (2), the resident fish production in Gilbert Bay was then estimated to be 340 tons per year:

$$F_p = 0.4 \times P_p \times 0.25 \times TE^{(TL-2)} = 0.4 \times 102{,}600 \text{ tons} \times 0.25 \times 0.1^{(3.48-2)} = 340 \text{ tons}$$

Based on the current ecosystem conditions, the partition of the theoretical total fish production for the four main resident fish species in Gilbert Bay is: 109 tons per year of Atlantic cod, 136 tons per year of Greenland cod, 48 tons per year of short horn sculpin, and 48 tons per year of winter flounder. The carrying capacity of the Gilbert Bay cod was calculated to be 286 tons.

$$B = F_p / (qW^{0.25}) = 109 / (2.2 \times 1128^{-0.25}) = 286 \text{ tons}$$

Considering different levels of primary production rate from 110 g C m^{-2} $year^{-1}$ to 250 g C m^{-2} $year^{-1}$, the fish production was calculated to be in the range from 197 tons to 447 tons per year. The partition of the theoretical total annual fish production for the four main resident fish species is: Atlantic cod (63-143 tons y^{-1}), Greenland cod (79-179 tons y^{-1}), short horn sculpin (28-63 tons y^{-1}), and winter flounder (28-63 tons y^{-1}); the carrying capacity of the Atlantic cod ranges from 166 tons to 377 tons (Table 2.10).

Table 2.10 Annual fish production of the four resident fish species, and the carrying capacity for Gilbert Bay cod with primary production rate ranging from 110 g C m^{-2} $year^{-1}$ to 250 g C m^{-2} $year^{-1}$ (Trophic level = 3.48, transfer efficiency = 10%).

Primary Production rate (g C m^{-2} y^{-1})	Fish production (ton y^{-1})					Gilbert Bay cod carrying capacity (ton)
	Total	Gilbert Bay cod	Greenland cod	short horn sculpin	winter flounder	
110	197	63	79	28	28	166
130	232	74	93	33	33	196
150	268	86	107	38	38	226
170	304	97	122	43	43	256
190	340	109	136	48	48	286
210	376	120	150	53	53	317
230	411	132	165	58	58	347
250	447	143	179	63	63	377

Using tag-recapture methods Morris *et al.* (2003) estimated the population of Gilbert Bay cod to be ≤ 70 tons in 2003. Considering different levels of primary production rate (Table 2.10), the biomass of 70 tons is approximately 100 to 300 tons less than the carrying capacity of the bay estimated from primary production and trophic dynamics.

2.3.3 Parameter sensitivity analysis

The parameter sensitivity analysis shows that if a fluctuation of ±10% were put on TL, TE, and Pr, the average changes in resident fish production would be 605 tons, 100 tons, and 68 tons respectively (Figure 2.3). The effect of the trophic level upon the estimation of annual fish production is 10 and 6 times higher than that of primary production and transfer efficiency (Table 2.11 and Figure 2.3). The result suggests that TL plays a more important role in estimating the carrying capacity than TE and Pr.

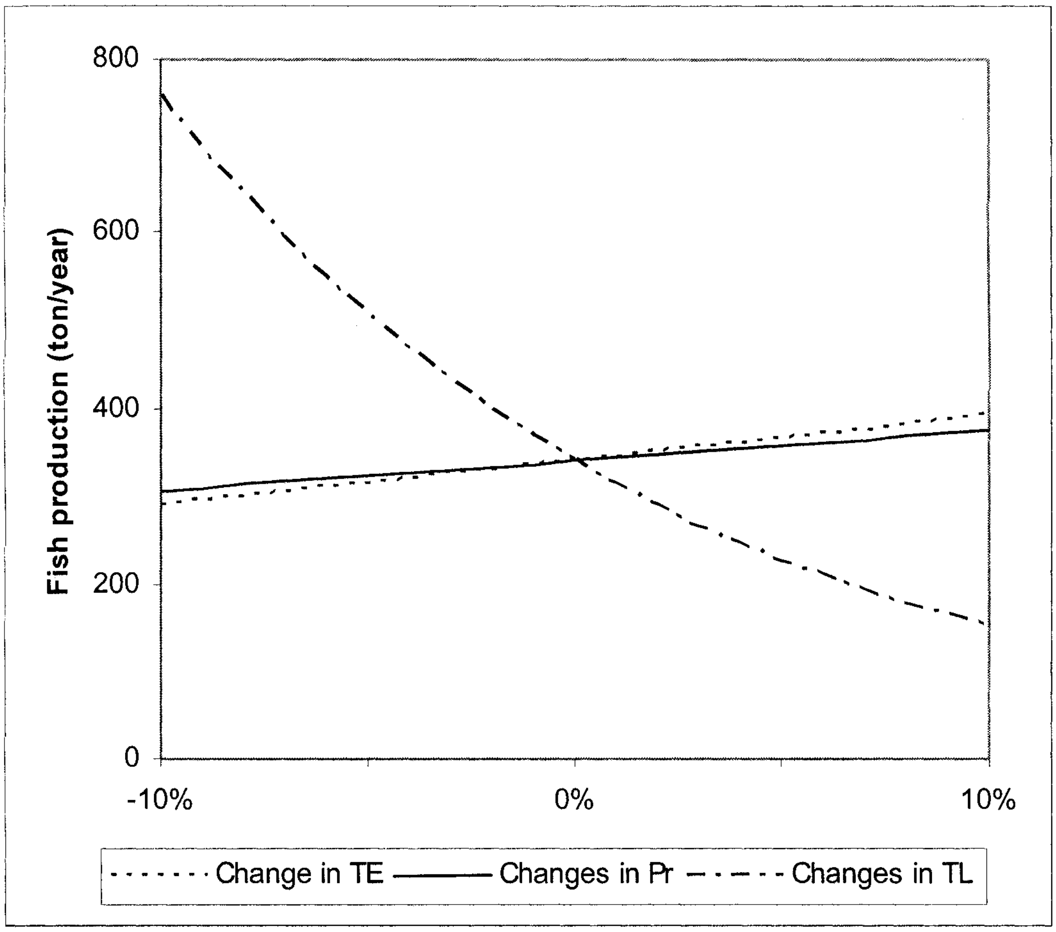


Figure 2.3 Comparison of the changes of resident fish production in Gilbert Bay when a change of ±10% was put on the initial values of the three common factors: trophic level of resident fish species (TL = 3.48), transfer efficiency (TE = 10%), and primary production rate (Pr = 190 g C m^{-2} $year^{-1}$).

Table **2.11** The variation of annual fish production based on different parameters. A fluctuation of ±10% was placed on the initial values of the three common factors: trophic level (TL = 3.48), transfer efficiency (TE = 10%), and primary production rate (Pr = 190 g C m^{-2} $year^{-1}$).

Annual fish production		TE=9%			TE=10%			TE=11%		
		Primary production rate (g C m-2 year-1)			Primary production rate (g C m-2 year-1)			Primary production rate (g C m-2 year-1)		
		171	**190**	**209**	**171**	**190**	**209**	**171**	**190**	**209**
Trophic level	**3.132**	605	672	739	681	757	833	759	843	928
	3.48	262	291	320	306	340	374	352	391	430
	3.828	113	126	138	137	152	168	163	181	200

2.4 Discussion

2.4.1 Trophic level and fish production

From the parameter sensitivity analysis we can see that for different ecosystems with the same area and primary production, the difference in resident fish production could be significantly associated with mean trophic level. In other words, higher primary production does not always lead to higher fish production, except when comparing the regions with similar structure in ecosystems. For example, the primary production is 17% higher on average on the Nova Scotian Shelf than in the North Sea. However the apparent zooplankton and macrobenthos production on the Scotian Shelf is 31% lower than in the North Sea and the overall fish catch from the Scotian shelf and slope is about 47% lower per unit area than the catch in the North Sea (Mills and Fournier, 1979).

This research is the first attempt to estimate the fish production in Gilbert Bay based on the structure of the ecosystem. It is also the first time that the trophic level of Gilbert Bay cod was estimated. The trophic level of Gilbert Bay cod (TL = 3.3) is the same as Atlantic cod feeding on the Newfoundland and Labrador continental shelf (Sherwood and Rose, 2004), but that value is likely lower than the historical value when capelin was the most important prey of offshore Atlantic cod (Lilly and Rice, 1983).

The annual fish production and carrying capacity for Gilbert Bay cod were estimated based on the current ecosystem conditions (resident fish species, trophic level, primary production, and so on). The combination of resident fish species and mean trophic level of fish may change over time due to natural ocean regime shifts (Hardie *et al.*, 2006) or fishing activity (Pauly *et al.*, 1998). The primary production may change due to terrestrial input and climate change. Any change of these ecosystem conditions might affect the results. For example, if the proportion of Gilbert Bay cod among the resident fish increases, the annual production of Gilbert Bay cod and the carrying capacity for Gilbert Bay cod would increase correspondingly based on the method used there.

2.4.2 Comparison with other estimates

Pauly and Christenson (1995) used the same bottom-up approach as I used, when they estimated the primary production required (PPR, g C year^{-1}) for the fish catch (Catch, g year^{-1}): PPR = (Catch/9)*$10^{(TL-1)}$, where TL is the trophic level of fish. The estimates are based on a 9:1 ratio of wet weight to carbon and 10% transfer efficiency per trophic level. Thus, if we know the primary production (P_p, g C year^{-1}) available in an area, we can calculate the fish production (F_p, g year^{-1}) that it could support by applying the revised equation ($F_p = 9*P_p / 10^{(TL-1)}$). This equation is the same as equation (2). Considering the mean trophic level of 3.48, the annual fish production in Gilbert Bay was calculated to be in range of 197 tons to 447 tons according to the primary production rate of 110 g C m^{-2} year^{-1} to 250 g C m^{-2} year^{-1}, which are the same as what I obtained.

Chlorophyll-*a* (chl-*a*) concentration data from Sea-viewing Wide Field-of-view Sensor (SeaWiFs) has been widely used to estimate primary production over global and local scales. Research carried out by Ware and Thompson (2005) found that there is a high correlation between the long term average catch (Y, tons km^{-2}) of resident fish and the mean annual chlorophyll-*a* concentration (chl-*a*, mg m^{-3}), such that Y = 0.436*chl-*a* – 0.38. I applied this equation to Gilbert Bay to compare the result with my calculation. The chl-*a* concentration was averaged from the biweekly SeaWiFS data from 1997 to 2002 provided by Dr. Guoqi Han, a research scientist at DFO. Figure 2.4 shows that the mean chl-*a* concentration along the Labrador coast near Gilbert Bay was about 3 mg m^{-3}. This value is higher than the satellite detectable chlorophyll value (0.41 mg m^{-3}) over the Grand Banks calculated by Prasad and Haedrich (1994).

Assuming the chl-*a* concentration in Gilbert Bay is 3 mg m^{-3}, in Gilbert Bay the long-term yield of resident fish will be 57 tons as calculated from the equation given by Ware and Thompson (2005). Considering a range of 0.25 to 0.4 for the catch to production ratio (Ware, 2000), the resident fish production might be 142 to 228 tons. The result is lower than my result presented earlier, which is 340 tons per year of the resident fish production in Gilbert Bay. This might be because of the difference in the fish community structure between these two regions. The equation Y = 0.436* chl-*a* – 0.38 derived for the large-scale Northeast Pacific may not be suitable for a coastal region of the North Atlantic, as we expect different food chain between these two regions. In other words, the mean trophic levels of the resident fish species in the two areas may be different. This again emphasizes that, as well as primary production, ecosystem structure should be taken into account while determining the fish production from the bottom-up approach.

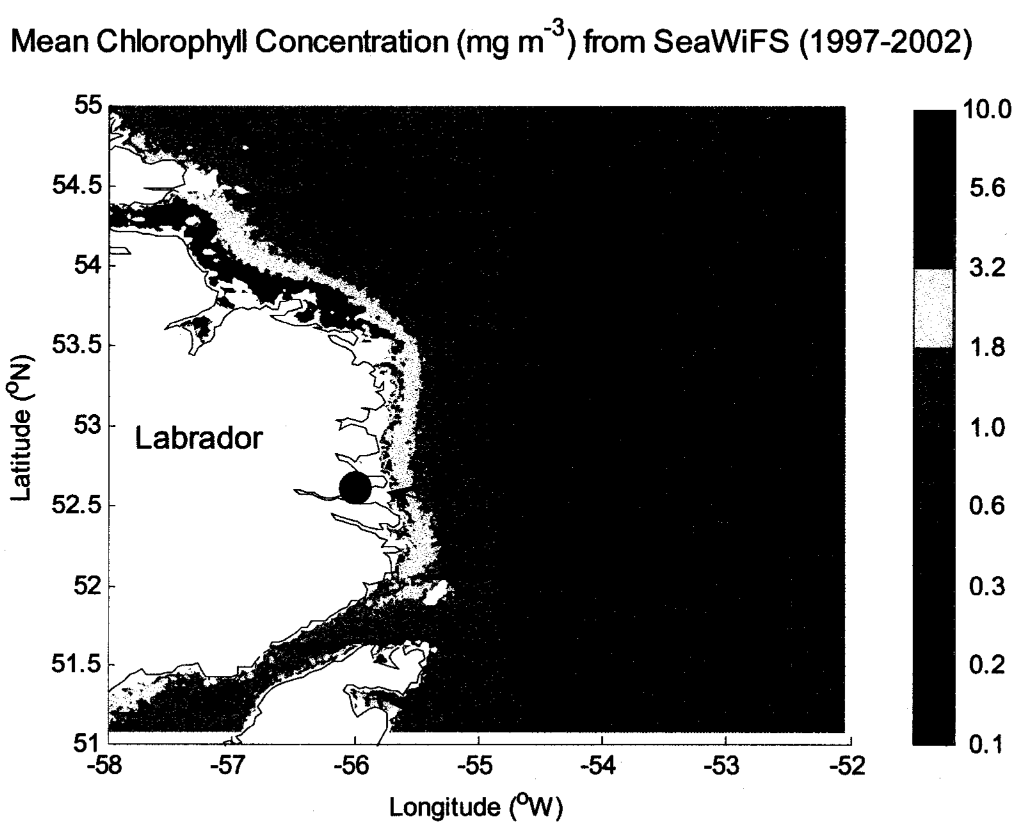


Figure 2.4 Mean chlorophyll-*a* concentration along the Labrador coast near Gilbert Bay using SeaWiFS data provided by Dr. Guoqi Han at DFO.

Historically, a spring fishery for Atlantic cod occurred in Gilbert Bay. About 23 metric tons of Gilbert Bay cod were caught per year (Wroblewski, 1998). Considering a ratio of 0.09 catch to biomass for Atlantic cod (Ware, 2000), the Gilbert Bay cod biomass would be 256 metric tons at that time. This value is very close to 286 tons, the estimated carrying capacity for Gilbert Bay cod assuming a primary production rate of 190 g C m^{-2} $year^{-1}$.

2.4.3 The possible influence of adjacent ecosystems on Gilbert Bay fish production

When calculating the annual resident fish production and carrying capacity for Gilbert Bay cod, I considered Gilbert Bay to be a closed system with local primary production in the bay as the only source of primary production available. However, Gilbert Bay is not totally isolated from adjacent waters. The exchange of seawater among Gilbert Bay and the Labrador Sea and Alexis Bay may affect the fish production in Gilbert Bay. Nutrient, phytoplankton, and zooplankton carried in or out of Gilbert Bay by currents may alter the food source for fish in the bay. The effect increases with increasing gradients between the adjacent ecosystems. Further research is needed to investigate these exchanges.

The arrival of non-resident fish in the bay (Wroblewski *et al.*, 2007) may also affect the food available to resident fish in Gilbert Bay by either consuming or contributing to the food of resident species. The effect may not be significant due to the relatively low biomass or short period of appearance of the non-resident fish in Gilbert Bay. The migratory marine species which spawn in Gilbert Bay may represent an extra food source for the resident fish. For example, capelin and sand lance coming into Gilbert Bay for spawning may become the food of resident Atlantic cod, Greenland cod, sculpin, and winter flounder. However, the appearance of capelin is an unpredictable event (Wroblewski, *et al.*, 2007). At this point it is impossible to estimate how much extra food is imported into the bay by capelin. In contrast, anadromous species as well as the species that migrate into Gilbert Bay to feed may compete for the local food source with resident fish species. In other words, the presence of these species may decrease the resident fish production. Unfortunately, it is difficult to estimate how much the presence of these species will lower the resident fish production with little information available on their behavior and resident time in the bay.

Chapter 3 Habitat Limitation to the Production of Atlantic Cod in Gilbert Bay

3.1 Introduction

Besides food, the availability of suitable habitat may also affect fish production by way of increasing or decreasing the survival of the individual fish, especially in the early life-history stages. The most critical habitat characteristics for Atlantic cod are thought to be those requirements at the stage when cod have settled to the bottom in the first year of life. In contrast, the habitat requirements for adult Atlantic cod are more diverse. In Chapter 2, I have estimated the maximum resident fish production and the ecosystem carrying capacity for Atlantic cod in Gilbert Bay by considering food limitation. In this chapter I consider whether the availability of suitable habitat could limit the production of Atlantic cod in Gilbert Bay. For example, mature fish need a place to spawn; juveniles need shelter to hide from predators. If the habitat requirements are not met, the population cannot be maintained.

To date, 25 fish species have been found in Gilbert Bay, but do they all share the same habitat in the bay? What is the habitat for Atlantic cod in Gilbert Bay? How might habitat availability affect the growth of the cod population in Gilbert Bay? In Chapter 2, I estimated the maximum annual fish production in Gilbert Bay based on the primary production within this ecosystem. I partitioned the resident fish production and calculated ecosystem carrying capacity for Atlantic cod from trophic dynamics. I then discussed the potential effects of the presence of the non-resident fish species on my calculation. In this chapter I present data on the benthic habitat at three sites in the main arm of the bay to describe the habitat availability to fish species in Gilbert Bay, especially to Atlantic cod.

In October 2006, a field survey was conducted to ground-truth multibeam data collected in 2002 in Gilbert Bay. Information on fish present at Site 1, Site 2, and Site 3 (Figure 2.2) is available from the fish fauna survey conducted in 2004 (Wroblewski *et al.*, 2007). In this chapter, I will discuss the benthic habitat at these three sites and the fish species present in these habitats.

3.1.1 How might habitat availability limit fish production

What is a fish habitat? Orth and White (1993) defined fish habitat as follows:

> "Habitat for fish is a place—or for migratory fishes, a set of places—in which a fish, a fish population or a fish assemblage can find the physical and chemical features needed for life, such as suitable water quality, migration routes, spawning grounds, feeding sites, resting sites, and shelter from enemies and adverse weather. Although food, predators, and competitors *are not* habitat, proper places in which to seek food, escape predators, and contend with competitors *are* part of habitat, and a suitable ecosystem for fish includes habitat for these other organisms, as well".

Habitat requirements usually change with life stages. As Rice (2005) concluded, in general there are four factors that influence a fish in selecting a habitat: physical conditions of water, food, shelter, and reproduction. Physical conditions of water include water temperature, salinity, oxygen, etc. Water quality influences habitat selection by fish at all life stages. Whatever life stage, the fish must live in a habitat within its physiological tolerances. In the juvenile stage, fishes are usually found in complex habitats where predator efficiency is significantly reduced

(Mattila, 1992; Lindholm *et al.*, 1999, 2001). In the adult stage, fish seek a habitat with food availability. In the reproduction stage, fish seek a spawning habitat.

Habitat availability may affect fish production by affecting the survival of the individual fish, especially in the early life-history stages. A complex habitat, for example, may increase shelter availability for juveniles and decrease the predator efficiency more than does less complex habitat, thus reducing predation mortality. Evidence suggests that low survivorship in post-settlement juveniles is due to predation (Houde, 1987; Tupper and Boutilier, 1995). Research has shown that predator efficiency is generally reduced with increasing habitat complexity (Mattila, 1992; Tupper and Boutilier, 1995; Lindholm *et al.*, 1999). In coastal areas, young cod often associate with structurally complex landscapes. Tupper and Boutilier (1995) demonstrated that survival of juvenile Atlantic cod positively correlate with habitat complexity in St. Margaret's Bay, Nova Scotia.

3.2 Fish Habitat and fish assemblage in Gilbert Bay

3.2.1 Fish habitat overview in Gilbert Bay

Gilbert Bay has the geographical features of a shallow fjord and estuary. Exposed bedrock occurs along most of the Gilbert Bay shoreline (Figure 3.1). Retreating glaciers 11,000 – 14,000 years before the present (Clark and Fitzhugh, 1992) left boulders scattered along the shoreline. Beaches of cobbles, pebbles, and coarse sand can be found at several locations in the bay (Wroblewski *et al.*, 2007).

