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Sablefish Aquaculture:
An Assessment of Recent Developments and Their Potential for Enhancing Profitability

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Cover image: Sablefish in a net pen at the Manchester Research Station (NWFSC), Port Orchard, Washington. Image captured from a GoPro video recording by S. Oden, Ocean Associates, Inc.

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Sablefish Aquaculture: An Assessment of Recent Developments and Their Potential for Enhancing Profitability

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Abbreviations

B.C.	British Columbia
BS/AI	Bering Sea/Aleutian Islands
CAD	Canadian dollar
CFS Model	Cash-Flow Simulation Model
CV	coefficient of variation
DFO	Canada Department of Fisheries and Oceans
EEZ	exclusive economic zone
FCR	feed conversion ratio
GOA	Gulf of Alaska
GSP	gross state product
H&G	fish processed into a headed and gutted product form
IMTA	integrated multitrophic aquaculture
IRR	internal rate of return
ITQ	individual transferable quota
MSA	Magnuson–Stevens Fishery Conservation and Management Act
MSC	Marine Stewardship Council
mt	metric ton
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NWFSC	Northwest Fisheries Science Center
RAS	recirculating aquaculture system
SD	standard deviation
TAC	total allowable catch
USD	United States dollar

Executive Summary

Sablefish is a highly marketable fish due to its flesh characteristics and buttery flavor. It is found in the Pacific, from Honshu Island, Japan, north to the Bering Sea, and southeast to Cedros Island, Baja California Sur, Mexico. Commercial harvests did not reach significant levels until the late 1960s, and the U.S. and Canada have historically exported 50 to 60% of their commercial sablefish catch, with Japan as the dominant buyer for several decades. Sablefish has more recently been recognized as a "white-tablecloth" seafood, often served as a seasonal or specialty dish at restaurants.

Despite a consistent, conservative management approach in North American sablefish fisheries, both stock biomass and landings have shown an overall downward trend—global harvests averaged over 50,000 mt per year from 1987–90, but, since 2010, annual harvests have averaged only 20,000 mt.

Because of its limited commercial availability, highly marketable characteristics, and potential to be grown in farming operations, there is strong interest among aquaculture producers and investors in sablefish. The National Marine Fisheries Service (NMFS), Canada Department of Fisheries and Oceans (DFO), University of Washington, and several private-sector and tribal partners have worked on hatchery and grow-out methods, hoping to improve prospects for the aquaculture of sablefish.

The current study was undertaken to describe the present status of sablefish aquaculture in the U.S. and elsewhere, and to perform an initial assessment of the financial viability of a sablefish aquaculture industry that utilizes existing technology, including use of all-female rearing stocks that have been developed at NMFS's Northwest Fisheries Science Center (NWFSC). In addition, the study examines prospective markets for farmed sablefish, the possibility of broadening the overall market for both farmed and commercial sablefish, and the potential economic effects that expansion of sablefish aquaculture could have on commercial sablefish fisheries. The project objectives were to:

- Provide a historic overview of sablefish aquaculture in the U.S. and internationally.
- Document the recent technological advancements in developing successful breeding and hatchery operations, including the development of "neomale" broodstock and female monosex fingerlings.
- Assess the potential financial benefits to the sablefish aquaculture operations resulting from the utilization of female monosex rearing stocks.
- Summarize the international and domestic markets for sablefish.
- Summarize the status of commercial harvest fisheries for sablefish off the coasts of Alaska, British Columbia, Washington, Oregon, and California.
- Determine potential price effects of an increased supply of sablefish by updating and revising the econometric model of the sablefish fishery originally developed by Huppert and Best (2004).

Chapter 2 provides a historic overview of sablefish aquaculture. There are currently very few active sablefish aquaculture grow-out operations, and those are primarily located in British Columbia, including Golden Eagle Sable Fish Inc., which produces its own juveniles for grow-out. In the United States, Troutlodge Marine Farms and Icicle Seafoods, both in Washington State, have performed grow-out trials of sablefish, but neither have continued their operations for a variety of reasons. NWFSC's Manchester Research Station is leading research in sablefish aquaculture, including advances in larval rearing techniques and in streamlining the costly hatchery phase. In addition, NWFSC scientists have directly addressed the issue of sexual growth dimorphism in sablefish by developing techniques that, without the use of genetic modifications, result in female monosex rearing stocks (Luckenbach et al. 2017). Initial trials comparing female monosex rearing stocks to standard mixed-sex rearing stocks indicate a 10.4% increase in the average weight of sablefish harvested after a two-year grow-out.

Chapter 3 is divided into three main sections, with the first two sections providing technical descriptions of sablefish hatchery (Section 3.1) and grow-out operations (Section 3.2). Section 3.3 contains an economic analysis and cash-flow simulation (CFS) model that compares the costs and revenues of net-pen operations with mixed-sex and female monosex rearing stocks.

The CFS Model estimates cash flows with mixed-sex and with female monosex rearing stocks in single net-pen operations under two alternative harvest regimes (550 and 729 grow-out days), four sets of assumptions regarding sales prices, and a range of juvenile costs, feed costs, and other annual costs. The CFS Model is considered a Monte Carlo simulation because it utilizes 5,000 independent estimates to account for variations in mortality events and the distribution of sizes across individuals during each grow-out period within a 10-year timeframe. The conclusions of the CFS Model indicate that using female monosex stocks could add between 11 and 15 percentage points to internal rates of return (IRRs) of existing mixed-sex facilities if growers are able to sell larger fish at a higher price per weight-unit than smaller fish (i.e., size-adjusted pricing). Even if growers must sell fish using a single price per weight-unit based on the average size of all fish harvested, the CFS Model results indicate female monosex stocks could add 6 to 7 percentage points to a company's IRR. These improvements could draw additional investment, leading to a viable, self-sustaining industry, with the caveat that large increases in the global supply of sablefish could put downward pressure on prices and, thus, profitability.

Chapter 4 summarizes sablefish market trends and provides specific examples and insights. The section draws on qualitative information from industry trade publications, academic reports, and popular press articles; telephone interviews conducted with seafood distributors and wholesalers; and a survey administered to selected seafood restaurants and restaurants' seafood purveyors around the country. The survey is reproduced in the Appendix.

On average over the 2005–15 period, the U.S. exported about half of its total sablefish landings and Canada exported around 60% (UNFAO 2018a), primarily to Japan. With a general decrease in the annual total allowable catch limits in North American sablefish fisheries, along with a general increase in prices, sablefish became more of a luxury food item in Japan. Larger sablefish are preferred and command a higher price because they are considered to have a higher oil content and superior taste than smaller sablefish.

The domestic market for sablefish has historically been small in comparison to export markets. In recent decades, however, sablefish has become increasingly prized in upscale restaurants as a premium-quality whitefish (Cascorbi 2007). A number of factors have contributed to the increased U.S. demand for sablefish. During the 1990s, Nobuyuki Matsuhisa, owner of the famed Nobu restaurant in New York City, introduced miso-glazed sablefish as its signature dish, with the dish symbolizing a new direction in Japanese cuisine (Burros 2001, Morimoto 2007, Olmsted 2016). In 2007, former Nobu head chef Masaharu Morimoto popularized the dish during an episode of the television show *Iron Chef America*. More recently, sablefish has gained popularity with American sushi chefs, who consider it a healthier, more environmentally friendly alternative to *unagi* (freshwater eel; Leu 2016).

Respondents to the survey and telephone interviews noted several advantages of farmed sablefish, including firm, white flesh; consistent supply; greater flexibility in marketing; freshness (ensuring a longer shelf life); and greater perceived levels of sustainability than wild harvests. Perceived disadvantages of farmed sablefish include their potentially smaller size in comparison to wild-caught fish, with respondents indicating that smaller fish will have lower yields and lower oil content.

Some of the dealers provided price information during interviews. One Midwest wholesaler noted that it recently purchased farmed sablefish for $8.14/lb for a dressed, head-on product. This price forms the basis for the "high-end" price used in the CFS Model developed in Chapter 3.

Chapter 5 summarizes the commercial fisheries for sablefish. The United States and British Columbia currently supply nearly 100% of the wild-caught sablefish from fisheries in Alaska, B.C., and off the coasts of Washington, Oregon and California.

Over the years, the Alaska, B.C., and U.S. West Coast fisheries have been brought under individual transferable quota (ITQ) management programs. In addition to improving the economic performance of the fisheries by reducing overcapacity, the ITQ programs have generated conservation benefits. Individual vessel accountability, together with improved catch monitoring, has generally helped keep harvests below TAC limits. The conservation benefits of these ITQ programs are reflected in positive third-party assessments of the impacts of the Alaska, B.C., and U.S. West Coast sablefish fisheries on fish populations and ecosystems. For example, the Marine Stewardship Council (MSC) certified the Alaska fixed gear sablefish fishery as being "sustainable and well-managed" in 2006. The U.S. West Coast limited entry groundfish trawl fishery was MSC-certified in 2014. Currently, approximately 70% of North American sablefish landings are MSC-certified (FishChoice Inc. 2018).

Commercial fisheries data from Alaska include detailed estimates of ex-vessel prices paid by processors to harvesters, as well as estimates of first wholesale product prices received by processors. In Alaska, most fish are delivered already headed and gutted, so processors receive a relatively low markup to wholesale prices, averaging just 17% from 2012–18. Ex-vessel prices based on round-weight equivalents averaged $4.50/lb from 2016–18 after adjusting for inflation to 2019 USD, while wholesale prices (in round-weight equivalents) averaged $5.29/lb. In addition to average price/lb of all fish sold, Alaskan data also include average ex-vessel prices paid for six different size classes of fish, from a low of $2.82/lb for 1.6-lb fish to a high of $5.79/lb for 11.1-lb and larger fish (all in 2019 USD). The wholesale prices from the commercial fishery in Alaska are used as the "low-end" prices in the CFS Model developed in Chapter 3.

Chapter 6 examines the basic economic concept of supply and demand and updates and revises a pre-existing econometric model of global supply and demand for sablefish. These econometric models address concerns of commercial harvesters and processors that, unless demand for sablefish increases, development of a large and vibrant sablefish aquaculture industry has the potential to reduce prices, thereby diminishing returns on investments in vessels, harvesting quotas, and processing facilities.

The econometric model developed in this study is an update of a model originally developed by Huppert and Best (2004) to explicity examine the potential impacts of aquaculture on prices in the commercial fishery. The updated model extends the time series of the original model by 12 years, to a total of 28 years (1988–2015) and adds a dummy/indicator variable for 2007. The statistical significance of the indicator variable and its positive coefficient suggest that an increase in aggregate sablefish demand occurred in or near 2007, perhaps as a result of heightened consumer awareness of sablefish through social media and the internet.

Both the original and the updated models (after adjusting both to 2019 USD) predict linear decreases in ex-vessel prices as sablefish supply increases. The results of the updated model indicate that for each 1,000-mt increase in global supply, the Alaska sablefish ex-vessel price would decrease by $0.077/kg. The effect is much smaller, however, in the U.S. West Coast and B.C. sablefish fisheries, with a decrease of only $0.040/kg and $0.039/kg, respectively. The estimates of price responses as a percentage of ex-vessel prices are noticeably lower in the updated model than in the original model—this is an indication that in the years between estimation of the two models, sablefish prices have become less sensitive to supply changes. The results of the updated sablefish econometric model, along with the findings from the market research summarized in Chapter 4, clearly indicate that the global and domestic markets for sablefish have expanded.

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1 Introduction

Sablefish (*Anoplopoma fimbria*), also known as black cod, is a deep-water species native to waters off Alaska; British Columbia (B.C.), Canada; and the U.S. West Coast. Its range spans from Baja California to Alaska and west to Japan through the Aleutian Islands. Sablefish are high in omega-3 fatty acids, and their flesh has a velvety texture, with large, yet delicate flakes and a sweet, buttery taste. While the landed weight of sablefish in U.S. commercial fisheries is not large compared with other species, the exceptionally high value of sablefish ranked it fifth among U.S. commercially harvested finfish in economic value for 2018—behind pollock, sockeye salmon, Pacific cod, and menhaden (NMFS 2020).

The supply of wild-caught sablefish in recent years has generally been limited to 20,000 mt or less. Despite a consistent, conservative management approach in North American fisheries, the long-term biomass trend has included several prolonged periods of decline, likely as a result of poor recruitment due to environmental conditions experienced early in life (Krieger et al. 2019). The average annual commercial harvest over the 2012–16 period was around half that of the 1992–96 period. Moreover, given the large geographic range and narrow window of optimal water temperatures observed through early development, sablefish may be disproportionately affected by future climate change-driven habitat alteration (Krieger et al. 2019).

As a result of these and other factors, there is strong interest within the National Marine Fisheries Service (NMFS) in the aquaculture of sablefish (NMFS 2018e). NMFS has invested in the development of technology to farm this species since 2008, with the view that the study of sablefish in a marine laboratory setting can lead to improving the potential of sablefish aquaculture as well as enhance the knowledge of the species's life history and its reproductive and growth physiology.

The current study was undertaken to describe the present status of sablefish aquaculture in this country and elsewhere, and to perform an initial assessment of the financial viability of a sablefish aquaculture industry that utilizes existing technology, including the use of all-female rearing stocks. In addition, the study examines prospective markets for farmed sablefish, the possibility of broadening the overall market for both farmed and commercial sablefish, and the potential economic effects that expansion of sablefish aquaculture could have on commercial sablefish fisheries (e.g., by placing downward pressure on ex-vessel prices).

The remainder of this report is organized as follows:

Chapter 2 summarizes the development of commercial sablefish aquaculture in Canada and the United States.

Chapter 3 is divided into three main sections, with the first two sections providing a technical description of the operations of sablefish hatchery (Section 3.1) and grow-out operations (Section 3.2). Section 3.3 contains an economic analysis that compares the costs and revenues of net-pen operations with mixed-sex and female monosex rearing stocks.

Chapter 4 provides a market analysis that describes the domestic and overseas markets for farmed and wild sablefish and examines the potential development of niche markets.

Chapter 5 summarizes information on the existing commercial fisheries for sablefish in the United States and B.C. These fisheries produce the vast majority of the global supply of sablefish.

Chapter 6 reprises the econometric model originally developed by Huppert and Best (2004) and assesses the potential impacts of an increased supply of farm-raised sablefish on market prices.

2 Overview of the Development of Sablefish Aquaculture

This section draws on information from industry trade publications, academic reports, and popular press articles to provide an overview of the historical development of commercial sablefish aquaculture.

2.1 Canada

Aquaculture of sablefish began in the 1960s, when researchers at the Pacific Biological Station of the Canada Department of Fisheries and Oceans (DFO; now Fisheries and Oceans Canada) demonstrated that juvenile sablefish captured from the wild adapted readily to confinement and grew well (Clarke and Pennell 2013). Juveniles up to two years of age inhabit inshore environments; therefore, they are more accessible than the more marketable adults that dwell in very deep water. Thus, it was natural to speculate that it could be profitable to capture fish at this earlier stage and culture them in marine floating net pens to a larger size (Huppert and Best 2004). However, this program was discontinued because of the difficulty in securing a reliable supply of wild juveniles for stocking farms (Clarke and Pennell 2013).

The problem of juvenile sablefish production was addressed in the 1980s and 1990s, when Canadian researchers developed methods for induced spawning of captive broodstock and embryo and larval incubation (Clarke and Pennell 2013). Pilot-scale sablefish hatcheries were operating in B.C. by the mid-1990s. The first commercial hatchery was established in 1998 by Island Scallops at its facilities on Vancouver Island, B.C.; the company produced its first fish in 2000 (Intrafish 2003a, Minkoff and Clarke 2003). Totem Oysters (later Totem Sea Farm) in Jervis Inlet, B.C., marketed the first commercial harvest of hatchery-raised sablefish from net pens in 2002 (Minkoff and Clarke 2003). In 2003, Sablefin Hatcheries[1] constructed a large hatchery on Salt Spring Island, B.C., capable of producing two million juveniles annually; its first spawning occurred in 2004 (Clarke and Pennell 2013, Chettleburgh 2016). During the early 2000s, the B.C. government approved 22 licenses for commercial sablefish farms and 18 applications from commercial Atlantic salmon (*Salmo salar*) farms that wanted to add sablefish to their existing licenses (Welch 2004). The majority of these license holders were located on Jervis Inlet and the west coast of Vancouver Island. At that time, sablefish were viewed as a potentially lucrative alternative species by B.C. salmon farms suffering from poor prices and a host of diseases (Intrafish 2002).

As the prospect for commercial sablefish aquaculture became a reality, a number of groups voiced their opposition, most notably Canadian commercial sablefish fishers. In 2004, the Canadian Sablefish Association filed a federal court injunction against DFO and Sablefin Hatcheries in a failed attempt to stop the transfer of the first hatchery sablefish to net pens. Its main concerns were that sablefish farm sites would expose the wild sablefish population to parasite, disease, and genetic risks (Fraser 2004). That same year, a risk-assessment

[1] Sablefin Hatcheries merged in 2008 with Sablefish Canada, which was acquired by Golden Eagle Sable Fish Inc. in 2014. As recently as January 2020, they were selling pen-raised sablefish under the Gindara Sablefish brand (see https://www.gindarasablefish.com/).

study conducted by the Centre for Coastal Health reported that it was not possible to quantify the magnitude of shared disease agents from cultured to wild sablefish (Stephen and Fraser 2004, cited in Cox 2004). Nevertheless, the study concluded that "it is likely that there will be an exchange of disease-causing agents between sablefish and salmon reared in captivity at the same site and plausible that there will be an exchange of disease-causing agents between cultured sablefish and wild marine fishes" (quoted in Cox 2004). Further, Sablefin Hatcheries reported at the time that it hoped to eventually produce ten million juveniles annually, which, if grown to a 3.5-kilogram (kg) size,[2] would total 35,000 mt, a production volume greater than the total North American wild catch. Members of the commercial fishing industry expressed concern that placing this additional volume on the market would drive sablefish prices down (Island Times Publishing 2003).

By 2010, three hatchery facilities in B.C. had succeeded in producing juveniles, and five companies reported sales of farmed sablefish, totaling about 860 mt with a value of over $10 million (Campbell and Koop 2009, Stoner and Ethier 2015). In the ensuing years, however, the number of companies actively farming sablefish has dropped. In 2016, annual production by Canada's sablefish aquaculture operations had fallen below 270 mt, with a value less than $3.5 million (DFO 2018d). In recent years, Golden Eagle Sable Fish has been the primary grower in B.C., and is one of the few companies with both a sablefish hatchery and grow-out sites.[3]

A challenge of sablefish aquaculture in Canada has been to achieve a consistent larval survival of 20% or more. A better understanding of nutrition at multiple life stages and of genetic selection within the species is key to improving the survival rate. Moreover, the high price for juveniles may have discouraged some Atlantic salmon farms from diversifying into sablefish; at $4–5.00 CAD per fish, stocking a grow-out facility was an expensive proposition. In the early 2000s, one hatchery destroyed 2.5 million larvae because of the limited demand for juveniles at that time (Intrafish 2003b).

There are signs, however, that sablefish hatcheries are making progress in overcoming these obstacles. In 2016, for example, Golden Eagle Sable Fish exceeded its production goal of 200,000 juveniles and is aiming to continue expanding capacity to 500,000 20-g fish within the next few years (Chettleburgh 2016).

In 2010, DFO assumed responsibility for issuing aquaculture licenses in B.C. as well as for the primary management and regulation of aquaculture in the province. A new set of regulations under the Fisheries Act were developed to ensure that the aquaculture industry in B.C. operates in a sustainable manner (DFO 2012). In 2017, 35 facilities were licensed to raise sablefish commercially. License holders must ensure that all juvenile sablefish are obtained from licensed hatchery sources (DFO 2018b). Currently, there about 400 acres of sablefish farms in Canada, compared to 12,000 acres of salmon farms (Flaherty et al. 2019).

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[2] The standard grow-out size assumed in the current report ranges from 2–2.8 kg.

[3] Sablefish Canada went into receivership after it was unable to pay off a debt of more than $10 million. After its hatchery with several hundred thousand fish, together with an estimated 250,000 sablefish in net pens, was put up for sale, numerous bids from U.S. and Canadian companies were reportedly submitted to the court-appointed receiver for all or parts of the hatchery and farm (Stilts 2014).

2.2 The United States

The first attempt to culture sablefish commercially in the United States was made by Unlimited Aquaculture Corporation in 2003. The Canadian company received approval to raise sablefish in land-based ponds at the Natural Energy Laboratory of Hawai'i's Ocean Science and Technology Park in Kona, Hawai'i. The first phase of the company's production facilities was started on a one-acre lot, but it hoped to expand its facilities and eventually provide 300 tons of sablefish a year to local restaurants as well as markets in Japan. The company reported that they planned to purchase 4-g juvenile sablefish from a Canadian hatchery and grow them to 4 kg in about 26 months (Gima 2003, Intrafish 2008).[4]

However, Unlimited Aquaculture could not raise enough sablefish to be commercially viable, as it lacked sufficient capital to expand its Hawai'i operation (Consillio 2007). In 2007, the facility was acquired by Troutlodge Marine Farms, a Washington-based company which invested a substantial amount in upgrades.[5] A key production constraint was the limited supply of juveniles, and the company initiated plans to develop its own on-site hatchery, a move critical to increasing production and cutting operating costs. In addition, in 2012, Troutlodge Marine Farms began producing juvenile sablefish at a leased portion of the former Washington Department of Fish and Wildlife's Point Whitney Shellfish Laboratory in Brinnon, Washington. The juveniles were sold to companies that raised them in net pens in Puget Sound and Canada (Troutlodge Marine Farms 2013). More recently, the company has ceased producing sablefish at the facility in Brinnon.

In 2011, the Washington-based seafood processor and wholesaler, Icicle Seafoods (which was purchased by Cooke Aquaculture Pacific in 2016), purchased 20,000 juvenile sablefish from Troutlodge Marine Farms and performed a grow-out trial in NMFS-owned net pens near the company's Atlantic salmon farm off of Bainbridge Island, Washington (Nadkarni 2012). The company began harvesting the fish in 2013 (Nadkarni 2013).

Despite these past and ongoing efforts, several challenges, including the lack of captive broodstock for a consistent supply of juveniles and the high cost and duration of larval rearing, have prevented the limited existing U.S. aquaculture operations from fully committing to growing sablefish. To address these challenges, University of Washington and NMFS scientists, through a National Oceanic and Atmospheric Administration (NOAA) National Sea Grant, have been partnering with tribes, academia, and industry to develop and transfer research technologies to commercially produce sablefish (NMFS 2018e). For example, over the past five years, NMFS researchers at the Manchester Research Station have been developing captive broodstock from wild fish caught off the Washington coast and have made significant advances in larval rearing techniques and in streamlining the costly hatchery phase. These improvements have included research on tank design (Cook

[4] Scientists at the Manchester Research Station in Port Orchard, Washington, note that growing a 4-kg sablefish in 26 months from 4-g juvenile may not be realistic (W. T. Fairgrieve and F. W. Goetz, NMFS/NWFSC, personal communications).

[5] Troutlodge Marine Farms is the former marine division of Washington-based Troutlodge, Inc., which is the world's leading producer of eyed trout eggs. In 2014, individuals who formerly owned Troutlodge formed PW Holdings, Inc., which, in partnership with Native Trust Seafood and the Jamestown S'Klallam Tribe, acquired the sablefish aquaculture portions of Troutlodge Marine Farms (Grinnell undated).

et al. 2015), elevated temperatures to shorten the larval rearing phase (Lee et al. 2017a, Cook et al. 2018), the substitution of inexpensive alternatives (e.g., clay) in place of algae for producing opacity in rearing water during the live-feed period (Lee et al. 2017b), and the use of dimethylsulfoniopropionate, a key nutrient for marine microorganisms, in increasing larval sablefish survival in an aquaculture setting (Lee et al. 2016).[6]

In addition, to capitalize on the more-rapid growth of female sablefish relative to males, NMFS scientists have directly addressed the issue of sexual growth dimorphism in sablefish by developing techniques that, without the use of genetic modifications, result in all-female (female monosex) rearing stocks (Luckenbach et al. 2017). The process involves first generating "neomale" sablefish for use as broodstock. Neomales are genotypically female individuals that have been steered toward developing as males by treatment during early development with either a dietary androgen, such as methyltestosterone (Luckenbach et al. 2017), or high temperature (Huynh et al. 2019). This induces the genotypic female sablefish to develop male gonads (i.e., testes). In time, the neomales sexually mature with all of the physical attributes of a male sablefish, but possess two X chromosomes rather than an X and a Y chromosome. Because of this, when normal female broodstock are bred with neomales, the neomales only pass on X chromosomes (not Y), and all of their offspring are normal, unmanipulated XX-genotype females. Since sablefish are long-lived, neomale broodstock can be used year after year for production of female monosex lines.

This indirect sex control strategy for monosex female production does not expose fish for consumption to any exogenous steroids and may therefore circumvent issues associated with marketing hormone-treated fish (Luckenbach et al. 2017). The approach also involves no genetic modification of the fish (i.e., non-GMO). Using this approach, the Manchester Research Station recently generated approximately 10,000 all-female juveniles as part of a pilot study for commercial harvest in floating marine net pens (Wiedenhoft 2017).[7] Since sablefish females grow significantly faster than males, the ability to produce all-female product is a significant commercial advantage for aquaculture (NMFS 2018e).