A survey of the fish fauna in Gilbert Bay was conducted in 2004. Three sites were repeatedly sampled (Site 1, Site 2, and Site 3) along the Gilbert Bay main arm (Wroblewski *et al.*, 2007). There were 22 other sites in the bay where fishes were collected in exploratory sampling by non-standardized methods (Kryger 2004). Atlantic cod were collected at three of these 22 exploratory sampling sites, designated as Site 4, 5, and 6 in Figure 3.2. Cod were collected by monofilament gillnet (2.4 m by 50 m with 2.4 cm stretch mesh) at Site 5 in The Shinneys. Cod were collected by hook and line at Site 4 in River out and Site 5 in Fox Cove Tickle near Williams Harbour.

Figure 3.1 Exposed bedrock along the Gilbert Bay shoreline.

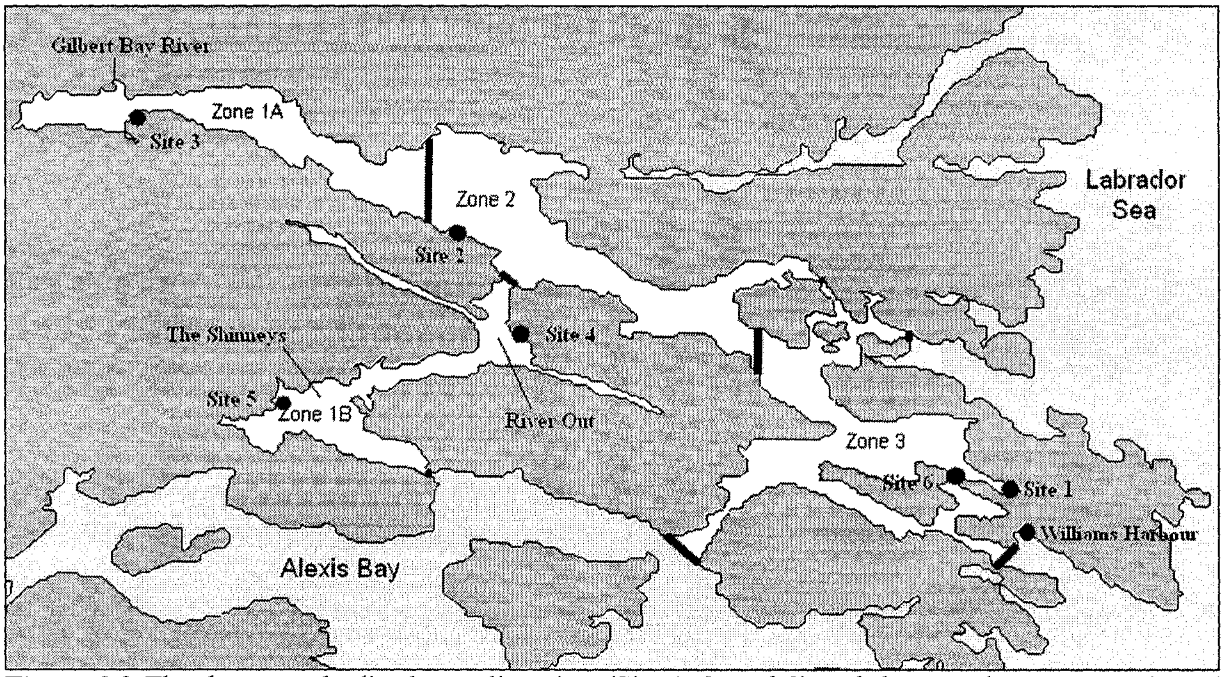


Figure 3.2 The three standardized sampling sites (Site 1, 2, and 3) and three exploratory sampling sites (Site 4, 5, and 6) where Atlantic cod were collected during the 2004 fish fauna survey in Gilbert Bay.

The location of the three standard sites was chosen based on the presence of a beach (Wroblewski *et al.*, 2007). Site 1 is located near the headlands of the bay (Figure 3.2). About 2 km from Site 1 is the deepest basin of Gilbert Bay (Figure 3.3). As the site closest to the Labrador Sea, the surface water salinity at this site is the highest among the three sites (Wroblewski *et al.*, 2007). Scattered boulders lie along the shore. Site 6 is located in Fox Cove Tickle near Williams Harbour (Figure 3.2 and 3.3).

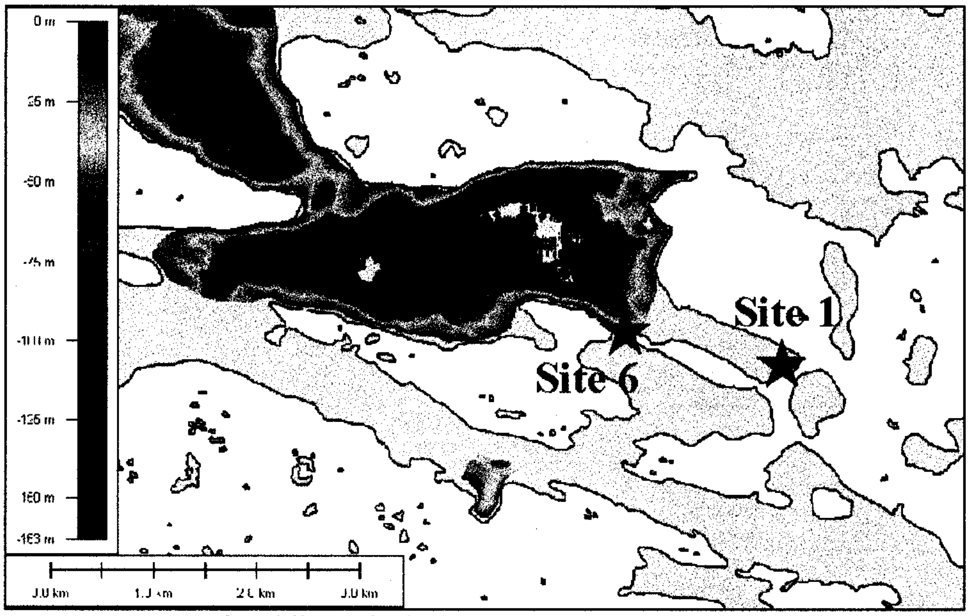


Figure 3.3 Map of multibeam bathymetry near Site 1 and Site 6. This figure was edited from Copeland *et al.*, 2006 Figure 51.

Site 2 is located near the area where The Shinneys joins the main arm of Gilbert Bay (Figure 3.2). The bathymetry near Site 2 is shown in Figure 3.4. The surface water salinity is lower than that of at Site 1 (Wroblewski *et al.*, 2007).

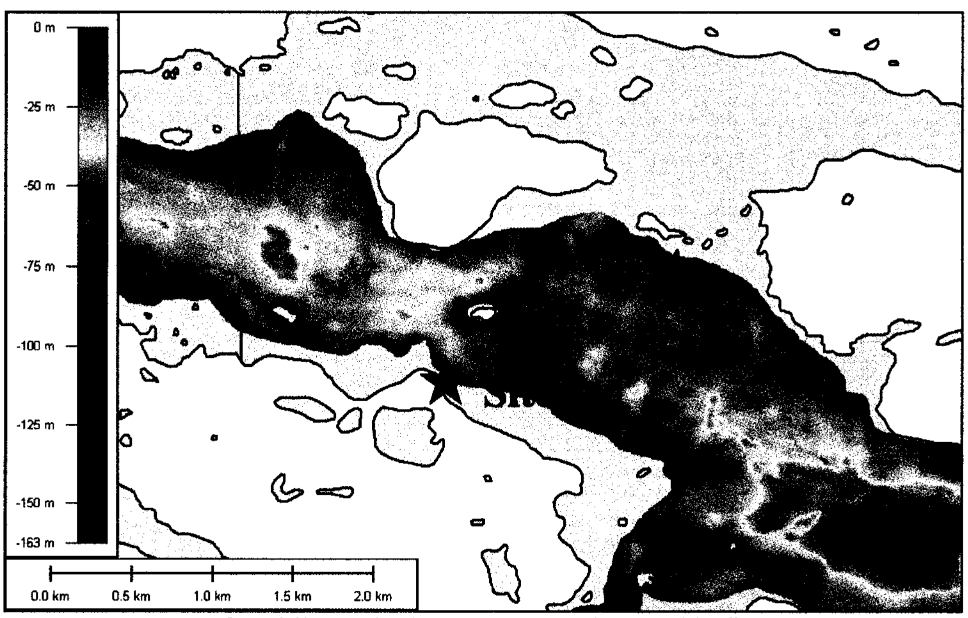


Figure 3.4 Map of multibeam bathymetry near Site 2. This figure was edited from Copeland *et al.*, 2006 Figure 51.

Site 3 is located on the shore opposite the mouth of the Gilbert River (Figure 3.2). As freshwater flows from the river, the surface water salinity is the lowest at the three sites. The width of the bay in this area narrows to about 500 m. It is a shallow part of the bay, with a mean depth of about 20 m. Figure 3.5 shows the bathymetry near Site 3.

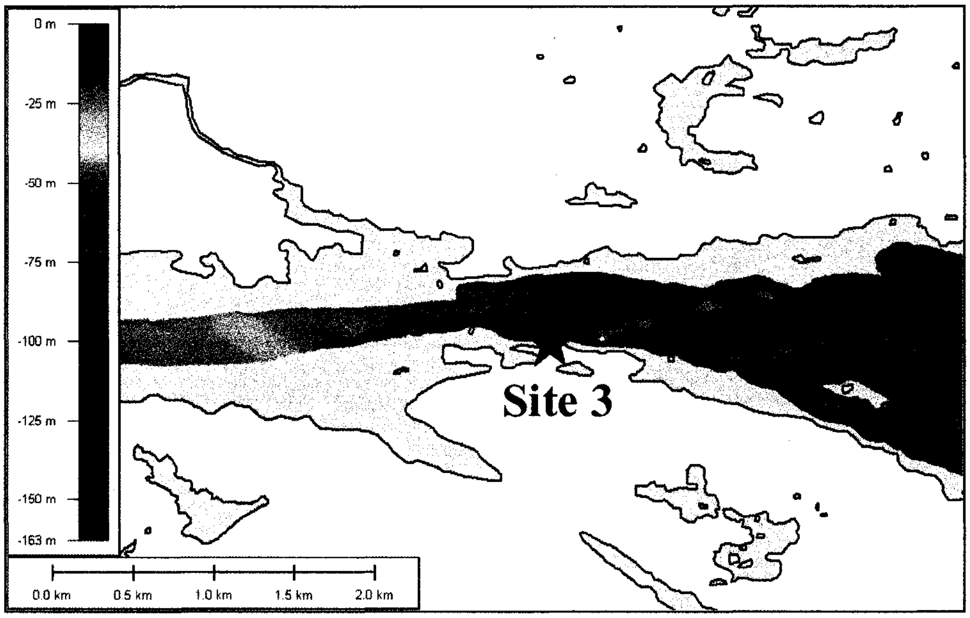


Figure 3.5 Map of multibeam bathymetry near Site 3. This figure was edited from Copeland *et al.*, 2006 Figure 51.

Site 4 is located in River Out (Figure 3.2), where the water is generally shallow (Figure 3.6). Coralline encrusted gravel is present in this region (Bell *et al.*, 2007). Site 5 is located near the mouth of the Shinneys Brook (Figure 3.6). The Shinneys is deeper than the River Out section (Figure 3.2). The analysis of backscatter data suggests that most of the deeper areas within The Shinneys have mud bottom (Bell *et al.*, 2007). Underwater diving observation conducted by Morris *et al.* (2002) found that coralline encrusted cobble substrate is present in shallow regions of The Shinneys.

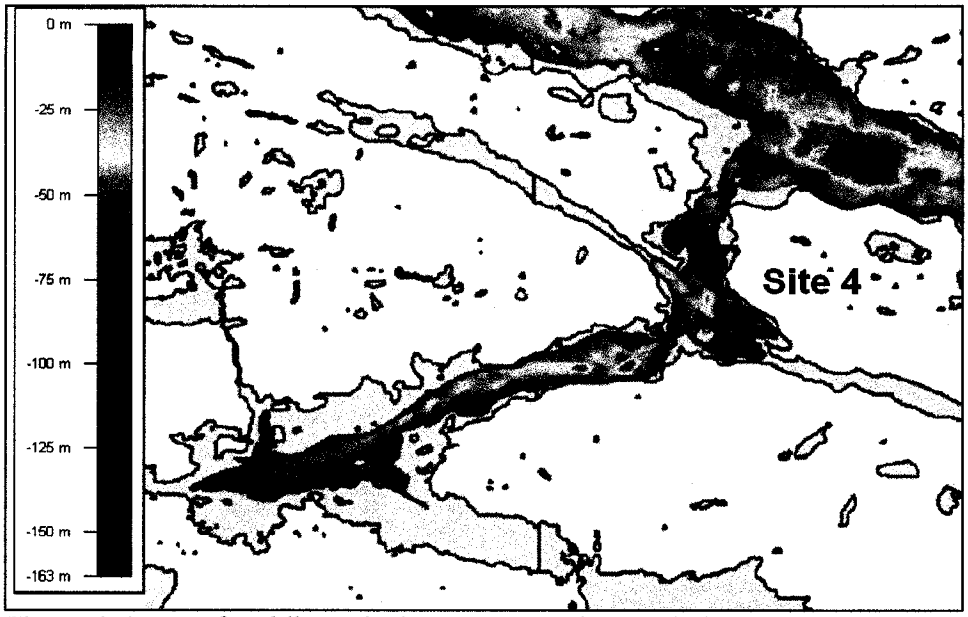


Figure 3.6 Map of multibeam bathymetry near Site 4 and Site 5.

3.2.2 Fish present at Site 1, 2 and 3

During the 2004 fish fauna survey, twenty-one species were collected at Site 1, Site 2, and Site 3. Species richness (S) was different among the three sites with the highest value at Site 1 (S=20) and lower values at Site 2 (S=12) and at Site 3 (S=13) (Wroblewski, *et al.*, 2007). The catch per unit effort (CPUE) data from sampling sites 1, 2 and 3 with a 10 m by 1.5 m beach seine during the daytime at depths between 0 and 1.5 m are shown in Figure 3.7. No Atlantic cod was collected at sites 1, 2, or 3 within this range of water depths.

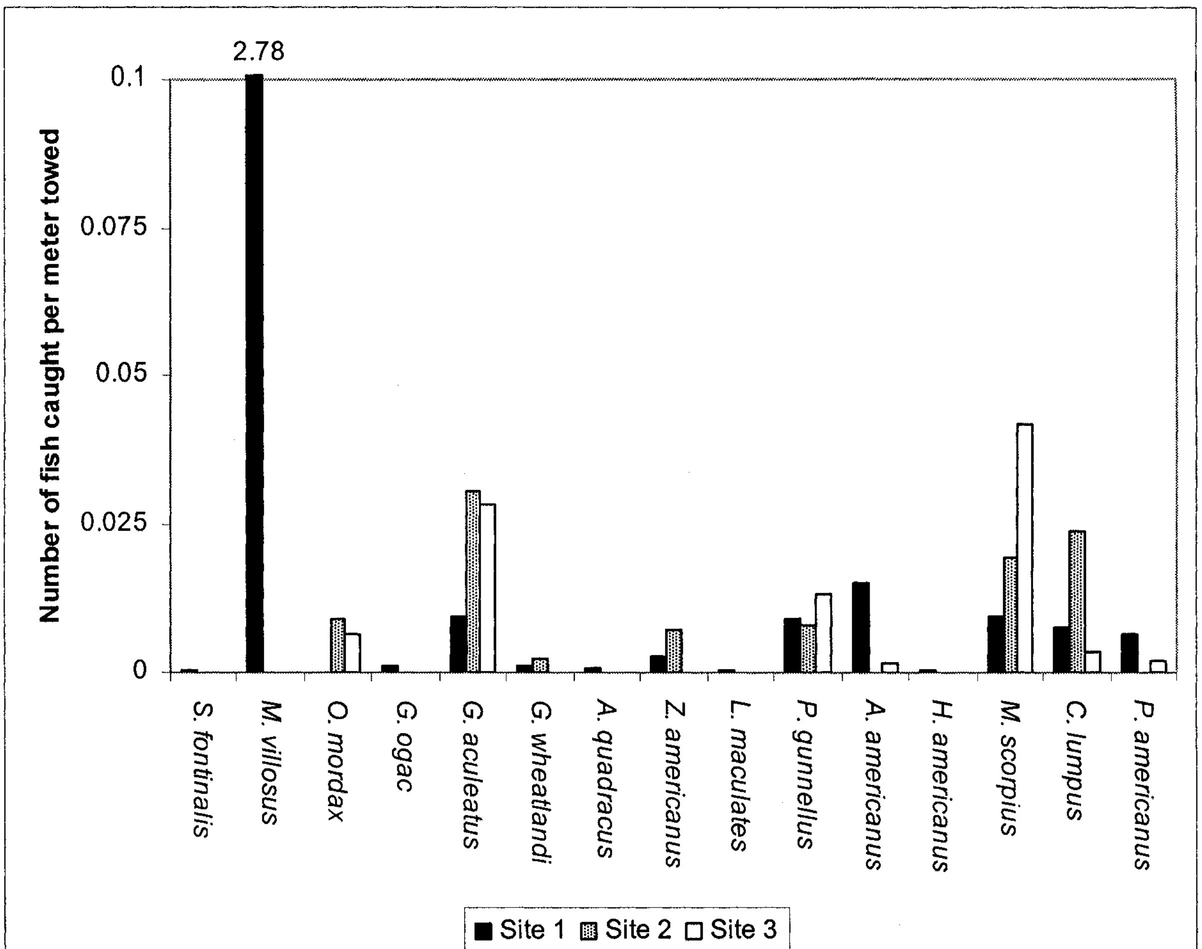


Figure 3.7 Catch per unit effort (number caught per meter towed) for each species collected with a 10 m by 1.5 m beach seine (10 mm stretch mesh) during the daytime at water depths between 0 and 1.5 m.

In sampling water depths between 0 and 5 m with a 25 m by 1.5 m beach seine, only one Atlantic cod was caught at Site 2 (Figure 3.8).

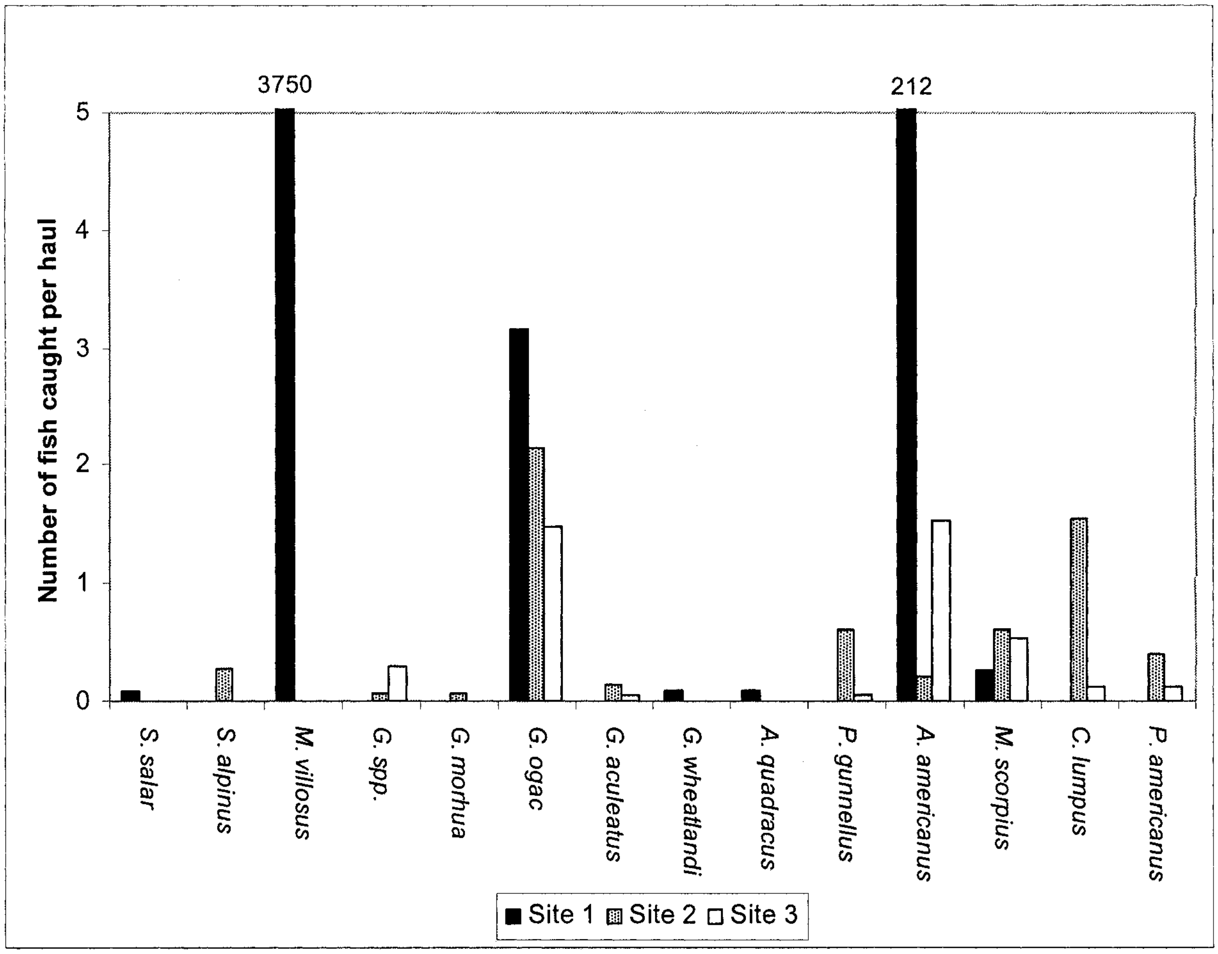


Figure 3.8 Catch per unit effort (number caught per haul) for each species collected with a 25 m by 1.5 m seine (10 mm stretch mesh) during the daytime at water depths between 0 and 5 m.

Sampling water depths between 3 m and 15 m by fishing with a 30 m by 3.7 m gillnet, Atlantic cod were collected at all three sites (Figure 3.9).

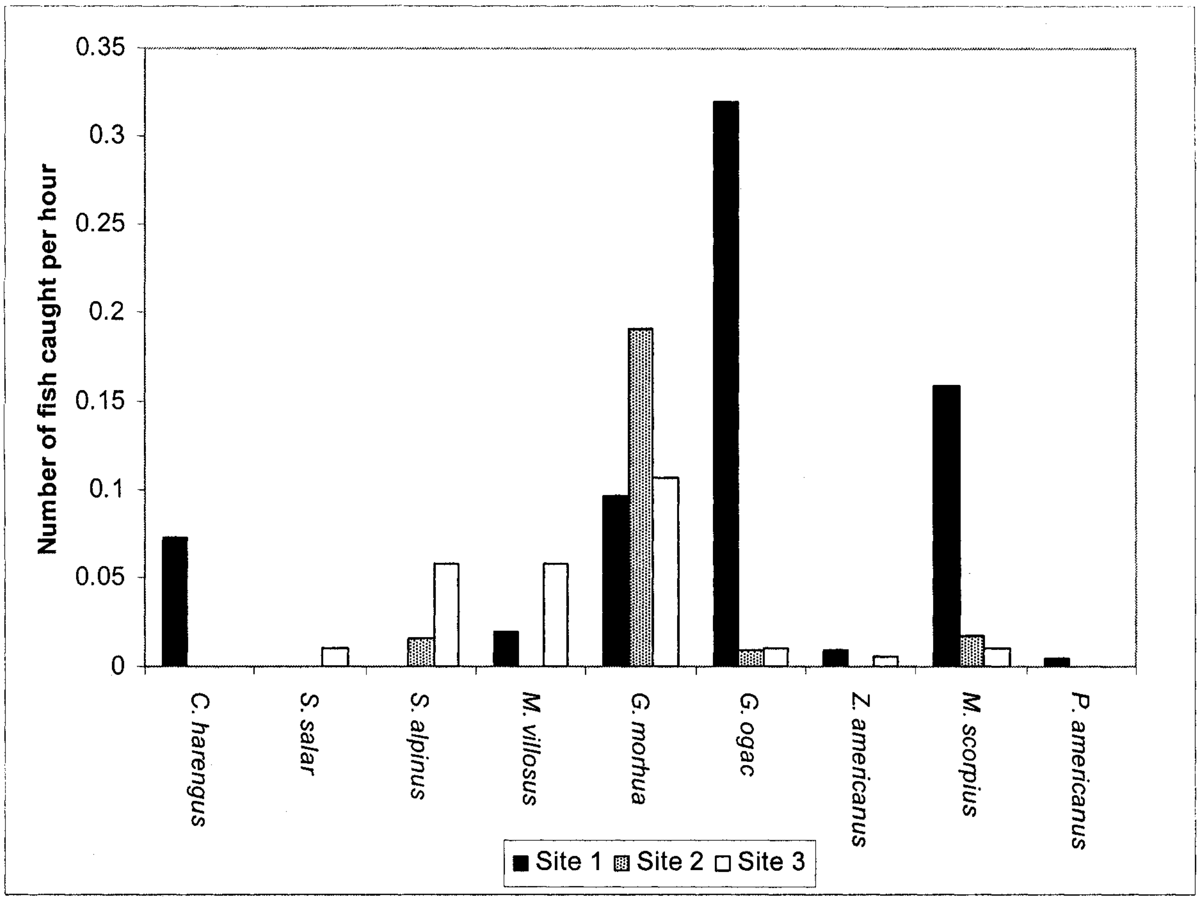


Figure 3.9 Catch per unit effort (number caught per hour) for each species collected with a 30 m by 3.7 m gillnet (7.6 cm stretch mesh) at water depths between 3 m and 15 m.

The length and age of the 150 Atlantic cod caught at the six sites during the 2004 survey is provided in Appendix 1. The ages of the cod were determined by counting the rings of otoliths (readings performed by Harry Hicks, retired employee of DFO Science Branch). Morris and Green (2002) found that male cod in the Gilbert Bay population mature at 4-6 years of age and females mature at 4-8 years of age. Assuming cod ≤ 3 years of age are not sexually mature (Morris and Green, 2002), these data indicate that juvenile cod are commonly found in The

Shinneys (Site 5) and River Out (Site 4), and are less common in the main arm of Gilbert Bay (Figure 3.10).

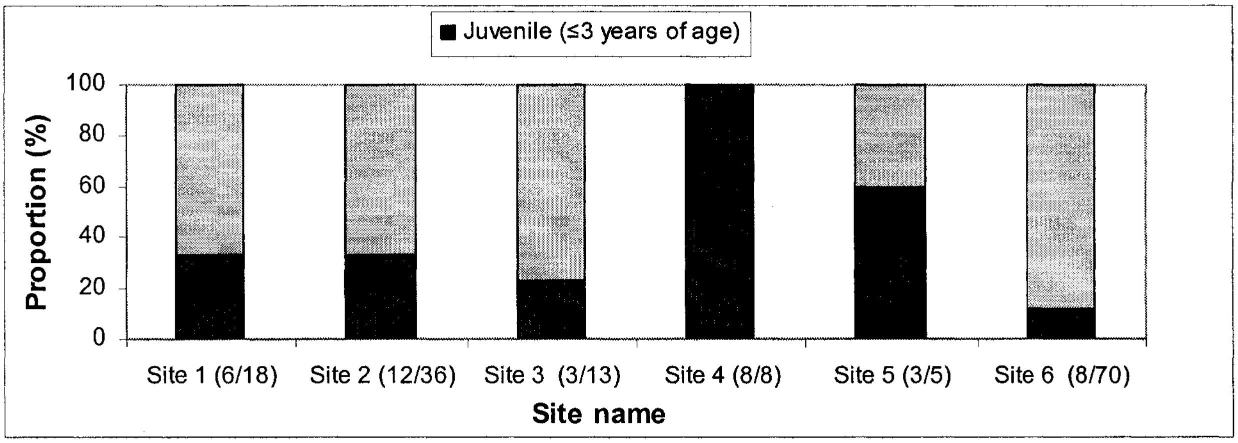


Figure 3.10 Frequency of juveniles (≤ 3 years old) in samples of Atlantic cod collected at Site 1, Site 2, Site 3, Site 4 (River Out), Site 5 (The Shinneys), and Site 6 (Fox Cove Tickle) during the 2004 fish fauna survey. The black colour represents the cod >3 years old. Refer to Figure 3.2 for the location of the sites.

3.2.3 Habitat of Atlantic cod

In coastal areas of Newfoundland, post-settlement juvenile cod (< 1 year old) associate with eelgrass (Gotceitas *et al.*, 1997; Linehan *et al.*, 2001; Laurel *et al.*, 2003), kelp (Keast *et al.*, 1987; Gotceitas *et al.*, 1997; Cote *et al.*, 2001, 2003), and gravel (Gregory and Anderson, 1997) habitats. Older juvenile cod (2-3 years of age) are found in varied habitats: kelp (Keats *et al.*, 1987; Cote *et al.*, 2003), coarse substrate (Gregory and Anderson, 1997; Gotceitas *et al.*, 1997; Cote *et al.*, 2001; Cote, 2002), and boulder substrate (Cote *et al.*, 2003).

Eelgrass beds grow in shallow coastal areas mainly associated with mud, silt, and sand substrates. In coastal areas of Newfoundland, eelgrass habitat provides suitable nursery grounds for juvenile cod (Gotceitas *et al.*, 1997; Linehan *et al.*, 2001; Laurel *et al.*, 2003). Juvenile Atlantic cod association with eelgrass and macroalgal habitats has been also shown throughout their range (Tveite, 1984; Borg *et al.*, 1997; Gotceitas *et al.*, 1997). In Gilbert Bay, the presence of eelgrass has not been confirmed. In the absence of eelgrass, juvenile cod in Gilbert Bay may associate with the coralline encrusted gravel substrate. Coralline algae, also known as calcareous red algae and maerl, coat pebbles and cobbles to form spatially complex habitats in shallow waters. In southwest Scotland, Kamenos *et al.* (2004) found that maerl that lacked macroalgal cover was an important nursery system for gadoids. Branching coralline algae have been observed in numerous places in Gilbert Bay, especially in the shallow areas of The Shinneys and River Out (Morris *et al.*, 2002; Bell *et al.*, 2007). Copeland *et al.* (2006) suggest that coralline algae are present in many places in Gilbert Bay, especially in the upper part of the main arm and River Out.

3.3 Material and Methods

3.3.1 Habitat sampling techniques

Video observation and benthic grab sampling of the seafloor can provide both qualitative and quantitative information about the bottom substrate and the associated biotic community. I used underwater video recording and benthic grab sampling to collect information on the bottom habitat complexity at Site 1, Site 2, and Site 3 (Figure 3.2).

Underwater video recording allows a direct view of geologic and biologic features of the seafloor. It is especially useful for observing areas with hard substrates such as cobble, boulder, and bedrock, where grab sampling has limited utility. Video data can provide a permanent and objective record of the habitat complexity. The disadvantage of this technique is that it can only observe the surface of the seafloor. Limited information on the presences of burrowing organisms, for example, worms and mud stars, is recorded.

Grab sampling is used to examine the subsurface sediment of the seafloor. Grab samples of sediment can provide information on the substrate composition and shallow burrowing fauna.

The disadvantage of grab sampling is the limited coverage area and type of substrate that can be sampled.

3.3.2 Benthic habitat data collection field work

The ocean bottom at Site 1, Site 2, and Site 3 was observed during the multibeam data ground-truthing fieldwork in Gilbert Bay conducted during the first week of October, 2006. A color digital video camera with a dive video housing secured to an aluminium crash cage was used to record the bottom features at the three sites. Two lasers attached to the crash cage spaced 15 cm apart provided a scale (Figure 3.11). The camera set was dropped to the seafloor from a speedboat every 10 meters within 100, 90, and 60 meters from the shoreline at Site 1, Site 2, and Site 3 respectively. Due to light limitation, the video was too dark to view the bottom deeper than 15 meters. A total of 25 drop camera points were completed. A white board with the site number and distance from shore written was recorded in the video to separate these drop points. The water depth profiles at the three sites were recorded by an acoustic depth sounder with GPS and chartplotter (Garmin GPSMAP 178/178C).

A Petit Ponar benthic grab sampler (Figure 3.10) operated from a winch on the speedboat was used to take grab samples. At each site (Site 1, 2, and 3), two grab samples were taken (a shallower water grab and a deeper water grab). Part of each grab sample was placed in a labelled plastic bag, frozen, and returned to the Geology Laboratory at Memorial University for analysis.

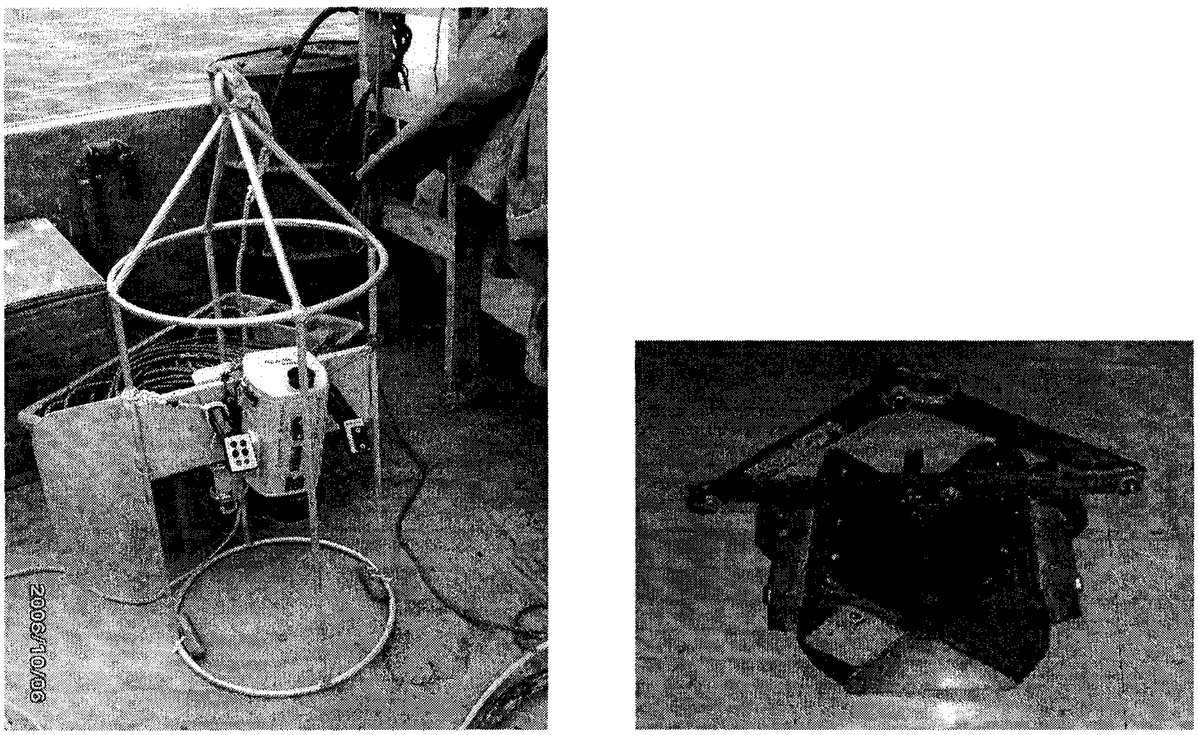


Figure 3.11 The video camera set (left) and the Petit Ponar benthic grab sampler (right) used in the field work. The area of grab at the sediment surface is about 0.04 m^2.

3.3.3 Data analysis

Data from each camera drop were analyzed by assigning the video to a visual substrate class based on the presence of boulders, cobbles, pebbles, sand, and mud. All species of flora and fauna were identified to genus level (Bell *et al.*, 2007).

The grab samples were classified according to the Wentworth scale (Wentworth 1922) and Krumbein phi scale (Table 3.1) for substrate classes. A sub-sample was taken from each of the grab samples that contained pebble to clay sized material. After the silt and clay were removed by wet sieving on a 0.064 mm sieve (the weight of silt and clay was calculated), the sub-samples were dried, put on a stack of seven sieves, and shaken on an electric shaker for 30 minutes. The remainder on each sieve were weighed and grouped. Then the Wentworth scale was used to determine the substrate components.

Table 3.1 Grain Size Scale.

Wentworth substrate class name		Grain size (mm)	Krumbein phi scale
Boulders			
		256	-0.8
Cobbles			
		64	-0.6
Pebbles			
		4	-0.2
Granules			
		2	-0.1
Sand	Very coarse sand		
		1	0
	Coarse sand		
		0.5	1
	Medium sand		
		0.25	2
	Fine sand		
		0.125	3
	Very fine sand		
		0.0625	4
Silt			
		0.0313	5
Clay			

3.4 Results

3.4.1 The bottom habitat at Site 1, Site 2, and Site 3

At Site 1, the subtidal zone within 30 m of the shoreline was relatively flat, with a bottom depth of about 1 m. Starting from 40 m off the shoreline the bottom drops off, then tends to be flat again between 70 m and 100 m from shore (Figure 3.12). At Site 2 the slope of the subtidal zone was steeper than at Site 1. The bottom slope increases between 40 m to 70 m from the shoreline

(Figure 3.13). Site 3 has the steepest bottom slope among the three sites (Figure 3.14). The slope was relatively constant out to 100 m from the shoreline.

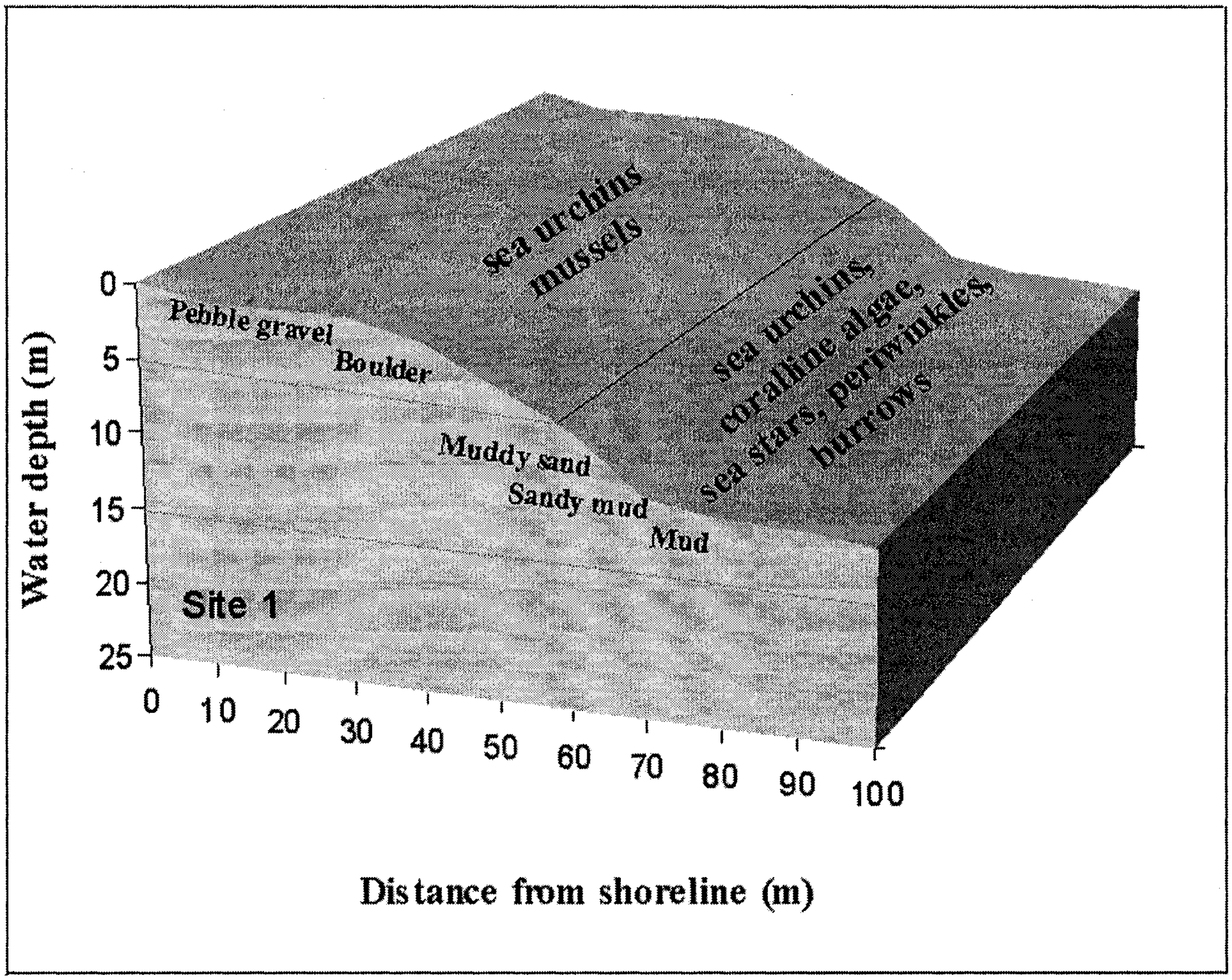


Figure 3.12 Subtidal zone profile, substrates, and benthos at Site 1.