Figure 1 shows average observed weights at age (days since stocking) of farm-raised sablefish collected by scientists at the Manchester Research Station for female monosex and mixed-sex stocks across several trials. In both cases, the average size at stocking was 75 g. The fitted third-order polynomials were developed using simple regression methodologies. Based on these results, the average individual in the female monosex stock will reach 2.5 kg (2,500 g) in 667 days, while the average individual in the mixed-sex stock will attain that same weight in 760 days. This represents a 12.2% reduction in required grow-out days to attain an average market weight of 2.5 kg and implies savings for aquaculture operations in terms of greater infrastructure utilization and reduced mortality. Alternatively, the average fish in a female monosex pen grown for two full years (730 days) after stocking would attain a weight of 2.7 kg, while the average fish in a mixed-sex pen would attain a weight of 2.4 kg.

[6] In earlier studies, scientists at NMFS's Alaska Fisheries Science Center examined temperature-dependent effects on wild-caught juvenile sablefish (Sogard and Olla 1998, Sogard and Olla 2001, Sogard and Spencer 2004).
[7] NMFS scientists and partners conducted a pilot-scale project at the Manchester Research Station with the Jamestown S'Klallam Tribe. Jamestown Seafood's Point Whitney Ventures, LLC, has been growing sablefish in the net pens at the research station for the past few years. It is anticipated that the knowledge and profits derived from the sale of these fish could be used by the tribe to establish net-pen grow-out for sablefish at other sites in the Pacific Northwest (NMFS 2018e).

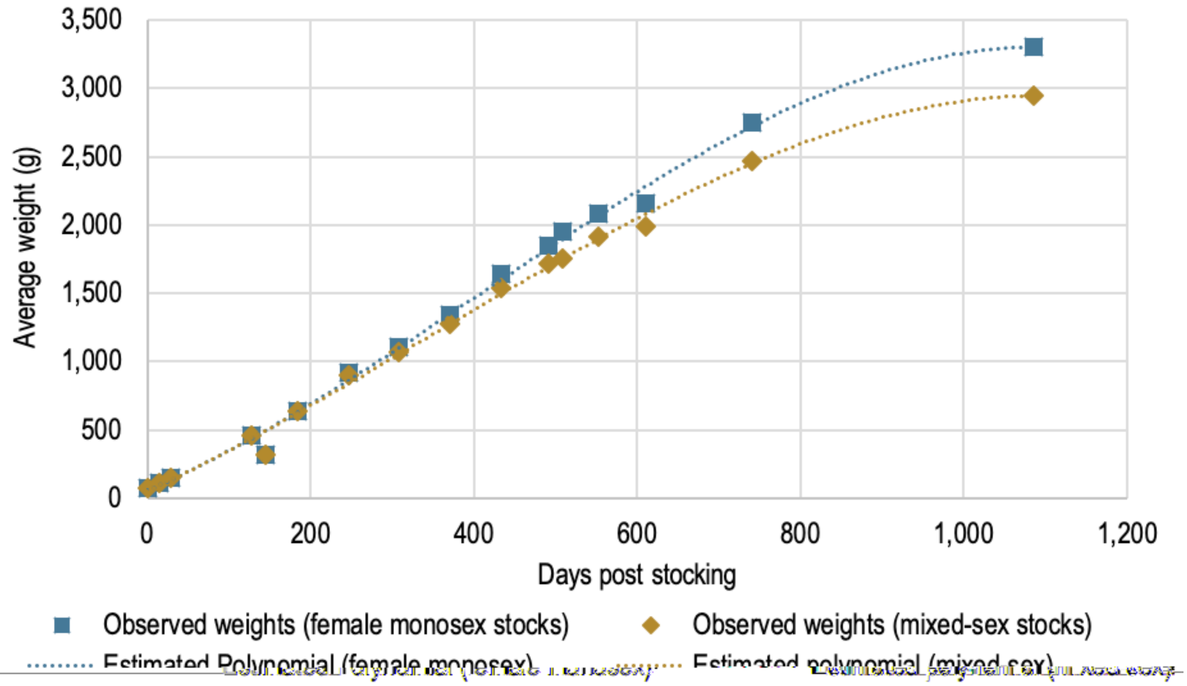

Figure 1. Observed and estimated growth curves for female monosex and mixed-sex stocks of sablefish. Source: Fairgrieve (unpublished).

It is clear that technologies described above could enhance the viability of aquaculture production of sablefish from the egg to market weight. Commercial production of sablefish could be done using either net-pen or recirculating aquaculture technologies—or some combination thereof. A sablefish farm would have to obtain new state and federal permits to grow sablefish in Washington State waters. There are currently sites permitted to grow Atlantic salmon in the Puget Sound region; however, recent Washington State legislation dictates that the culture of this non-native species may only continue until existing leases expire.[8] One company, Cooke Aquaculture Pacific, owns and operates all the commercial net pens in Puget Sound (Wiedenhoft 2017). In part due to the complex and costly regulatory process, no new commercial net pens for rearing any finfish have been approved in Washington for many decades (NMFS 2018e).[9]

[8] Opposition to farming Atlantic salmon in net pens in Puget Sound increased significantly after a net pen owned by Cooke Aquaculture Pacific failed and accidently released thousands of fish into the surrounding waters in August 2017 (Clark et al. 2018). As a result of this incident, the Washington State Legislature passed a law that banned the use of net pens to raise Atlantic salmon and other non-native finfish species in the state by 2022. In March 2018, the legislation was signed by Washington Governor Jay Inslee (Le 2018).

[9] All existing commercial marine net-pen aquaculture in Washington is in state waters with leases of state-owned aquatic lands. In addition to federal and state permitting requirements, local authorities in Washington also require permits. The permitting process is subject to public consultations and appeal at both state and local levels. A one-stop permit application, the Joint Aquatic Resources Permit Application, is available to applicants and used by most regulatory authorities. Management guidelines developed by the state in the 1980s and 1990s are being updated and revised through a collaborative effort by three state departments (Ecology, Fish and Wildlife, and Agriculture) and NOAA, with advice from tribal interests. The new guidance is expected to inform all aspects of net-pen siting and management (DFO and NOAA 2018).

An alternative to net pens is to use land-based tanks to grow fish. NMFS previously provided two batches of 7,000 fry to Global Blue Technologies/Perciformes Group, a Texas-based aquaculture company that hopes to grow sablefish commercially in an indoor recirculating aquaculture system (RAS; Wiedenhoft 2017). Whereas net-pen aquaculture systems depend on an "open" flow method to provide a growing environment for fish and to assimilate waste products by exchanging water between the aquaculture system and the surrounding environment, a RAS farm recirculates the water within the system. A first harvest of 300 lb of sablefish was packed in ice and shipped to a Maryland distributor catering to Washington, D.C., white-tablecloth restaurants (Parker 2017). In 2018, the company announced that it is pursuing a site to build a commercial facility designed to produce around 90 mt of sablefish a year using the same type of RAS technology developed in Texas (Dodd 2018).

Even if suitable marine aquaculture sites are found in the Pacific Northwest, there will likely be opposition to sablefish farming from certain groups. Some U.S. commercial fishers have already expressed concern about potential competition. In particular, they are concerned that the sablefish aquaculture technology will be exported to a country with low labor costs (Le 2017). Should farms with these cost advantages scale up production and supply markets in Japan, Europe, and elsewhere, prices for wild product coming out of U.S. West Coast and Alaska fisheries could be driven down (Ess 2017) absent expansion of the market for sablefish.[10] This pattern of aquaculture technology being exported from the United States to other producer countries, which then supply wealthier consumer countries, has been seen with other farmed fish and shellfish, most notably shrimp (Hall 2004). The concerns among commercial harvesters would need to be considered and addressed if sablefish aquaculture is to secure permits to operate in Washington State waters. In addition, sablefish aquaculture in the United States is likely to be opposed by some individuals and groups for environmental, recreational, or viewscape reasons.

Ultimately, it will be state and federal regulatory agencies that will determine the ability of the sablefish aquaculture industry to secure permits and to operate either in marine waters or land-based systems. The coastal states in which marine net-pen aquaculture currently occurs maintain jurisdiction over marine activities out to three nautical miles from shore, and each state has a system for leasing areas of its coastal zone for net-pen farms. This type of aquaculture must comply with a suite of state and federal laws and with city and/or county regulations. State governments often impose requirements that are more stringent than federal requirements (Rust et al. 2014, DFO and NOAA 2018). Recently, through the Canada–United States Regulatory Cooperation Council's Joint Forward Plan, DFO and NOAA/NMFS compared the applicable regulations and management approaches used in each country. Both countries have implemented comprehensive legislative and regulatory measures for the sector under the following five key themes: siting and management of aquaculture operations; habitat and water quality; fish health and therapeutants; genetics and fish escapes; and other living marine resource interactions (DFO and NOAA 2018).

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[10] This argument assumes that the market for sablefish is static. Chapter 4 in this report examines the potential for expanding sablefish markets. Chapter 6 examines sablefish supply and demand and describes how expansion of markets can mitigate downward price pressures that could evolve if the market for sablefish is less dynamic.

2.3 Other Countries

There has also been interest in culturing sablefish outside of Canada and the United States. In Mexico, researchers from the National Fisheries Institute and Centre for Scientific Research and Higher Education of Ensenada have been working on the development of biotechnology for farming and breeding sablefish (Murias 2013). It is considered a species with high potential for aquaculture in Mexico (Sanchez-Serrano et al. 2014), and seafood producers in the country have expressed interest in obtaining monosex stock for production (Wiedenhoft 2015).[11]

In addition, there are reports of a growing market for sablefish in South Korea (Washington Sea Grant 2017), and Korean seafood producers have also shown an interest in applying new sablefish aquaculture technologies, including monosex production (Wiedenhoft 2015).[12,13] However, there are no reports of commercial sablefish aquaculture production in either South Korea or Mexico as of yet.

Although information is limited, there appears to be increasing interest in sablefish aquaculture in China. Research on sablefish breeding and culture is being conducted at the Yellow Sea Fisheries Research Institute and other institutions in the country (Yellow Sea Fisheries Research Institute 2019), and sablefish farming has reportedly been introduced into the aquaculture industry in Shandong Province (Wang et al. 2017).[14]

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[11] In the early 1980s, Mexico promoted joint ventures with South Korean and Japanese companies to initiate a sablefish fishery off the west coast of Baja California Sur and attempted to develop a domestic market for the species. However, most of the catch was exported because, at the time, the demand for sablefish by Mexican consumers was low (Sonu 1980).

[12] *Eundaegu-jorim* (braised sablefish) is a favorite seafood dish in South Korea and is often found in Korean food restaurants (Chaedan 2012).

[13] South Korean researchers are currently assessing the growth performance of juvenile sablefish under various environmental conditions to verify the possibility of culturing the species in Korea (Kim et al. 2017a, Kim et al. 2017b). In addition, with funding from the U.S.–Korea Joint Coordination Panel for Aquaculture Cooperation, NWFSC and the National Fisheries Research and Development Institute of South Korea are examining the role that taurine and other amino acids play in the growth and feeding of sablefish (Johnson et al. 2015b, data.gov 2018).

[14] According to Xiong et al. (2016), China's rapid economic development has increased demand for high-quality marine fish, and sablefish is among the valuable marine fish species recently appreciated in the country.

3 Sablefish Aquaculture Operations and Their Costs

Based on information from NWFSC and other sources, the following two subsections provide estimates of the costs of sablefish production focused on the two major phases of sablefish aquaculture: hatchery production of juveniles, and grow-out of juveniles to harvestable size. Each subsection is prefaced by a description of the operational steps and activities involved in the respective phase.

3.1 Hatchery Operations

Producing gametes and rearing larvae of marine finfish species, sablefish included, is considered much more difficult than it is for salmonids (Huppert and Best 2004). However, great strides have been made by NOAA researchers and commercial producers in closing the life cycle of sablefish in captivity and developing reliable methods for induction of reproductive development and larval rearing through the hatchery phase of production (Washington Sea Grant 2017).

This section describes the steps in hatchery production of sablefish juveniles ready for rearing in grow-out sites and estimates the annual operational costs of a commercial hatchery.

3.1.1 Steps in sablefish juvenile production

Step 1. Obtain and spawn broodstock.

Wild sablefish spawn from January to March between California and B.C., with peak spawning activity in February (Hunter et al. 1989, Guzmán et al. 2017). Sablefish broodstock are often collected from the wild by longline during summer to early fall in preparation for spawning in captivity in winter to early spring. At NWFSC, filial-1 (F1) generation broodstock, including some males and all neomales, are currently used in production, but a selective breeding program has not yet been established. Broodstock are maintained in low-light conditions at a temperature of 5–6°C to simulate the deep-water conditions in which they reproductively mature and spawn in the wild.

To monitor female and male reproductive development leading up to spawning, a noninvasive technique, ultrasonography (or ultrasound), is typically employed to visualize the internal anatomy (Cook et al. 2015). Once oocytes of female broodstock are estimated to be ~1.2 mm in diameter by ultrasound, the fish are implanted with slow-release pellets containing gonadotropin-releasing hormone analog to induce final maturation. Approximately 10–14 days after implantation, they are assessed again by ultrasound and, when the ovaries have sufficiently matured, eggs are stripped for in vitro fertilization with milt collected from male (XY sperm, for mixed-sex production) or neomale broodstock (XX sperm, for female monosex production). Female broodstock may spawn 4–6 times over a period of 12–14 days in the hatchery and can have a total fecundity of 250,000–500,000 eggs.

Some sablefish producers in Canada have successfully used photoperiod manipulation to phase-advance or -delay broodstock groups so that they spawn at different times of the year. This type of approach can make gametes available nearly year-round for larval production.

Step 2. Incubate eggs.

Fertilized eggs are typically incubated in 5–6°C seawater in complete darkness. Assessment of rates of fertilization and symmetry of the embryonic cell divisions (targeting the 8–16 cell stage) is used to determine the quality of each spawn (Cook et al. 2015). After fertilization, sablefish eggs have a diameter of 1.8–2.0 mm. On Day 10 post-fertilization, just prior to hatch, the eggs are collected and disinfected with an antibacterial/antifungal reagent before being transferred to yolk-sac incubators/silos where they will hatch (Cook et al. 2015). At 5–6°C, sablefish eggs typically hatch from 12–14 days post-fertilization. However, the larvae are maintained in the yolk-sac incubators/silos for ~30 more days to allow for nearly complete yolk sac absorption, prior to any exogenous feeding.

Step 3. Rear larvae.

Once target yolk-sac absorption is reached (~45 days post-fertilization), the larvae are ponded. A white light is used to attract larvae to the surface of the yolk-sac incubators/silos so that they can be efficiently captured and transferred to rearing tanks. Larval rearing tanks are filled with "green water"—turbid water created by mixing in *Nannochloropsis oculata* paste—and enriched rotifers on which the larvae first feed. The larvae are typically fed enriched rotifers at a targeted density from ~Day 1–18 post-ponding, with feeding rates based on tank volume and stocking density. Light levels at the tanks are controlled by layering shade cloth over the lights mounted above, with light intensity increasing with larval development. Water temperature starts at 10–12°C and reaches 14–15°C before the end of the larval phase (Lee et al. 2017a, Cook et al. 2018). Starting at the second week post-ponding, turbidity can be maintained with inexpensive clay instead of *N. oculata* paste (Lee et al. 2017b).

From ~Day 18–42 post-ponding, the larvae are fed enriched *Artemia* nauplii and from ~Day 43–52 they are weaned onto a dry formulated diet (at 12°C [Cook et al. 2015], noting that the schedule is compressed at higher temperatures). The weaning process typically takes about seven days, with live feed gradually reduced over time. At the end of the weaning process, turbidity is no longer necessary. After weaning is completed, the larvae are generally manually size-graded into two to three groups to reduce cannibalism and increase feed efficiency, greatly increasing survival to juvenile size.

Step 4. Move juveniles to nursery.

Approximately 100 days are needed from fertilization until weaned juveniles can be moved into nursery tanks. The fully weaned juveniles (~0.3 g in weight, 55 mm in length) are counted and transferred to nursery tanks. In the nursery tanks, the juveniles are typically size-graded and grown for as long as 100 more days up to ~75 g, although they can be distributed to net pens or tanks for grow-out at sizes as small as 10–20 g. Total time from fertilization to distribution of 75-g juveniles is ~200 days.

3.1.1.1 Year-round availability of juvenile sablefish

Year-round availability of juveniles could be an important component of an aquaculture industry that hopes to provide fresh product of a consistent size on a year-round basis. To understand why this is the case, imagine a grower with multiple pens wishing to sell consistently sized sablefish into the market. If juveniles are only available six months a year, then the grower will have to manipulate feeding and harvesting schedules in order to produce market-size fish every month and will very likely face several months in which at least some of its primary infrastructure—its net pens and/or tanks—are unstocked. For example, if the last fish are harvested from a pen one week after the last juveniles are available, the grower will need to leave the pen empty for nearly six months until the next supply of juveniles is available. Even if it is assumed that two full months are used to repair and clean pens and to allow them to sit fallow to reduce the spread of disease,[15] the farm will lose four months of productivity following harvest.

As noted above, if the demand for year-round availability of juveniles is sufficiently high, hatchery operators can extend the spawning seasons beyond the natural months of sablefish spawning via photoperiod manipulation. In addition, hatchery operations can further extend availability of juveniles by selling larger juveniles or even reducing the amount of feed provided after weaning to slow their growth.

3.1.2 Hatchery costs and output

While rearing sablefish from eggs to juveniles presents some technological and economic challenges, Huppert and Best (2004) note that the experience of the Atlantic salmon industry from the late 1980s through 2000 suggests that as sablefish hatcheries overcome problems of operation, the cost per juvenile will trend downward as more hatcheries scale up operations. According to Huppert and Best (2004), however, the price for sablefish juveniles is unlikely to ever be as low as the price of salmon juveniles, since the complexity of rearing sablefish larvae will always be greater than that of rearing salmon juveniles. This point is debatable because of the high fecundity of sablefish relative to salmon.

A successful sablefish hatchery will need equipment and operational controls for maintaining long-lived broodstock, adjusting temperature and light conditions to induce spawning over an extended period of time, incubating the embryos, and rearing larvae to juveniles. Because a live diet is essential for early feeding, the hatchery will require incubation facilities for rearing and enriching rotifers and *Artemia*.

A full assessment of the costs of commercial sablefish hatchery operations has not been undertaken, but as recently as September 2016, growers were willing to pay $3.00 per fingerling (Chettleburgh 2016) for 20-g fish.[16] Further, female monosex juveniles have sold in

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[15] Letting net pens sit fallow to reduce the spread of disease is a standard practice in Atlantic salmon aquaculture; it is included in the Scottish Salmon Farming Code of Good Practice (Scottish Salmon Producers Organisation 2014). It is unknown whether the practice of fallowing pens will become standard in commercial sablefish operations.
[16] The article actually reports prices of $4.00/20-g juvenile, but since the article was published in Canada and does not specify USD or CAD, it is assumed that cited prices are CAD. The USD–CAD exchange rate at the time the article was published was 1.32 USD/CAD, and even though there is considerable volatility in the exchange rate, on 17 February 2020 it was again 1.32 USD/CAD (Markets Insider 2020).

Washington for $4.25 per fish (J. A. Luckenbach, personal communication). Figure 2 shows the annual operational costs of an Atlantic salmon hatchery that produces juveniles ready for rearing in grow-out sites. The cost estimates were compiled by F. Asche (University of Florida, personal communication) based on information published by the Norwegian Directorate of Fisheries. The costs are adjusted for inflation to 2018 dollars by expense category and calculated as cost per juvenile produced. The largest component of juvenile Atlantic salmon production is labor wages, which range from 21 to 28 cents per juvenile. Other significant expenses include the cost of eggs and vaccinations. In total, the cost of production ranges from $1.06 to $1.46 per juvenile. This range is consistent with estimated salmon hatchery costs provided by Huppert and Best (2004). It must be reiterated that the hatchery costs for salmon in Figure 2 represent national averages for the large and already-mature Norwegian salmon aquaculture industry, and thus provide what should be considered a lower bound for sablefish hatchery costs.

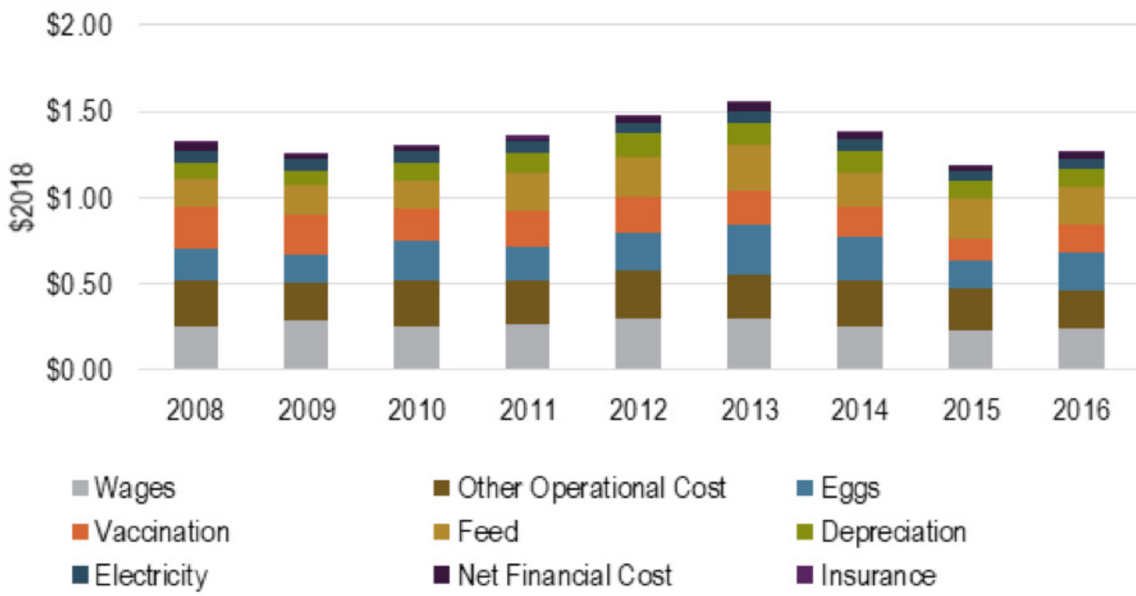

Figure 2. Costs for Atlantic salmon hatchery per juvenile, 2008–16. Adjusted for inflation to 2018 dollars. Source: Asche (personal communication).

3.2 Grow-Out Operations

In contrast to the challenge of rearing sablefish from eggs to juveniles of appropriate size/age for introduction to grow-out sites, raising juveniles to harvestable size appears to be an extension of existing salmon rearing practices. Sablefish appear to be resistant to some of the pathogens that affect farmed Atlantic salmon, and vaccines are being developed to control other types of disease.[17] However, sablefish farmers will need to experiment and perfect disease-control methods, as sablefish affected by pathogens may have poor flesh quality and high mortality during grow-out (Arkoosh et al. 2018).

[17] NMFS researchers are currently testing vaccines to control disease in cultured sablefish, as preventing a disease is more practical than having to treat it with antibiotics once it occurs (Arkoosh and Dietrich 2015, Arkoosh et al. 2018). Aside from vaccines, factors associated with stocked sablefish (i.e., nutritional status, size, age, and behavior) and their environment (temperature, dissolved oxygen, and contaminants) can also influence the ability to successfully prevent or manage an infection (Arkoosh and Dietrich 2015).

This section describes the steps in raising sablefish from juvenile to market size in a marine net-pen aquaculture facility, and estimates the facility's major annual direct production costs.

3.2.1 Steps in sablefish rearing to market size

Step 1. Purchase juveniles from hatchery.

Sablefish juveniles are typically sold at a size of ~10–20 g, but can be 75 g or larger.

Step 2. Move juvenile fish to net pens in open water.

Transport of juveniles from the hatchery to net pens can be done by totes in trucks, custom-made tank trucks, or live-haul vessels. Transport methods should be equipped with oxygen and water-quality monitoring systems. The juvenile sablefish are typically vaccinated against bacterial pathogens (e.g., atypical *Aeromonas salmonicida*) after a few weeks, which reduces the use of antibiotics during the later stages of grow-out.

Step 3. Feed and care for fish for 22–30 months.

Juvenile sablefish are fed nutrient-dense, dry pellets that include essential vitamins and minerals (Canadian Aquaculture Industry Alliance 2018). Studies of feed conversion ratios (FCRs)[18] for rearing sablefish through a full grow-out cycle have been limited, although Reid et al. (2017) report that FCRs increase with the size of fish, from an average FCR of 1.34 for 60–920-g fish to an average FCR of 1.62 for fish >920 g. Global Blue Technologies/ Perciformes Group provides another reference point—they indicate a 1.1 FCR in their RAS tanks (Perciformes Group 2019). Based on these findings and FCRs in the Norwegian Atlantic salmon industry, this study assumes a conservative FCR of 1.5. As shown in Figure 1, sablefish grow relatively quickly for 550–600 days post-stocking, after which growth rates begin to decline. As discussed in Section 2.2, NMFS researchers have conducted trials using female monosex stocks to improve growth rates. The use of female monosex stocks can lead to marked productivity gains in terms of annualized production per day (see Section 3.3).

Step 4. Harvest fish and transport to processing plant.

In larger operations, fish are generally harvested frequently (e.g., weekly) to ensure year-round availability in markets. In smaller operations, or if juvenile fish are not available year-round, fish within a given pen may all be harvested at the same time. The fish are typically fasted for a few days before slaughtering. In small operations, the fish may be harvested by hand and brailed from the net pens. Larger operations may contract live- or dead-haul commercial fishing vessels to perform this service. Fish may also be harvested using traditional Japanese methods that reduce tissue damage caused by excessive pH and lactic acid build-up (Sablefish Canada 2014a, Browne Trading Company 2018). To improve product quality, fish may be bled before being transported to a processing plant for custom processing. Note that the farm operation is assumed to maintain ownership of the fish even after they are sent to the processing facility.

[18] FCR is calculated as the total weight gained over a period of time divided by the total volume of feed. FCR is a common industry metric used to gauge the efficiency of various feeds and rearing operations. Because of the small number of sablefish grow-out operations, there does not appear to be an industry standard FCR for sablefish. The FCR for Atlantic salmon net-pen operations in Norway is reported to be ~1.3 (Aas et al. 2019).

Step 5. Process fish.

Depending on buyers' needs, the fish may be processed into a dressed product (head-on and gutted), headed-and-gutted (H&G) product, or fillets. It is assumed that fish will be slaughtered and bled at the farm site, then transported to an offsite processing facility where further fee-based custom processing occurs. Growers may also undertake their own processing, but this generally requires additional permitting from regulatory agencies. Typical recovery rates from round weight are as follows: dressed, head-on—89%; dressed, head-off (western cut)—68%; dressed, head-off (eastern cut)—63%;[19] skin-on fillet—40%; skinless fillet—35% (USOFR 2015).[20]

Sablefish Canada (now Golden Eagle Sable Fish Inc., which markets the Gindara Sablefish brand) has also explored the market for live sablefish, harvesting the 1.0- to 1.5-kg fish preferred by some international buyers (Sablefish Canada 2014c).

Step 6. Sell fish independently or through brokers.

Operators may sell their harvests directly to restaurants or market chains, or they may choose to sell to fish brokering firms who then resell and distribute the fish to retail or food-service firms. Selling direct can result in higher profits to the farm operation, but also means a significant commitment in time and effort (and therefore costs) for marketing. The farm gate price is defined as the price received by the farm minus marketing and transportation costs. Note: we are assuming that sablefish operations will maintain ownership of their fish after it is processed and that they then sell their product directly to users or utilize brokers; the farm gate price is therefore akin to the first wholesale price received by processors in commercial fishery operations.

Technically, the farm gate price will be specified in terms of dollars per delivered weight. In the discussion that follows, we have chosen to simplify terms and to focus on the round-weight (whole-fish) equivalent of farm gate prices. As an example, assume that a sablefish farm operation sells 50% of its annual production as head-on dressed fish for $11.24/kg, and the remaining 50% of its production as eastern-cut H&G fish for $15.87/kg—both prices have been reduced to account for marketing and transportation costs. Since head-on dressed fish have a product recovery rate of 89%, the round-weight farm gate price equals $10.00/kg (mathematically: $11.24/kg × 0.89% = $10.00/kg). Similarly, the farm's eastern-cut H&G fish has a $10.00/kg round-weight farm gate price, because the yield from round weight to eastern-cut H&G fish is 63% (i.e., $15.87/kg × 63% = $10.00/kg).

The farm gate price that sablefish operators receive is undoubtedly a critical factor in whether operations can be financially viable. Unfortunately, there is not a great deal of information available on the domestic market prices for farm-raised sablefish or, for that matter, on domestic wholesale prices for commercially harvested sablefish. Chapters 4, 5, and 6 all include discussions of sablefish market prices.

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[19] For the eastern-cut fish, the pectoral girdle is removed along with the head. Western-cut fish include the pectoral girdle. Eastern-cut fish—which have historically been the primary wholesale product form for commercial fisheries—is also referred to as collar-off or Japanese-cut (J-cut) fish.

[20] Standard product recovery rates for groundfish species harvested in Alaska are embedded in Federal Regulations at 50 CFR Appendix Table 3 to Part 679, available at https://go.usa.gov/xGNwa.

Table 1. Estimated average wholesale/farm gate prices in round-weight equivalents for Gulf of Alaska and Midwest brokered sablefish by round-weight market size category.

Round-weight equivalent market size categories (kg)	0–1.44	1.44–2.16	2.16–2.88	2.88–3.60	3.60–5.04	5.04+
Alaska round-weight equivalent first-wholesale price/kg	$7.29	$7.93	$9.40	$10.84	$12.97	$14.86
Midwest round-weight equivalent farm gate price/kg	$12.69	$13.81	$16.36	$18.86	$22.57	$25.85

Note: Alaska market size categories assume fish are delivered as eastern-cut H&G product with a yield of 63% from round weight. Alaska prices represent 3-yr average from 2016–18 and are adjusted for inflation to 2019 USD. Source: Estimated by Northern Economics, Inc., using data in Armstrong and Cunningham (2018) and Fissel et al. (2019).

A relatively high market price is described in Section 4.2.2. In this case, a Midwest wholesaler reports purchases of B.C. farmed sablefish for $17.95/kg ($8.14/lb) for a dressed, head-on product. This value can be used to estimate a farm gate price by taking into account the broker's commission and the cost of transporting the product between broker and wholesaler. According to industry representatives, a broker will typically charge a fee of 5% of the sales price ($0.90/kg or $0.41/lb). A shipping cost of $1.54/kg ($0.70/lb) was estimated based on an average of trucking and air freight rates for shipping fresh fish from B.C. to the Midwest. After deducting the shipping cost and brokerage fee, the average farm gate price for fish sold by this particular broker is calculated to be $15.51/kg ($7.04/lb) for a dressed, head-on product. Assuming that the yield from round weight (whole) to a dressed, head-on product is 89%, the average round-weight farm gate price would be $13.81/kg ($6.26/lb).

A second wholesale market price scenario is developed based on wholesale prices received by Gulf of Alaska-based processors in the commercial sablefish fishery selling eastern-cut H&G product. With Alaska-based data it is possible to estimate sized-based wholesale prices by size category.[21] Wholesale prices by size category are explained and developed in Section 5.2.4 and shown here in Table 1. The data in the table reflect inflation-adjusted round-weight equivalent average prices in kilograms from 2016–18. During those years, the average inflation-adjusted first wholesale price for eastern-cut H&G sablefish from the Gulf of Alaska across all size categories was $8.39/lb (see Table 12). This is translated to a round-weight equivalent price of $5.29/lb by dividing by 0.63 (the product recovery rate or yield from round weight). Table 1 uses the same size categories as used in Alaska—adjusted to round weights from the traditional eastern-cut categories—and assumes that the same relative price relationships across size categories as experienced in Alaska can be realized by sablefish growers selling into the domestic market. If it is further assumed that the average round weight of fish sold by the Midwest broker in the preceding paragraph was 2 kg, then the prices shown in Table 1 reflect equivalent prices by size category for fish sold by that broker.

[21] Data on first wholesale prices by product type are estimated by NMFS (Fissel et al. 2019) but are not reported by market size category. Ex-vessel prices and volumes are available from Alaska Department of Fish and Game (ADFG) by market size category, delineated in terms of pounds of eastern-cut H&G fish. The authors assume, based on industry sources, that wholesale prices by market category will be proportional to ex-vessel prices by size category.

3.3 Comparisons of Costs and Revenues in Mixed-Sex and Female Monosex Net-Pen Operations

Operating costs for sablefish farms include direct farm costs (e.g., stock, feed, additives, labor, insurance, maintenance, utilities, etc.), and in some cases processing and packaging costs. Huppert and Best (2004) estimated the costs of rearing sablefish in net pens to a size of 3 kg to be about as much per unit weight as the cost of rearing Atlantic salmon (roughly $1.60/kg). Given an 85% survival rate for juveniles, and a $2.85 price for juveniles, they estimated that the final product cost/kg would be roughly $4.00.[22] However, this estimate is highly dependent on a number of factors—the assumed price of juveniles, survival to harvestable size, the target market weight, product yield, and the cost of rearing and processing. Given the likely range of juvenile fish costs and survival rates, Huppert and Best (2004) estimated that the cost per kilogram of final product ranged from $6.00 (50% survival and juvenile cost of $3.50) to $3.30 (99% survival and juvenile cost of $1.25). The best estimate of Huppert and Best (2004) was that cost levels would most likely be approximately centered between these extremes. Since the expected cost of farmed fish/kg of product was well below the ex-vessel price/kg round weight, the authors concluded that sablefish aquaculture could be profitable.

This section examines the question of whether the ability to generate female monosex grow-out stocks can meaningfully improve the basic profitability of sablefish aquaculture. To make this determination, a 10-year cash-flow simulation model of a single net-pen operation for sablefish was developed. The Cash-Flow Simulation Model (CFS Model) estimates cash flows with standard mixed-sex rearing stocks or, alternatively, with female monosex rearing stocks under two alternative harvest regimes, four sets of assumptions regarding farm gate prices, and a range of juvenile costs, feed costs, and other unspecified annual costs. The CFS Model is considered a Monte Carlo simulation because it utilizes 5,000 independent estimates to account for variations in mortality events and the distribution of sizes across individuals during each grow-out period within the 10-year time frame.

While the driving factor behind the potential benefits of a female monosex operation is the differential rate of growth between male and female sablefish, there are several external variables affecting fish growth rate, including water temperature, genetic factors of wild-caught broodstock, and rearing environment (net pen versus land-based tank). There is still uncertainty as to how these variables, whether in isolation or in combination with each other, affect fish growth. Consequently, the CFS Model results presented below should be regarded as first approximations of potential for increased returns to sablefish farms from female monosex operations. Each iteration of the CFS Model utilizes a multistep process, as follows:

1. Estimate the expected survival and weight distribution of harvested sablefish in a single net pen stocked with either 55,000 female monosex juveniles or 55,000 standard mixed-sex juveniles. The growth, potential mortality, and end-weight are estimated independently for each of the 55,000 juveniles stocked within

[22] G. Knapp (University of Alaska, personal communication) estimated that rearing costs, including capital cost, for large-scale (10 million lb/year) operations raising Atlantic salmon are approximately $1.33/pound (in 2018 USD), or $2.92/kg. Asche (personal communication) reports that data from Norwegian Fisheries Directorate indicate that during 2008–16 the average cost/kg was $4.17/kg (in 2018 USD).

each iteration of the simulation. Each juvenile is assigned a random number that represents its relative size position within the normal distribution of the population at the target harvest date or target harvest weight.[23]

2. Estimate mortality in the simulation using an average annual mortality of 5%/yr implemented over the entire grow-out period, with no difference between male and female fish or between smaller fish and larger fish. If fish are reared for three years, then 15% will have died before harvest. In the simulation model, 15% of all stocked fish are randomly pre-assigned a day of "premature" death from 1 to 1,096 (the number of days in a 3-yr grow-out period). If the pre-assigned death date is less than the number of days in the modeled grow-out period, then the fish "dies prematurely" and is not sold; otherwise, the fish is sold with all other harvested fish.
3. Estimate feed provided for each fish, assuming a 1.5 FCR[24] over the entire grow-out period or until such time as it dies through random mortality or is harvested. The cost of feed assumes a feed cost of $1.80 per kg ($1.86/kg after adjusting to 2019 USD).[25]
4. Estimate the mean size of the surviving fish at any given day after stocking (up to three years) within each pen by the respective growth patterns shown in Figure 1.[26] A single, nonvarying standard deviation is applied to all fish in each pen.
5. Assume the labor costs for rearing and processing sablefish are comparable to those used in an economic model of an Atlantic salmon net-pen operation constructed by Knapp (personal communication).[27] Processing costs were estimated in 2013 to be $1.05/fish ($1.23/fish in 2019 USD). Grow-out labor costs are calculated per net pen per operating day at $142/day, then adjusted for inflation to 2019 USD ($166.38/day).[28]
6. Calculate total labor, feed, and processing costs of the harvested fish, assuming that only fish surviving through the entire grow-out period are harvested for processing.
7. Calculate the total revenue from harvested and processed fish using the farm gate inflation adjusted prices from Table 1. Model results will be discussed with respect to four alternative farm gate price scenarios as follows:
   a. Farm gate prices (round-weight) by size category using Alaska wholesale prices.
   b. Farm gate prices (round-weight) by size category using Midwest broker prices.
   c. Farm gate prices without size categories using Alaska wholesale prices.
   d. Farm gate prices without size categories using Midwest broker prices.

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[23] Throughout this discussion of the CFS Model, weights of individual fish are shown in grams, while aggregate harvests of fish are shown in kilograms.

[24] The simulation model uses a "daily FCR" of 1.5 for each fish that is alive at the beginning of the day, and assumes that the operator accurately estimates the exact amount of feed required to satiate each fish.

[25] Aquaculture feeds are sold as commodities. The $1.80/kg ($1.86/kg in 2019 USD) was indicated to be a reasonable feed price at the start of the project in 2017. McCullough (2019) indicates that feed cost for growing Atlantic salmon were €1.462/kg or $1.64/kg using the €/$ exchange rate of that date. The rate of $1.86/kg is considered a conservative estimate of feed costs, but the CFS Model results include an assessment of impact to IRRs of a 12% reduction in feed costs to $1.64/kg.

[26] The NMFS data are based on multiple growth-rate studies and represent conservative estimates of fish growth over time. Fish in the studies were fed to satiation with a nutrient-rich diet. It is also important to note that NMFS has implemented no selective breeding to date, so there is potential to greatly improve growth and performance.

[27] Labor cost per day and fish processing costs per fish are taken from Knapp (personal communication), who assumes a fully functioning salmon net-pen operation with 16 net pens (100 ft × 100 ft), 14 full-time employees, and an annual production of 1.54 million kg. Thus, although the CFS Model is estimating cash flows from a single pen, operating costs are based on a larger, industrial-scale operation.

[28] Processing, labor, and feed costs are inflated with the Federal Reserve Economic Data (FRED) Producer Price Index, Seafood Product Preparation and Packaging: Fresh and Frozen Seafood Processing.

Table 2. Operating cost assumptions for key variables used in the CFS Model.

Variable	Assumption
Number of juveniles stocked	55,000
Weight of juveniles at stocking (g)	55
Purchase price of juveniles ($/fish)	3.00
Total cost of stocked juveniles ($/grow-out period)	165,000
Daily feed conversion ratio	1.5
Average annual mortality	5%/yr applied at a flat rate over 3 yr
Labor cost per day per net pen ($/day)	142.49 (or 166.38 in 2019 USD)
Feed cost ($/kg)	1.80 (or 1.86 in 2019 USD)
Processing cost ($/fish)	1.06 (or 1.23 in 2019 USD)

Sources: Knapp (personal communication), Fairgrieve (personal communication), and interviews with industry representatives.

The cost assumptions for key variables used in the CFS Models are summarized in Table 2.

No reliable information was available for many other production costs that a sablefish aquaculture facility could incur, including depreciation, maintenance/repairs, insurance, fuel, utilities, pharmaceutical products, taxes, permitting, and overhead costs such as administration.[29] In the CFS Model, these "other annual costs" are combined with returns to owners (profits) as part of the gross margin and treated as a model result rather than an input.

The process in Steps 1 through 7 above is repeated 5,000 times in the Monte Carlo portion of the simulation. Each iteration varies by randomly reassigning mortality and overall growth rate index numbers to each of the 55,000 stocked fish.[30] Each iteration results in a slightly different survival, harvest by size category, total harvest, feed volumes, and total revenue. The results from each iteration are manually stored and, in the end, the mean values for all 5,000 iterations are used to generate cost and revenue estimates for each grow-out period.

The 10-year cash flow portion of the CFS Model extends the mean grow-out period for each stock type over two alternative 10-year rearing strategies with assumed farm gate prices in order to calculate long-term annual rates of return. Once the net pen is harvested, it is assumed that the pens are restocked with juveniles at the base price of $3.00 regardless of the season in which restocking occurs. The two alternative rearing strategies described below were developed to highlight the differences in returns to operators when using traditional mixed-sex rearing stocks versus the use of female monosex stocks.

[29] Estimates of additional annualized costs for the salmon net-pen aquaculture industry have been developed (Knapp, personal communication) and are on the order of $1.00/kg, or approximately $100,000 per year. However, because salmon aquaculture is a mature industry, and the available estimates are for operations that are much larger than those contemplated here, the estimates are not directly applied in the model.

[30] Each fish is randomly assigned a growth rate index number between 0 and 1, which determines its position in the cumulative distribution of fish growth. For example, fish assigned a growth-rate index number of 0.1 do not grow as fast as fish assigned a growth-rate index number of 0.75. Fish assigned growth-rate index numbers <0.5 grow slower than average, while fish assigned growth-rate index numbers >0.5 grow faster than average. Estimates of standard deviations, which define the distributions about the mean, were provided by Fairgrieve (unpublished data).

- **Strategy 1** utilizes a short grow-out period of 550 days for both mixed-sex and female monosex stocks. On the day of harvest and the two following days, an extra 10-person temporary crew is employed to facilitate the harvest and to quickly repair and clean the pen over a two-day period, after which the pen (or a new pen) is restocked for the next grow-out period.[31] Under this strategy, six full grow-out periods can be completed in the 10-year period covered by the CFS model, with an additional 342 rearing days of a seventh grow-out. At 550 days, the average fish in a mixed-sex pen will be 1,891 g, while the average in a female monosex pen will be 2,069 g. A shorter grow-out period may be considered advantageous compared to a longer grow-out period because the daily growth rates of fish (the slope of the polynomial growth curves; Figure 1) are less likely to have begun to plateau. In addition, a shorter grow-out period reduces the risk from premature mortality of fish that have already reached marketable size.
- **Strategy 2** utilizes a longer 729-day grow-out period for both mixed-sex and female monosex stocks. As in the previous strategy, an extra 10-person temporary crew is employed to facilitate the harvest and quickly repair and clean the pen over a two-day period, after which the pen is restocked for the next grow-out period. Under this strategy, five full grow-out periods can be completed during the 10-year period covered by the CFS model. After 729 days, the average fish in the mixed-sex pen will weigh 2,423 g, while the average fish in the female monosex pen will weigh 2,706 g. The 729 day grow-out period may be advantageous relative to Strategy 1 because of the relative uncertainty of the year-round availability of juveniles with which to restock. If juveniles are only available in colder months, the 729 day grow-out period ensures that restocking occurs in colder months.[32] In addition, because the Alaska longline fishery is closed from 15 November–15 March, this strategy may be able to realize relatively higher prices.

The same base-case farm gate price is assumed for both strategies—specifically, the size-based wholesale prices from the Gulf of Alaska commercial sablefish fishery shown in Table 1. Total revenue for each iteration is calculated by multiplying the prices by size category by the total weight of harvested fish in each size category. As mentioned briefly above, an important feature in the 10-year cash flow portion of the CFS Model is the estimation of "gross margins." Gross margins are the difference between total revenue and variable operating costs. In this case, gross margins include costs for energy, repairs/maintenance, insurance, administrative overhead, and annualized capital replacement costs. These costs are generally assumed to be equivalent on an annual basis regardless of the stock type used. Also included in gross margins are returns to owners (profits), if they exist.

Two other terms are used in reporting results from the CFS Model:

1. **Annual Profit**: Calculated as the annualized return to the owner as gross revenue less total annualized cost (both variable operating costs and all other annual costs).
2. **Internal Rate of Return (IRR)**: This is the discount rate that forces the net present value of a project (e.g., the 10-year cash flow of a net pen) to equal zero.
    a. If the IRR equals zero, then other annual costs plus operating cost exactly equals gross revenues on an annualized basis.

[31] For purposes of this analysis, no post-harvest fallowing of the pen is assumed.
[32] Under Strategy 1, three of the restocking dates occur in July, while remaining restocking dates occur in January.

b. If the IRR is greater than zero, then the project is making some contribution to owners (profit) above and beyond annualized expenditures.
  - If IRR is greater than 5%, the project likely exceeds the annual rate of inflation.
  - If IRR is greater than 10%, the project is likely generating positive returns to owners, even after accounting for inflation and the cost of capital. However, the project may not be generating high enough returns to offset the levels of risk associated with the project.
  - If IRR is greater than 15%, the project is likely generating positive returns to owners even after accounting for inflation, cost of capital, and the levels of risk associated with the project.

3.3.1 Cash flow simulation model results for Strategy 1: A 550-day grow-out period

This section summarizes CFS Model results for Strategy 1 assuming round-weight farm gate prices equal to the size-based wholesale prices from Alaska and noting that all dollar values are reported in 2019 USD. Figure 3 shows the variations in the distributions of harvested sablefish after a 550-day grow-out period from two of the 5,000 iterations. Over all 5,000 iterations of the CFS Model, both stocks averaged 50,868 harvested fish per grow-out. In general, the female monosex net pens produce larger fish on average (2,069 g) than the mixed-sex net pens (1,891 g). Because of the assumed size-based pricing, the average farm gate price for the female monosex fish was $8.63/kg, while the average price for mixed-sex stocks was $8.35/kg.

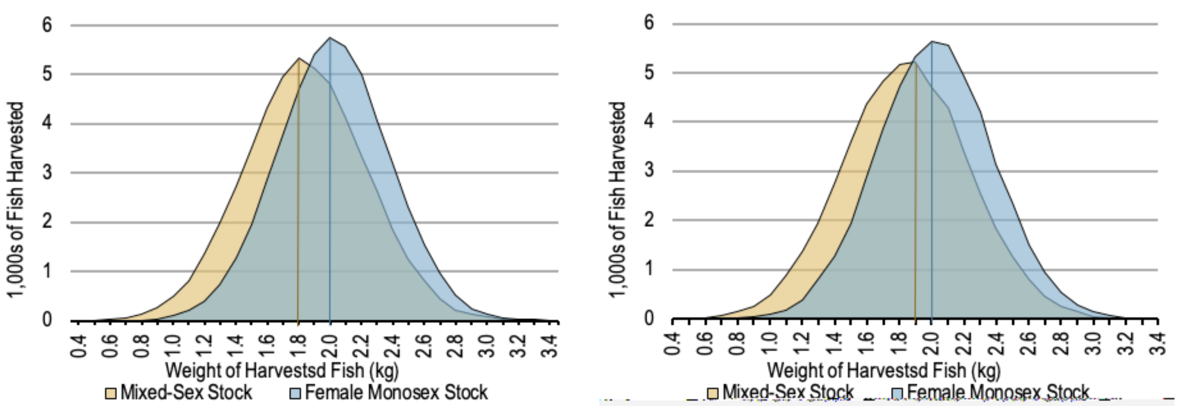

Figure 3. Distributions of harvested sablefish weights with a 550-day grow-out period in mixed-sex and female monosex net pens in randomly selected iterations.

Figure 4 shows the distributions of total harvest weight for all 5,000 iterations. The mean total harvest weight for mixed-sex stocks was 96,197 kg with a standard deviation of 148 kg, while the mean total harvest was 105,243 kg for female monosex stocks with a standard deviation of 153 kg. The difference in the two means is 9,046 kg—more than 50 times the greater of the two standard deviations. The fact that there is zero overlap between distributions of total harvest weight for the two stock types implies that the distributions are statistically different.[33]

[33] A one-tailed t-test comparing the difference in mean total harvests indicates $P < 0.00001$.

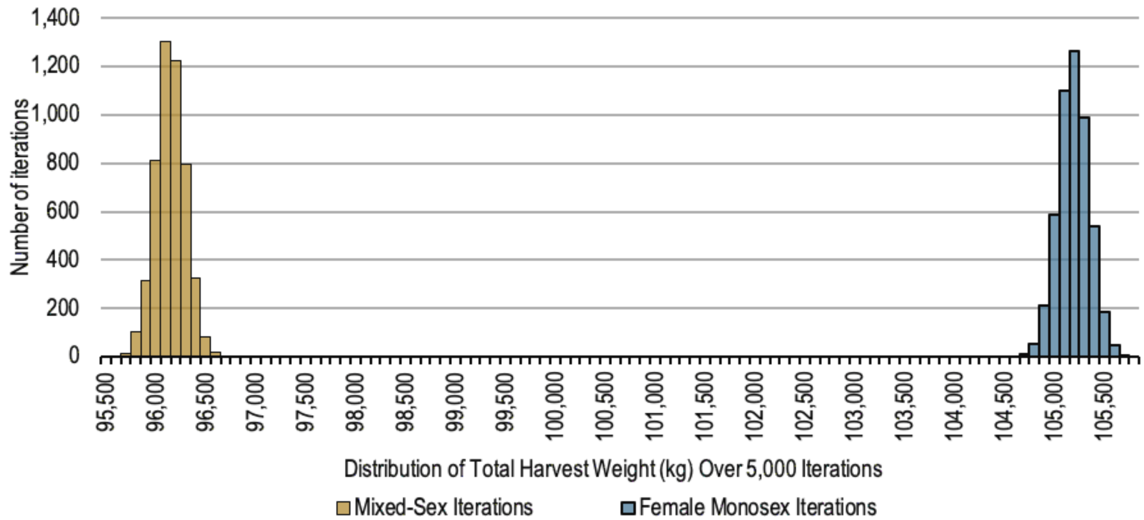

Figure 4. Distribution of total harvest by stock type with a 550-day grow-out period across all iterations.