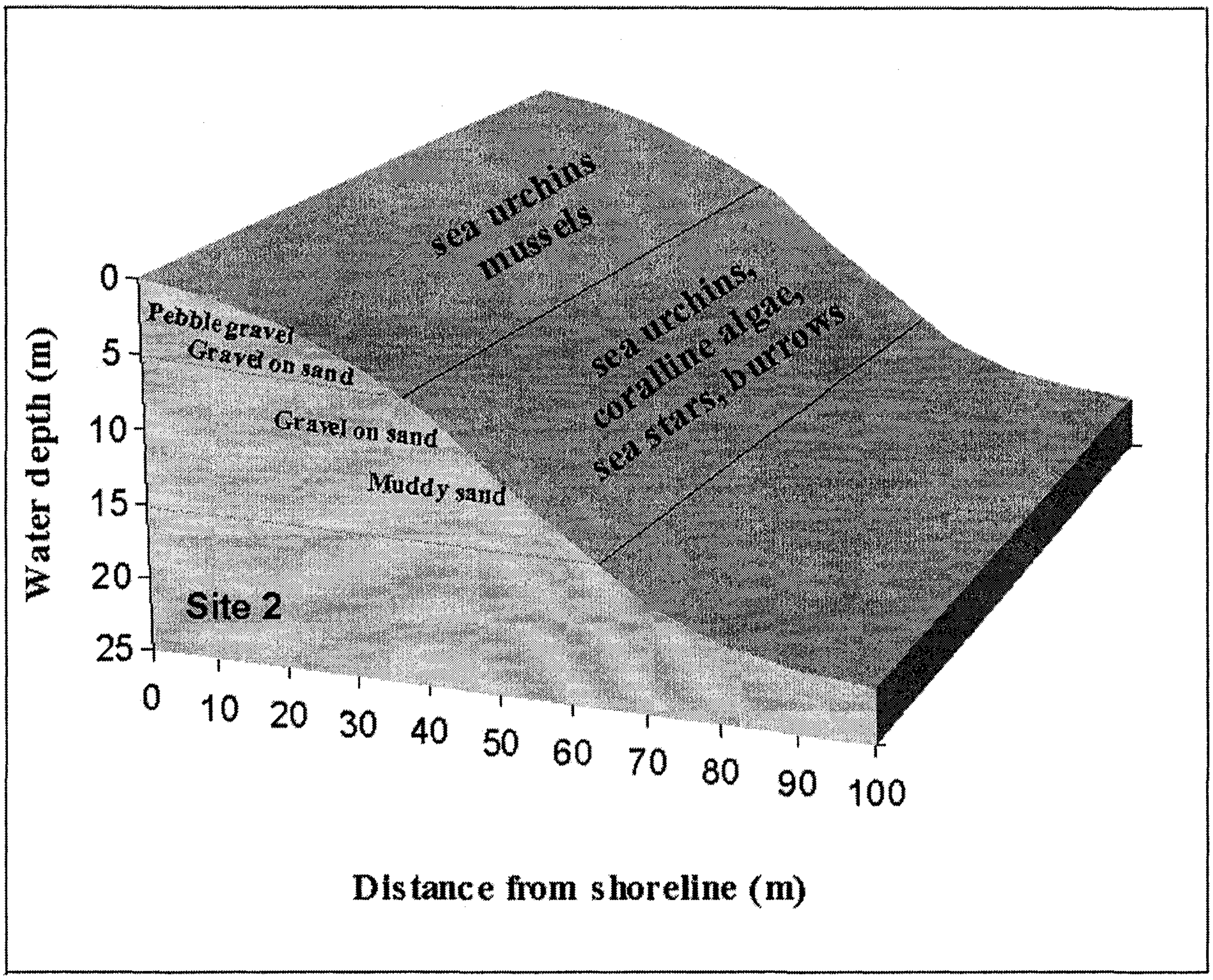


Figure 3.13 Subtidal zone profile, substrates, and benthos at Site 2. The sea bottom deeper than 15 m could not be observed with the video camera due to light limitation.

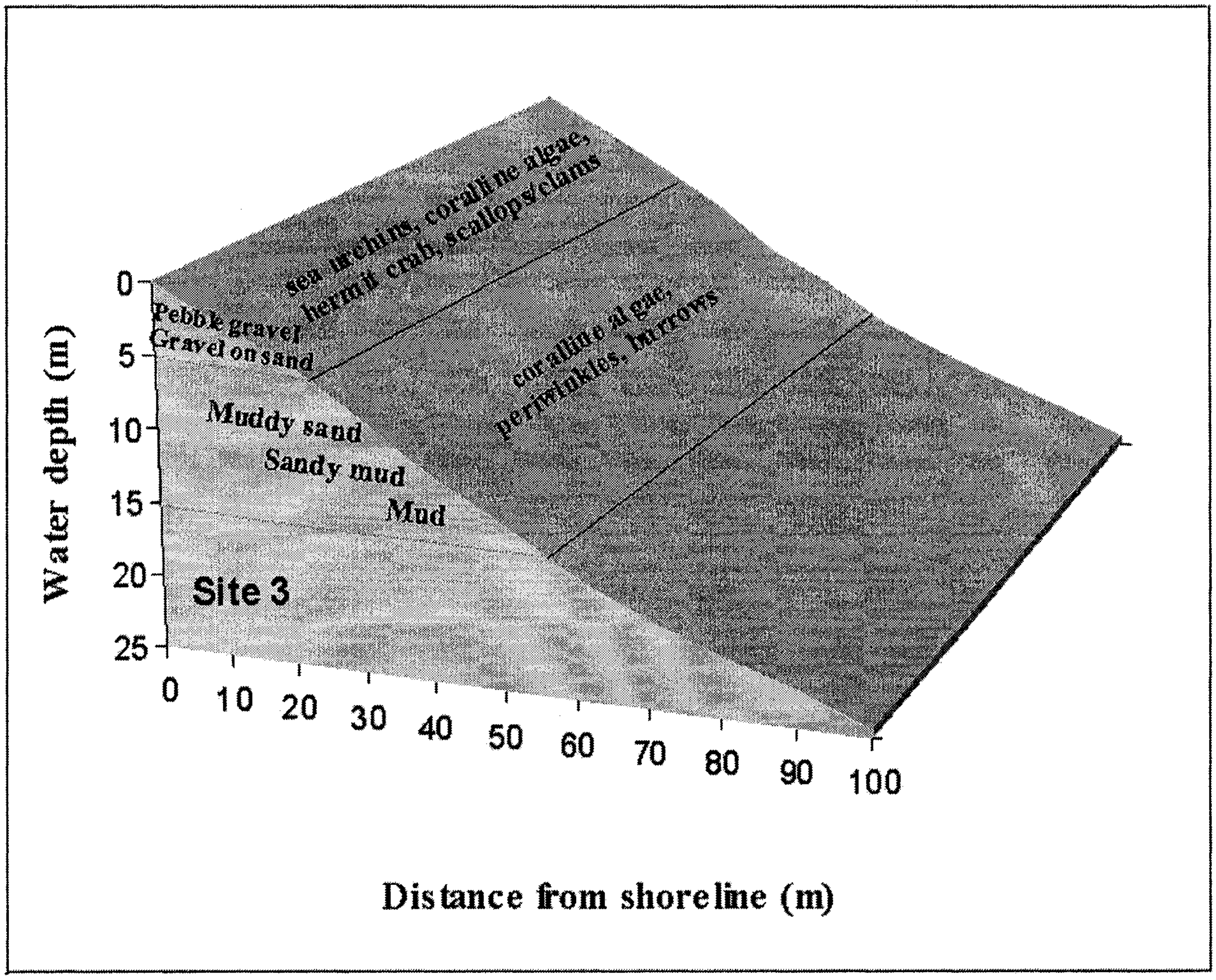


Figure 3.14 Subtidal zone profile, substrates, and benthos at Site 3. The sea bottom deeper than 15 m could not be observed with the video camera due to light limitation.

The bottom substrates at the three sites were different, although all sites showed the same trend of decreasing hardness with increasing depth (Table 3.2). The general hardness of the ocean bottom (within 100 m from the shoreline) was highest at Site 1 and lowest at Site 3. The benthos found at all three sites included sea urchins, blue mussels, coralline algae, and burrows (Figure 3.12, 3.13, and 3.14).

At Site 1, the bottom substrate shallower than 1.5 m depth was composed of pebble gravel populated by blue mussels (<4 cm in length). Coralline algae were found growing on cobble where the water depth was greater than 5 m.

Cobbles on pebble gravel with coarse sand was the main substrate in shallow water (<1.5 m) at Site 2. Blue mussels were abundant in this area. Branching coralline algae was abundant at the bottom at depth of 5-7 m. The bottom substrate at depths between 10 m and 15 m was muddy sand with scattered cobbles/boulders.

The substrate in shallow water (<1.5 m) at Site 3 was composed of pebble gravel with a small percentage of sand. Branching and encrusting coralline algae attached to relatively large rocks were common at depths 3-5 m. The bottom substrate deeper than 15 m was sandy mud and mud with scattered cobbles/boulders.

Figures 3.15, 3.16 and 3.17 depict the substrates captured on video at Site 1, 2 and 3.

Table 3.2 Habitat classes at Site 1, Site 2, and Site 3 observed by the drop down video camera at 10 m interval from the shoreline.

Habitat class	**Site 1 (Distance seaward from shoreline, m)**										**Site 2 (Distance seaward from shoreline, m)**						**Site 3 (Distance seaward from shoreline, m)**					
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**10**	**20**	**30**	**40**	**50**	**60**	**10**	**20**	**30**	**40**	**50**	**60**
Boulders and cobbles on pebble gravel				X																		
Pebble gravel with scattered cobbles, high coverage of mussels and shells											X											
Pebble gravel			X																			
Pebble gravel with high coverage of mussels and shells	X	X																				
Pebble gravel on sand with scattered cobbles												X										
Pebble gravel on sand with scattered cobbles covered with coralline algae																	X					
Pebble gravel on sand, high coverage of coralline algae													X	X				X				
Muddy sand with pebbles and cobbles covered with coralline algae, shells						X									X							
Pebbles on sandy mud, some coralline algae							X															
Pebbles with thin mud veneers and scattered cobbles on sandy mud, some coverage of coralline algae					X														X			
Sandy mud with lone cobbles covered with coralline algae, burrows								X								X						
Sandy mud with burrows and shells									X											X	X	
Mud with burrows and scattered cobbles/boulders with bryozoans/coralline algae growing on the surface										X												X

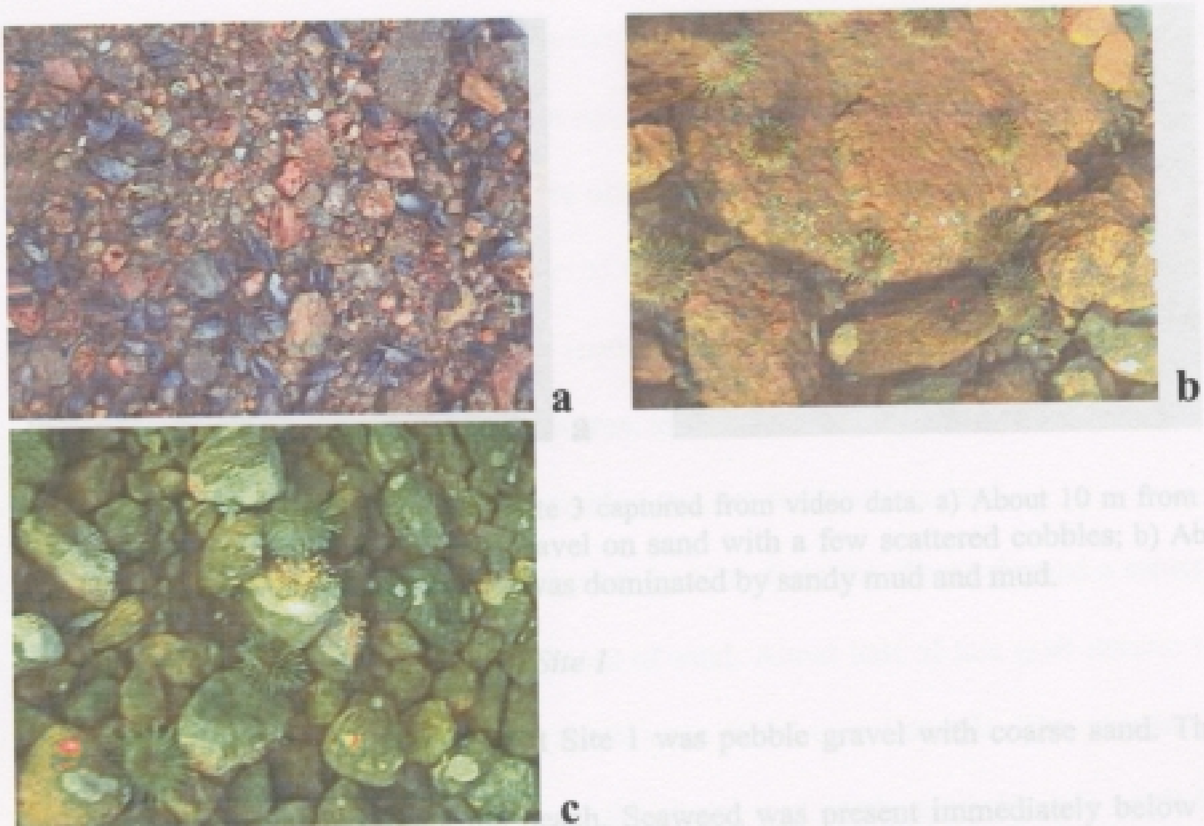


Figure 3.15 Pictures of substrates at Site 1 captured from video data. a) About 10 m from the shoreline, the substrate was mostly pebble gravel; b) The rocky bar of boulders and cobbles on pebble gravel at 40 m from the shoreline; c) About 50 m from the shoreline, the feature of the seafloor changed to pebbles with thin mud veneers and scattered cobbles on muddy sand bottom.

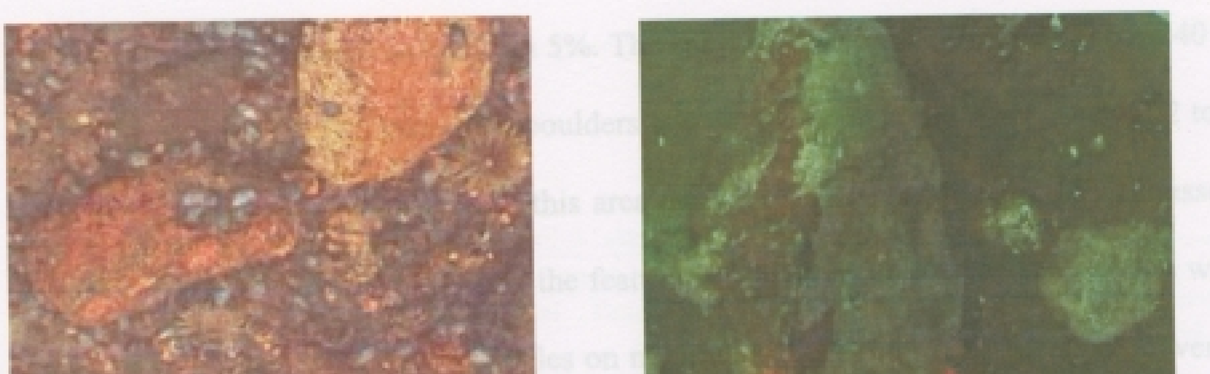
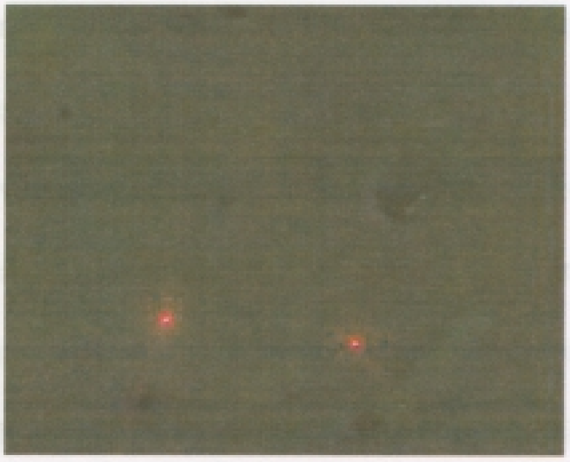


Figure 3.16 Pictures of substrates at Site 2 captured from video data. a) About 10 m from the shoreline, the substrate was cobble and pebble gravel; b) About 50 m off the shoreline, the substrate was muddy sand with pebbles and scattered cobbles/boulders, most with some coverage of coralline algae.

a



b

Figure 3.17 Pictures of substrates at Site 3 captured from video data. a) About 10 m from the shoreline, the substrate was pebble gravel on sand with a few scattered cobbles; b) About 50 m from the shoreline, the substrate was dominated by sandy mud and mud.

3.4.2 Detailed habitat description of Site 1

The substrate on the beach at Site 1 was pebble gravel with coarse sand. There were boulders scattered along the beach. Seaweed was present immediately below the high tide line. At 10 m seaward from the shoreline, the substrate was mostly pebble gravel with about 40% coverage of mussels and a few sea urchins. This habitat did not change until 30 m from the shoreline, where the pebbles became more angular and the mussel coverage declined to less than 5%. The substrate was very different at about 40 m from the shoreline, a 'rocky bar' of boulders and cobbles on pebble gravel. About 2 to 3 times more sea urchins appeared in this area than the shallower areas, and few mussels were present. Outside the rocky bar, the features of the seafloor changed to pebbles with thin mud veneers and scattered cobbles on muddy sand bottom. Coralline algae covered some of the cobbles and pebbles (less than 5% coverage). A few sea urchins were present in this area as well. The coverage of coralline algae increased to about 5% to 10% at 60 m seaward from the shoreline, while the number of sea urchins was about the same. The seafloor became muddier and the proportion of pebbles declined. This trend continued with increasing distance from shoreline. The substrate at 70 m off the shoreline was sandy mud with about 50% pebble coverage, with coralline algae growth on top of some pebbles. Dead tree branches were observed on the seafloor. Sea urchins, scallop shells, and periwinkles were also observed there. At 80 m and further off the shoreline, the bottom substrate was dominated by sandy mud or mud (as it grew deeper) with round burrows. A few cobbles occurred in this area, all covered with coralline algae. In addition to sea urchins, scallop shells, and periwinkles, one sea star was recorded.

The grab sample inside the rocky bar (~ 20 m from the shore) showed a substrate of pebble gravel with a very small amount of sand. About half of this grab sample was mussel and mussel shell. A few clam shells were found in the sample. The grab sample from outside the rocky bar (~ 80 m off the shore) was sandy mud. Several small live clams were buried in the mud.

The grain size of the grab sample taken in the shallow area was composed of about 96% gravel, 4% sand, and very small amount mud. The grain size of the grab sample taken at deeper area was composed of about 10% gravel, 74% sand, and 16% mud (Table 3.3).

Table 3.3 The grain size of the grab samples taken at Site 1.

Class name	phi scale	Shallow area at Site 1			Deeper area at Site 1		
		mass in interval (g)	% of total weight	Proportion (%)	mass in interval (g)	% of total weight	Proportion (%)
gravel	-2.0	290.40	93.15	96.23	1.30	7.72	10.1
	-1.0	9.60	3.08		0.40	2.38	
sand	0.0	3.90	1.25	3.53	0.30	1.78	74.2
	1.0	2.60	0.83		0.30	1.78	
	2.0	2.50	0.80		1.10	6.53	
	3.0	1.90	0.61		7.30	43.35	
	4.0	0.10	0.03		3.50	20.78	
mud	>4.0	0.75	0.24	0.24	2.64	15.68	15.7

3.4.3 Detailed habitat description of Site 2

The substrate on the beach at Site 2 was pebble gravel with a small amount of coarse sand. Mussel shells and seaweed were washed up along the beach. At 10 m seaward from the shoreline, the substrate was cobble and pebble gravel. Bits of coralline algae were growing on the top of some cobbles. About 30% of the bottom was covered with mussels and mussel shells. Some sea urchins were found in this area. At 20 m off the shoreline the substrate changed to pebble gravel on sand with some scattered cobbles. Very few mussels were recorded by the video; however, the number of sea urchins remained constant. The highest coverage of coralline algae was recorded at 30 m to 40 m seaward from the shoreline, where more than half of the rocks were covered with coralline algae. The substrate was pebble gravel on sand. A few sea urchins were captured by video camera as well. The substrate at 50 m off the shoreline was muddy sand with pebbles and scattered cobbles, most with some coverage of coralline algae. Scallop/mussel/clam shells and sea urchins were present in this area. The seafloor at 60 m off the shoreline had a higher proportion of the shell hash. A small sea star was observed. The video images at 70 m off the shoreline and deeper are too dark to be analyzed.

Two grab samples were retrieved in shallow water (~ 20 m off the shoreline at Site 2). The first grab sample contained only one cobble with a small amount of coralline algae growing on the surface. The second grab sample contained one cobble and a sea urchin. The grab sample from a deeper area of Site 2 (~ 60 m from the shoreline) contained mussels and mussel/clam/scallop shells plus pebbles with a small amount of sand.

The grab samples taken at both shallow and deeper areas did not have enough sediment in the grab to process. Therefore, the compositions of the grain size were 100% gravel (Table 3.4).

Table 3.4 The grain size of the grab samples taken at Site 2.