Table 3 summarizes estimated operating costs for key variables during each 550-day grow-out period for both stock types under Strategy 1 over the 5,000 iterations of the CFS Model. Feed costs are the only listed cost element that differs in any given iteration or between the two stock types. This is a result of the assumption that both stocks have the same 1.5 FCR. Both stocks start with the same number of 55-g juveniles, but total harvests of female monosex stocks are on average 9,000 kg higher—that additional growth requires ~13,500 kg of additional feed. The higher revenues generated from the female monosex stock due to greater total harvest weight and larger average fish sizes more than offset the higher expenditures for feed. Gross margins in each grow-out period for female monosex stock exceed gross margins for mixed-sex stocks by $78,483.

Table 3. Average costs and revenues for each 550-day grow-out period under Strategy 1 in 2019 USD.

	Operating costs for key variables over the 550-day grow-out period						
Stock Type	**Juveniles**	**Labor**	**Feed**	**Processing**	**Total operating cost**	**Total revenue**	**Gross margin**
Mixed-sex	165,000	96,773	271,085	62,627	595,485	803,588	208,103
Female monosex	165,000	96,773	296,951	62,627	621,351	907,937	286,585

Note: Labor costs include the three-day harvest and post-harvest surge in preparation for restocking.

Figure 5 shows histograms summarizing the distributions of gross margin per grow-out period for mixed-sex and female monosex operations over 5,000 iterations under Strategy 1. The mean gross margin for female monosex grow-out was $286,585 with a standard deviation of $1,195, while mean gross margin for mixed-sex stocks was $208,103 with a standard deviation of $1,097. The fact that over the 5,000 iterations there is no overlap in gross margins indicates that the distributions for the two stock types are statistically different.[34]

[34] A one-tailed t-test comparing the difference in mean gross margins indicates $P < 0.00001$.

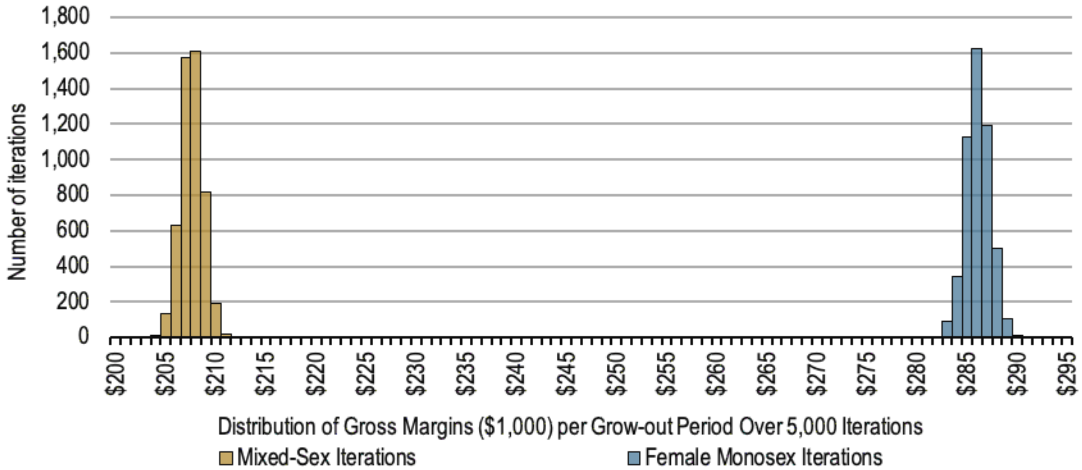

Figure 5. Distribution of gross margins for mixed-sex and female monosex operations under Strategy 1. Note: Assumes that farm gate prices are equal to average Alaska size-based wholesale prices.

Table 4 summarizes and compares annualized gross margins and imputed values of profits and other annual costs at five levels of IRR (0% to 20%) from the CFS Model for mixed-sex and female monosex operations over a 10-year period under Strategy 1. One of the key results of the CFS Model are the estimates of annualized gross margins for the two stock types, which remain constant for a given strategy regardless of the discount rate used to calculate IRRs. The use of annualized gross margins not only facilitates stock-type comparisons, but also enables comparisons between different strategies. For mixed-sex operations, the annualized gross margin is $137,801, while the annualized gross margin for female monosex operations is $189,759. The higher average annualized gross margin for female monosex operations under Strategy 1 implies improved profitability if female monosex stocks are used in net-pen operations, regardless of the actual magnitude of other annual costs.

Table 4. Comparisons of margins and profits at five levels of internal rate of return under Strategy 1.

Assumed IRR	**0%**	**5%**	**10%**	**15%**	**20%**
Mixed-sex operations	Annualized 10-year cash flows with mixed-sex pens under Strategy 1				
Imputed annual profits	$0	$21,700	$42,074	$61,253	$79,354
Imputed other annual costs	$137,801	$116,101	$95,728	$76,548	$58,447
Annualized gross margin	$137,801	$137,801	$137,801	$137,801	$137,801
Female monosex operations	Annualized 10-year cash flows with female monosex pens under Strategy 1				
Imputed annual profits	$0	$24,202	$46,902	$68,253	$88,384
Imputed other annual costs	$189,759	$165,557	$142,857	$121,506	$101,375
Annualized gross margin	$189,759	$189,759	$189,759	$189,759	$189,759
Female monosex operations	Imputed margins, profits, and IRRs if other annual costs are equalized at levels estimated for mixed-sex-operations				
Annualized gross margin	$189,759	$189,759	$189,759	$189,759	$189,759
Assume other annual costs = mixed-sex annual costs for each IRR level	$137,801	$116,101	$95,728	$76,548	$58,447
Imputed annual profit	$51,958	$73,658	$94,031	$113,211	$131,312
Imputed IRR	11.2%	16.3%	21.5%	26.6%	31.7%
Increase in female monosex IRRs assuming other annual costs from mixed-sex operations	11.2%	11.3%	11.5%	11.6%	11.7%

Note: Farm gate prices are assumed to equal size-based wholesale prices from Alaska.

The first two result rows in the mixed-sex and female monosex sections of Table 4 show the imputed levels of profits and other annual costs under the five IRR levels. If other annual costs equal the gross margin, then profits are zero and the IRR is zero. If other annual costs for the mixed-sex operation are $116,101, then profits are $21,700 and the operation generates an IRR of 5%.[35] Note that under all of the IRRs shown, the annualized gross margin remains constant and imputed profit + imputed other annual costs = the annualized gross margin.

There does not appear to be any reason why other annual costs of female monosex grow-out operations should be higher than other annual costs of mixed-sex operations. Thus, the last section of Table 4 calculates the imputed profits and imputed IRRs[36] for female monosex operations assuming their other annual costs equal the other annual costs imputed for mixed-sex operations for each IRR level. It then recalculates the imputed profit and IRRs for the female monosex operations. As shown in the bottom line of the table, female monosex operations generate more than 11% higher IRRs than mixed-sex operations if other annual cost for both types of operations are equalized. It should be noted that the percentage point differences will vary by scenario and with different pricing assumptions.

3.3.2 Cash flow simulation model results for Strategy 2: A 729-day grow-out period

This section summarizes CFS Model results for Strategy 2, which utilizes a 729-day grow-out period (~two years) for both stock types. To enhance comparisons across strategies, the base-case for Strategy 2 assumes the same farm gate prices assumed for Strategy 1—specifically, the size-based wholesale prices for Alaska as shown in Table 1. Under Strategy 2, the female monosex net pens produced larger fish on average (2,706 g) than the mixed-sex net pens (2,423 g). Given that both stocks were reared for the same number of days, the number of fish harvested was equal, at 49,520 per grow-out. An average of 120,001 kg was harvested from mixed-sex pens in each grow-out period, while an average of 133,988 kg was harvested from female monosex pens—a difference of 13,987 kg per grow-out.[37] Given that the average size of fish harvested from the female monosex pens was larger and that size-based prices are assumed, the average price from the female monosex pens was $9.95/kg while the average price from mixed-sex pens was $9.42/kg.

Table 5 summarizes the mean estimated operating costs, revenues, and gross margins during each 729-day grow-out period for both stock types under Strategy 2 over the 5,000 iterations of the CFS Model. Feed costs comprise the only difference in key operating costs. However, the higher revenues generated from the female monosex pens due to larger average fish size more than offset the greater expenditures for feed. On average, gross margins in each grow-out period for female monosex stocks exceed gross margins for mixed-sex stocks by $162,523.[38]

[35] The CFS model utilizes Excel's goal-seeking tool to iteratively search for the magnitude of other annual costs that will set the 10-year NPV of cash flow equal to zero for each of the listed IRRs.
[36] IRRs are found using Excel's goal-seeking tool to iteratively search for the discount rate that will set the 10-year NPV of cash flow equal to zero for each assumed level of other annual costs.
[37] The standard deviation over the 5,000 iterations of total harvested weight for mixed-sex stocks was 204 kg, while the standard deviation for female monosex stocks was 218 kg. There was zero overlap between the two distributions over the 5,000 iterations, and a one-tailed t-test indicates $P < 0.00001$.
[38] The SD of gross margins for mixed stocks was $1,829; for female monosex stocks, $2,068. There was zero overlap between the two distributions over the 5,000 iterations, and a one-tailed t-test indicates $P < 0.00001$.

Table 5. Average costs and revenues for each 729-day grow-out period under Strategy 2 in 2019 USD.

	Operating costs for key variables over the 550-day grow-out period						
Stock Type	**Juveniles**	**Labor**	**Feed**	**Processing**	**Total operating cost**	**Total revenue**	**Gross margin**
Mixed-sex	165,000	126,536	345,692	60,968	698,196	1,130,624	432,428
Female monosex	165,000	126,536	386,220	60,968	738,724	1,333,675	594,951

Table 6 summarizes and compares annualized gross margins and imputed annual profits and other annual costs at five levels of IRRs under Strategy 2. It has the same format as Table 4, shown above for Strategy 1. For mixed-sex operations, the annualized gross margin is $216,218 while the annualized gross margin for female monosex operations is $81,251 higher (37.6% higher) at $297,468. As with Strategy 1, the significantly higher annualized gross margin for female monosex operations under Strategy 2 implies improved profitability if female monosex stocks are used.

The bottom section of Table 6 imputes IRRs after setting other annual costs for the female monosex operations equal to the imputed other annual costs for mixed-sex operations at each of the five IRR levels. As shown in the bottom line of the table, IRRs for female monosex operations are an average of 12.7% higher than IRRs for mixed-sex operations.

Table 6. Comparisons of margins and profits at five levels of internal rate of return under Strategy 2.

Assumed IRR	**0%**	**5%**	**10%**	**15%**	**20%**
Mixed-sex operations	Annualized 10-year cash flows with mixed-sex pens under Strategy 1				
Imputed annual profits	$0	$29,535	$57,034	$82,710	$106,745
Imputed other annual costs	$216,218	$186,683	$159,184	$133,508	$109,472
Annualized gross margin	$216,218	$216,218	$216,218	$216,218	$216,218
Female monosex operations	Annualized 10-year cash flows with female monosex pens under Strategy 1				
Imputed annual profits	$0	$34,390	$66,369	$96,189	$124,069
Imputed other annual costs	$297,468	$263,078	$231,099	$201,279	$173,399
Annualized gross margin	$297,468	$297,468	$297,468	$297,468	$297,468
Female monosex operations	Imputed margins, profits, and IRRs if other annual costs are equalized at levels estimated for mixed-sex-operations				
Annualized gross margin	$297,468	$297,468	$297,468	$297,468	$297,468
Assume other annual costs = mixed-sex annual costs for each IRR level	$216,218	$186,683	$159,184	$133,508	$109,472
Imputed annual profit	$81,251	$110,786	$138,285	$163,960	$187,996
Imputed IRR	12.5%	17.6%	22.7%	27.8%	32.8%
Increase in female monosex IRRs assuming other annual costs from mixed-sex operations	12.5%	12.6%	12.7%	12.8%	12.8%

Note: Farm gate prices are assumed to equal size-based wholesale prices from Alaska.

3.3.2.1 Comparison of Scenario 1 to Scenario 2

Gross margins under Scenario 2 are higher than gross margins under Scenario 1 regardless of the stock type. Within the assumptions used in the scenarios and the CFS Model, this implies that sablefish net-pen operators will be better off with 729-day grow-out periods than with 550-day grow-out periods.

While gross margins under Scenario 2 are higher than gross margins under Scenario 1 for both stock types, it must be reiterated that farm gate prices under both scenarios assume that higher prices are paid for larger fish, as is experienced in the Alaska commercial fishery. As documented in the following section, which examines the sensitivity of initial CFS Model results to alternative assumptions, the assumption of size-based prices has a large impact on generated revenues and thus a large impact on gross margins and imputed levels of profits.

It must also be noted that there is no real basis for assuming that other annual costs under Strategy 2 will be higher than under Strategy 1. As an example, look at the imputed other annual costs for female monosex stocks with 5% IRR: under Scenario 1, the imputed value of other annual costs is $165,557; under Scenario 2, it is $263,078, a difference of $97,521. If we had assumed that other annual costs under Scenario 2 were in fact $165,557 (as in Scenario 1), the imputed IRR under Scenario 2 increases to 21.5%. If a similar exercise were undertaken for mixed-sex stocks, the IRR under Scenario 2 would increase from 5% to 18.6%. In both cases, it is clear that the longer grow-out period under Scenario 2 appears to generate larger gross margins than the shorter grow-out period assumed under Scenario 1.

3.3.3 Sensitivity of CFS Model results to changes in key variables

This section extends the CFS Model by testing the sensitivity of gross margins and imputed levels of profitability to changes in key variables, including: 1) a single farm gate price rather than size-based pricing, 2) farm gate prices based on the higher prices reported by the Midwest broker as discussed in Table 1, and 3) lower feed costs as reported in Footnote 25.

3.3.3.1 Single farm gate prices vs. size-based farm gate prices

The base-case for Scenarios 1 and 2 assumes that farm gate prices correspond to the size-based wholesale prices received by processors in Alaska in 2019 USD. Size-based farm gate pricing assumes that net-pen operators are able to charge higher prices for larger fish and will receive lower prices for smaller fish, and that price categories are identical to the categories listed in Table 1. Size-based pricing appears to be more advantageous to female monosex operations than mixed-sex operations because a larger percentage of harvested fish will fall into size categories with higher prices. This is demonstrated in Figure 6, which shows the volume harvested by size category under Scenarios 1 and 2.

If growers do not have market power with buyers to charge differential prices for fish in each size category, and instead can only negotiate a single price based on the average weight of all fish sold, then some of the benefits of switching to female monosex stock are reduced.

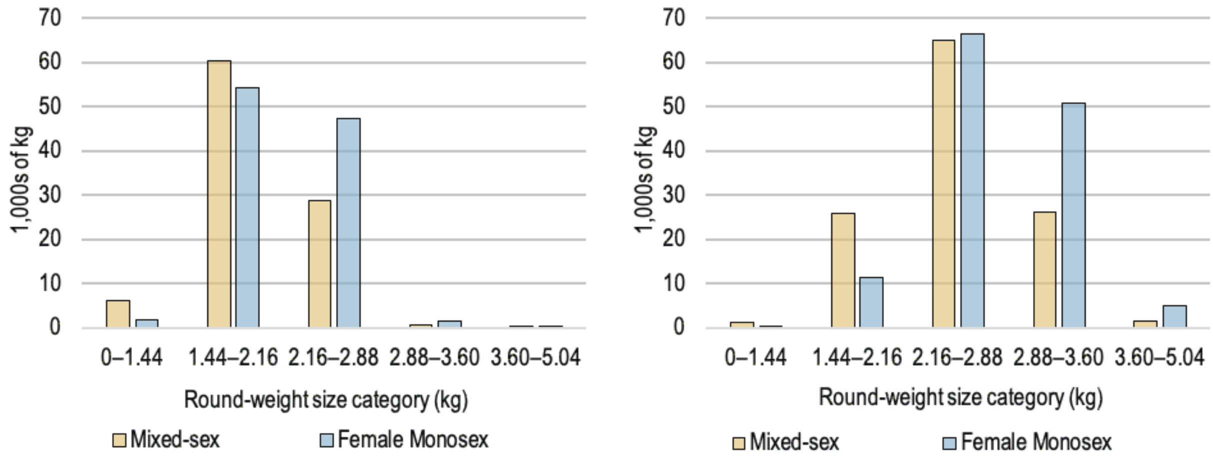

Figure 6. Volumes of harvested sablefish by stock type and size category under Scenarios 1 and 2.

Table 7 summarizes annualized gross margins, other annual costs, and profit for Strategy 2, with the difference that growers are assumed to receive a single price for all harvested fish based on the size of the average fish harvested. Under Scenario 2 with 729-day grow-out periods, the average size of harvested fish for both mixed-sex and female monosex stocks falls in the third size category (2,160–2,880 g), so the assumed price is $9.40/kg. Under a single price assumption, the annualized gross margin for mixed-sex stock falls by $1,257 to $214,861, and the annualized gross margin for female monosex stock decreases by $37,146 to $260,323. The bottom line of the table shows the improved IRRs that result from the use of female monosex stocks. Over the five levels, the improved IRRs average just 7.1% higher than the mixed-sex stock, compared to average improvements of 12.7% if size-base prices are assumed. If Scenario 1 were used to demonstrate the impact of average pricing vs. size-based pricing, the bottom-line IRR differences would average 6.9% compared to 11.4%. Clearly, the assumption that growers can negotiate size-based prices with buyers is an important factor in realizing all of the benefits from female monosex stocks.

Table 7. Comparisons of profit indicators at 5 levels of IRR under Strategy 2 with a single average price.

Assumed IRR	**0%**	**5%**	**10%**	**15%**	**20%**
Mixed-sex operations	Annualized 10-year cash flows with mixed-sex pens under Strategy 1				
Imputed annual profits	$0	$29,470	$56,909	$82,530	$106,514
Imputed other annual costs	$214,861	$185,391	$157,952	$132,332	$108,347
Annualized gross margin	$214,861	$214,861	$214,861	$214,861	$214,861
Female monosex operations	Annualized 10-year cash flows with female monosex pens under Strategy 1				
Imputed annual profits	$0	$32,614	$62,953	$91,257	$117,731
Imputed other annual costs	$260,323	$227,709	$197,369	$169,065	$142,592
Annualized gross margin	$260,323	$260,323	$260,323	$260,323	$260,323
Female monosex operations	Imputed margins, profits, and IRRs if other annual costs are equalized at levels estimated for mixed-sex-operations				
Annualized gross margin	$260,323	$260,323	$260,323	$260,323	$260,323
Assume other annual costs = mixed-sex annual costs for each IRR level	$214,861	$185,391	$157,952	$132,332	$108,347
Imputed annual profit	$45,461	$74,932	$102,371	$127,991	$151,975
Imputed IRR	12.5%	17.6%	22.7%	27.8%	32.0%
Increase in female monosex IRRs assuming other annual costs from mixed-sex operations	12.5%	12.6%	12.7%	12.8%	11.7%

Note: Farm gate prices are set at $9.40/kg—the Alaska wholesale price for fish in the 2,160–2,880 g category.

3.3.3.2 Impacts of higher farm gate prices

As indicated in Table 1 and discussed in more detail in Section 4.2.2, there are reports of wholesale prices for farmed sablefish sold in the U.S. that are considerably higher than the wholesale prices reported from the commercial fishery in Alaska. The prices reported by the Midwest broker are 74% higher than Alaska prices. This section examines the effect that higher farm gate prices have on the relative bottom-line improvements that can be expected from the use of female monosex stocks compared to the use of mixed-sex stocks.

Table 8 summarizes annualized gross margins, other annual costs, and profit for Strategy 2 assuming that the prices reported by the Midwest broker are the basis for size-based prices rather than wholesale prices in Alaska. The higher prices clearly impact gross margins, as well as imputed estimates of other annual costs and profits. For mixed-sex stocks, gross margins increase by $418,371 to $634,588 from the base case under Scenario 2. Similarly, annualized gross margins for female monosex operations increase by $493,506 to $790,975. The bottom line of Table 8 shows the calculated improvement in IRRs that are estimated for growers if they stock their net pens with female monosex fish rather than mixed-sex fish. On average, IRRs are estimated to increase by 15%. Under the base case of Scenario 2, the improvement attributable to the use of female monosex stocks averaged 13.5% (Table 6). Thus, while higher prices clearly generate higher margins and profits, the relative improvement attributable to female monosex stocks is relatively small—i.e., IRRs increase 1.5% relative to the base case.

Table 8. Comparisons of profit indicators at 5 levels of IRR under Strategy 2 with Midwest broker prices.

Assumed IRR	**0%**	**5%**	**10%**	**15%**	**20%**
Mixed-sex operations	Annualized 10-year cash flows with mixed-sex pens under Strategy 1				
Imputed annual profits	$0	$49,545	$95,504	$138,258	$178,134
Imputed other annual costs	$634,588	$585,043	$539,084	$496,330	$456,454
Annualized gross margin	$634,588	$634,588	$634,588	$634,588	$634,588
Female monosex operations	Annualized 10-year cash flows with female monosex pens under Strategy 1				
Imputed annual profits	$0	$57,994	$111,748	$161,714	$208,279
Imputed other annual costs	$790,975	$732,981	$679,226	$629,261	$582,696
Annualized gross margin	$790,975	$790,975	$790,975	$790,975	$790,975
Female monosex operations	Imputed margins, profits, and IRRs if other annual costs are equalized at levels estimated for mixed-sex-operations				
Annualized gross margin	$790,975	$790,975	$790,975	$790,975	$790,975
Assume other annual costs = mixed-sex annual costs for each IRR level	$634,588	$585,043	$539,084	$496,330	$456,454
Imputed annual profit	$156,386	$205,931	$251,891	$294,645	$334,521
Imputed IRR	14.4%	19.7%	25.0%	30.3%	35.5%
Increase in female monosex IRRs assuming other annual costs from mixed-sex operations	14.4%	14.7%	15.0%	15.3%	15.5%

3.3.3.3 Sensitivity of CFS Model results to changes in prices for feed

While all costs impact profitability, the price of feed is one of the more important factors. Female monosex operations use more feed than mixed-sex operations, so the cost of feed is particularly important when assessing the relative benefits of using female monosex stocks. As shown in Tables 3 and 5, feed expenditures are the only variable cost components that differ between the two stock types. This section looks at both feed price reductions and feed price increases.

First, we assume that feed prices are reduced from $1.86/kg to $1.64/kg as reported in Footnote 25—an 11.8% reduction. Under Scenario 2, the lower feed prices increase the annualized gross margin for mixed-sex stocks over the 10-year CFS Model by $38,465. Increases in the annualized gross margin for female monosex stocks are even higher, at $42,974. If the lower feed prices had been used in Table 6—which summarizes the base case for Scenario 2—the bottom-line IRRs summarizing the relative advantage of female monosex stocks would have averaged 13.5%, or 0.9% higher than the bottom-line IRRs for the base case for Scenario 2.

If we examine the impacts of an increase in feed prices of the same magnitude (i.e., from $1.86/kg to $2.08/kg), annualized gross margins under Scenario 2 for female monosex stocks decline by $48,377, but annualized gross margins for mixed-sex stocks decline by only $43,301. Further, the bottom-line increase in IRR percentages for female monosex relative to mixed-sex stocks from Table 6 would average 11.7%, down by a full percentage point from the base case.

3.3.3.4 Conclusions from the sensitivity tests

There are several conclusions to be drawn from the sensitivity tests of the CFS Model:

- If product prices are higher and costs are unchanged, then the relative advantage of female monosex over mixed-sex stocks increases.
- Size-based pricing for harvests is particularly beneficial to operations using female monosex stocks. If growers receive a single price per unit of weight for all harvested fish, the benefits of using female monosex stocks relative to mixed-sex stocks are still positive, but are reduced.
- The profitability of operations using female monosex stocks is more sensitive to changes in feed prices than that of operations using mixed-sex stocks.

3.3.4 Multibatch harvesting: An initial examination of an alternative grow-out strategy

The two grow-out strategies used in the CFS Model both relied on a single pen and a single harvesting operation for all fish in the pen. Given the natural variation in growth within both mixed-sex and female monosex rearing stocks, a multibatch harvesting strategy can take advantage of the variation in growth rates and can enable the grower to supply fish of a target size to market over regular intervals. Multibatch harvesting appears to be a common practice in larger operations with multiple pens.

A multibatch process distributes the harvest of market-weight fish, as shown in Figure 7. The mixed-sex operation, which assumes partial harvests, includes 11 separate harvests staggered by three weeks each, except for the second harvest, which is one month after the first harvest. Harvests occur over a period of ~220 days. The female monosex operation schedule includes 12 harvests staggered by two weeks each, except for the second and third harvests, which are staggered by three weeks. Harvests occur over a period of ~170 days. Each harvest extracts all fish within a net pen that are at least 2.5 kg. The harvests range from 5,000 to 9,000 kg, except for the final harvest, which includes all undersized fish.

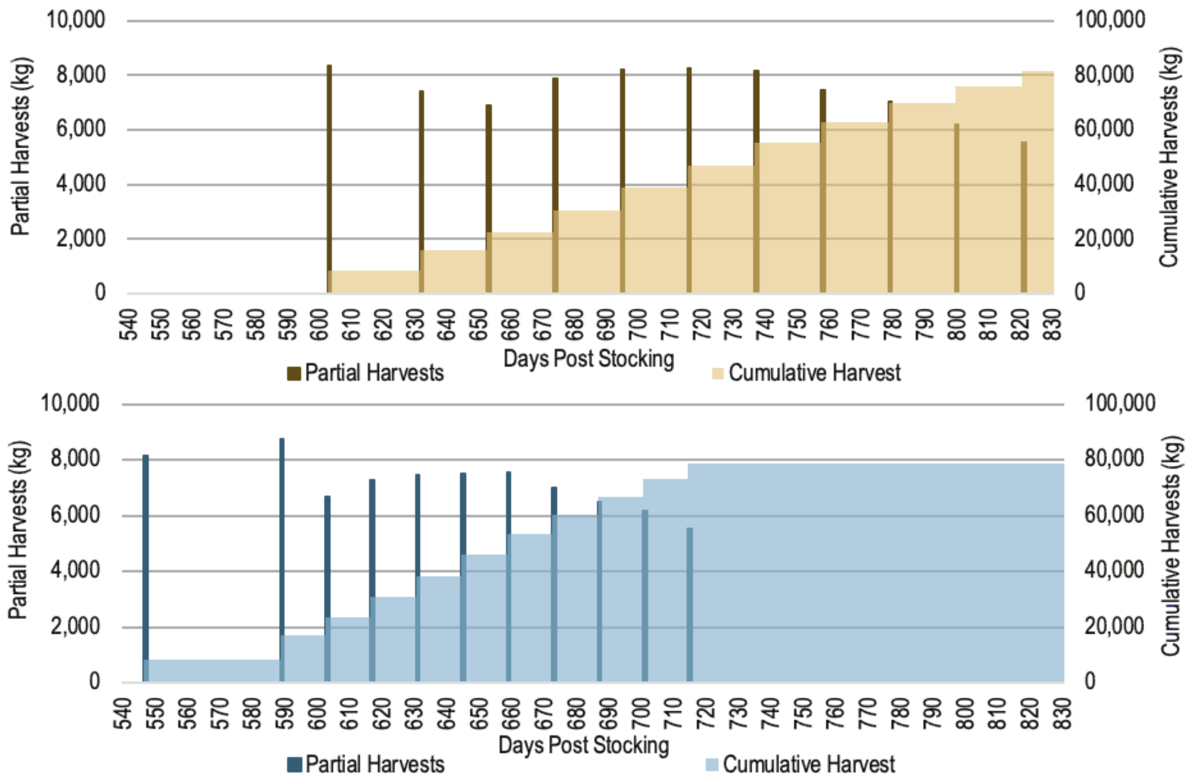

Figure 7. Example partial harvesting schedule of target market-weight sablefish.

The multibatch harvest schedule presented in Figure 7 extracts the fish at regular intervals, allowing the operator to tailor its harvest schedule to fit the needs of buyers. It is possible that a buyer would be willing to pay a premium per unit weight of fish as part of a long-term supply agreement. For example, a constant, reliable supply would allow a restaurant to maintain fresh sablefish as a regular menu item. This could in turn lead to larger overall demand for sablefish.

It is clear from Figure 7 that using female monosex rearing stocks will result in a shorter grow-out period than is possible with mixed-sex operations. The quicker turnover means that net pens and other farm infrastructure will have greater utilization rates in female monosex operations than in mixed-sex operations. While this is clearly beneficial to an operation's bottom line, the complexity of simulating multibatch harvesting operations within the CFS Model requires much more detail on the costs of infrastructure and labor utilization in sablefish operations than is currently available. It is sufficient to say that utilizing multibatch harvesting appears to further enhance the potential financial benefits of female monosex stocks to sablefish aquaculture operations.

3.3.5 Conclusions regarding the economic benefit of female monosex stocks

The results of the CFS Model demonstrate the economic benefit of the use of female monosex stocks in net-pen operations when compared to mixed-sex stocks. Though not explicitly tested, the economic benefits of rearing female monosex stocks would likely translate to land-based (RAS) operations.

The sablefish aquaculture industry, while showing promise, has not grown to a mature industry replete with hatchery operations able to supply juveniles to a larger number of grow-out operations. While there continue to be a few sablefish farms, the small number of active operators provides evidence that the economics of sablefish aquaculture (when combined with the costs of satisfying regulatory requirements) are only marginally attractive to investors. This lack of growth in the current industry is an indication that, while the returns on investment may be positive, they are not sufficiently high to attract additional entrants into the market. In terms used by the CFS Model, IRRs for the existing mixed-sex industry are most likely less than 10%.

The conclusions of the CFS Model, as demonstrated in the bottom lines of Tables 4, 6, and 8, indicate that using female monosex stocks could add 11–15% to the IRRs of existing mixed-sex facilities, if growers are able to market harvests by size category. Even if growers must accept prices based on the average size of fish harvested, the CFS Model results indicate that use of female monosex stock could add 6–7% to their IRRs. These improvements could be large enough to draw additional investment sufficient to result in a viable, self-sustaining industry, with the caveat that large increases in the global supply of sablefish could put downward pressure on market prices. Market prices, commercial supplies of sablefish, and an econometric model of the global sablefish market are provided in Chapters 4–6.

4 Overseas and Domestic Sablefish Markets

To capture sablefish market trends and provide specific examples and insights, this section draws on qualitative information from industry trade publications, academic reports, and popular press articles; telephone interviews conducted with seafood distributors and wholesalers; and a survey administered to a sample of selected seafood restaurants and restaurant seafood purveyors around the country.

4.1 International Markets

On average over the 2005–15 period, the United States exported about half of its total sablefish landings, and Canada exported around 60% (UNFAO 2018a). For several decades, sablefish was primarily exported to Japan (where it is commonly called *gindara*). It was historically a relatively inexpensive fish that was typically consumed during the winter months in northeastern Japan, especially in Tokyo and Kanagawa Prefectures. It competed with species such as rockfish and turbot, which had similar seasons and prices, and it was sometimes a substitute for salmon when salmon prices were high (Niemeier 1989).

By 1990, the Japanese sablefish fishery had been completely shut down, and Japanese demand for the species became entirely supplied by imports (Sonu 2014). With a general decrease in the annual TAC limits in North American sablefish fisheries and a general increase in sablefish prices, sablefish became more of a luxury food item in Japan. Economic recessions in Japan in the 1990s and late 2000s also affected the affordability of sablefish for Japanese consumers.

According to Sonu (2014), sablefish is currently sold in Japanese retail stores for home consumption in steak and fillet form, and as *kasuzuke* (marinated in rice wine lees). It is prepared in various ways for the table. The most popular dish is fish stew, typically consisting of sliced fish, vegetables, and soup stock. The dish continues to be consumed primarily during the winter. Sablefish steaks and fillet, as well as *kasuzuke*, are also grilled, broiled, or baked and consumed year-round. Sablefish may be used as *sashimi* (thinly sliced raw fish), especially in northern Japan, but it is not smoked, dried, or canned. Today, sablefish competes in the Japanese market primarily with Patagonian toothfish (*Dissostichus eleginoides*, called *mero* in Japan), which has a similar color, oil content, and flesh quality (Huppert and Best 2004, Sonu 2014).

The sablefish exported to Japan is sold almost exclusively as a frozen, minimally processed (e.g., headed-and-gutted) product (Warpinski et al. 2016). Sablefish is usually sold directly to licensed buyers at production-center wholesale markets located at Japanese ports of landing and consumer-center wholesale markets located in cities with populations of more than 200,000. It is also sold directly to processors or representatives of supermarket chains (Sonu 2014).

Huppert and Best (2004) indicate that the Japanese market for sablefish and certain other types of fish is sensitive to color and oil content (preferring white flesh and high oil content). Larger sablefish are preferred and command a higher price because they are considered to have a higher oil content than smaller sablefish. Presumably, the Japanese demand for larger fish from Alaska and B.C. sablefish fisheries reflects this preference (smaller sablefish from

U.S. West Coast fisheries have typically filled demand in the other smaller markets, including the domestic market; Warpinski et al. 2016).[39] However, the recent abundance of smaller fish in North American sablefish fisheries and the corresponding decrease in the price per unit have reportedly created a different dynamic in the Japanese sablefish market. As discussed in Section 5.1, strong recruitment of age classes from 2014 and 2015 have begun showing up in domestic sablefish fisheries as 1.0–1.5 kg fish. With much of the harvest volume tied up in smaller fish, sablefish retail prices in Japan fell to a point of making sablefish available to a different demographic. As one U.S. West Coast seafood processor noted, "They've learned how to use the smaller fish in markets over there" (Ess 2018).

To date, the amount of imports of farmed sablefish into Japan has been small, with no imports occurring in the last two years. The major exporter has been Blue Link, a distributor for Golden Eagle Sable Fish, which sells the fish in Japan under the *Kirari* label (Blue Link 2018). Sablefish raised to a weight of 2–3 kg are semi-dressed at the production site, and the fresh fish is then air-freighted to Japan. The import price of this type of sablefish tends to be slightly higher than wild, frozen, dressed sablefish, because the fish are intended for raw consumption (The Suisan Times 2009). Farmed sablefish has been sold in Hokkushin, Japan's largest seafood store, Gatten, a popular chain of restaurants specializing in sushi, and in Tokyo's Tsukiji Market by Chuo-gyorui Company, one of Japan's largest wholesalers of fishery products (Sablefish Canada 2014b).

In addition to the limited supply of farm-raised sablefish, Huppert and Best (2004) note that a possible stumbling block to expanded imports to Japan could be inadequate quality. In order to better understand the market for farmed sablefish in Japan, the study contacted Ben Tsuji, an expert in international seafood markets.[40] According to Tsuji, most of the farmed sablefish exported to Japan has been fresh, although there have been some shipments of frozen product (B. Tsuji, True Marine International, LLC, personal communication). Most of the farmed sablefish has been purchased by rotating (conveyor belt) sushi restaurants. Tsuji notes that perceptions of the quality of farmed sablefish vary across commercial seafood buyers. Some say that farm-raised sablefish has a softer, more succulent texture than wild-caught fish, making it more suitable for sushi, while others claim that it has an objectionable smell and taste that renders it less desirable. It is Tsuji's opinion that in order for a market of farmed sablefish to be established in Japan, the price must be lower than wild-caught fish.

Figure 8 shows that with the increased interest in sablefish from other overseas markets, Japan's share of the U.S. sablefish supply has declined. In particular, export sales to other Asian markets have increased in recent years. While there was a dramatic increase in the amount of sablefish shipped to China in the mid-2000s, it is believed that the majority of this product was re-exported to Japan. More recently, however, much of the sablefish exported to China is likely being retained for domestic Chinese consumption due to its growing

[39] Historically, the U.S. West Coast sablefish fishery has been dependent on the Japanese market. However, according to a Washington-based seafood processor/wholesaler, over the past decade an increasing proportion of the larger (>2.3 kg) fish have been sold in the European market (predominately the Netherlands). Currently, most of the fish sent to Japan are less than 2.3 kg (D. Besecker, Dana E. Besecker Co., personal communication).
[40] The personal judgments of market experts and leaders are utilized throughout this chapter. While these individuals were asked to provide their best objective perspectives, the viewpoints presented are opinions and may be based on limited information.

popularity in that country (Stewart 2017). Product shipped to other Asian (e.g., South Korea) and European markets was largely for local consumption. Japan's dominance in the overseas market for sablefish has diminished for a number of reasons. Aside from the increased sales in other foreign markets, perhaps the primary explanation is that the palates of Japan's younger generations differ from those of older Japanese, with younger consumers increasingly opting for Western dishes based on meat and poultry rather than seafood (Falsey 2016).

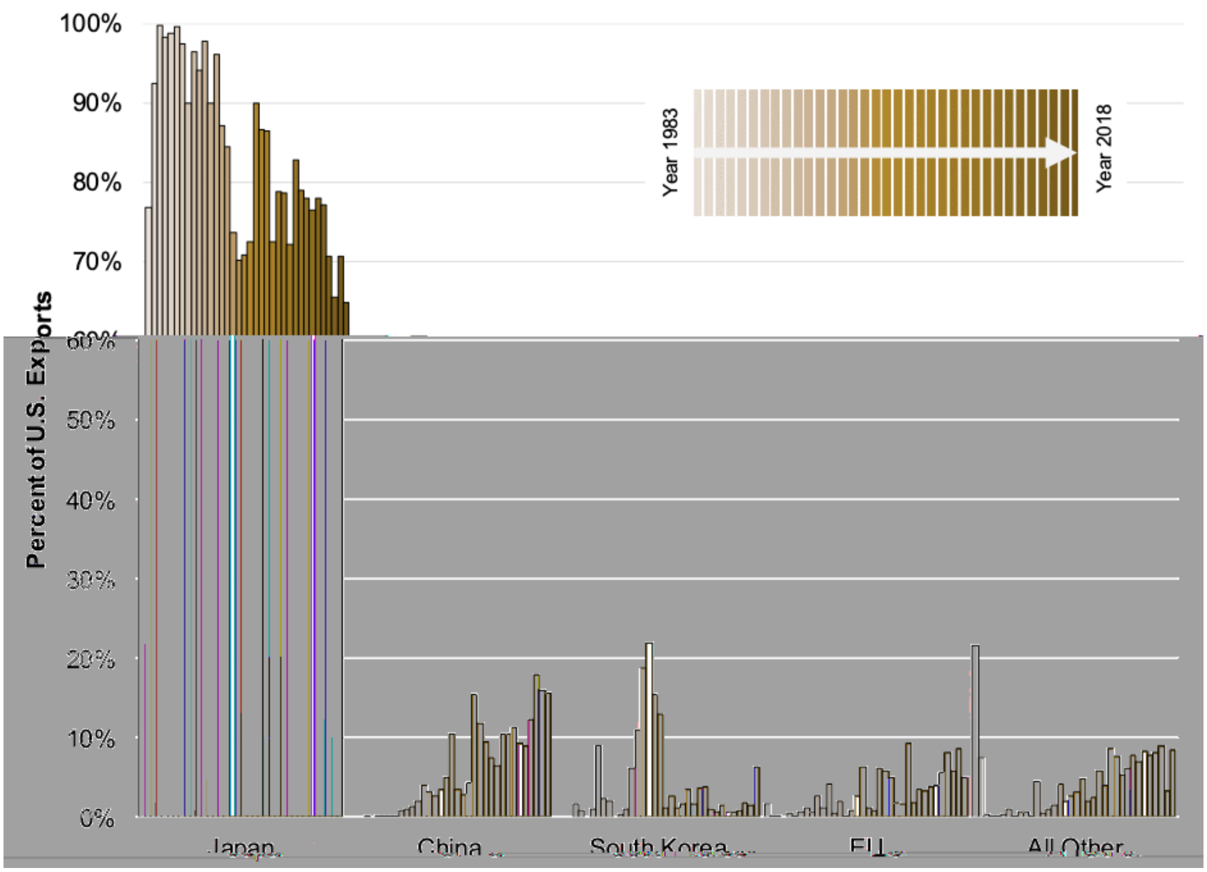

Figure 8. U.S. sablefish exports to Japan and other countries as a percentage of total U.S. exports. Source: NMFS (2018d).

4.2 Domestic Market

The domestic market for sablefish is small in comparison to export markets. In the United States, sablefish has several market names in its processed forms. According to the USFDA (2018), the only acceptable name for sablefish product labeling in interstate commerce is *sablefish*. However, vernacular names include *butterfish*, *sable*, *skil*, *skilfish*, *beshow*, and *coalfish*, as well as the widely used *black cod*.[41]

[41] According to Grantham (2010), in 1916, John N. Cobb, then editor of *Pacific Fisherman*, convinced the U.S. Bureau of Fisheries (now NMFS) to launch a black cod marketing campaign. The first step of the marketing effort was renaming black cod as sablefish.

The high oil content of sablefish makes it ideal for smoking—it won't lose its flavor or texture in the process—and smoked "sable" has long been a working-class Jewish deli staple in New York City (Burros 2001, Cascorbi 2007). While it is normally hot-smoked, it can also be cold-smoked. In addition, Scandinavian immigrants, especially on the U.S. West Coast, found its firm flesh a good substitute for Atlantic cod (Cascorbi 2007). Still, for many years the domestic market for sablefish was limited; the small amount of sablefish absorbed by the market sold for much less than the prices fetched in Japan (Intrafish 2004). One press report indicates that the soft, buttery texture of sablefish appealed more to Asians than to Americans, who tended to prefer fish with firmer, flakier flesh (McClatchy-Tribune Information Services 2010).

In recent decades, however, sablefish has become increasingly prized in upscale restaurants as a premium-quality whitefish (Cascorbi 2007). It has especially become popular in the growing number of U.S. restaurants that feature Asian or Pan-Asian cuisine (Redmayne 2002). A number of factors probably contributed to the increased demand for sablefish in the U.S. market. During the 1990s, Nobuyuki Matsuhisa, owner of the Japanese-Peruvian restaurant Nobu in New York City, introduced miso-glazed sablefish as the restaurant's signature dish, with the dish symbolizing a new direction in Japanese cuisine (Burros 2001, Morimoto 2007, Olmsted 2016). A few years later, former Nobu head chef Masaharu Morimoto popularized the dish during an episode of the cable-television program *Iron Chef America*. In the early 2000s, sablefish was marketed as a substitute for Patagonian toothfish (which is widely distributed in the U.S. seafood market under the name *Chilean sea bass*) because of its similar taste and texture. Patagonian toothfish was being overfished in all oceans, and the "Take a Pass on Chilean Sea Bass" media campaign of environmental advocacy groups bolstered the consumption of sablefish in the United States (Redmayne 2002). More recently, sablefish has gained popularity with American sushi chefs, with some chefs considering it a more environmentally friendly and healthy alternative to freshwater eel, or *unagi* (Leu 2016).

4.2.1 Seafood restaurant survey

In order to better understand the U.S. sablefish market, including the potential development of a market for farmed sablefish, a survey was administered to a sample of seafood restaurants and restaurant seafood purveyors around the country. Although the restaurants surveyed are not necessarily a representative sample of U.S. seafood restaurants, the survey results offer additional insights about the demand for sablefish in the U.S. food service industry.

A list of over 61 restaurants to survey was developed through a variety of sources, including economists working in seafood marketing, the Monterey Bay Aquarium Seafood Watch, online searches, and personal communications. Of the 61 restaurants identified, the study was able to contact 35 and email them an invitation to complete a survey on SurveyMonkey (see Appendix for the complete survey instrument).[42] Of the 35 restaurants contacted, 16 completed at least part of the survey. In order to enhance the sample size, numerous reminder calls and emails were made. Twelve restaurants never responded to the survey request, and eight stated they were not interested in filling out a survey. Two of those eight restaurants indicated that they were not interested in completing the survey because they only served wild fish.

[42] https://www.surveymonkey.com/

All respondents to the survey indicated familiarity with sablefish, and 94% of the 16 restaurants that answered Question 1 said that they have served sablefish in the past. However, only 44% of these restaurants are currently serving sablefish (Question 2). Of the 14 restaurants that answered Question 3, 57% said that they had sourced sablefish from local wholesale markets, while 35% had sourced from national markets. Two restaurants reported that they procured sablefish directly from Alaska producers. Three of the eight restaurants that answered a question regarding purchases of farmed sablefish indicated that they had made such purchases. None of the restaurants acquired their farmed sablefish directly from foreign or domestic aquaculture operations. Of the six restaurants that answered Question 4 regarding reasons why sablefish was not served, one-third mentioned lack of supply. Other respondents to this question stated that the high price of sablefish was a constraint. When asked whether there was high demand for sablefish from their customers, half of the 14 restaurants that responded answered yes and half answered no (Question 5). Of the 14 restaurants that answered Question 6, 43% stated that customers specifically ask for sablefish. 79% of the 14 restaurants that responded to Question 7 said that the size of the fish they purchase matters to them or their customers.

When asked if they have ever served farmed fish or shellfish (e.g., tilapia, Atlantic salmon, oysters), all of the 14 restaurants that responded said yes (Question 8). 71% of the 14 restaurants that answered Question 9 said that they would be interested in a consistent supply of farmed sablefish if it was available. Serving a farmed product that is known to be sustainably produced (e.g., received a Best Aquaculture Practices certification) mattered to 86% of the 14 respondents to Question 10.

When asked the open-ended question of the average price per pound they paid for sablefish, the 13 respondents gave an array of answers, including $10/lb for H&G product, $21.50/lb for a fillet, and $6–$9/lb for a whole fish. The majority of these respondents were willing to pay more for sablefish of a consistent size and quality.

The prices reported for a sablefish entrée ranged from $22 to over $45. One restaurant noted that the price of the sablefish would determine entrée pricing, as it expected to make a $20 profit per meal. Two other restaurants stated that for a 6–7-oz fillet at $12/lb they would charge $24–$32 per entrée. Restaurants surveyed indicated that they typically prepare sablefish using an Asian *kasu* (miso, sake, and sugar) marinade, or pan sear or wood-oven roast sablefish fillets or steaks with skin on.

Additional comments provided by respondents at the end of the survey included:

- “Sablefish is one of our most popular items.”
- “Sablefish is a great fish for restaurants.”
- “It would be great to have an additional source of sablefish and the potential of aquaculture is great. Would be a good industry for the U.S. demand will remain constant because the product is well thought of when handled well.”
- “Sustainability. That is my number one concern.”
- “Sablefish is always a popular item when we feature it.”
- “Sablefish is not high on our list. We serve it maybe once or twice a year.”

Table 9. Summary of survey responses.

Question	*n*	Response	%
1 Have you ever served sablefish at your establishment?	16	Yes	94
		No	6
2 Do you currently serve sablefish?	16	Yes	44
		No	56
3 Where have you made wholesale purchases of sablefish in the past? (Please choose all that apply)	14	n/a	7
		Locally	57
		National markets	36
		International markets	0
		Other	14
4 If you do not purchase or prepare sablefish, why not?	8	Lack of demand	0
		Lack of supply	33
		Other reasons	67
5 Do you see high demand for sablefish from your customers?	14	Yes	50
		No	50
6 Do any of your customers specifically ask for sablefish?	14	Yes	43
		No	57
7 Does the size of the fish that you purchase matter to you or your customers?	14	Yes	79
		No	21
8 Do you ever prepare and serve fish (of any species) that has been farmed (e.g., tilapia, Atlantic salmon, oysters)?	14	Yes	100
		No	0
9 Would you be interested in a consistent supply of farmed sablefish if it were available?	14	Yes	71
		No	29
10 Would it matter to you if the fish were sustainably produced (i.e., the fish had Best Aquaculture Practices [BAP] certification)?	14	Yes	86
		No	14

4.2.2 Seafood distributors and wholesaler interviews

Additional information on sablefish markets was collected from telephone interviews with seafood distributors and wholesalers in the Pacific Northwest, California, New England, Mid-Atlantic, and Midwest. According to interviewees, the U.S. and European markets for sablefish have grown substantially over the past 15 years. In part, this shift from a former exclusively Asian market occurred because of social media and the internet.

Interviewees noted a number of advantages of farmed sablefish, including firm, white flesh; consistent supply; freshness (ensuring a longer shelf life); less bruising; food safety; and sustainability. In addition, farmed sablefish offers greater marketing flexibility. With wild-caught fish, distributors must build up inventories of frozen fish to cover periods when the fishing season is closed.[43] Even during the season, wild fish deliveries may be unreliable (i.e., if vessels are delayed by weather/other variables). With farmed fish, distributors can potentially fulfill orders for fresh fish with little or no delay. For example, retail businesses typically want fish delivered on Tuesday for the weekend, and Friday for the earlier part of the week. Having fresh fish consistently available could help distributors and wholesalers meet this schedule.

[43] One of the sources interviewed for this report is working to develop fresh and flash-frozen sablefish markets on the East Coast from commercial landings.

Perceived disadvantages of farmed sablefish include their potentially smaller size in comparison to wild-caught fish. For instance, B.C. farmed sablefish have tended to be relatively small because of the higher production costs of raising larger fish. Smaller fish are less desirable for some uses due to the lower yield during processing and lower oil content. Demand for farmed sablefish is likely to increase if growers can cost-effectively raise fish that are 5-lb grade or larger, as these sizes are better suited to value-added markets, or if a pan-sized fillet market is developed. In addition, some interviewees felt that to expand the market for farm-raised sablefish, the price must be significantly lower than wild-caught fish, at least initially. A lower price would encourage buyers to sample farmed fish, and over time they are expected to gain confidence in the quality and supply of farmed product.

According to interviewees, restaurant chefs currently prefer portions more than fillets from round fish because they look better on the plate and are easier to cook. The ideal size for a main plate item is a 6-oz portion or, alternatively, a 1¼- to 1¾-lb fillet. There is little demand by restaurants for H&G product, which suggests there could be additional market opportunities for pan-sized sablefish fillets.

One interviewee commented that many restaurant customers who are served portions can't distinguish between sablefish and Chilean sea bass. Currently, the demand for wild-caught sablefish on the East Coast is relatively low because of its price relative to that of sea bass. Sablefish fillets are $17.95/lb delivered, whereas sea bass is $15.95/lb, and halibut, which is another competing product, is $16.95/lb. If the sablefish price were reduced to $11.95–$12.95/lb, there would be a significant uptick in demand.