Class name	phi scale	Shallow area at Site 2			Deeper area at Site 2		
		mass in interval (g)	**% of total weight**	**Proportion (%)**	**mass in interval (g)**	**% of total weight**	**Proportion (%)**
gravel	-2.0	1148.60	100	100	474.00	100	100
	-1.0	0	0		0	0	
sand	0.0	0	0	0	0	0	0
	1.0	0	0		0	0	
	2.0	0	0		0	0	
	3.0	0	0		0	0	
	4.0	0	0		0	0	
mud	>4.0	0	0	0	0	0	0

3.4.4 Detailed habitat description of Site 3

The beach at Site 3 was sandier than the other two sites. The substrate at 10 m seaward from the shoreline was pebble gravel on sand with a few scattered cobbles. Many rocks were covered with coralline algae. The animals recorded by the video camera include sea urchins, a jellyfish, a hermit crab, and a scallop. At 20 m off the shoreline, the percentage of sand increased. Most rocks were covered with thin coralline algae veneers. Not many live animals were found in this area, except for one scallop, one sea urchin, and some clam/scallop shells. The substrate at 30 m from the shoreline was mostly sandy mud with a number of pebbles. Shells, burrows, and one winkle were recorded. At 40 m and further off the shoreline, the bottom substrate was dominated by sandy mud and mud. As the water grew deeper, the burrows became more numerous and the scattered cobbles/boulders became bigger. Bryozoans were found growing on the top of the cobbles (or small boulders) at 60 m off the shoreline.

The grab sample from the shallow water at Site 3 contained one sea urchin, seaweed, several pebbles, and a small amount of sand. The grab sample from the deeper water at Site 3 contained pebbles in sandy mud.

The grain size of the grab sample taken in the shallow area was composed of about 99% gravel, 1% sand, and very small amount of mud. The grain size of the grab sample taken at deeper area was composed of about 69% gravel, 26% sand, and 56% mud (Table 3.5).

Table 3.5 The grain size of the grab samples taken at Site 3.

Class name	phi scale	Shallow area at Site 3			Deeper area at Site 3		
		mass in interval (g)	% of total weight	Proportion (%)	mass in interval (g)	% of total weight	Proportion (%)
gravel	-2.0	210.30	98.59	98.6	249.41	66.51	69.19
	-1.0	0.00	0.00		10.03	2.67	
sand	0.0	0.00	0.00	0.98	31.00	8.27	25.55
	1.0	0.00	0.00		19.73	5.26	
	2.0	0.20	0.09		19.73	5.26	
	3.0	0.80	0.38		19.73	5.26	
	4.0	1.10	0.52		5.64	1.50	
mud	>4.0	0.90	0.42	0.4	19.73	5.26	5.26

3.5 Discussion

3.5.1 Nearshore habitat of the resident fishes in Gilbert Bay

The observations at Site 1, Site 2, and Site 3 show that the hardness of the bottom substrate at the three sites decreases with the water depth: at water depths less than 5 m, the substrate was mainly cobble or pebble gravel and at water depths between 5 m and 15 m, the substrate was dominated by muddy sand or sandy mud with scattered cobbles/boulders. Coralline algae were primarily recorded at Site 2 and Site 3 where water was about 5 m deep.

During the 2004 fish fauna survey, juveniles of Greenland cod, short horn sculpin, and winter flounder, were found in shallow water (< 5 m) at the three sites over pebble gravel substrate (Table 3.6). In contrast, only one 0-year Atlantic cod (measuring 9.8 cm) was caught in these areas. This result suggests that the pebble gravel substrate in shallow water is used by juvenile Greenland cod, juvenile short horn sculpin, and juvenile winter flounder, but is not a suitable habitat for juvenile Atlantic cod.

Table 3.6 Standard length (SL) of fishes collected by standardized sampling in day time in Gilbert Bay during the 2004 fish fauna survey. A 10 m by 1.5 m beach seine with 10 mm stretch mesh size was used at water depth <1.5 m. A 25 m by 1.5 m beach seine with 10 mm stretch mesh size was used at water depth of 0-5 m. A 30 m by 3.7 m gillnet with 7.6 cm stretch mesh size was used at water depth of 3-15 m. See Figure 3.2 for location of Sites 1, 2, and 3. (Wroblewski *et al.*, 2007 and unpublished data)

Species	Common name	**SL range (cm) at Site 1**			**SL range (cm) at Site 2**			**SL range (cm) at Site3**		
		<1.5 m	0-5 m	3-15 m	<1.5 m	0-5 m	3-15 m	<1.5 m	0-5 m	3-15 m
C. harengus	Atlantic herring			14-34						
S. salar	Atlantic salmon		21							52.2-55.3
S. alpinus	Arctic char			46		32.5-46.6	39.5-43.5			30.5-40.6
S. fontinalis	brook trout	5.6								
M. villosus	capelin	12-15.0	14	14-14.6						12.5-15.4
O. mordax	rainbow smelt				2-3.7			3-5.5		
G. morhua	Atlantic cod			29.2-53.2		9.8	29.3-55			27-56.5
G. ogac	Greenland cod	2-25.5	6-16.5	25.5-48.8		3.9-10.5	26-30.8		3.4-6.1	30.5
G. aculeatus	threespine stickleback	2.5-6.3			2.4-6	5.2-5.7		2.8-7.2	1.9	
G. wheatlandi	blackspotted stickleback	2	5.4		3.8-5.5					
A. quadracus	fourspine stickleback	4.5	5.4							
P. pungitius	ninespine stickleback									
Z. americanus	ocean pout	5.1-40		40-42.5	9.8					41.9
L. maculatus	daubed shanny	11								
P. gunnellus	rock gunnel	10-24.0			9-13.2	8.5-15.5		9.3-13.5	8.2	
A. americanus	American sand lance	4.9-14.7	5.5-12.4			5-10.1			4.6-12.3	
H. americanus	sea raven	2								
M. scorpius	short horn sculpin	1.7-31	12.6-24	36.9-20	3.5-14	1.8-30	15.5-26	1.9-7	3.2-27	32-37
C. lumpus	lumpfish	1.5-6.1			1.1-2.9	1.5-3		1.9-2.2	2-3.0	
P. americanus	Winter flounder	3.6-21.3		19.8-30		21.5-29.2		3.5	9.5-27.5	

Greenland cod

Juvenile Greenland cod were caught in shallow water (<5 m) associated with pebble gravel substrates (Table 3.6). The average SL caught at Site 1, Site 2, and Site 3 were 10.5 cm, 5.5 cm and 4.6 cm, respectively. Almost all (70/74) adults (average SL=34cm) caught were at Site 1 (consistently throughout the sampling period) in water depth of 3-15 m where substrates were mainly soft (pebbly sand to sandy mud), although Site 2 and 3 have similar substrates at water deeper than 5 m depth.

Short horn sculpin

Juvenile short horn sculpin (SL<10 cm) occurred in shallow water (<1.5 m) associated with pebble gravel substrates while adults were caught at Site 1 over pebbly sand to sandy mud bottom. Adult short horn sculpin were collected on relatively smooth bottoms. Only 4 out of 88 short horn sculpin caught in water depth <5 m were larger than 20 cm (SL) and the average SL of short horn sculpin in those areas was 8.7 cm.

Winter flounder

Winter flounder was found at all three sites over substrates of pebble gravel to sandy mud. Juvenile winter flounder were found on pebble gravel substrate in shallow water (depth <1.5 m), while adult winter flounder were collected on smooth bottoms in relatively deep water (depth <5 m) (Table 3.6). The average SL of the winter flounder caught with the small beach seine in water depth less than 1.5 m was 14 cm. The average SL of the winter flounder caught with the big beach seine in water depth less than 5 m was 25 cm. This is consistent with the known habitat of winter flounder: soft muddy to moderately hard bottoms (Scott and Scott, 1988).

Atlantic cod

As shown in Table 3.6, all of the Atlantic cod collected, except one juvenile, were caught in water depths between 3 and 15 m among the three sites, where the bottom substrates range from pebbly sand to sandy mud with scattered cobbles/boulders. Most of these substrate had benthic organisms, such as coralline algae, sea stars, periwinkles, scallops, and burrows (worms or clams), which are the main food of Gilbert Bay cod (Morris and Green, 2000). The range of Atlantic cod standard lengths (SL) caught at the three sites was between 27.0 and 56.5 cm. This suggests that Atlantic cod present at these sites were mainly adults. This is consistent with previous studies that suggest Gilbert Bay cod overwinter and spawn in The Shinneys (Green and Wroblewski, 2000; Morris and Green, 2002) and some of the adults move into Gilbert Bay main arm during the summer (Green and Wroblewski, 2000). Combined with these habitat observations, it may be that adult Atlantic cod in Gilbert Bay are associated with scattered cobbles/boulders on soft substrate and some coverage of coralline algae. This agrees with Morris *et al.* (2002) stating "Gilbert Bay cod were frequently observed in areas having large boulders".

The Shinneys has been identified as an important nursery ground for Gilbert Bay cod (Green and Wroblewski, 2000; Morris and Green, 2002; Morris *et al.*, 2002). With large areas of subtidal mud, the mouth of the Shinneys Brook is one of the few areas in Gilbert Bay where one might find eelgrass (Copeland *et al.*, 2006). During the 2006 ground-truthing survey, rockweeds were found at the mouth of the Shinneys Brook, but no eelgrass was observed (Bell *et al.*, 2007). The 2004 fish fauna survey found higher proportions of juvenile Atlantic cod at River Out and The Shinneys (Figure 3.10), where there is a high coverage of branching coralline algae. This suggests that branching coralline algae is a suitable habitat for juvenile Atlantic cod in Gilbert Bay. Atlantic cod of undetermined size were observed by video camera over coralline algae habitat at River Out during the 2006 ground-truthing survey (Bell *et al.*, 2007). Branching coralline algae may be suitable habitat for juvenile fish because it has both spatial complexity for avoidance of predators as well as various invertebrates which are prey for cod. Copeland *et al.* (2006) and Bell *et al.* (2007) suggested that coralline algae are more abundant in River Out, The Shinneys, and the upper part of the main arm in Gilbert Bay. Further research is needed to confirm the habitat of juvenile Atlantic cod in Gilbert Bay.

3.5.2 Implications for Atlantic cod production in Gilbert Bay

Research has pointed out that the availability of suitable habitat for juvenile Atlantic cod might limit production (Tupper and Boutilier, 1995; Cote *et al.*, 2004), as high mortality rate in post-settled juveniles is primarily due to predation (Houde, 1987; Tupper and Boutilier, 1995). Predator efficiency is reduced with increasing habitat complexity (Mattila, 1992; Tupper and Boutilier, 1995; Lindholm *et al.*, 1999). The results from the 2004 fish fauna survey and the 2006 habitat survey suggest that branching coralline algae on gravel substrate is habitat for juvenile Atlantic cod in Gilbert Bay. Consequently, the availability of this habitat might be an important factor governing the production of Atlantic cod in Gilbert Bay. Branching coralline algae may be more abundant in River Out, The Shinneys, and the upper part of the main arm in Gilbert Bay (Bell *et al.*, 2006, 2007). Is there sufficient habitat for the juvenile cod produced in Gilbert Bay? Currently, there is no adequate information to answer this question. Nevertheless, from my estimation in Chapter 2 that the historical abundance of Atlantic cod in Gilbert Bay (256 tons) is about 3 times higher than the population size in 2003, I expect that the population would still be able to grow above the present population size. Beside food and habitat availability there are other factors that may influence fish production, e.g., sea water temperature, disease, predator abundance (seals), and human activity (fishing). These factors also need to be considered because they interact with each other.

Chapter 4 Modeling the Population Dynamics of Atlantic Cod in Gilbert Bay

4.1 Introduction

4.1.1 Purpose of the model

Using tag-recapture methods Morris *et al.* (2003) estimated the population of Gilbert Bay cod to be ≤ 70 tons in 2003. Given this estimate of the abundance, one might ask whether the current population biomass is low, relative to the carrying capacity of the bay. In Chapter 2, I calculated the carrying capacity for Atlantic cod in Gilbert Bay to be 166 to 377 metric tons. The abundance of 70 tons estimated by Morris *et al* (2003) is about 100 to 300 tons lower than the estimated carrying capacity. In this chapter I will calculate the time it would take for the cod population to reach the carrying capacity by modeling Gilbert Bay cod population dynamics.

Population dynamics refer to the variations of the population abundance and age structure over time. The first principal of population dynamics is the exponential law deduced in 1789 by Malthus. In 1838, Pierre-Francois Verhulst derived the logistic growth equation, representing the fact that populations do not continue unrestricted exponential grow (Hutchinson, 1978). The logistic model and its relatives ignore the population age structure and treat all individuals equally. Changes in population abundance reflect the relative rates of birth and death. In reality, the rates of birth and death for fish usually differ among individuals depending particularly on their age and sex. For example, fecundity of a female Atlantic cod in a population increases with its body size, which is a function of age (May, 1967). The Leslie matrix population model integrates population abundance and population age structure particularly clearly (Caswell 2001). A population projection model could be a useful tool in fishery management. Using the model, one can project the abundance and age structure of a population into the future, determine the important factor(s) governing population dynamics, and test the effects of different management strategies.

Gilbert Bay cod is a genetically distinguishable population of northern Atlantic cod (Ruzzante *et al.*, 2000; Beacham *et al.*, 2002; Hardie *et al.*, 2006). Improper management could deplete this population. By modeling the population dynamics with different parameters and projecting the population into the future, one can quantitatively compare the effects of different management options. For example, what is the most important factor governing the growth of the population? When will it be appropriate to allow a food/recreational fishery in Gilbert Bay? Fishing activity may lead to a decline of the population. On the other hand, harvesting fish at a population level close to the carrying capacity might increase its growth rate. The projection of the cod population over time provides a baseline of whether and when a fishery could be opened.

Another concern regarding the rebuilding of Gilbert Bay cod is the potential value of the local population to the recovery of offshore Atlantic cod stocks. Theoretically, when a population in one area is too large for the local environment to support, individuals will spread out to unoccupied areas (MacCall, 1990). Since the collapse of northern Atlantic cod in the early 1990s, there has been no clear evidence of recovery of this stock, especially in the offshore region. Inshore cod populations may not have reached the level which could prompt inshore cod to migrate offshore (Rose *et al.*, 2000). It is very difficult to test whether and when this movement will happen on a large scale. With its small geographic area, Gilbert Bay, however, is a case study. By comparing the model prediction with future observations of Gilbert Bay cod movement, we may understand the recovery mechanism.

4.1.2 Leslie matrix

First described by P. H. Leslie in 1945, the Leslie matrix (also known as a population projection model) is an age-structured model with which to forecast population growth by applying survival and fertility rates to age classes. The model is commonly used in conservation biology to simulate the changes in animal populations over time (Crouse *et al.*, 1987). It is a special case of the general matrix A such that

$$N_{(t)} = AN_{(t-1)} \tag{6}$$

or

$$\begin{bmatrix} n_1 \\ n_2 \\ . \\ n_i \end{bmatrix}_t = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1i} \\ a_{21} & a_{22} & \cdots & a_{2i} \\ . & . & \cdots & . \\ a_{j1} & a_{j2} & \cdots & a_{ji} \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ . \\ n_i \end{bmatrix}_{t-1} \tag{7}$$

where $N_{(t)}$ is the number of individuals of each age class at time t. The population projection matrix A takes into account the age-specific fertilities (F_i) and survival probabilities (P_i) as its first row and sub-diagonal elements respectively. For a species with a four-year life span, the population projection model can be written as follows:

$$\begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix}_t = \begin{bmatrix} F_1 & F_2 & F_3 & F_4 \\ P_1 & 0 & 0 & 0 \\ 0 & P_2 & 0 & 0 \\ 0 & 0 & P_3 & 0 \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{bmatrix}_{t-1} \tag{8}$$

Each population matrix *A* has a dominant eigenvalue λ. In reference to the exponential population growth equation: $N_t = N_0 e^{rt}$, the dominant eigenvalue λ of *A* is equal to e^r, where r is the intrinsic growth rate of the population. Thus, if $\lambda > 1$ (or $r > 0$) the population will grow, if $\lambda < 1$ (or $r < 0$) the population will decline, and if $\lambda = 1$ (or $r = 0$) the population size will stay the same. Each population projection matrix *A* has a right eigenvector *w* and left eigenvector *v* corresponding to λ such that

$$Aw = \lambda w \qquad \text{and} \qquad vA = \lambda v \tag{9}$$

The right eigenvector w represents the stable age distribution of the population, and the left eigenvector v gives the age-specific reproductive value of the population (Goodman, 1968).

4.1.3 Sensitivity analysis

Another benefit of using the Leslie matrix population model is the ability to conduct a sensitivity analysis. Sensitivity analysis of vital demographic rates (age-specific rates of survival and fecundity) is one of the most important tools in quantitative population ecology. Sensitivity analysis measures the changes of the model projections relating to the changes in demographic parameters. In the population projection model, the dominant eigenvalue λ of the Leslie matrix A is related to the intrinsic growth rate of the population ($\lambda = e^r$). Thus, the sensitivity of λ to the matrix A allows one to evaluate the importance of each age-specific rate of survival or fertility to the growth of the population. The most widely applied sensitivity analysis in conservation management is elasticity analysis, which allows us to compare the effects of changes in parameters (e.g. fertility and survival) on the growth of the population. The elasticities of λ with respect to all parameters in the Leslie matrix always sum to 1 (Caswell, 2001). So the elasticity represents the contribution (proportion) of every age-specific survival and fertility to the population growth rate.

4.2 Materials and Methods

4.2.1 The Leslie matrix for the Gilbert Bay cod population

The age-structured population projection model was used to investigate the population dynamics of the Atlantic cod in Gilbert Bay. To construct a population projection matrix for Gilbert Bay cod, I assumed a maximum life span of 20 years. P_i and F_i represent the age-specific survival rates and fertility rates. Thus, the form of the population projection matrix can be constructed as follows:

$$\begin{bmatrix} F_1 & F_2 & \ldots & F_{19} & F_{20} \\ P_1 & 0 & \ldots & 0 & 0 \\ 0 & P_2 & \ldots & 0 & 0 \\ . & . & . & . & . \\ 0 & 0 & \ldots & P_{19} & 0 \end{bmatrix}$$

The age-specific survival rate refers to the probability that individual cod in each age class will survive to the next age class. The rates were estimated from the definition of the survival probability:

$$P_i = e^{-(f_i + m_i)} \qquad (10)$$

where f_i and m_i are fishing mortality and natural mortality for age class i (e.g. Beverton and Holt, 1957; Rothschild, 1986). Since commercial fishing for cod is not permitted in Gilbert Bay, the fishing mortality is set to zero in the calculation. The natural mortality for Atlantic cod older than one year is usually assumed to be 0.2 per year (Pinhorn 1975, Fahrig *et al.*, 1998). Recently, a higher value for natural mortality has been suggested for northern cod (Shelton *et al.*, 2006). In Chapter 3, I discussed the importance of habitat availability to population growth, particularly regarding the changes in the mortality of juvenile Atlantic cod. To investigate the effect of higher natural mortality on rebuilding times for the Gilbert Bay cod population, I used three different values (0.2, 0.3, and 0.4 per year) for natural mortality.

The first row of the population matrix is the age-specific fertility (per-capita fertility of each age class), which refers to the number of cod that are produced by each individual at each age class and which survive to age 1. The age-specific fertilities for Gilbert Bay cod were calculated from the fecundities of each age class. Atlantic cod are very prolific. A female cod of 80 cm in length may produce two million eggs. The number of eggs produced at age i is related to the length of female cod (May, 1967):

$$Fecundity_i = 0.5 * length_i^{3.42} \qquad (11)$$

However, mortality in the first year of life is very high. As many as 99.9% of individuals die in the first few months of life. Only about 15 out of one million survive to age one. Hutchings (1999) estimated the survival from birth to age 3 years for the cod on the northern Grand Bank to be $1.13\times10^{-6}\pm1.11\times10^{-6}$. Anderson and Gregory (2000) calculated the survival from birth to age 3 years of northern cod to be 4.7×10^{-7} to 5.6×10^{-6}. Considering natural mortalities for one-year-old Atlantic cod of 0.2 to 0.4 per year, the survival of the cod from egg to age 1 would be about 10^{-6} to 10^{-5}. Assuming that females comprise 50% of the population and all eggs spawned are fertilized (Anderson and Gregory, 2000), the age-specific fertility can be derived from the following equation:

$$F_i = \frac{1}{2} \times Fecundity_i \times P_0 \qquad (12)$$

where P_0 , the survival of the cod from egg to age 1, is assumed to be 10^{-5} in my calculations. Morris and Green (2002) found that the smallest mature female of the Gilbert Bay cod population was 31.4 cm in length, and aged 4 years. So I set F_1, F_2, *and* F_3 to zero. Figure 4.1 shows the age-structured life cycle graph for the Gilbert Bay cod population.