Interviewees noted that a potential obstacle to marketing farmed sablefish on the U.S. West Coast is the general bias against farmed fish among some groups of seafood consumers in the region, together with the growing number of west coast seafood consumers who have developed relationships with harvesters through Community Supported Fishery organizations, farmers' markets, and other direct marketing strategies.[44] Strong relational ties between distributors and harvesters may also discourage the introduction of farmed fish into market channels. These obstacles don't appear to exist in the Midwest market, where distributors have no qualms about relying predominately on farmed fish. According to one Midwest wholesaler, farmed sablefish is priced right. Recently, the wholesaler purchased sablefish raised by Golden Eagle Sable Fish from Sea Agra Seafood, a B.C.-based broker, for $8.14/lb for a dressed, head-on product. In turn, the wholesaler can sell the dressed, head-on product to retailers for $10.80/lb (or $21.95/lb skin-on filleted, $22.95/lb skin-off filleted, and $26.94/lb skin-off portioned). On the other hand, a California distributor thought that the B.C. farmed product was priced too high.

[44] Studies show that Hawai'i consumers also prefer wild-caught fish to the farm-raised counterpart (Davidson et al. 2012, NMFS 2018b).

4.3 Potential International and Domestic Niche Markets for Farmed Sablefish

The following sections discuss potential ways sablefish aquaculture operations could create new market opportunities and distinguish farmed sablefish from wild sablefish by supplying sablefish products with varying characteristics. The markets described are not mutually exclusive; for example, small, fresh farm-raised sablefish might be considered more desirable by sushi chefs for whom serving seafood acquired from demonstrated environmentally friendly sources is a high priority.

4.3.1 Fresh farmed sablefish

While the implementation of individual transferable quota (ITQ) programs in Alaska, B.C., and U.S. West Coast fisheries increased the potential for year-round availability of fresh sablefish (Cascorbi 2007), most of the sablefish caught in these fisheries is frozen. Some sablefish aquaculture operations have seen the relative scarcity of fresh fish as a marketing opportunity. As early as 2009, Sablefish Canada (now Golden Eagle Sable Fish Inc.) was sending fresh fish to Japan for higher-value raw uses, such as sushi and sashimi (Lee-Young 2009). In 2014, Sablefish Canada launched a marketing campaign in Europe, offering restaurants and high-end retail outlets a year-round supply of "premium fresh sushi-grade sablefish" as an alternative to the "defrosted wild-caught Black Cod that Europe has received over the years." Customers included Amador, the three-star German restaurant, and Manor, the largest department store chain in Switzerland (Sablefish Canada 2014a).

Quality differences between fresh and frozen sablefish have been asserted, but these differences are a matter of debate. According to some reports, knowledgeable chefs and fishers insist that because of its high oil content, the fish freezes well, making it difficult to distinguish between fresh and frozen. Others contend that frozen sablefish can be mushy. As one U.S. seafood buyer remarked, "When you get it fresh there is a night and day difference in appearance and texture. The texture is silky in the mouth, it flakes cleanly, and it has a moist flake" (Burros 2001).

A potential problem with fresh fish is that it may pose a parasite risk to humans, in contrast to fish that has been frozen and stored at a sufficiently low temperature. A reported advantage of fresh farm-raised sablefish over fresh wild-caught sablefish is that the former may be less likely to have parasites, especially if they are reared in a RAS. Farmed fish, in general, have a significantly lower risk of parasites than their wild counterparts because their diet consists of feed pellets rather than parasite-infected prey. Parasite-free fish are considered more suitable for the sushi and sashimi market.[45] A recent spate of articles in the popular press warn consumers about eating wild-caught fish, including sablefish, because of the parasite hazards (e.g., Zukin 2015). While the human health risks of eating fish that

[45] The U.S. Food and Drug Administration's guidance to processors of fish and fishery products in the development of Hazard Analysis Critical Control Point plans identifies parasites as a potential hazard of many types of fish, including sablefish. According to the agency's classification of this hazard, it applies "where the processor has knowledge or has reason to know that the parasite-containing fish or fishery product will be consumed without a process sufficient to kill the parasites, or where the processor represents, labels, or intends for the product to be so consumed" (USFDA 2011).

have parasites may be exaggerated (Iso 2018), a fish that can be advertised as parasite-free may have a market advantage, especially if it is intended to be served in raw preparations. In addition, one seafood buyer maintains that, "Some parasites found in wild sable can cause the fish to liquefy while cooking. Though there is no danger to humans if consumed, when this happens it can still ruin the texture of the fish, making it inedible" (Gimbar 2014).

Parasite-free fresh sablefish may also be desired by producers of smoked sablefish, as it would not require additional cooking. With a number of recent popular press articles (e.g., Rosenbaum 2013) extolling the merits of smoked sablefish offered in some New York City delicatessens, it is likely that the domestic demand for this sablefish product has increased. In 2013, Sablefish Canada reported that about 40% of its farmed sablefish was sold in North America, mainly smoked for lox for the U.S. East Coast market (Nadkarni 2013).

4.3.2 Small farmed sablefish

As discussed in Section 4.1, Japanese consumers have long preferred larger-sized sablefish. Some seafood buyers indicate that there is also a higher demand for larger fish in the domestic sablefish market (Armstrong and Cunningham 2018). As described in Section 5.2.4, there is a clear delineation in ex-vessel value across weight categories.

However, Section 4.1 notes that the increased landings of small sablefish have spurred seafood buyers to find alternative outlets. Available information suggests sablefish aquaculture operations have previous experience tapping into these new markets for small fish. In a recent marketing promotion of farmed sablefish conducted by Global Blue Technologies, some chefs requested the company to harvest smaller sablefish—weighing 0.4–0.5 kg instead of 2 kg or larger—for the sushi/sashimi market (Wiedenhoft 2017, Perciformes Group 2018). As noted in Section 3.2.1, in the early 2000s, Sablefish Canada successfully accessed a new live-fish market in B.C., harvesting the 1.0–1.5-kg fish preferred by this market.[46] The company also examined the feasibility of entering live-fish markets in Asia to provide additional revenue (Sablefish Canada 2014c).

Smaller sablefish may also be preferred over larger ones because they are likely to have a lower mercury content (Besecker, personal communication). According to USFDA (2017), wild-caught sablefish have moderately high concentrations of mercury, comparable to those in albacore and yellowfin tuna. In general, farm-raised fish may have less exposure to mercury than wild, free-foraging fish because they are usually fed a controlled diet. However, fish raised in floating marine net pens can still absorb mercury from their environment (Scheer and Moss 2011).

4.3.3 Eco-friendly farmed sablefish

As described in Section 5.1, approximately 70% of North American sablefish landings are certified by the Marine Stewardship Council (MSC) as being caught in "sustainable and well-managed" fisheries. By the late 2000s, the MSC's distinctive blue label began to appear on wild-caught sablefish products sold in Japan (Inoue 2007).

[46] The company developed a transport system specifically for live sablefish with the purpose of eliminating mortalities and ensuring the fish are in prime condition at the end of the transport (Sablefish Canada 2014c). Prices received were not reported.

Notwithstanding this certification, commercial sablefish fisheries have some adverse environmental impacts, including the bycatch problems described in Sections 5.3.6, 5.4.1.6, and 5.4.2.5. Sablefish farms would avoid the bycatch problems, but, as noted in Section 2.2, aquaculture operations may have their own adverse environmental impacts.

The survey results presented in Section 4.2.1 suggest that serving a farmed seafood product that is known to be sustainably produced mattered to a large proportion of U.S. seafood restaurants. In general, sablefish tend to be considered an aquaculture species of low environmental impact, and hence a "green" or sustainable option (Tlusty et al. 2011). Over the years, some sablefish aquaculture operations have endeavored to take advantage of consumers' willingness to pay a premium for seafood perceived as eco-friendly and healthy. For example, Totem Sea Farm, an aquaculture operation in B.C. that has since ceased rearing sablefish, was an adherent to the Canadian Organic Aquaculture Standards, which are a set of voluntary standards that were published by the Canadian General Standards Board under the sponsorship of DFO (Stoner and Ethier 2015).[47] The sablefish raised by Totem Sea Farm were stocked at low densities, and their feed was certified organic.[48] Fish trimmings from herring factories were used to provide the bulk of protein in the feed, and no antibiotics, coloring, or hormones were incorporated (Gimbar 2014). As a result of these environmental safeguards, Seafood Watch gave Totem Sea Farm's sablefish a "Best Choice/Green" ranking—i.e., they were "well managed and caught or farmed in environmentally friendly ways" (Stoner and Ethier 2015).

Similarly, Sablefish Canada advertised that it used "specially formulated organic diets with no colorants or hormones," and that it adhered to a "stocking density of 8 kg per cubic metre, which is lower than most organic stocking densities" (Sablefish Canada 2014a). Further, the company noted that its fish are "humanely euthanized with a traditional Japanese method that eliminates any tissue damage" caused by excessive pH and lactic acid build-up (Sablefish Canada 2014a, Browne Trading Company 2018).

Since the early 2010s, Sablefish Canada/Golden Eagle Sable Fish has been experimenting with an integrated multitrophic aquaculture (IMTA) system in its sablefish aquaculture operations (DFO 2016b). Just downstream of the sablefish net pens, scallops and mussels are grown which feed off the nutrients from the sablefish and then filter the water, which moves downstream finally reaching a kelp farm (PureFish 2018). An IMTA system involves combining the culture of fed organisms (finfish or shrimp) with the culture of organisms that extract either dissolved inorganic nutrients (seaweeds) or particulate organic matter (shellfish; Chopin 2006, Reid et al. 2017). Some of the food, nutrients, and byproducts considered lost in finfish monoculture are recaptured and converted into food, fertilizers, and energy to produce extractive crops of commercial value. Marketable species that could be co-cultured with sablefish include kelp,

[47] The standards include limits on the types of chemicals an aquaculture operation can use (National Standard of Canada 2012, Standards Council of Canada 2018). In the United States, while there currently is no certification for organic aquaculture production, the U.S. Department of Agriculture National Organic Program is in the process of developing organic practice standards for aquaculture (USDA 2018).
[48] According to Canada's organic aquaculture standards, the maximum stocking for sablefish is 10 kg/m^3. Density requirements are quite variable and depend on many factors, such as production system (e.g., recirculation systems, type of water), species, production stage of the animal, and water quality. Other stocking densities may be considered if they meet certain requirements (National Standard of Canada 2012).

mussels, scallops, oysters, sea urchins, and sea cucumbers. These species would provide a sablefish aquaculture operation additional revenue and economic diversification. Ideally, all the components of cultivation have an economic value, while the environmental costs of fed monoculture are internalized (Chopin et al. 2012, Simon Fraser University 2018).

As discussed in Section 2.2, sablefish aquaculture in the United States is likely to be opposed by some individuals and groups for environmental reasons as sablefish farms scale up production.[49] For sablefish farms to fully benefit from the perceived higher sustainability of farmed fish, it is likely that growers will need to refine their branding and marketing. One way they can promote their particular product is by clearly communicating to consumers what it is (and is not). For example, a survey of salmon consumers in the Pacific Northwest found that they were supportive of more sustainable aquaculture production systems and willing to pay a price premium for IMTA products (Yip et al. 2012). However, the authors of the survey study noted that this price premium can only be realized if industry explicitly communicates the benefits of IMTA products to consumers. Acquiring various product certifications can be helpful toward promoting sustainable products, but they may not be sufficient. Consumers may want to know additional details about the product and the way in which it was produced, including the grow-out technique (e.g., closed versus open containment; IMTA versus monoculture), genetic makeup, feed ingredients, etc.

[49] This opposition may arise even if the farms adopt typical environmental safeguards, especially if the farms utilize floating marine net pens at grow-out sites. For example, about one-quarter of the active net-pen Atlantic salmon farms in B.C. are certified by the Aquaculture Stewardship Council (Arnold and Roebuck 2017). However, a number of environmental advocacy groups have been critical of the Aquaculture Stewardship Council's application of its certification standard requirements to these farms, and they have rejected Seafood Watch's ranking of B.C. net-pen farmed Atlantic salmon as a "Good Alternative" seafood choice (Arnold and Roebuck 2017, Foster 2018). Moreover, some Canadian food industry groups, such as Chefs' Table Society of British Columbia, have voiced disapproval of net-pen farmed Atlantic salmon (Scout Magazine 2018, Rasmussen 2018). Over the years, similar signs of resistance to net-pen farming of Atlantic salmon have also appeared in the United States (Cherry 2017). More recently, more than 100 members of the U.S. fishing industry, including fishers, seafood buyers and processors, and restaurateurs, signed an open letter to the U.S. House of Representatives and Senate expressing their opposition to net-pen finfish aquaculture in the U.S. EEZ (National Fisherman Team 2019).

5 Commercial Sablefish Fisheries

This section summarizes the existing commercial fisheries for sablefish in the United States and Canada. In addition to documenting global supply, the summary describes the management system, fishing periods, participation, harvests, revenues, size-distribution of harvests, estimated values of individual transferable quota, and bycatch.

5.1 Overview

Sablefish are found in the Pacific Ocean, from Honshu Island, Japan, north to the Bering Sea, and southeast to Cedros Island, Baja California Sur (Figure 9). Large adults are uncommon south of Point Conception, California (DFO 2016a, PFMC 2016). Adult sablefish are found near soft bottom along the continental slope and in shelf gullies and deep fjords, living at depths of up to 2,700 m. Juveniles migrate inshore for several years, where they can be found in shallow waters, and then migrate offshore as adults (DFO 2018c).

Sablefish recruitment is variable, with strong year-classes that occur periodically (DFO 2018c, Krieger et al. 2019). For example, the 2014 year-class is the largest year-class in the history of recruitment estimates, and 2.5 times higher than any other year-class observed in the current recruitment regime (Hanselman et al. 2017). Evidence of this strong recruitment has recently appeared in both Alaska and U.S. West Coast fisheries as an abundance of 1–1.5-kg fish (Armstrong and Cunningham 2018, Ess 2018). Sablefish spawn along the continental

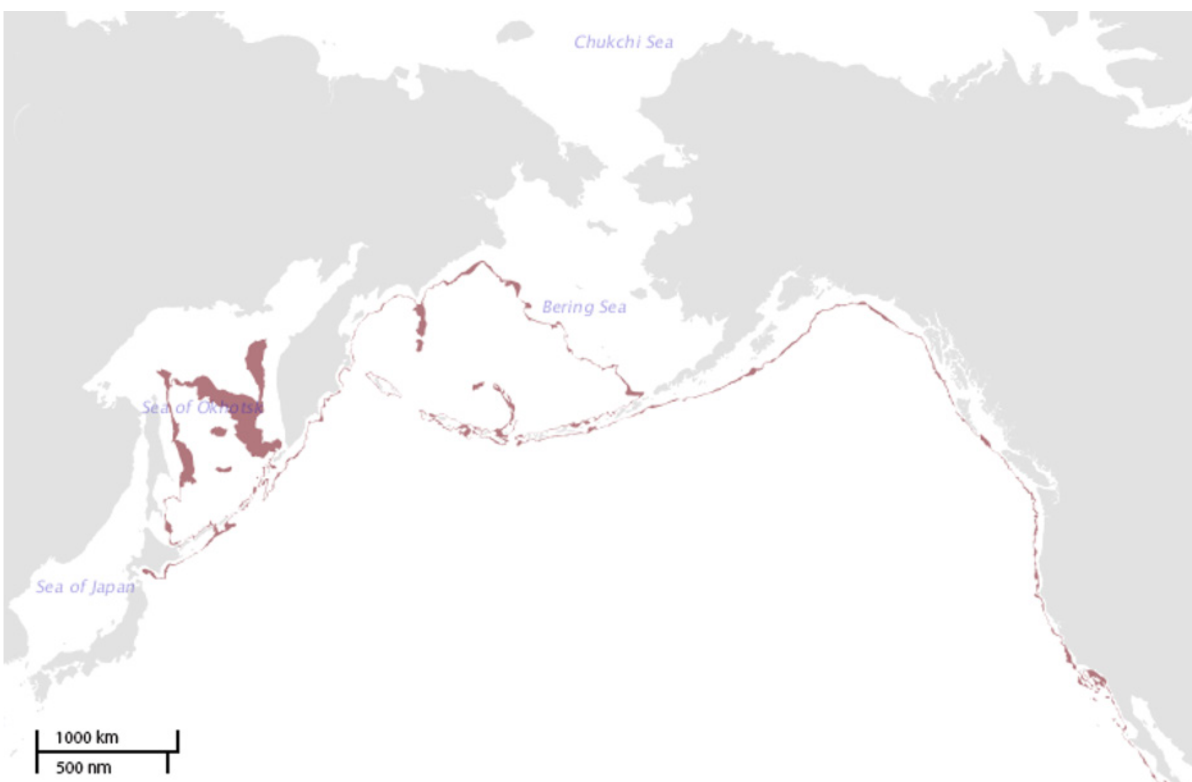

Figure 9. Geographical distribution of sablefish. Source: UNFAO (2018b).

shelf of the United States and Canada at depths of at least 1,500 m (700-m average) in January–April, with peak spawning in February (Mason et al. 1983, Fujiwara and Hankin 1988). Larval sablefish are found in surface waters over the shelf and slope in April and May. Juveniles migrate inshore over the following six months and rear in nearshore and shelf habitats until age-2–5, when they migrate offshore and into fisheries. Depending on location, growth may be rapid, with faster-growing fish of both sexes maturing somewhat younger and at a larger size than slower-growing fish. Mason et al. (1983) found that, on average, females were larger than males (58 cm and 52 cm, respectively), and 50% of males and females spawned for the first time at age-5. Maximum size is ~80 cm, and the oldest sablefish aged to date was 113 years old. Age, growth, and maturity parameters vary considerably among areas and depths (Mason et al. 1983, Fujiwara and Hankin 1988, DFO 2018c).

Sablefish were traditionally thought to form two populations based on differences in growth rate, size at maturity, and tagging studies (Hanselman et al. 2017). The northern population reportedly inhabited Alaska and northern B.C. waters and the southern population inhabited southern B.C., Washington, Oregon, and California waters, with mixing of the two populations occurring off southwest Vancouver Island and northwest Washington. However, recent genetic work by Jasonowicz et al. (2017) found no population substructure throughout their range along the U.S. West Coast to Alaska and suggested that observed differences in growth and maturation rates may be environmentally driven or due to phenotypic plasticity. In addition, tagging studies and modeling results have demonstrated that sablefish can traverse great distances, covering the expanse of ocean from the coast of Alaska to the U.S. West Coast (Krieger et al. 2019).

Although there is no evidence of genetically distinct populations, and there is sufficient movement among areas to consider sablefish throughout their range as one population, management and stock assessments are performed on a smaller scale (DFO 2018c). Independent stock assessments are conducted by NMFS for the U.S. EEZ off the coast of Alaska and the U.S West Coast, and by DFO for waters off B.C. DFO conducts separate analyses for northern and southern B.C. waters, with a split at approximately lat 51.25°N based on differing patterns of recruitment and growth (DFO 2018c).

With its high ex-vessel value per pound, sablefish is one of the most desirable species in the groundfish fisheries off Alaska, B.C., and the U.S. West Coast. These fisheries produce the vast majority of the global supply of sablefish, which averaged ~20,000 mt/yr in 2008–16 (Figure 10). Alaska accounts for roughly 75–80% of the U.S. sablefish catch, and around 65–70% of the global catch (Armstrong and Cunningham 2018). Canada catches roughly 10–15% of the global supply of sablefish, and the U.S. West Coast catches 20–30% of the global supply. The species is targeted by an array of different gear types within these fisheries.

Sablefish have been exploited since the end of the 19th century by U.S. and Canadian fishers. Until the late 1950s, sablefish fisheries were exclusively U.S. and Canadian fisheries, ranging from off northern California northward to Kodiak Island in the Gulf of Alaska (GOA). Catches were relatively small, averaging less than 5,000 mt through the 1950s, and generally limited to areas near fishing ports. However, heavy fishing of sablefish by foreign vessels in the waters off Alaska beginning in the late 1960s led to a substantial population decline (Hanselman et al. 2017). In 1976 and 1977, the United States and Canada, respectively, established a 200-nautical mile EEZ, which put an end to foreign fishing for sablefish in U.S. and Canadian waters.

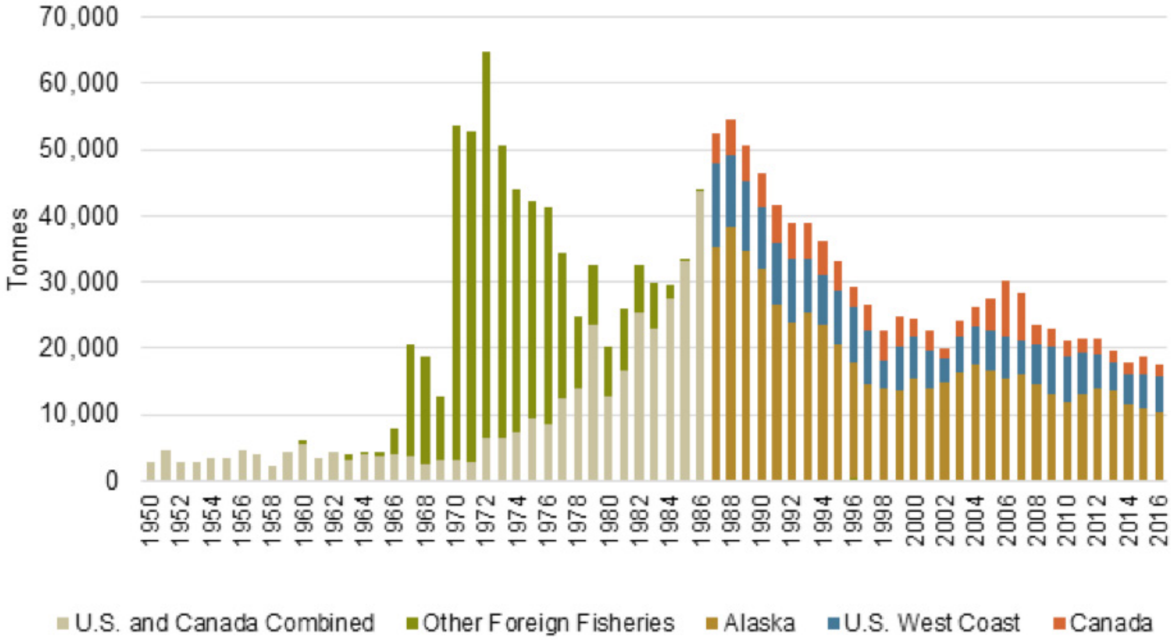

Figure 10. Global catch of sablefish, 1950–2016. Sources: DFO (2014), Johnson et al. (2015a), Hanselman et al. (2017), DFO (2018a), and UNFAO (2018a).

Over the years, the Alaska, B.C., and U.S. West Coast fisheries that account for the large majority of the sablefish caught have been brought under various ITQ management programs. In addition to improving the economic performance of the fisheries by reducing fishing overcapacity, the ITQ programs have generated conservation benefits. Individual vessel accountability, together with improved catch monitoring, has generally helped keep harvests below TAC limits. In addition, the management change decreased harvest and discard of immature fish. Fishers are able to choose where they fish, in contrast to a "derby" fishery in which fishers often fished less-productive grounds (e.g., shallower water that young fish inhabit) due to an incentive to compete with one another to catch as much as possible before the TAC was reached. In choosing their grounds, fishers presumably target larger, older fish, and due to this selection, the stock can provide a greater yield at the same target fishing rate (Sigler and Lunsford 2001). The elimination of the derby also reduced the problem of "ghost fishing" (caused by fishers cutting loose faulty gear to save time as they "raced for fish")—the abandoned gear could continue to fish and trap animals, entangle and potentially kill marine life, smother habitat, and act as a hazard to navigation (Jones and Bixby 2003, Sporer 2008, NOS 2018).

The conservation benefits of these ITQ programs are reflected in positive third-party assessments of the impacts of the Alaska, B.C., and U.S. West Coast sablefish fisheries on fish populations and ecosystems. For example, the MSC certified the Alaska fixed gear sablefish fishery as being "sustainable and well-managed" in 2006. The U.S. West Coast limited entry groundfish trawl fishery was MSC-certified in 2014. The B.C. fixed gear sablefish fishery was certified in 2010, but the fishery withdrew its MSC certification in 2013.[50] Currently, approximately 70% of North American sablefish landings are MSC-certified (~90% of Alaska landings and ~40% of U.S. West Coast landings; FishChoice, Inc. 2018).

[50] The reason for the voluntary withdrawal from MSC certification was not made public by the fishery clients (Arnold and Fuller 2017).

Below is additional information about the four directed fisheries for sablefish in North America: the Alaska fixed gear fishery, the B.C. fixed gear fishery, the U.S. West Coast fixed gear fishery, and the U.S. West Coast trawl fishery.

5.2 Alaska Fishery

5.2.1 Management

Starting in 1976, the United States began exercising management and conservation authority over fisheries resources within 200 nautical miles of its coasts under the Fishery Conservation and Management Act (currently the Magnuson–Stevens Fishery Conservation and Management Act [MSA]). Domestication of the Alaska sablefish fishery soon followed. Catch in the late 1970s was restricted to about one-fifth of the peak foreign vessel catch in 1972. However, the number of participants in the domestic GOA fixed gear sablefish fishery steadily increased, and to stay within the TAC, NMFS began to shorten the previously year-round season in 1984. By 1994, the season was 10 days, warranting the label of an open access derby fishery (Hanselman et al. 2017). In the early 1990s, the North Pacific Fishery Management Council began developing an ITQ program under the MSA for vessels using fixed gear (pot gear and all hook-and-line gear including longline, handline, jig, and troll gear) to harvest sablefish in the GOA and Bering Sea/Aleutian Islands (BS/AI) federal management subareas (Fina 2011).

Implemented in 1995, the ITQ program issues shares of the TAC for sablefish to individuals based on 1988–90 sablefish landings in the GOA and BS/AI. To maintain historical fleet composition, quota is classified for use by vessel type (catcher–processor or catcher vessel) and length, with limits on the use of shares outside of their designated vessel type and size class. Class A shares are designated for freezer longline vessels and do not have a vessel length restriction. Class B shares are to be fished on vessels greater than 60 ft in length, while Class C shares are to be fished on vessels equal to or less than 60 ft (Fina 2011). In addition, to maintain the small-vessel, owner/operator character of the fleet, catcher vessel quota carries owner-on-board requirements, limits on the use of hired skippers, and leasing prohibitions, and may be transferred only to individuals (not corporations or partnerships). Further, only persons able to demonstrate active time as crew in commercial fisheries are permitted to acquire quota. Most quota is divisible and transferable subject to consolidation limits.

Vessels are required to hail in/out, and there is comprehensive dockside monitoring at all main ports and random monitoring at smaller ports. Onboard observer coverage varies by vessel size classes, with no coverage for vessels <60 ft, 30% for vessels 60–125 ft, and 100% coverage for vessels >125 ft (Fina 2011).

In recent years, approximately 30% of vessels eligible to fish in the ITQ fishery participate in both the halibut and sablefish fisheries. The season dates have varied by several weeks since 1995, but the monthly pattern has been from March to November, with the majority of landings occurring in May through June (Hanselman et al. 2017).

5.2.2 Participation

Figure 11 shows that between the baseline years (1992–94) and 2014, the number of vessels dropped 56% in the sablefish fishery. The trend of consolidation has continued to occur each year, with only a few exceptions. The fishery dropped from 615 active vessels in the first year of the program to 315 vessels by 2014.

Many sablefish fishers are also active in the Alaska halibut fishery, which is managed under an ITQ program as well. The percentage of all sablefish and halibut vessels fishing in both fisheries has been relatively stable at just under 25% over the last six years. The fishing season for both fisheries currently extends from March to November (NPFMC 2016).

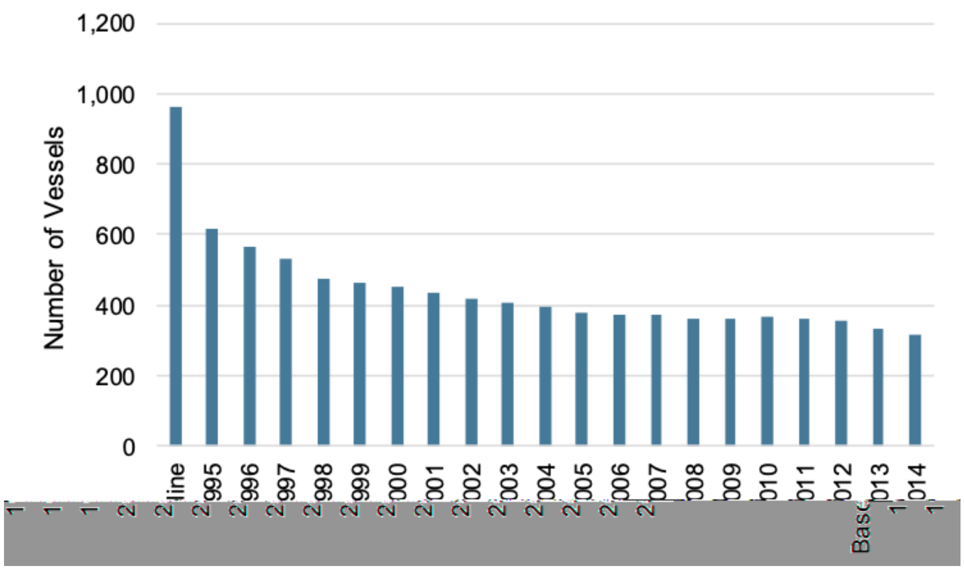

Figure 11. Number of vessels participating in the Alaska sablefish fixed gear fishery, baseline to 2014. Source: NPFMC (2016).

5.2.3 Landings

Although sablefish is assessed as one stock throughout the waters off Alaska, the TAC is set separately for the GOA and BS/AI. The GOA typically accounts for upwards of 90% of the annual Alaska catch (Armstrong and Cunningham 2018). In addition to being targeted in the ITQ fishery, sablefish are caught incidentally in directed trawl fisheries for other species groups, such as rockfish and deep-water flatfish (Hanselman et al. 2017). The TAC in each management subarea is allocated across gear types, with harvest specifications generally apportioning 50% of the TAC for trawl gear and 50% for fixed gear in the BS; 25% for trawl gear and 75% for fixed gear in the AI; 20% for trawl gear and 80% for fixed gear in the Western and Central GOA; and 5% for trawl gear and 95% for fixed gear in the Eastern GOA. Most trawl gear fisheries are closed for directed fishing for sablefish, and the entire trawl gear sablefish TAC is used for incidental catch of sablefish in trawl fisheries targeting other species (NPFMC 2016). Five Alaska State fisheries land sablefish outside the ITQ program; the major state fisheries occur in the Prince William Sound, Chatham Strait, and Clarence

Strait, and the minor fisheries in the northern GOA and AI. The minor state fisheries were established by the state in 1995, primarily to provide open access fisheries to fishers who could not participate in the ITQ fishery (Hanselman et al. 2017).

Table 10 shows catch in the Alaska sablefish fishery by management subarea. The TAC in the GOA is typically fully utilized, while the TAC in the BS/AI is rarely fully utilized. Exceptional recruitment fueled increased abundance and increased catches during the late 1980s, which coincided with the domestic fishery expansion (Hanselman et al. 2017). Catches declined during the 1990s, increased in the early 2000s, and have since declined to <11,000 mt in 2017 (Hanselman et al. 2017). The estimated total biomass and spawning biomass of sablefish in the waters off Alaska have shown a general downward trend since the 1960s, although a very large 2014 year-class caused estimates of total biomass to increase in 2017 (Hanselman et al. 2017).

When the ITQ program was implemented, the use of longline pot gear in the GOA sablefish fishery was prohibited. In 2017, however, this prohibition was removed in response to reports from sablefish ITQ fishers that depredation by killer and sperm whales was adversely affecting the sablefish fleet in the GOA (USOFR 2016). The reports indicated that whales were removing or damaging sablefish caught on hook-and-line gear before the gear was retrieved. Pots are longlined with approximately 40–135 pots per set. Since 2004, longline pot gear has accounted for over 50% of the ITQ fishery catch in the BS and up to 34% of the ITQ fishery catch in the AI. However, catches in pots have declined significantly in recent years in the AI (only 12 mt in 2015). Pot catches began occurring in the GOA in 2017, but they have made up a small proportion of the ITQ fishery catch.

Table 10. Catch (mt) in the Alaska sablefish fishery by management subarea, 1992–2017.

Year	Aleutian Islands	Bering Sea	Gulf of Alaska	Total
1992–99 (annual avg.)	1,155	688	17,308	18,847
2000	1,049	742	13,780	15,570
2001	1,074	864	12,127	14,065
2002	1,119	1,144	12,486	14,748
2003	1,118	1,012	14,282	16,411
2004	955	1,041	15,524	17,520
2005	1,481	1,070	14,035	16,585
2006	1,151	1,078	13,323	15,551
2007	1,169	1,182	13,607	15,958
2008	899	1,141	12,511	14,552
2009	1,100	916	11,046	13,062
2010	1,047	753	10,131	11,931
2011	1,026	707	11,245	12,978
2012	1,205	743	11,920	13,869
2013	1,063	634	11,947	13,645
2014	821	314	10,453	11,588
2015	431	211	10,331	10,973
2016	349	532	9,376	10,257
2017	470	1,110	9,089	10,670

Source: Hanselman et al. (2017).

5.2.4 Size distribution and value by size

Vessels using trawl gear catch older, larger fish less frequently than those using fixed gear, because trawling often occurs on the continental shelf in shallower waters (<300 m) where younger, smaller sablefish typically reside (Hanselman et al. 2017). Based on the length compositions of sablefish from Alaska fisheries by gear type presented in Hanselman et al. (2017) and the length–weight relationship provided by Sigler et al. (2004), it is estimated that an average sablefish caught with fixed gear in the waters off Alaska weighs 3.25 kg, while the average fish caught with trawl gear weighs 2.95 kg. Information about the quantities of fish landed by size class is not available.

ADFG fish tickets report delivered pounds of sablefish size in the following standardized weight categories, which assumed an eastern-cut H&G fish: 1–2 lb, 2–3 lb, 3–4 lb, 4–5 lb, 5–7 lb, and 7+ lb (Armstrong and Cunningham 2018). These inflation-adjusted values are shown in Figure 12 for the fixed gear fisheries in the GOA after further adjustments to match fleetwide average ex-vessel prices reported by NMFS (Fissel et al. 2019). The figure shows that the per-unit ex-vessel value of sablefish is strongly influenced by fish size. In 2018, an increase in small fish deliveries due to the aforementioned 2014 recruitment event, together with a larger Alaska sablefish TAC and frozen inventory holdovers from 2017, caused downward pressure on prices across all weight categories (NWFCS 2018). Note that the average price each year is approximately equal to the average of prices for 4–5-lb and 5–7-lb fish. Table 11 shows the average price (2012–18) for each market category as a percentage of the fleetwide average price for the year.

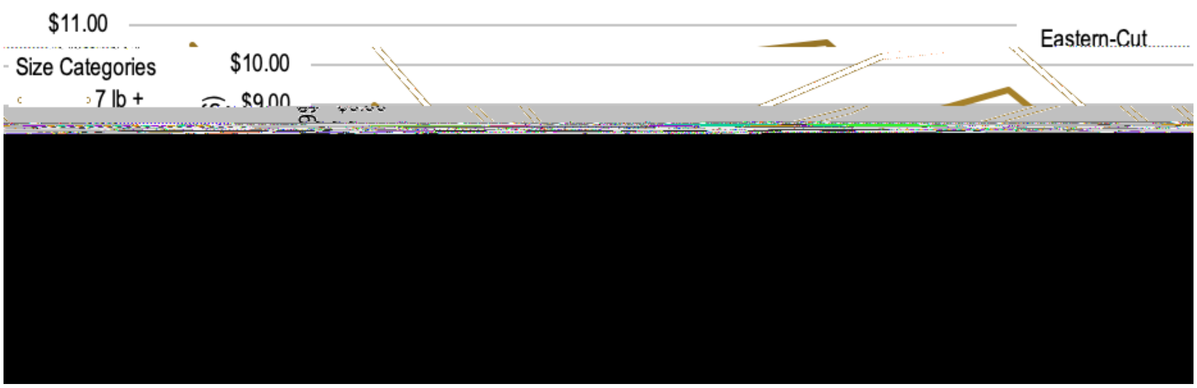

Figure 12. Inflation-adjusted average annual ex-vessel price in the Gulf of Alaska sablefish fishery by eastern-cut weight category, 2012–18. Note: Weight categories are based on eastern-cut H&G fish—the form in which harvesters traditionally delivered fish to buyers and processors. Prices have been adjusted for inflation using U.S. Bureau of Labor Statistics producer price index for unprocessed and prepared seafood (available: https://data.bls.gov/timeseries/WPU0223). Source: Developed by Northern Economics, Inc., from data in Armstrong and Cunningham (2018) and Fissel et al. (2019).

Table 11. Price by size category as a percentage of the average reported price.

Eastern-cut size category	1–2 lb	2–3 lb	3–4 lb	4–5 lb	5–7 lb	7+ lb
Category prices as % of avg. price	63%	68%	81%	93%	111%	127%

Source: Developed by Northern Economics, Inc.

NMFS generates estimates of fleetwide ex-vessel prices over all size categories based on round-weight equivalents (i.e., NMFS adjusts the weight of fish landed in an eastern-cut form up to its estimated round weight by dividing by 63%—the average yield from round-weight to eastern-cut fish). NMFS also generates estimates of the average wholesale price received by processors on a product-by-product basis. NMFS does not provide either ex-vessel or wholesale price estimates in sized-based categories. Table 12 shows three sets of prices for sablefish harvested in the GOA. The first row shows round-weight equivalent ex-vessel prices actually reported by NMFS (Fissel et al. 2019). The second row shows estimated ex-vessel prices if fish are landed as eastern-cut fish. The third row shows NMFS estimates (Fissel et al. 2019) of wholesale prices for H&G product—almost all of which is sold as eastern-cut fish (J. Woodruff, Icicle Seafoods, Inc., personal communication). While estimates of wholesale prices by market size category are not available from NMFS, the differences by size mirror differences seen in ex-vessel prices by size (Woodruff, personal communication) as shown in Figure 12 and Table 11.

Table 12. Round-weight and estimated eastern-cut average ex-vessel prices and eastern-cut wholesale prices for Gulf of Alaska sablefish, 2012–18. All prices are USD/lb sold, adjusted for inflation to 2019 USD.

Prices, USD/lb	2012	2013	2014	2015	2016	2017	2018	2016–18 average
Round-weight ex-vessel	$5.18	$3.66	$4.12	$4.31	$4.77	$5.36	$3.83	$4.50
Eastern-cut ex-vessel	$8.22	$5.82	$6.54	$6.84	$7.57	$8.50	$6.09	$7.14
Wholesale H&G product	$8.49	$6.67	$7.53	$7.49	$8.81	$9.61	$6.93	$8.39
Wholesale round-weight	$5.35	$4.20	$4.74	$4.72	$5.55	$6.06	$4.36	$5.29

Source: Developed by Northern Economics, Inc., from data in Armstrong and Cunningham (2018), Fissel et al. (2019).

Table 13 provides estimated average (2016–18) round-weight equivalent prices at the ex-vessel and wholesale levels in both pounds and kilograms for the market categories described in Figure 12. A 63% product recovery rate is used to translate eastern-cut H&G product to round-weight equivalents. The proportions developed in Table 11 relating fleetwide average ex-vessels prices to size categories are used to assign average wholesale prices to size categories. Note that round-weight equivalent prices in kilograms are used in the CFS Model developed in Section 3.3.

Table 13. Average estimated ex-vessel and wholesale round-weight equivalent prices by size category for Gulf of Alaska sablefish, 2016–18. Prices are adjusted for inflation to 2019 USD.

Round-weight size categories, USD/lb	1.6–3.2 lb	3.2–4.8 lb	4.8–6.3 lb	6.3–7.9 lb	7.9–11.1 lb	11.1+ lb
Ex-vessel prices	$2.82	$3.08	$3.66	$4.19	$4.99	$5.79
Wholesale prices	$3.31	$3.60	$4.26	$4.92	$5.88	$6.74
Round-weight size categories, USD/kg	**0.72–1.44 kg**	**1.44–2.16 kg**	**2.16–2.88 kg**	**2.88–3.60 kg**	**3.60–5.04 kg**	**5.04+ kg**
Ex-vessel prices	$6.22	$6.80	$8.06	$9.24	$11.01	$12.77
Wholesale prices	$7.29	$7.93	$9.40	$10.84	$12.97	$14.86

Source: Developed by Northern Economics, Inc., from data in Armstrong and Cunningham (2018), Fissel et al. (2019).

5.2.5 Quota price

As noted above, most quota in the Alaska fixed gear sablefish fishery is divisible and transferable subject to consolidation limits. Table 14 shows the sale price of quota by vessel class. In general, the quota price is a good indication of the expected profitability of the fishery.

Table 14. Sale price, in 2015 USD, of quota in the Alaska fixed gear sablefish fishery by vessel class, 2000–15. Note: Due to confidentiality issues, quota prices can only be provided for years when there were at least three quota transactions for the vessel class.

Year	Class A	Class B	Class C
2000	$16.67	$9.33	$9.33
2001	$15.21	$10.29	$8.90
2002	$11.59	$9.39	$7.89
2003	$12.44	$9.69	$8.85
2004	$14.51	$10.71	$10.03
2005	—	$10.48	$9.79
2006	$10.59	$9.25	$9.40
2007	$6.29	$10.60	$10.59
2008	$12.68	$10.90	$10.97
2009	$11.06	$12.57	$11.60
2010	$13.72	$14.75	$12.48
2011	$18.01	$16.20	$18.88
2012	$9.05	$14.96	$20.12
2013	$17.57	$16.53	$19.81
2014	—	—	$14.67
2015	—	$15.53	$13.64

Source: NPFMC (2016).

5.2.6 Bycatch

The ITQ program likely has reduced bycatch in the fixed gear fishery because of the slower pace of the fishery and the incentive to maximize value from the catch. Discards of sablefish by vessels using longline gear are minimal, typically less than 5% of total catch. Sablefish typically account for 90% or more of the total catch with this gear. At times, however, giant grenadiers may be a significant catch, and they are almost always discarded. During the 2011–17 period, grenadier bycatch varied from 5,081–11,523 mt. Other species that have catches >1 mt/yr are corals, snails, sponges, sea stars, and miscellaneous fishes and crabs (Hanselman et al. 2017).

5.3 British Columbia Fishery

5.3.1 Management

Soon after Canada established its EEZ in 1977, a small group of fishers in B.C. recognized the potential for exporting sablefish to Japan and established a directed sablefish fishery using Korean trap longline gear (Sporer 2008). Harvests began to increase significantly as more vessels entered the fishery and as fishing technology improved. In 1981, DFO established a limited entry program, with 48 vessels receiving sablefish commercial fishing licenses. DFO closed the fishery when it estimated that the TAC had been taken. To compete and maintain their share of the catch, vessel owners invested in bigger boats, fished with more crew, fished 24 hours a day, deployed extra gear, used packer vessels to transport additional gear to the fishing grounds, and adopted new technology. As fishing capacity increased, the fishing season dropped from 245 days in 1981 to 14 days in 1989 (Sporer 2008).

Following several months of consultation with the fishing industry, DFO implemented an ITQ program in the fixed gear sablefish fishery in 1990 on a trial basis. Each licensed sablefish vessel was allocated a percentage of the TAC using a formula in which 70% of the allocation was based on a licensed vessel's best catch in either 1988 or 1989, and 30% was based on the vessel's overall length. The trial effort proved successful, and an ITQ program was fully established in 1997. There is no annual limit on either the total number of quota transfers or the total quantity transferred. Quota is separable from license and divisible into one-pound increments. Initially, quota could be transferred annually, but reverted to the originating license at the start of the following season. Currently, quota can be transferred among licensed vessels on a temporary or permanent basis. Vessels are permitted to fish at any time, but must hail in/out. Landings are only permitted at designated ports, and industry-funded dockside monitors record all landings. In addition, industry pays for all direct costs of 100% at-sea observer coverage. While the sablefish fishery is open all year, a significant proportion of the catch occurs between September and March, to take advantage of greater market demand (Jones and Bixby 2003, Sporer 2008).

Currently, 4 mt/yr are allocated from the sablefish TAC to the aquaculture industry to support broodstock collection for sablefish aquaculture. The fixed gear sablefish fishery is allocated 91.25% of the balance of the TAC, with approximately one-third of this being caught by bottom longline and two-thirds caught using the Korean trap longline (Boudreau et al. 2017). The remainder of the TAC is allocated to First Nations, research entities, and a groundfish trawl fishery that catches sablefish incidentally.

The fixed gear sablefish fishery was included in the Commercial Groundfish Integration Program that began in 2006 and was made permanent in 2010. This multispecies management program focuses on individual vessel accountability for all groundfish catch (both retained and released), ITQs, and reallocation of these quotas between vessels and fisheries to cover catch of nondirected groundfish species (DFO 2018e). Under the program, each commercial groundfish vessel is required to acquire quota to account for mortality of all legal/marketable-sized groundfish that are managed under species and area TAC limits, including sablefish. The program allows fixed gear sablefish vessels to lease quota for sablefish and other groundfish species to and from other groundfish sectors, opening up new revenue avenues (Nelson 2007).

5.3.2 Participation

As noted above, the fixed gear sablefish fishery is limited to 48 licenses. Table 15 shows the number of commercial fishing licenses actually issued each year by DFO for the fishery over the 2007–16 period. Not all licensees participate in the fishery each year, and Table 15 also shows the number of licensed vessels in the fishery that were active. Over the 2007–17 period, an average of 28 vessels participated in the fishery each year.

Table 15. Number of licensed and active vessels in the British Columbia fixed gear sablefish fishery, 2007–17. Note: Does not include aboriginal vessels licensed to fish sablefish with fixed gear.

Vessels	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Licensed	48	48	48	48	43	43	42	42	41	41	n/a
Active	28	27	32	28	32	34	28	27	28	27	23

Sources: DFO (2016a) and a data request submitted to DFO by Northern Economics, Inc.

The Commercial Groundfish Integration Program allows sablefish fishers to keep several other groundfish species when fishing for sablefish, including cod, halibut, dogfish, flatfish, and rockfish. As noted above, the sablefish fishery typically occurs between September and March. During the summer months, fishers target various other species, such as albacore.

5.3.3 Landings

Figure 13 displays the TAC and landings in all the B.C. sablefish fisheries from 1981 through 2010. The estimated total biomass and spawning biomass of sablefish in the waters off B.C. have shown a general downward trend, similar to that in Alaska waters (DFO 2014, 2016c, Hanselman et al. 2017).

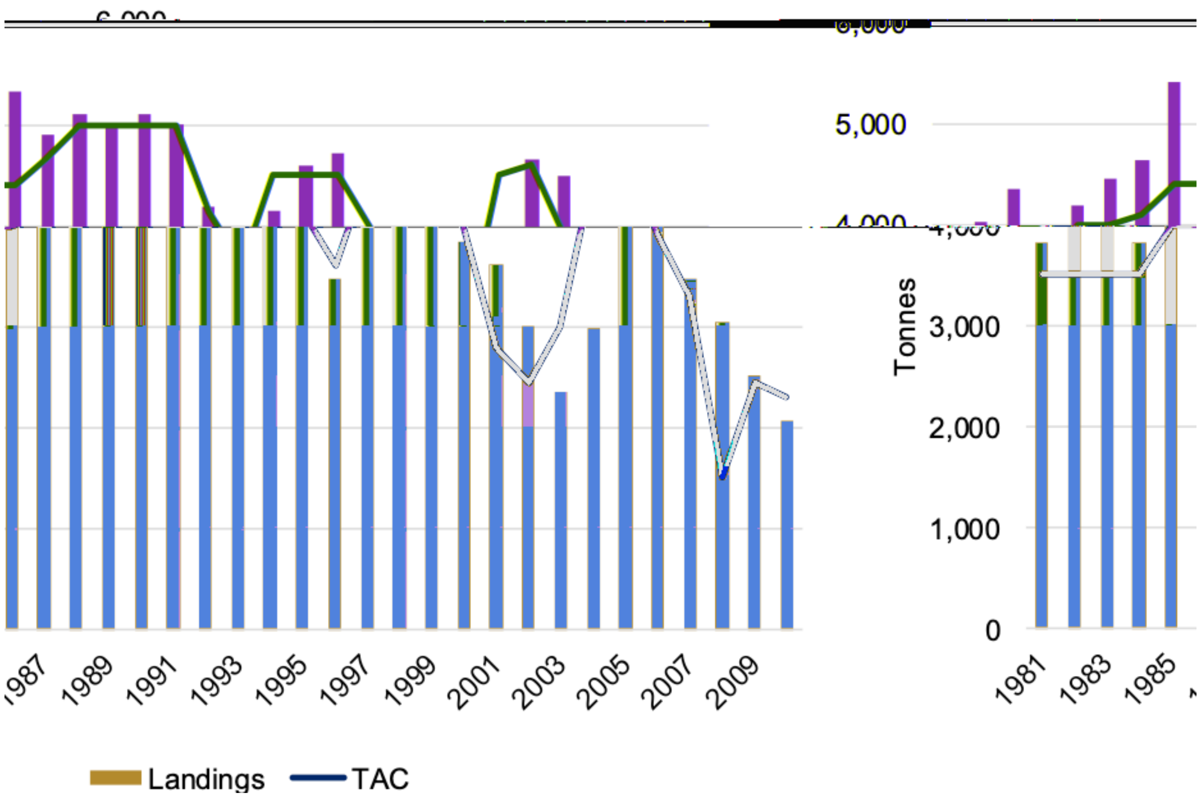

Figure 13. Total allowable catch and landings (mt) in the British Columbia sablefish fisheries, 1981–2010. Source: Cox et al. (2011).

5.3.4 Size distribution

Assonitis (2008) reported differences in the size selectivity of the gear types that catch sablefish in the waters off B.C., with bottom longline gear selecting for the largest size classes of sablefish, Korean trap longline gear selecting for intermediate sizes, and trawl gear selecting for small sablefish below the minimum size limit (i.e., <55 cm fork length). Jones and Cox (2018) report the same size selectivity patterns across gear types. As in the Alaska sablefish fishery, the depth distribution of the gear likely accounts for some of the size selectivity observed among gear types, with vessels using bottom longline and Korean trap longline gear operating in depths greater than 200 m, and vessels using trawl gear operating in waters between 100 and 200 m. Information about the quantities of fish landed by size class is not available.