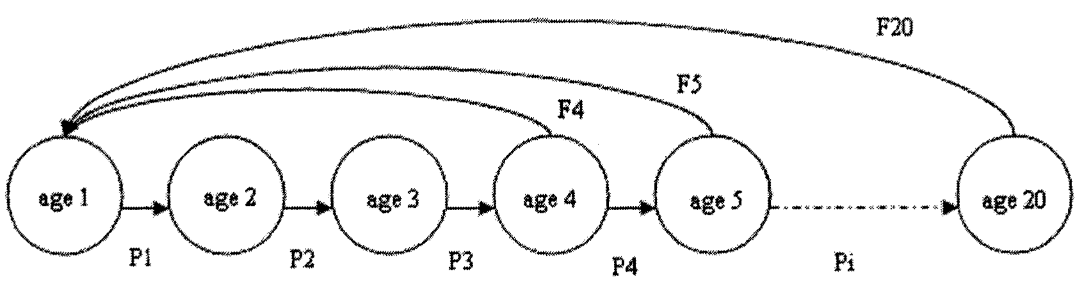


Figure 4.1 The age-structured life cycle graph for Gilbert bay cod. Each circle represents one age class.

4.2.2 The population projection model for Gilbert Bay cod

To project the Gilbert Bay cod population into the future, I applied the Leslie matrix population model:

$$\begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ \cdot \\ n_{19} \\ n_{20} \end{bmatrix}_t = \begin{bmatrix} 0 & 0 & 0 & F_4 & \dots & F_{19} & F_{20} \\ P_1 & 0 & 0 & 0 & \dots & 0 & 0 \\ 0 & P_2 & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & P_3 & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & P_4 & \dots & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot & \cdot \\ 0 & 0 & 0 & 0 & \dots & P_{19} & 0 \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ \cdot \\ n_{19} \\ n_{20} \end{bmatrix}_{t-1} \quad (13)$$

The initial numbers of cod at each age classes were estimated from the initial cod biomass and a stable age distribution which was derived from the right eigenvector of the population projection matrix.

The weight-length (total length) relationship, $W = 5.9*10^{-3}*L^{3.11}$ (Morris and Green, 2002), and length-at-age (fork length) relationship, $L = 33.2*A^{0.183}$ (Smedbol, 1999; Ruzzante *et al.*, 2000) were used to convert between cod numbers and cod biomass (Figure 4.2). For Atlantic cod which have truncate tails, fork length approximates to total length.

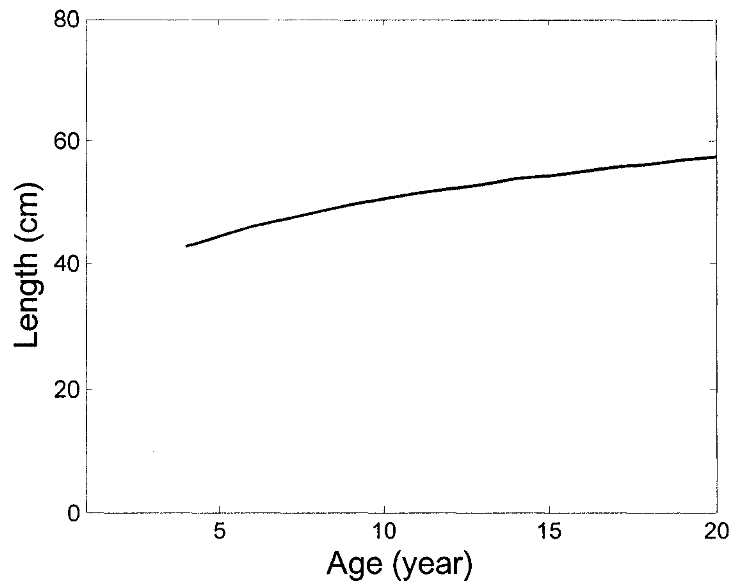


Figure 4.2 The length-age relationship of Atlantic cod caught in 1996 and 1997 in Gilbert Bay. Data from Smedbol (1999).

4.2.3 Sensitivity analysis

To examine the sensitivity of age-specific fecundities and survival probabilities to the growth of population, the elasticity of the dominant eigenvalue of the Leslie matrix for the Gilbert Bay cod population was calculated by using the equation:

$$E = \left(\frac{a_{ij}}{\lambda} \frac{\partial \lambda}{\partial a_{ij}} \right) \tag{14}$$

where E is the elasticity matrix representing the elasticities of λ with respect to each scalar in the population projection matrix (Caswell, 2001). Since the population projection matrix contains the age-specific fertilities and probabilities of survival, the sensitivity analysis shows how they contribute to the growth of the population ($\lambda=e^r$). We can express the contribution (%) of each scalar in the population projection matrix (fertility and survival rate) to the growth of the Gilbert Bay cod population.

4.3 Results

4.3.1 Gilbert Bay cod life table

According to the calculations, the eggs that Gilbert Bay cod may produce (for the age classes of 4 to 20) range from 190,000 to 520,000. Overall, the fertilities range from 0.95 to 2.6 for cod of age 4 to 20 (Figure 4.3). The fertility of 20-year-old Gilbert Bay cod was calculated at 2.6, which means that on average only 2.6 individuals out of 520,000 progeny survive their first year of life.

Figure 4.3 Fertility (the number of cod that are produced by each individual at each age class and which survive to age 1) for Gilbert Bay cod.

For natural mortalities of 0.2, 0.3 and 0.4 per year, the age-specific probabilities of survival of cod (age$\geq$1) are 0.819, 0.741, and 0.670, respectively. The fertility for Atlantic cod in Gilbert Bay used in this model is shown in Table 4.1.

Table 4.1 Fertility for Atlantic cod in Gilbert Bay.

Age class	Length (cm)	Fecundity	Fertility
1	-	0	0
2	-	0	0
3	-	0	0
4	42.8	189700	0.9485
5	44.6	218132	1.0907
6	46.1	244498	1.2225
7	47.4	269262	1.3463
8	48.6	292732	1.4637
9	49.6	315126	1.5756
10	50.6	336606	1.6830
11	51.5	357296	1.7865
12	52.3	377293	1.8865
13	53.1	396675	1.9834
14	53.8	415507	2.0775
15	54.5	433841	2.1692
16	55.1	451724	2.2586
17	55.8	469192	2.3460
18	56.3	486281	2.4314
19	56.9	503017	2.5151
20	57.4	519427	2.5971

4.3.2 Gilbert Bay cod population growth rate and its stable age distribution

Considering a natural mortality of 0.2 per year, the population grows exponentially with λ=1.2023 and the intrinsic rate of growth r=0.18 per year. If the natural mortality increases to 0.3 per year, however, the population still grows exponentially, but λ=1.1043 and the r decreases to 0.1 per year. With a natural mortality of 0.4 per year, the population size will hardly increase because the r of the population is 0.015 per year (λ=1.0147).

The stable age distribution of the Gilbert Bay cod population is shown in Figure 4.4, calculated for natural mortalities of 0.2, 0.3, and 0.4 per year. The proportion of the fish (number) in each age class decreases with age. The number of fish in age 1 class is about 5 times that in age class 5 and 32 times that in age class 10. The number of fish 4 years old and younger accounts for approximate 80% of the total number of individuals in the population. The natural mortality rate affects the stable age distribution as well, but not as much as it affects the value of r. The stable age distributions are slightly different based on the natural mortalities of 0.2, 0.3, and 0.4 per year. As the natural mortality increases, the proportion of younger fish increases slightly.

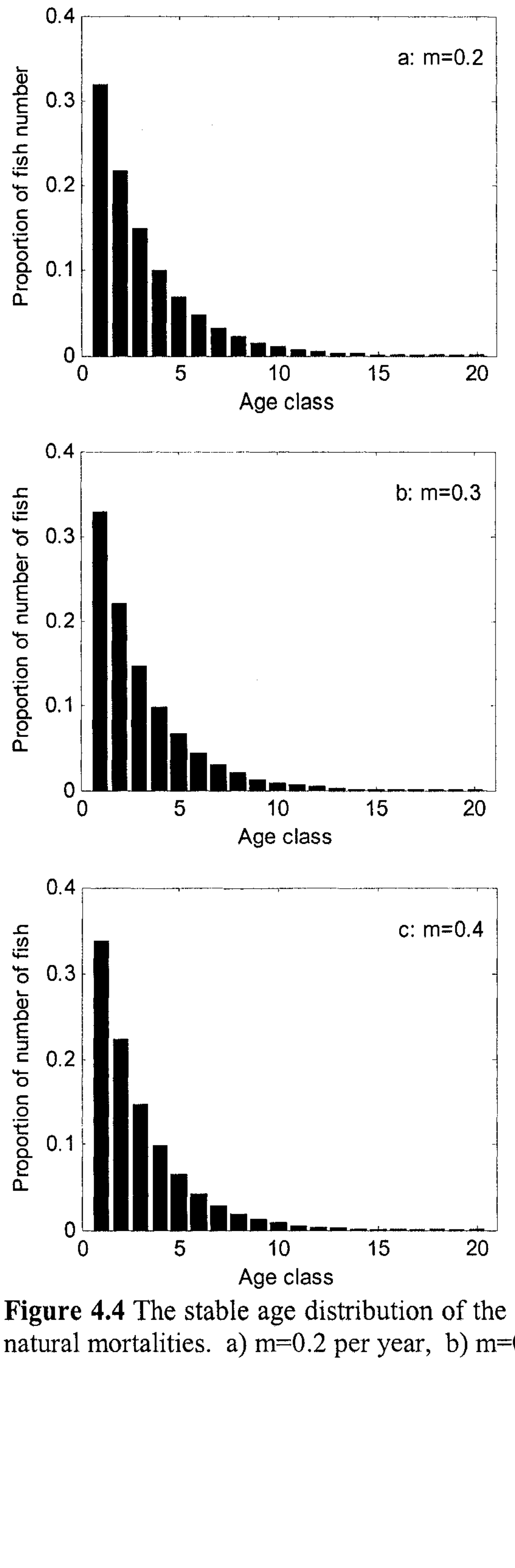


Figure 4.4 The stable age distribution of the Gilbert Bay cod population with different values of natural mortalities. a) m=0.2 per year, b) m=0.3 per year, c) m=0.4 per year.

4.3.3 Projection of the Gilbert Bay cod population into the future

To project the Gilbert Bay cod population into the future, an initial standing biomass of 70 tons in 2003 (Morris, *et al.*, 2003) was set. Corresponding to different natural mortalities of 0.2, 0.3, and 0.4 per year, the population size in the year 2006 could be 122 tons, 94 tons, and 73 tons, respectively. The projection forecasts population size will reach 768 tons, 254 tons, and 85 tons, respectively by year 2016. Depending on a natural mortality of 0.2, 0.3, and 0.4 per year with no fishing mortality, the Gilbert Bay cod population would reach the carrying capacity of 286 tons by 2011, 2018, or 2063, respectively.

As I estimated in Chapter 2, the carrying capacity for Gilbert Bay cod may range from 166 tons to 377 tons, based on different possible primary production rates (110 g C m^{-2} $year^{-1}$ to 250 g C m^{-2} $year^{-1}$). When the natural mortality equals 0.2 per year and there is no fishing mortality, it will take 2 and 7 years for the cod population to reach its upper and lower boundaries of carrying capacity (in the year of 2008 and 2013). If we increase the natural mortality to 0.3 per year and maintain a moratorium on fishing, it will take 6 years for this population to reach the lower estimate of the carrying capacity. Recently, a higher value for natural mortality ($\geq$0.4) has been suggested for cod on the shelf off southern Labrador to the northern Grand Bank for the period 1996-2000 (Shelton *et al.*, 2005). With a natural mortality as high as 0.4 per year, the Gilbert Bay cod population will hardly increase (Figure 4.5).

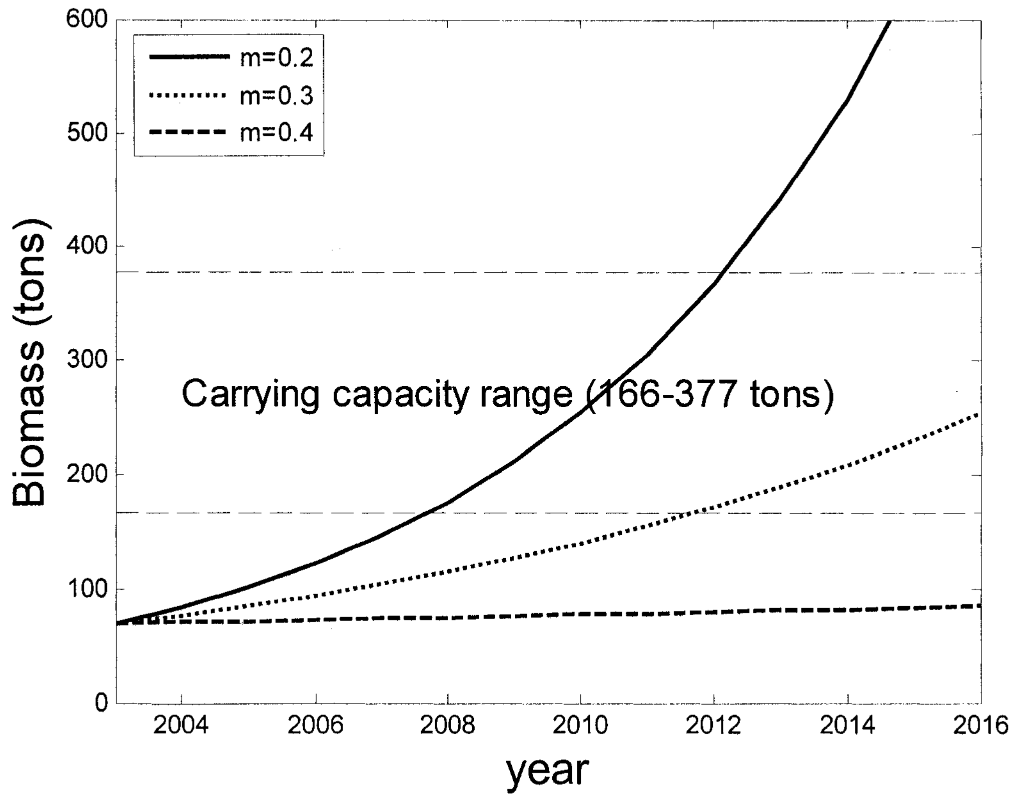


Figure 4.5 The projections of Gilbert Bay cod population biomass using different natural mortalities (m). The starting cod biomass in 2003 is 70 tons (Morris and Green, 2003).

The starting biomass is an important factor in the rebuilding time. The initial conditions affect the time to reach the bay ecosystem carrying capacity. The only available estimate of Gilbert Bay cod biomass is from Morris *et al.* (2003) who estimated the abundance by tag and recapture methods during the period of 1998 and 2002. They suggest the biomass of cod larger than 30 cm in Gilbert Bay is between 42 and 60 tons. To illustrate the effect of initial biomass on the rebuilding time, I ran the model assuming different initial values of cod biomass in 2003. Starting biomass of 50 tons, 100 tons, and 150 tons were set to run the model at three natural mortalities: 0.2, 0.3 and 0.4 per year (Figures 4.6, 4.7, and 4.8).

With the natural mortality of 0.2 per year and fishing mortality of zero, if the starting biomass of 2003 is 50 tons, the population would reach the carrying capacity of 286 tons by year 2013, reach the lower estimate of carrying capacity in year 2010, and will not reach the upper estimate until 2014. If the starting biomass of 2003 is 100 tons, the population would reach the carrying capacity of 286 tons by year 2009, reach the lower estimate of carrying capacity in 2006, and reach the higher estimate of carrying capacity in year 2011 (Table 4.2).

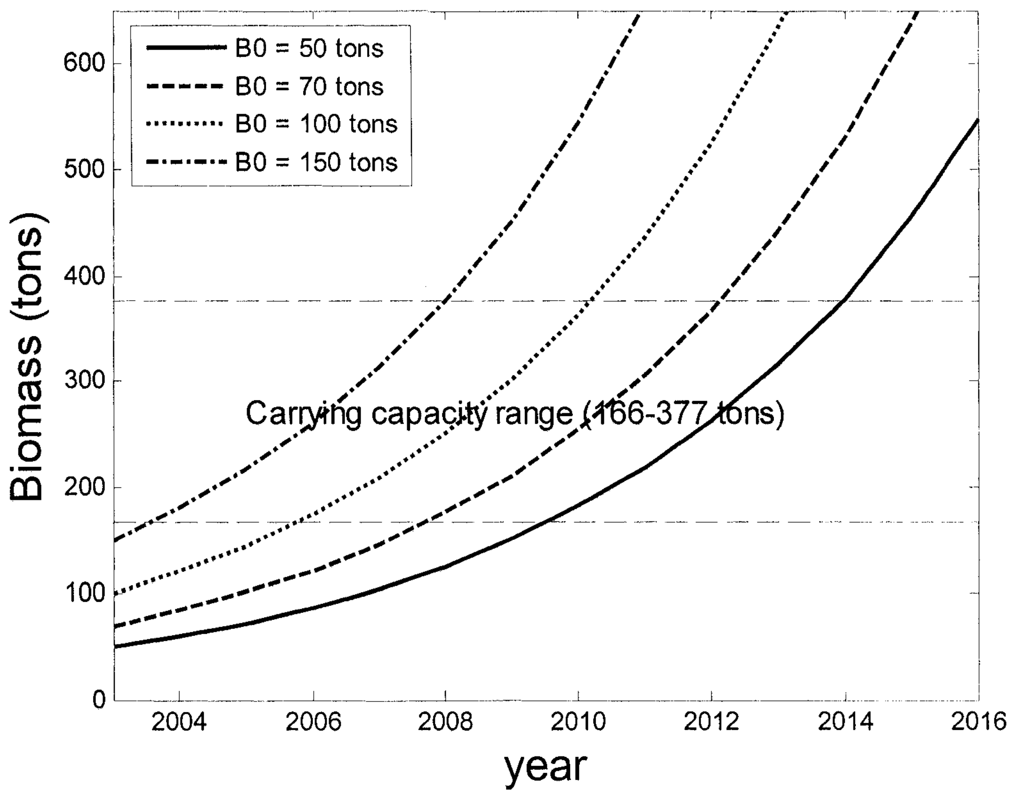


Figure 4.6 Comparison of rebuilding times for the Gilbert Bay cod population to reach the bay ecosystem carrying capacity, assuming different initial biomass values B_0. (m=0.2 per year).

With the natural mortality of 0.3 per year and fishing mortality of zero, if the cod starting biomass in 2003 is 50 tons, the population would reach the carrying capacity of 286 tons by year 2021 and reach the lower estimate of carrying capacity in year 2016. If the starting biomass of 2003 is 100 tons, the population would reach the carrying capacity of 286 tons by year 2014, reach the lower estimate of carrying capacity in year 2009, but will not get to the higher estimate of carrying capacity within 10 years (Table 4.2).

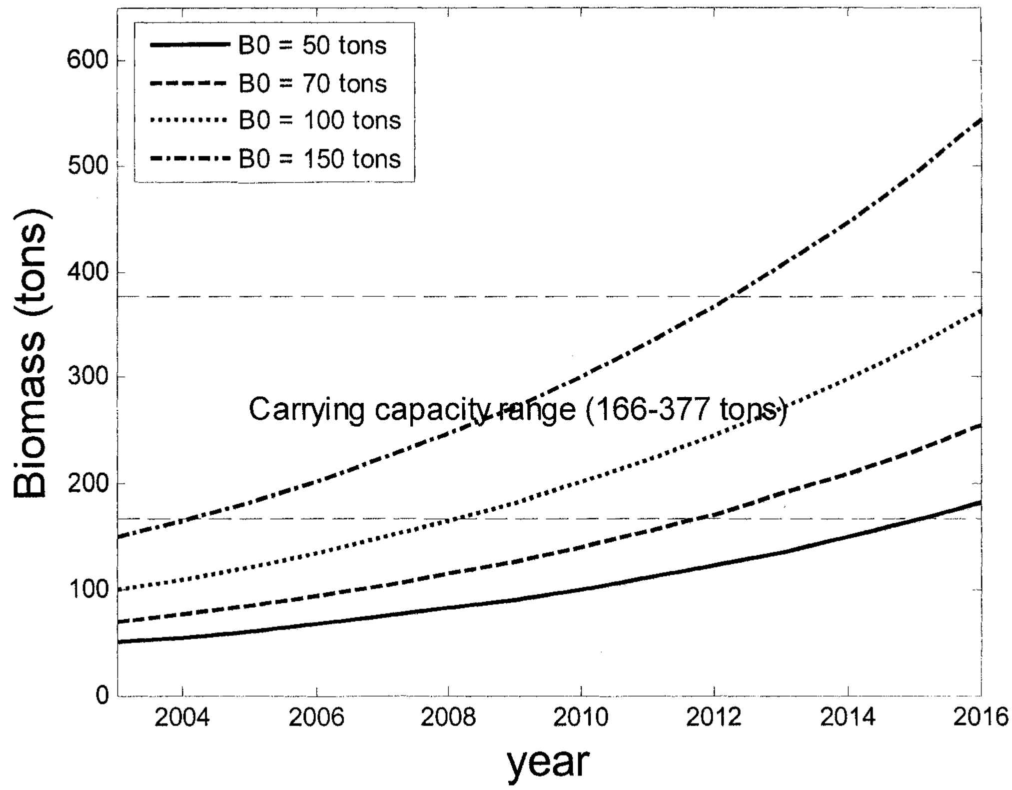


Figure 4.7 Comparison of rebuilding times for the Gilbert Bay cod population to reach the bay ecosystem carrying capacity, assuming different initial biomass values B_0. (m=0.3 per year).

With a natural mortality of 0.4 per year and a fishing mortality of zero, the population will increase slowly. Even with the starting biomass of 150 tons, the population would only increase by 16 tons, reaching the lower estimate of the carrying capacity in 5 years and would reach the carrying capacity of 286 tons by year 2048. With the starting biomass of 100 tons, the population will not approach the lower estimate of the carrying capacity after 10 years (Table 4.2).

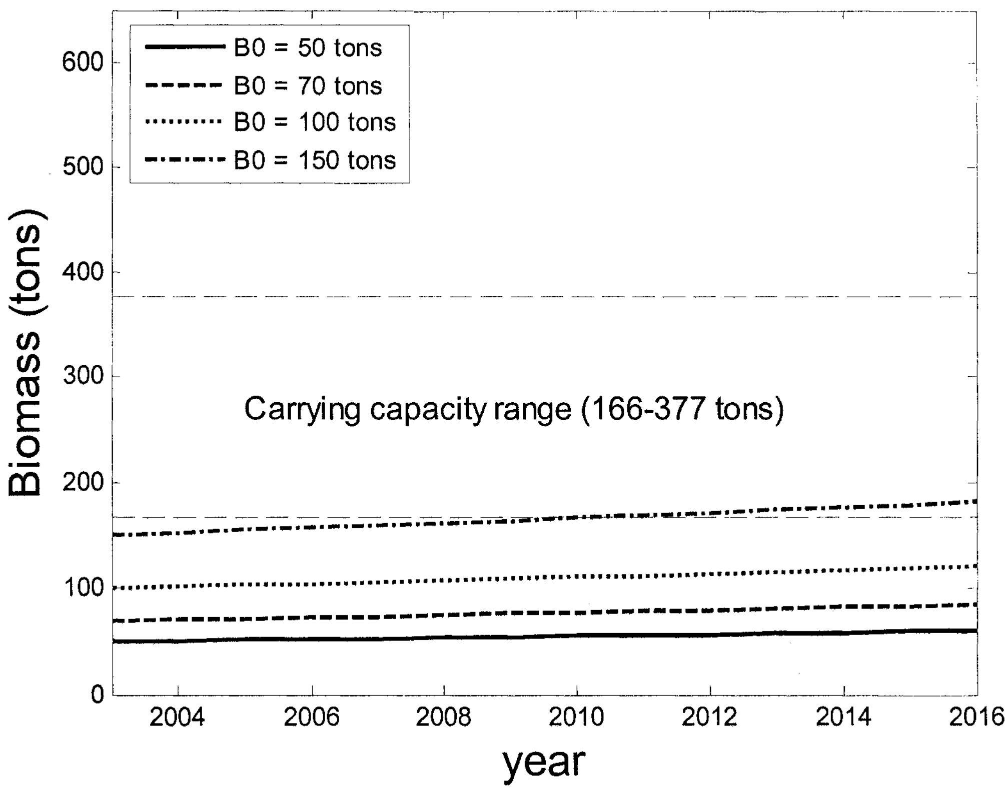


Figure 4.8 Comparison of rebuilding times for the Gilbert Bay cod population to reach the bay ecosystem carrying capacity, assuming different initial biomass values B_0. (m=0.4 per year).

Table 4.2 The year that the Gilbert Bay cod population reaches its carrying capacity. Parameter m is natural mortality; f is fishing mortality; B_0 is initial biomass; K1 is the lower estimate of the carrying capacity; K2 is upper estimate of the carrying capacity.

Initial biomass in 2003	m=0.2 and f=0		m=0.3 and f=0		m=0.4 and f=0	
	K1=166 (tons)	K2=377 (tons)	K1=166 (tons)	K2=377 (tons)	K1=166 (tons)	K2=377 (tons)
B=50 tons	2010	2014	2016	2024	2086	2142
B=70 tons	2008	2013	2012	2020	2063	2119
B=100 tons	2006	2011	2009	2017	2038	2095
B=150 tons	-	2008	-	2013	2010	2067

4.3.4 Sensitivity analysis

The elasticity analysis shows that the contributions of survival probabilities to the population growth rate are always more than that of the fertilities for all of the age classes. The highest contributions are credited to the survival probabilities of cod at age groups younger than 5 years of age. This suggests the survival of juvenile cod is important to the growth of the cod population. The survival of juveniles at age 1, 2, and 3 have a total contribution of about 45% to the dominant eigenvalue (λ), which is related to the growth rate (r) of the population ($\lambda = e^r$). The contributions of fertilities to the population growth rate are higher at age classes of 4 and 5 years than the rest of the age classes. They only get to the peak value of about 3%, then decline. The overall contributions of survival and fertility to λ are 85% and 15%, respectively. I applied three different natural mortalities (0.2, 0.3, and 0.4 per year); the elasticity trends are the same (Figure 4.9).

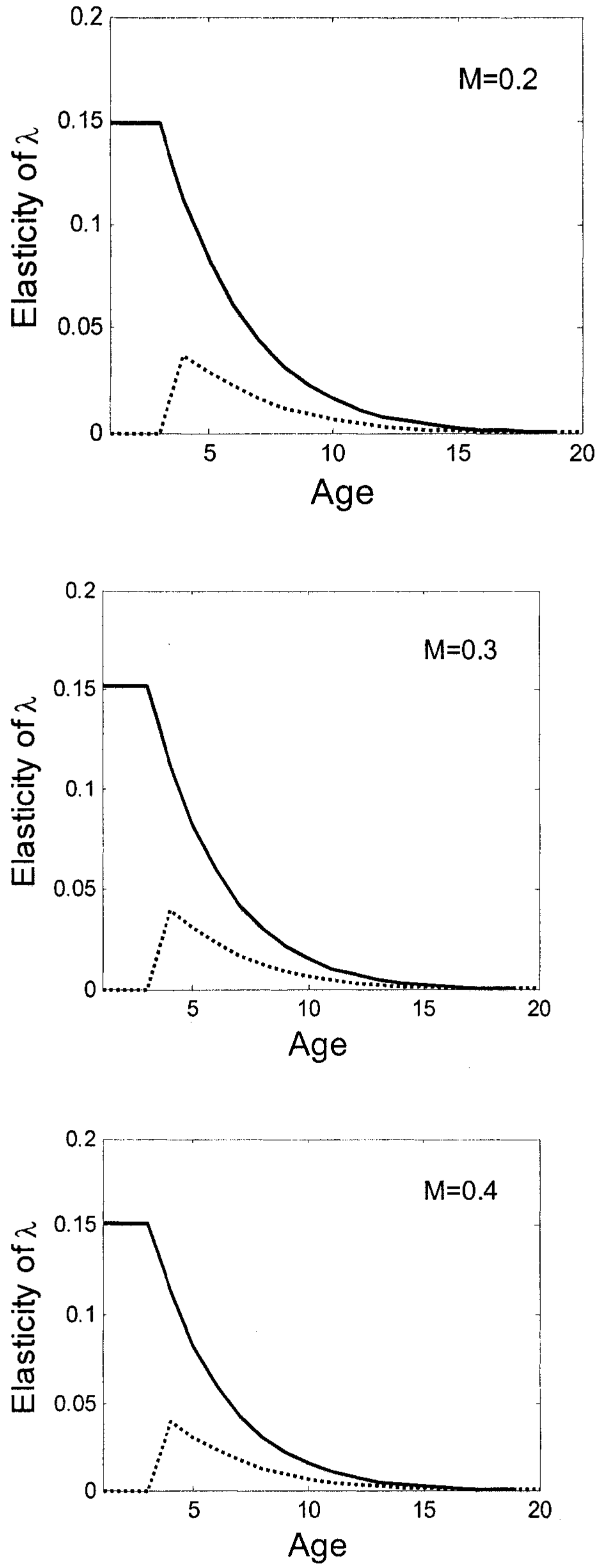


Figure 4.9 The elasticity of λ for Gilbert Bay cod with natural mortalities of 0.2, 0.3, and 0.4 per year. Fishing mortality was considered as zero. The solid lines represent the age-specific survival probabilities; the dotted lines represent the age-specific fertilities.

4.4 Discussion

4.4.1 Gilbert Bay cod population dynamics

The fertilities of Gilbert Bay cod at each age class are lower than that of Atlantic cod on the Labrador continental shelf because of their smaller size at age. Morris and Green (2002) suggested that the cold water temperature and insufficient food might explain the slow growth of individuals. The difference in length between Gilbert Bay cod and shelf cod increases rapidly with age. A 5-year-old Gilbert Bay cod may be only 3 cm smaller than a shelf cod of the same age; however, a 17-year-old Gilbert Bay cod is about 30 cm smaller than a shelf cod at the same age. As a result, the difference of fertilities between Gilbert Bay cod and shelf cod has the same trend. At about age 5, there is little difference in fertility between them. But at age 20, the fertility of Gilbert Bay cod might be much lower than that of shelf cod due to their smaller body size (Figure 4.10, 4.11).

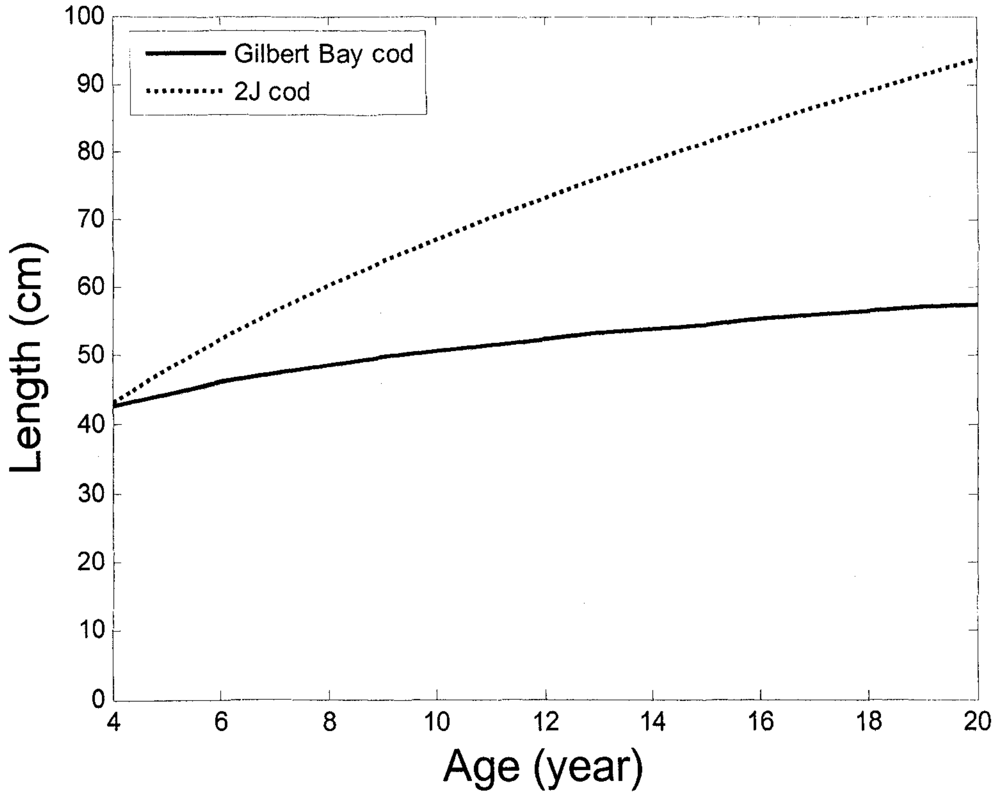


Figure 4.10 Comparison of length at age for Gilbert Bay cod and Atlantic cod in NAFO Div. 2J. The solid line refers to Gilbert Bay cod. The dotted line refers to 2J cod. Length-at-age relationship for Gilbert Bay cod: $L = 33.2*A^{0.183}$ (Smedbol, 1999). The length-at-age curve for 2J cod was generated by using the annual average data from research vessel surveys between 1978 and 1995 presented as Table 31 in Shelton *et al.* (1996).

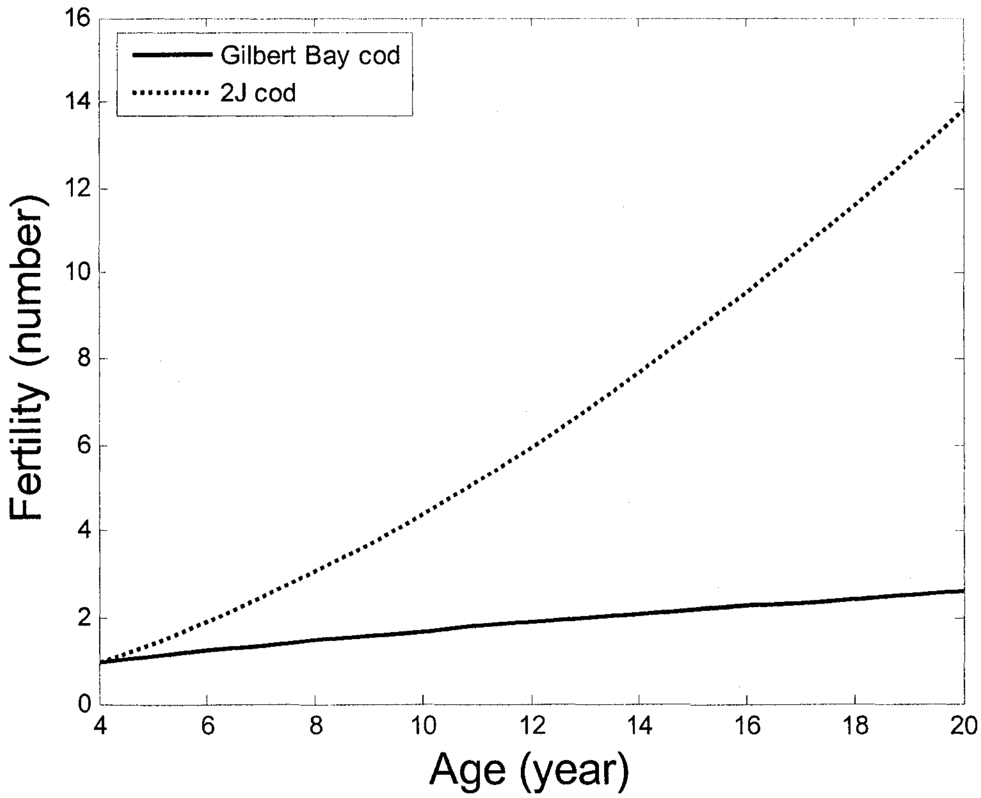


Figure 4.11 Comparison of fertility at age for Gilbert Bay cod and Atlantic cod in NAFO Div. 2J. The solid line refers to Gilbert Bay cod. The dotted line refers to 2J cod.

I used natural mortalities of 0.2, 0.3, and 0.4 per year for all the calculations. The results show that with natural mortality of 0.4 per year, the population will hardly grow.

The results from the elasticity analysis indicate that early juvenile survivorship is more important to the population growth rate than the fertility. The result indicates that management strategy should focus on protecting juvenile cod and their habitats in Gilbert Bay. As a result, any fishing of young cod in Gilbert Bay should be avoided. However, λ is not actually composed of independent contributions from each scalar in the population projection matrix, which means that the elasticities of λ will change with the changes of survival and fertility.

4.4.2 Effect of fishing mortality on population growth rate

Under the natural mortalities of 0.2 and 0.3 per year without any fishing mortality, Gilbert Bay cod may reach or approach the lower estimate of the carrying capacity in the next 10 years, regardless of the assumed starting biomass. On June 8, 2006, the Minister of Fisheries and Oceans announced the 2006 Recreational Groundfish fishery in Newfoundland and Labrador and the Lower North Shore of Quebec from 1 August to 4 September 2006. The daily bag limit was 5 fish per individual and a boat limit of 15 fish. The Gilbert Bay Steering Committee requested DFO exclude fishing activities from the Gilbert Bay Marine Protected Area. We can use the model to predict how fishing would affect the growth of the population if a recreational fishery were allowed to take place in management zone 3 (Figure 3.2). I calculated the population growth rate under different levels of fishing activities. I assume that one person catches 5 fish per day with the average weight of 1 kg; and a current standing biomass is 70 tons. The numbers of fish that might be caught were estimated from the three assumptions listed below:

1). The number of fishers: 25, 50, 75, 100, 150

2). The days of fishing: 10, 20, 30, 35

3). The proportion of Gilbert Bay cod in the recreational catch (otherwise offshore cod migrating to the coast): 100%, 50%, 20%

The fishing mortality may add up to 0.47 per year to the total mortality. In other words, if 150 people catch 5 fish per day for 35 days and the fish caught are all Gilbert Bay cod, the total mortalities will increase to 0.67, 0.77, and 0.87 per year under the natural mortality of 0.2, 0.3, and 0.4 per year respectively; the population growth rates of Gilbert Bay cod will decrease from 0.18, 0.1, and 0.015 per year to -0.21, -0.3, and -0.38

per year (Table 4.3-4.9). Overall, a total mortality of 0.43 per year or greater may cause this population to decline under the fertility schedule which was used in this study.

Table 4.3 The number of Gilbert Bay cod which might be caught in the recreational/food fishery, assuming one person catches 5 fish per day.

Fishers	proportion of Gilbert Bay cod in catch = 100%				proportion of Gilbert Bay cod in catch = 50%				proportion of Gilbert Bay cod in catch = 20%			
	Number of days fishing				Number of days fishing				Number of days fishing			
	10	20	30	35	10	20	30	35	10	20	30	35
25	1250	2500	3750	4375	625	1250	1875	2187.5	250	500	750	875
50	2500	5000	7500	8750	1250	2500	3750	4375	500	1000	1500	1750
75	3750	7500	11250	13125	1875	3750	5625	6562.5	750	1500	2250	2625
100	5000	10000	15000	17500	2500	5000	7500	8750	1000	2000	3000	3500
150	7500	15000	22500	26250	3750	7500	11250	13125	1500	3000	4500	5250

Table 4.4 The total mortality rate (per year) of the Gilbert Bay cod population if there is a recreational/food fishery, assuming one person catches 5 fish per day. The natural mortality is 0.2 per year.

Fishers	Proportion of Gilbert Bay cod in catch = 100%				Proportion of Gilbert Bay cod in catch = 50%				Proportion of Gilbert Bay cod in catch = 20%			
	Number of days fishing				Number of days fishing				Number of days fishing			
	10	20	30	35	10	20	30	35	10	20	30	35
25	0.22	0.24	0.26	0.26	0.21	0.22	0.23	0.23	0.20	0.21	0.21	0.21
50	0.24	0.27	0.31	0.33	0.22	0.24	0.26	0.26	0.21	0.21	0.22	0.23
75	0.26	0.31	0.38	0.41	0.23	0.26	0.28	0.30	0.21	0.22	0.23	0.24
100	0.27	0.35	0.44	0.49	0.24	0.27	0.31	0.33	0.21	0.23	0.24	0.25
150	0.31	0.44	0.59	0.67	0.26	0.31	0.38	0.41	0.22	0.24	0.27	0.28

* Total mortality = natural mortality + fishing mortality
Fishing mortality = - Ln (1 – catch biomass/total biomass)

Table 4.5 The growth rate (per year) of the Gilbert Bay cod population if there is a recreational/food fishery, assuming one person catches 5 fish per day. The gray color represents a decrease in population. The natural mortality is 0.2 per year.

	Proportion of Gilbert Bay cod in catch = 100%		Proportion of Gilbert Bay cod in catch = 50%		Proportion of Gilbert Bay cod in catch = 20%	
	Number of days fishing		Number of days fishing		Number of days fishing	
Fishers	20	35	20	35	20	35
25	0.15	0.13	0.17	0.16	0.17	0.17
50	0.12	0.08	0.15	0.13	0.17	0.16
75	0.10	0.01	0.13	0.10	0.17	0.15
100	0.06	-0.06	0.12	0.08	0.16	0.14
150	-0.02	-0.21	0.10	0.01	0.15	0.11

* The population growth rates were calculated from the Leslie matrix by taking into account the fishing mortalities.

Table 4.6 The total mortality rate (per year) of the Gilbert Bay cod population if there is a recreational/food fishery, assuming one person catches 5 fish per day. The natural mortality is 0.3 per year.

Fishers	Proportion of Gilbert Bay cod in catch = 100%				Proportion of Gilbert Bay cod in catch = 50%				Proportion of Gilbert Bay cod in catch = 20%			
	Number of days fishing				Number of days fishing				Number of days fishing			
	10	20	30	35	10	20	30	35	10	20	30	35
25	0.32	0.34	0.36	0.36	0.31	0.32	0.33	0.33	0.30	0.31	0.31	0.31
50	0.34	0.37	0.41	0.43	0.32	0.34	0.36	0.36	0.31	0.31	0.32	0.33
75	0.36	0.41	0.48	0.51	0.33	0.36	0.38	0.40	0.31	0.32	0.33	0.34
100	0.37	0.45	0.54	0.59	0.34	0.37	0.41	0.43	0.31	0.33	0.34	0.35
150	0.41	0.54	0.69	0.77	0.36	0.41	0.48	0.51	0.32	0.34	0.37	0.38

* Total mortality = natural mortality + fishing mortality
Fishing mortality = - Ln (1 – catch biomass/total biomass)

Table 4.7 The growth rate (per year) of the Gilbert Bay cod population if there is a recreational/food fishery, assuming one person catches 5 fish per day. The gray color represents a decrease in population. The natural mortality is 0.3 per year.

Fishers	Proportion of Gilbert Bay cod in catch = 100%		Proportion of Gilbert Bay cod in catch = 50%		Proportion of Gilbert Bay cod in catch = 20%	
	Number of days fishing		Number of days fishing		Number of days fishing	
	20	35	20	35	20	35
25	0.07	0.05	0.09	0.08	0.10	0.10
50	0.04	-0.01	0.07	0.05	0.10	0.08
75	0.01	-0.08	0.05	0.01	0.09	0.07
100	-0.03	-0.15	0.04	-0.01	0.08	0.06
150	-0.11	-0.30	0.01	-0.08	0.07	0.03

* The population growth rates were calculated from the Leslie matrix by taking account in the fishing mortalities.

Table 4.8 The total mortality rate (per year) of the Gilbert Bay cod population if there is a recreational/food fishery, assuming one person catches 5 fish per day. The natural mortality is 0.4 per year.

Fishers	Proportion of Gilbert Bay cod in catch = 100%				Proportion of Gilbert Bay cod in catch = 50%				Proportion of Gilbert Bay cod in catch = 20%			
	Number of days fishing				Number of days fishing				Number of days fishing			
	10	20	30	35	10	20	30	35	10	20	30	35
25	0.42	0.44	0.46	046	0.41	0.42	0.43	0.43	0.40	0.41	0.41	0.41
50	0.44	0.47	0.51	0.53	0.42	0.44	0.46	0.46	0.41	0.41	0.42	0.43
75	0.46	0.51	0.58	0.61	0.43	0.46	0.48	0.50	0.41	0.42	0.43	0.44
100	0.47	0.55	0.64	0.69	0.44	0.47	0.51	0.53	0.41	0.43	0.44	0.45
150	0.51	0.64	0.79	0.87	0.46	0.51	0.58	0.61	0.42	0.44	0.47	0.48

* Total mortality = natural mortality + fishing mortality
Fishing mortality = - Ln (1 – catch biomass/total biomass)

Table 4.9 The growth rate (per year) of the Gilbert Bay cod population if there is a recreational/food fishery, assuming one person catches 5 fish per day. The gray color represents a decrease in population. The natural mortality is 0.4 per year.

Fishers	Proportion of Gilbert Bay cod in catch = 100%		Proportion of Gilbert Bay cod in catch = 50%		Proportion of Gilbert Bay cod in catch = 20%	
	Number of days fishing		Number of days fishing		Number of days fishing	
	20	35	20	35	20	35
25	-0.02	-0.04	0.01	-0.01	0.01	0.01
50	-0.04	-0.1	-0.02	-0.04	0.01	-0.01
75	-0.08	-0.16	-0.04	-0.07	-0.002	-0.02
100	-0.11	-0.23	-0.04	-0.1	-0.01	-0.03
150	-0.19	-0.38	-0.08	-0.16	-0.02	-0.05

* The population growth rates were calculated from the Leslie matrix by taking account in the fishing mortalities.

4.4.3 Could the Gilbert Bay cod population contribute to the recovery of the offshore cod population?

Having once supported the largest fishery in Atlantic Canada, northern Atlantic cod encompassed a vast geographic area off Newfoundland and Labrador before the population collapsed in the early 1990s due to over exploitation. The current offshore Atlantic cod stock size is estimated at only 19,000 tons in Northwest Atlantic Fishery Organization (NAFO) management units 2J + 3KL (DFO, 2005). Most of the cod remaining in Newfoundland waters are found in inshore areas (Smedbol *et al.*, 1998; Rose, 2003; Wroblewski *et al.*, 2005). Recent studies suggest that rebuilding inshore stocks might be the key to the rebuilding of the full stock complex (Rose *et al.*, 2000; Wroblewski *et al.*, 2005).

In an isolated area a fish population will stop growing at its carrying capacity due to the limit of environmental resources. In Gilbert Bay, however, there are two openings to the Labrador Sea and one to neighboring Alexis Bay. When the cod population rebuilds beyond what the local ecosystem can support, some individual cod may move out off the bay and migrate to adjacent coastal areas. The metapopulation theory (Hanski and Simberloff, 1997) suggests that movements among subpopulations are possible (Figure 4.12). Early studies indicate that the northern Atlantic cod stock complex contained many subpopulations (Templeman, 1962, 1979; Lear, 1984; Taggart *et al.*, 1995; Wroblewski, *et al.*, 1996). Smedbol and Wroblewski (2002) identified four subpopulations of the northern Atlantic cod population: the Hamilton-Belle Isle-Funk Island Bank subpopulation, the Northern Grand Bank subpopulation, the Trinity Bay subpopulation, and the Gilbert Bay subpopulation. As one of the subpopulations of northern Atlantic cod, the movement of Gilbert Bay cod among the other subpopulations is possible. Based on the ideal free distribution theory, animals have the ability to move among places to maximize their evolutionary fitness (Fretwell and Lucas, 1969; Fretwell, 1972; MacCall, 1990). The test of ideal free theory on pike (*Esox lucius*) proved the adaptive movement of this species between two basins of a natural lake to maximize lifetime fitness (Haugen *et al.*, 2006; Morris, 2006). Morris (2006) emphasized the importance of the animal ideal free distribution to population dynamics.

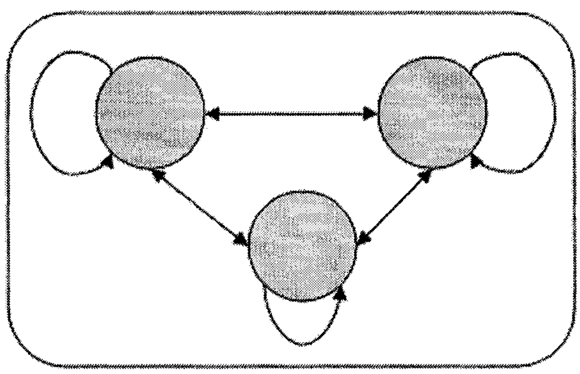


Figure 4.12 The structure of metapopulation, redrawn from Kritzer and Sale (2004). The gray circles represent subpopulations within the larger region bounded by the outer square. Arrows represent the sources of offspring.

Brown (1957) envisioned that there is a threshold level of habitat suitability governing the migration of a population between original and new habitats. The movement is limited when the population density is below this level, but active when the density is above this level. There might be an abundance threshold necessary for Atlantic cod to migrate to pre-occupied areas (Rose *et al.*, 2000). Wroblewski *et al.* (2005) suggesting that the abundance threshold for inshore cod is possibly the carrying capacity of the inshore environment. If fish currently in the inshore could recolonize the offshore spawning grounds, then allowing the inshore biomass to increase makes the offshore movement more likely to happen.

4.4.4 Discussion of assumptions

My model of population dynamics of Atlantic cod in Gilbert Bay was based on several assumptions. The Atlantic cod population in Gilbert Bay is genetically distinguishable from other Atlantic cod populations (Ruzzante *et al.*, 2000; Beacham *et al.*, 2002; Hardie *et al.*, 2006). The migration of Gilbert Bay cod is largely restricted to movements within the bay (Green and Wroblewski, 2000). These facts indicate that Atlantic cod in Gilbert Bay is a closed population. However, the appearance of offshore cod in Gilbert Bay during summer (Green and Wroblewski, 2000) and the movement of Gilbert Bay cod out of the bay may limit the validity of model projections of cod biomass in the bay.

Secondly, when applying the Leslie matrix to the Gilbert Bay cod population, a maximum lifespan (20 years) was assumed for all individuals in the population. The fertility and survival rates used in the model were assumed not to change from year to year within the projected interval, and the survival rates for the cod at ages ≥ 1 were considered to be constant.

Thirdly, as no information is available regarding Gilbert Bay cod survivorship, the elasticity analysis was conducted using assumed survival rates for this population. The natural mortalities of 0.2, 0.3, and 0.4 per year are reasonable values for Atlantic cod. However, the actual survival rate for Gilbert Bay cod in nature could be different, which would change the elasticity analysis.

Chapter 5 Summary and conclusions

5.1 Summary

The goals of this research were to estimate the annual production of resident fishes in Gilbert Bay, calculate the ecosystem carrying capacity for Atlantic cod, and model the Atlantic cod population dynamics. The resident fish production was estimated based on the bottom-up approach, considering the primary production available for the food chain in the bay. The four species considered residents of Gilbert Bay: Atlantic cod, Greenland cod, short horn sculpin, and winter flounder (Wroblewski *et al.*, 2007) composed 32%, 40%, 14%, and 14% of the total resident fish biomass, respectively. The trophic level of Atlantic cod in Gilbert Bay was estimated at 3.3, which is the same value as estimated for Atlantic cod on the Newfoundland and Labrador continental shelf (Sherwood and Rose, 2004). The annual resident fish production was estimated at 340 tons per year, based on a primary production rate of 190 g C m^{-2} $year^{-1}$. The partition of the theoretical fish production among the resident species are: Atlantic cod (109 tons per year), Greenland cod (136 tons per year), short horn sculpin (48 tons per year), and winter flounder (48 tons per year). The ecosystem carrying capacity for Atlantic cod in Gilbert Bay is 286 tons under current ocean climate conditions.

Considering the uncertainty of the primary production rate, a range of 110 g C m^{-2} $year^{-1}$ and 250 g C m^{-2} $year^{-1}$ was considered in order to give a baseline of resident fish production under all possible primary production rates. Based on this range, resident fish production would be 197 tons per year to 447 tons per year. The partition of this theoretical fish production into the resident species are: Atlantic cod (63-143 tons per year), Greenland cod (79-179 tons per year), short horn sculpin (28-63 tons per year), and winter flounder (28-63 tons per year). The range for the ecosystem carrying capacity for Atlantic cod in Gilbert Bay is 166-377 tons.

There are three major factors that affect the calculation of fish production: primary production, trophic level, and transfer efficiency. The sensitivity analysis of these three parameters shows that the resident fish production is most sensitive to the trophic level value.

The habitat survey provided visual information regarding the substrate class and benthos at three sites in the main arm of Gilbert Bay. The substrates at the three sites had a similar trend: the hardness of the bottom decreases with increasing water depth. On the other hand, the bottoms were different in local details. The general hardness of the ocean bottom (within 100 m from the shoreline) was highest at Site 1 and lowest at Site 3. The benthos recorded during the survey included scallops, sea stars, sea urchins, blue mussels, a hermit crab, periwinkles, and coralline algae. Juveniles of many fish species in Gilbert Bay primarily used cobble and pebble gravel substrates. The observations suggest that the pebble gravel substrate in shallow water was used by juvenile Greenland cod, short horn sculpin, and winter flounder, but is not a suitable bottom type for juvenile Atlantic cod. Branching coralline algae may be the suitable habitat for juvenile Atlantic cod in Gilbert Bay, but further research is needed to confirm this. Adult Atlantic cod in Gilbert Bay are associated with scattered cobbles/boulders on soft substrate and some coverage of coralline algae.

An age-structured Leslie model was applied to project the Gilbert Bay cod population over time. The model was run at three different values of natural mortality, 0.2 per year, 0.3 per year, and 0.4 per year (assuming fishing mortality is zero). The growth rates of Gilbert Bay cod were calculated to be 0.18 per year (if m=0.2), 0.1 per year (if m=0.3), and 0.0015 per year (if m=0.4). Starting with a standing biomass of 70 tons (Morris *et al.*, 2003) in 2003, Gilbert Bay will reach the carrying capacity of 286 tons in year 2011 (if m=0.2), year 2018 (if m=0.3), and year 2063 (if m=0.4). The rebuilding time was also estimated assuming an initial standing biomass of 50 tons, 100 tons, and 150 tons under the three natural mortalities. The results show that, as expected from the mathematical structure of the model, a higher initial standing biomass leads to a faster rebuilding of Atlantic cod in Gilbert Bay. However, assuming a natural mortality of 0.4 per year, the cod population will grow slowly even with an initial standing biomass of 150 tons, and would reach the carrying capacity of 286 tons by year 2048.

The recreational/food fishery will deplete the population. In order to show how fishing mortality affects the population growth rate, different levels of food/recreational fishing activities were applied to the Leslie model. The model shows that fishing mortality could add up to 0.47 per year to the total mortality of Gilbert Bay cod.

The elasticity analysis shows that the age-specific survivals, especially at the juvenile stage, contribute the most to the population growth. This suggests that protecting juvenile cod and their habitats is most important to the population growth.

5.2 Limitations of the research

This is a first-order calculation of resident fish production and the ecosystem carrying capacity for Atlantic cod in Gilbert Bay. Because the required information is limited, one must make assumptions or consider a possible range of those uncertain factors. For example, the trophic levels of the fish species in Gilbert Bay other than Atlantic cod must be estimated from the literature, as there are no studies of diet for these fish species in Gilbert Bay. The primary production rate in Gilbert Bay was assumed to be in the range of 110 g C m^{-2} $year^{-1}$ and 250 g C m^{-2} $year^{-1}$ to investigate annual fluctuations of the primary production due to environmental conditions. All calculations were based on three natural mortalities of 0.2, 0.3, and 0.4 per year because of the lack of information on actual mortality in the field.

An age-structured Leslie matrix was used to project the rebuilding time of the cod population in Gilbert Bay. However, this model was based on the following assumptions:

1. Gilbert Bay cod was considered to be a closed population.
2. A maximum lifespan (20 years) was assumed for all individuals in the population.
3. The fertility and survival rates used in the model were assumed not to change from year to year within the projected interval.
4. The survival rates for the cod at age ≥ 1 were considered to be constant.
5. The elasticity analysis was conducted using assumed survival rates for this population. The natural mortalities of 0.2, 0.3, and 0.4 per year are reasonable values for Atlantic cod. However, the actual survival rate for Gilbert Bay cod is unknown. Dramatically different values would change the elasticity analysis.

5.3 Implications and recommendations

The Gilbert Bay MPA has a conservation plan to protect the local cod population and its habitat. Continuing research and monitoring within the MPA can provide the stakeholders and management committee a better understanding of the local ecosystem and guide them in future management decisions. The information on the carrying capacity of the bay for cod can guide decisions regarding a recreational/food fishery for cod in Gilbert Bay. The sensitivity analysis of Gilbert Bay cod population dynamics provides a scientific basis for protecting juveniles and their habitats. Modeling the population dynamics under different parameters also allows us to make comparisons among the potential recovery strategies.

Another advantage of establishing an MPA is that we can treat the relatively small region as a case study area before applying conservation methods to a larger spatial context. A study of the cod population in Gilbert Bay may give some guidance for northern cod population management.

The most important element for modeling is direct observation, which can both improve the accuracy of estimations and test the model predictions. As I mentioned before, there are many assumptions made in this calculation due to the lack of observation data. To get a better estimate, further research needs to be done in Gilbert Bay including measurement of primary production and the diet composition of the other three resident species. Given the estimated rebuilding time of Gilbert Bay cod, estimates of cod abundance in Gilbert Bay will be needed to test our prediction. Research to map the bottom habitats of Gilbert Bay is ongoing (Copeland *et al.*, 2006). This will make possible of mapping the juvenile cod distribution over the whole bay.

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Appendix 1:

Length and age of Atlantic cod (*Gadus morhua*) collected in Gilbert Bay, Labrador during the 2004 fish fauna survey (Wroblewski, unpublished data). See Figure 3.2 for location of sites 1-6.

Site name	Standard length (cm)	Total length (cm)	Age
Site 1	31.2	34	3
Site 1	29.5	31.5	3
Site 1	32	35	3
Site 1	30	32.9	3
Site 1	33	36.7	3
Site 1	30.6	32.7	3
Site 1	29.5	32	4
Site 1	32.5	35	4
Site 1	51	55	4
Site 1	46	49	4
Site 1	34	36	4
Site 1	37.5	40.5	4
Site 1	51	55	5
Site 1	37	39.5	5
Site 1	45	49	5
Site 1	44	47.5	6
Site 1	49.6	54	8
Site 1	53.2	58	10
Site 2	9.8	10.5	1
Site 2	28.7	31	3
Site 2	26.4	29	3
Site 2	33	35	3
Site 2	24	25.5	3
Site 2	27.7	30.8	3
Site 2	29.5	32.7	3
Site 2	30	32.8	3
Site 2	30.3	33	3
Site 2	29.2	31.5	3
Site 2	27.6	30.7	3
Site 2	31.4	34	3
Site 2	28.2	31	4
Site 2	30.3	33	4
Site 2	29.3	32	4
Site 2	32	34	4
Site 2	31.4	35	4
Site 2	29.8	32.7	4
Site 2	31.6	34	4
Site 2	34.4	37.7	4

Appendix 1 (continued):

Site name	Standard length (cm)	Total length (cm)	Age
Site 2	28.1	31	4
Site 2	43.5	47	5
Site 2	36	39	5
Site 2	31.7	34	5
Site 2	37	40	5
Site 2	37.5	41.5	5
Site 2	43.8	47.8	5
Site 2	41.6	45	6
Site 2	42.5	46.4	6
Site 2	42.7	47	6
Site 2	39.5	42.7	7
Site 2	42	46	7
Site 2	37	39.5	8
Site 2	40	43.5	8
Site 2	52.4	56.5	8
Site 2	56	61	12
Site 3	33	35	3
Site 3	27	29.5	3
Site 3	30.2	32	3
Site 3	31.4	34	4
Site 3	37.5	39.5	4
Site 3	29.1	31.9	4
Site 3	32.3	35	4
Site 3	37.6	41	5
Site 3	41.7	45	6
Site 3	43.4	47	6
Site 3	44.5	48	7
Site 3	44.5	48	7
Site 3	57	61.8	7
Site 4	22.5	24.5	2
Site 4	29.4	31.6	3
Site 4	26.8	29.7	3
Site 4	29.5	32	3
Site 4	33.3	35.8	3
Site 4	26.5	29	3
Site 4	29	31.4	3
Site 4	29.6	32.1	3
Site 5	20.1	22.5	2
Site 5	27.5	30.5	3
Site 5	24.7	27	3
Site 5	33.6	36.7	4
Site 5	48.7	55	6

Appendix 1 (continued):

Site name	Standard length (cm)	Total length (cm)	Age
Site 6	33.6	37	3
Site 6	37	40	3
Site 6	35	37.5	3
Site 6	41	43.5	3
Site 6	35.5	38	3
Site 6	37.5	40	3
Site 6	38	41	3
Site 6	37.5	40	3
Site 6	42	45.5	4
Site 6	46.5	50	4
Site 6	42	45.5	4
Site 6	43	45.5	4
Site 6	44	47	4
Site 6	43.5	47	4
Site 6	39	41.5	4
Site 6	42	45.5	4
Site 6	41	44.5	4
Site 6	41	44	4
Site 6	49	52.5	4
Site 6	35.5	38	4
Site 6	39	41.5	4
Site 6	40	43	4
Site 6	43	46.5	4
Site 6	49.5	53	4
Site 6	42	45	4
Site 6	45.5	48.5	4
Site 6	43	45.5	4
Site 6	42	45	4
Site 6	46.5	50	4
Site 6	47	50.5	4
Site 6	41	44.5	4
Site 6	45	48	4
Site 6	47	51	4
Site 6	40	43.5	4
Site 6	47	50	4
Site 6	44.5	48.5	5
Site 6	43.4	46.5	5
Site 6	46.5	51	5
Site 6	51	54.5	5
Site 6	39.5	42.5	5
Site 6	38	41	5
Site 6	36	38	5
Site 6	42	45	5
Site 6	47.5	50.5	5

Appendix 1 (continued):

Site name	Standard length (cm)	Total length (cm)	Age
Site 6	37.5	40.5	5
Site 6	48.5	52	5
Site 6	46.5	49	5
Site 6	43	46.5	5
Site 6	42	44.5	5
Site 6	52	56	6
Site 6	43	46.5	6
Site 6	44	47.5	6
Site 6	44.4	48	7
Site 6	44.5	48.7	7
Site 6	43	46.5	7
Site 6	38	41	7
Site 6	51.5	55.5	7
Site 6	42	45	7
Site 6	43	47.4	8
Site 6	47	50.5	8
Site 6	36	38.5	8
Site 6	43	46	8
Site 6	41	44	8
Site 6	39	42.5	8
Site 6	54.5	59	8
Site 6	50.5	54.5	8
Site 6	60	65	8
Site 6	41.5	45	9
Site 6	45.5	50.5	9
Site 6	54	56	10