5.3.5 Quota price

The sale and lease prices for sablefish quota are shown in Table 16. In 2016, the lease rate was pegged at $5.25 (CAD) per J-cut pound. For small isolated transactions motivated by the need to cover incidental catch, the lease rates can be substantially higher. The lessor generally pays the DFO management fees for the fixed gear sablefish fishery (about $0.25 CAD per lb; Nelson 2016).

Table 16. Sale and lease prices (CAD per J-cut pound) of quota in the British Columbia sablefish fishery, 2000–15. Note: Sale price is very approximate in some years due to a low number of transactions.

Year	Sale price	Lease price
1998	$21.00	$2.00
1999	$25.00	$2.75
2000	$36.00	$4.25
2002	$38.00	$4.00
2004	$40.00	$3.40
2005	$35.00	$2.50
2006	$29.00	$2.40
2007	$32.00	$2.20
2008	$25.00	$2.40
2009	$35.00	$4.25
2010	$37.00	$4.25
2011	$55.00	$6.00
2012	$60.00	$5.25
2013	$60.00	$3.35
2014	$47.50	$3.45
2015	$55.00	$3.85
2016	$75.00	$5.25

Sources: Nelson (2000, 2007, 2010, 2016) and Simpson (2017).

5.3.6 Bycatch

The fixed gear sablefish fishery discards about one-third of its total catch each year, with bottom longline vessels discarding 41% of their catch and Korean trap longline vessels discarding 32%. The largest portions of the discards consist of spiny dogfish, juvenile or otherwise nonquota Pacific halibut, arrowtooth flounder, and juvenile sablefish (Boudreau et al. 2017). As noted above, sablefish <55 cm are released at sea by regulation.

5.4 U.S. West Coast Fisheries

From the early 1900s to the early 1980s, management of the sablefish fishery off the U.S. West Coast was the responsibility of the individual coastal states (California, Oregon, and Washington). After the adoption of the Groundfish Fishery Management Plan by the Pacific Fishery Management Council in 1982, responsibility rested with PFMC and NMFS (Johnson et al. 2015a).[51] While the assessment of the sablefish stock is coastwide, federal management of sablefish has long been divided at lat 36°N (~20 mi south of Point Sur, California), with separate allocations of the TAC for the northern and southern fisheries divided by this line. The allocation for the northern fishery is substantially higher than that for the southern (approximately 74% and 26% of the TAC, respectively; PFMC and NMFS 2014).

The first regulations established coastwide for the sablefish fishery were implemented as trip limits in 1982. Beginning in 1983, additional trip limits were imposed on landings of sablefish less than 56 cm in length, which are considered incidental catch. In 1987, an allocation of northern sablefish was established that provided 52% to the trawl fleet and 48% to the fixed gear fleet. This allocation was later adjusted to 58% and 42% for trawl and fixed gear, respectively (PFMC and NMFS 2014). In 1993, a license limitation program was instituted for the groundfish fishery that was designed to control the capacity of the groundfish fishing fleet by limiting: a) the number of fishing vessels, b) the number of vessels using each of the three specified gear types (trawl, pot/trap, and longline), and c) vessel length, to prevent increases in harvest capacity (NMFS 2018a). Of the nontribal commercial optimum yield of sablefish, 90.6% was allocated to the limited entry fishery and 9.4% was allocated to an open-access fishery (PFMC and NMFS 2014).[52]

The wild-caught fish allocated to sablefish aquaculture operations for broodstock are considered part of the TAC. Typically, these operations contract fixed gear vessels to collect fish for broodstock. The amount of sablefish collected for this purpose represents a very small portion of the overall commercial landings (Stoner and Ethier 2015).

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[51] Nearshore, fixed gear groundfish fisheries that harvest sablefish are jointly managed by PFMC and state authorities in Oregon and California; there is no nearshore groundfish fishery in state-managed waters off the coast of Washington (NMFS 2018f).

[52] Vessels using all gear types other than trawl, trap/pot, and longline were left in the open access groundfish fishery, and a small open access opportunity was also provided for fixed gear vessels that did not qualify for limited entry permits (PFMC and NMFS 2014).

Figure 14 summarizes harvest specifications (optimum yield or annual catch limit) and landings in the U.S. West Coast sablefish fisheries. During the 2005–16 period, the annual percent of the harvest specification landed averaged 83%.

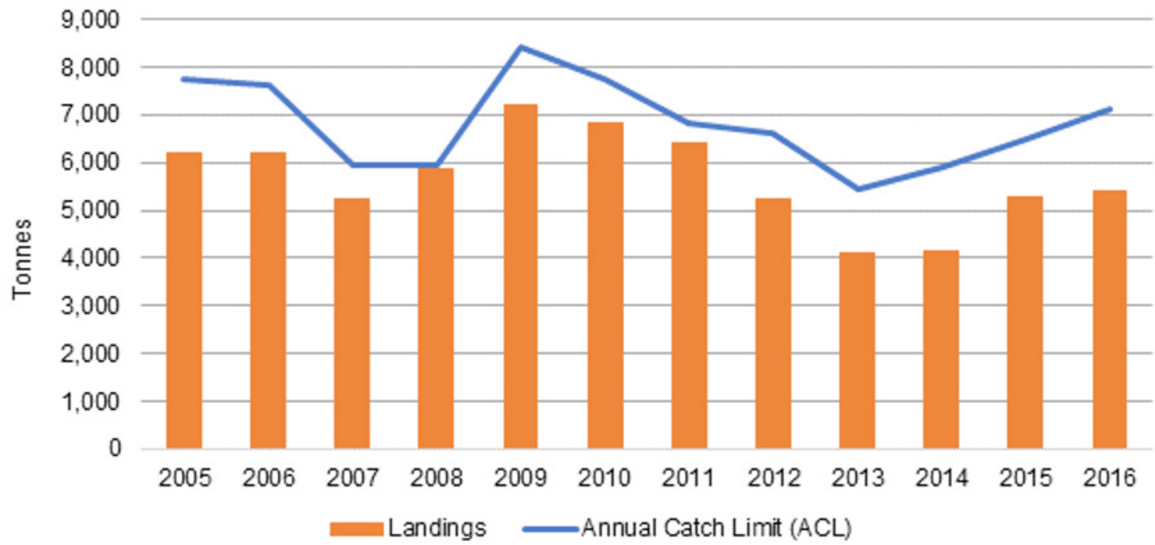

Figure 14. Harvest specifications and landings (mt) in the U.S. West Coast sablefish fisheries, 2005–16. Source: Johnson et al. (2015a).

The following sections describe the two fisheries that target sablefish: the fixed gear sablefish fishery and the groundfish trawl fishery. A number of other U.S. West Coast fisheries, such as the at-sea whiting trawl fishery, catch sablefish incidentally (PFMC and NMFS 2010).

5.4.1 Fixed gear sablefish fishery

5.4.1.1 Management

During the late 1980s and early 1990s, the fixed gear (trap/pot and longline) sablefish fleet south of lat 36°N landed all of its allowed harvest in a daily trip limit fishery. The fixed gear sablefish fishery in the northern area was managed as a derby fishery characterized by increasing reductions in season lengths. By 1997, nine days (25 August–3 September) were set aside for the open season, with a mop-up period from 1–15 October (Johnson et al. 2015a). PFMC moved to develop an ITQ program for the fishery, but the 1996 reauthorization of the MSA included a moratorium on implementing new ITQ programs, which brought deliberations on a sablefish ITQ program to a halt. As a stopgap measure to control increasing capacity and deteriorating seasons in the northern fixed gear sablefish fishery, a sablefish endorsement program was implemented in 1997. Under this program, limited entry permit holders were eligible for sablefish endorsements based on their permit history. A fixed gear sablefish endorsement was added to permits that had a history of landing more than 16,000 lb of sablefish in any one year from 1984–94 (PFMC and NMFS 2014).

Public Law 106-553, an appropriations bill for NOAA, contained a continuation of the ITQ program moratorium through 1 October 2002, but the bill included an exception for the U.S. West Coast fixed gear sablefish fishery (PFMC and NMFS 2014). In 2001, a permit stacking program was implemented in the northern fixed gear fishery. The program is a type of ITQ program in which each fixed gear sablefish-endorsed limited entry permit is assigned to one of three tiers. The permit's tier level determines the poundage of sablefish that can be landed by that permit each season. Sablefish endorsements and their tiers may not be transferred separately from the limited entry permits. NMFS biennially or annually announces the size of the cumulative trip limit for each of the three tiers associated with the sablefish endorsement, such that the ratio of limits between the tiers is approximately 1:1.75:3.85 for Tiers 3, 2, and 1, respectively. Currently, up to three permits can be stacked onto a single vessel, allowing that vessel to harvest the cumulative limits associated with each of those permits. This ownership limitation was intended to prevent concentration of harvest privileges in the fishery (PFMC 2016).

The ITQ program also includes other provisions, including a prohibition on the ownership of permits by corporations or other business entities, a permit-owner-on-board requirement, a limit on the number of permits any individual or entity (individually and collectively) can own or hold, and a prohibition on at-sea processing (PFMC 2016).[53] An extended sablefish season (1 April–31 October) was fully implemented in 2002 (PFMC and NMFS 2014). Catch accounting in the fishery is based on landed catch derived from electronic fish tickets. In addition, stratified random sampling is used to select vessels with limited entry sablefish-endorsed permits for at-sea observer coverage for all trips that land sablefish against their tiered sablefish quota (NMFS 2018a). From 2002–10, observers were present for an average of 26% of limited entry fixed gear sablefish landings (Driscoll 2014).

5.4.1.2 Participation

The ability of fixed gear vessels to stack permits, together with the establishment of a sablefish endorsement and tier system, has facilitated a reduction in fleet capacity. Figure 15 shows the number of vessels participating in the fixed gear sablefish fishery prior to and following implementation of the ITQ program. Annual participation from 1996–2000 (prior to the program) averaged 146 vessels, compared to an average of 90 vessels after the program was implemented (2002–13), a 38% decrease.

The fixed gear sablefish fishery is limited to a primary season from 1 April–31 October. When not targeting sablefish, the fixed gear vessels target species such as nearshore rockfish, thornyheads, and spiny dogfish (PFMC and NMFS 2010).

[53] Nearly all of the vessels in the fixed gear sablefish fishery deliver their iced catch to shoreside processors, but some exempted vessels freeze their catch at sea (NMFS 2018a).

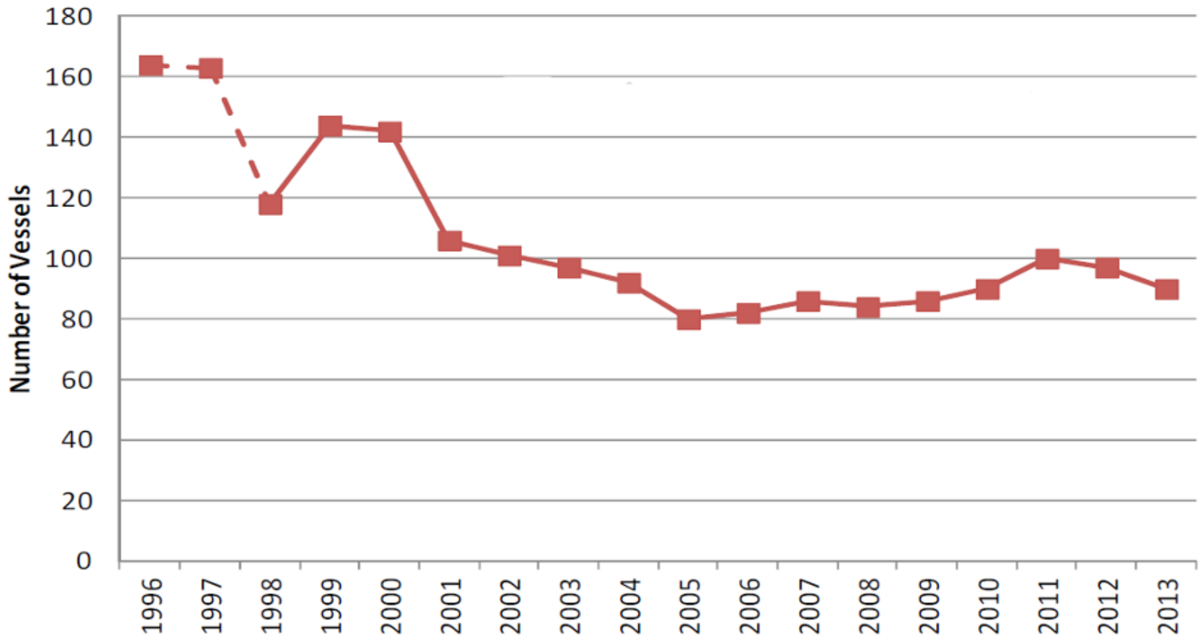

Figure 15. Number of vessels participating in the U.S. West Coast limited entry fixed gear sablefish fishery, 1996–2013. Note: The number of vessels and landings in the primary season fishery prior to 1998 was not recorded separately from the total fishery; numbers are estimates based on counts of vessels in the limited entry fishery that landed at least 1 mt of sablefish north of Santa Barbara County, California, within the appropriate season period. Source: PFMC (2016).

5.4.1.3 Landings

Figure 16 displays the fixed gear sablefish fishery allocation and landings from 1996–2013. Since the implementation of the ITQ program, landings have remained below the allocation, even though both the allocation and landings have been decreasing steadily since 2010. The latest U.S. West Coast sablefish stock assessment indicates that the stock has generally been in decline since the 1980s (Johnson et al. 2015a). Although not considered overfished, it is in the precautionary zone, which causes more restrictive harvest levels to be implemented.

5.4.1.4 Size distribution

Based on the length-frequency distributions of the retained catch by gear type in U.S. West Coast sablefish fisheries presented in Johnson et al. (2015a) and a length–weight relationship provided by Parks and Shaw (1988), it is estimated that an average sablefish caught with fixed gear weighs 1.72 kg, while the average fish caught with trawl gear weighs 1.57 kg. The broadest size spectrum was observed in longline (hook-and-line) gear landings, the largest individuals were observed in pot/trap gear landings, and the smallest sablefish were observed in trawl gear landings (Johnson et al. 2015a). As in the Alaska and B.C. sablefish fisheries, the depth distribution of each gear type likely influences the size distribution of the catch. Information about the quantities of fish landed by size class is not available. Information about the quantities of fish landed by size class is not available. As a result of the size differences, sablefish caught with fixed gear is 20–60% more valuable per pound, on average, than sablefish caught with trawl gear (PFMC and NMFS 2017).

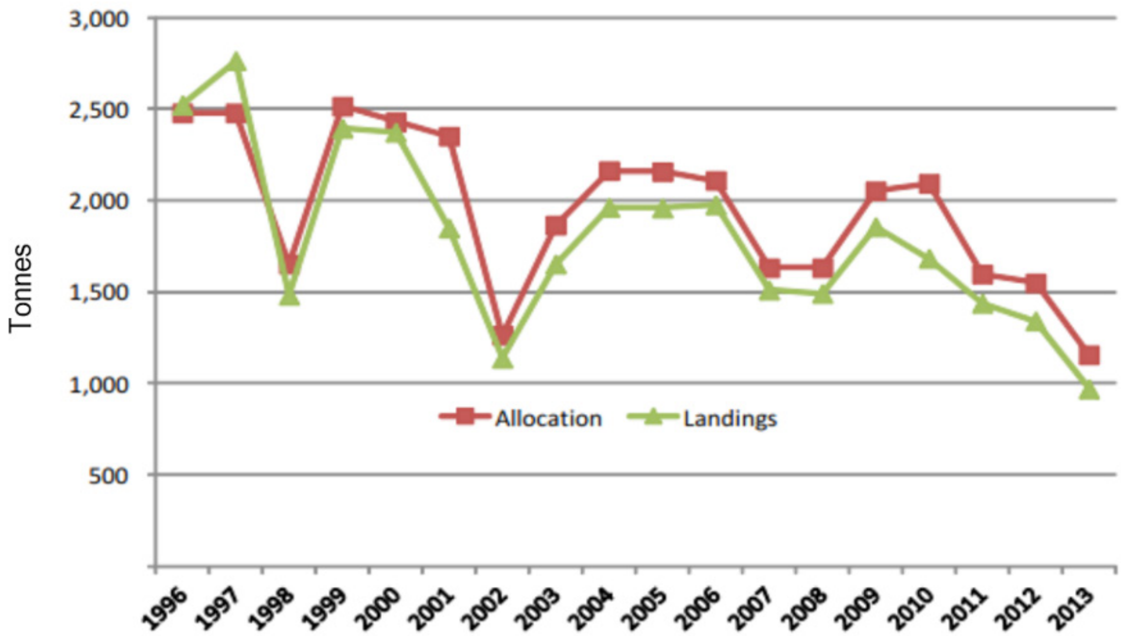

Figure 16. Sablefish allocations and landings (mt) in the U.S. West Coast limited entry fixed gear fishery, 1996–2013. Source: PFMC (2016).

5.4.1.5 Permit price

Information on sablefish permit prices is too limited for use in determining any trends in the permit values over time, but Table 17 shows a sample of offerings of tier permit prices from a broker's website. This snapshot shows a preponderance of trading for Tier 3 permits (the lowest quota level).

Table 17. Listings of U.S. West Coast fixed gear sablefish-endorsed permits offered for sale on dock street brokers by permit type.

Permit type	Asking price (USD)	Updated	Notes
Tier 1	825,000	11/26/2012	Pot endorsed.
Tier 3	13,000	04/14/2014	Lease available for 2014 season.
Tier 3	140,000	02/21/2014	Price reduced, good to 51 ft.
Tier 3	145,000	02/25/2014	Sold.
Tier 3	155,000	03/10/2014	Sold.
Tier 3	165,000	08/23/2013	Make offer.
Tier 3	170,000	04/02/2013	
Tier 3	197,000	10/15/2013	Good to ~70 ft.
Tier 3	208,000	01/25/2013	

Source: PFMC and NMFS (2014).

5.4.1.6 Bycatch

Catch in the fixed gear sablefish fishery is composed mostly of sablefish, with incidental catch primarily composed of spiny dogfish, Pacific halibut, rockfish species, and skates. Vessels retain the portion of catch that is marketable and permitted to be landed. The portion of their catch which is not marketable or for which regulations prohibit landing is discarded at sea. Northern sablefish smaller than 56 cm are released at sea by regulation. In addition to market and regulatory discards, smaller sablefish may be discarded, as fishers seek to maximize the value of their landed catch allowances (NMFS 2018a). Discard rates ranged from 9–26% for vessels using longline gear over the 1986–2013 period, while for vessels using traps/pots, discards ranged from 11–39% (Johnson et al. 2015a).

5.4.2 Groundfish trawl fishery

5.4.2.1 Management

The groundfish trawl fishery targets sablefish, together with a variety of other groundfish species. Prior to 2011, the fishery was managed primarily through the use of trip limits. These evolved from simple per-trip limits in the 1980s to cumulative periodic (monthly or bimonthly) limits by the mid-1990s. In addition to sablefish-specific limits, various limits were in place for the overall landings of deep-water complex species (Johnson et al. 2015a). In 2011, an ITQ program was implemented for the shoreside sector of the groundfish trawl fishery. The program includes individual allocations for 30 species, including sablefish. Program provisions include limits on the amount of quota an entity can own and a vessel can use, and an industry-funded observer program with 100% coverage. Entry into the ITQ fishery is limited to holders of limited entry trawl permits, but gear-switching is allowed, such that fixed gear can be used to catch sablefish in the fishery (PFMC 2017).

5.4.2.2 Participation

Table 18 shows the number of vessels targeting sablefish in the groundfish trawl fishery. During the first five years of the ITQ program, an average of 16 vessels took advantage of the gear-switching provision each year. An average of six vessels switched from using trawl gear to fixed gear to target sablefish at least part of the year.

Table 18. Number of vessels targeting sablefish in the U.S. West Coast groundfish trawl fishery by area, 2011–15.

Year	Vessels in northern area	Vessels in southern area
2011	85	12
2012	82	10
2013	77	7
2014	76	8
2015	72	8

Source: PFMC (2017).

The groundfish trawl fishery harvests a variety of species at various times of the year. In recent years, petrale sole has made up the bulk of the January and February trawl fishery, with Dover sole and sablefish also playing a large role during those months. From March through May, the "DTS strategy" (Dover sole, thornyheads, and sablefish) is the focus of trawl effort. Beginning in May and June, target species typically begin transitioning from deeper depths along the continental slope and deep portions of the shelf to shallower portions of the shelf, and effort in the fishery follows suit. From May through October, the fishery targets species such as "other flatfish," Dover sole, and petrale sole along the continental shelf, while other vessels choose to pursue pink shrimp during those months. On 15 June, the primary season for the shoreside Pacific hake fishery opens, and many trawlers focus on that species in June, July, and often into August, depending on the length of the fishery. In November and December, many trawl vessels transition over to the Dungeness crab fishery, but several trawlers remain in the fishery and target petrale sole and some DTS species (PFMC and NMFS 2010).

5.4.2.3 Landings

On average, the number of vessels targeting sablefish that switched from trawl gear to fixed gear caught 7% of the total northern sablefish quota. An additional 10 vessels, on average, that had not previously fished in the groundfish trawl fishery purchased or leased trawl permits and quota to fish with fixed gear in the ITQ program. Most of these vessels had permits with fixed gear sablefish endorsements. On average, these vessels caught 21% of the northern sablefish quota. Vessels using trawl gear caught 64% of the northern sablefish quota (PFMC 2017).

Table 19. Sablefish allocations (mt) and catch (mt) in the U.S. West Coast groundfish trawl fishery by area and gear type, 2000–16.

		Catch			
Year	**Allocation**	**Pot/Trap**	**Trawl**	**Longline**	**Total**
2000	—	0	2,599	0	2,599
2001	—	0	2,491	0	2,491
2002	—	0	1,519	0	1,519
2003	—	0	1,641	0	1,641
2004	—	0	1,420	0	1,420
2005	—	0	1,161	0	1,161
2006	—	0	1,947	0	1,947
2007	—	0	2,143	0	2,143
2008	—	0	2,630	0	2,630
2009	—	0	2,606	0	2,606
2010	—	0	2,185	0	2,185
2011	3,077	363	1,335	121	1,819
2012	2,981	381	1,149	0	1,530
2013	2,430	170	1,091	0	1,261
2014	2,641	0	1,054	0	1,054
2015	2,919	465	1,045	0	1,510
2016	3,205	540	1,109	0	1,649

Sources: Data request submitted to PSMFC by Northern Economics, Inc., and NMFS (2018f).

During the 2011–15 period, catch of northern sablefish made up between 84% (2011) and 95% (2013) of all sablefish caught in the groundfish trawl fishery. The utilization rates of northern sablefish quota have been among the highest of any quota species in the ITQ program, ranging from 87% (2012) to 95% (2015; see Table 19). However, utilization rates of southern sablefish quota have been much lower. Southern sablefish quota utilization was highest in the first year of the program (84%), but it has not surpassed 50% since then (PFMC 2017).

5.4.2.4 Quota price

Table 20 shows brokerage quota pound prices for northern sablefish in the groundfish trawl fishery from 2011–17. Quota pound prices for southern sablefish are considerably lower.

5.4.2.5 Bycatch

The groundfish trawl fishery catches a variety of groundfish and nongroundfish species. The early estimates of discard rates for the groundfish trawl fishery from the 1980s averaged 36.3% of total catch. More recent trawl estimates have ranged from 5.5% in 2008 to 59.0% in 2002. After the implementation of the ITQ program in 2011, discard rate estimates for the groundfish trawl fleet dropped to as low as 0.5% in 2012, with the highest observed rate of 1.1% in 2013 (Johnson et al. 2015a).

Table 20. Prices of northern sablefish quota pounds sold on Jefferson State Trading Company. Note: With respect to the U.S. West Coast groundfish trawl fishery, quota pounds are the amount of fish, expressed in round weight of fish, that a quota owner is allowed to catch during a fishing year. Quota pounds are issued annually to each quota owner based on the amount of quota that they own, and the amount of fish allocated to the ITQ program. Quota pounds have the same species/species group and area designations as the quota from which they are issued.

Year	Number of transactions	Price/quota pound (USD)
2017	33	$1.32
2016	43	$1.19
2015	29	$1.18
2014	30	$1.09
2013	18	$0.94
2012	29	$1.02
2011	23	$1.12

Source: Jefferson State Trading Company (2018).

6 Sablefish Supply and Demand

As noted by NMFS (2018b), one reason that the expansion of marine aquaculture, particularly in the United States, is the subject of much debate, is the potential for market interactions between wild-caught and farm-raised fish. Marine aquaculture has had demonstrated impacts on U.S. market supply and demand for salmon (Knapp et al. 2007, Williams et al. 2009), shrimp (Keithly et al. 1993, Gillig et al. 1998, Asche et al. 2012, Tabarestani et al. 2017), and a number of other species (Bjørndal and Guillen 2016).

This section provides a conceptual discussion of changes in supply and demand in the sablefish market; summarizes past studies of the market structure for sablefish and the likely price effects of sablefish aquaculture; and updates the econometric analysis of global market demand for sablefish developed by Huppert and Best (2004). The updated analysis will enable projections of price changes that could be expected with increases in global sablefish supply.

6.1 Economics of Sablefish Supply and Demand

Figures 17 and 18 provide a diagrammatic illustration of market factors that could come into play with sablefish aquaculture. The combined TAC for the commercial fisheries is the black line perpendicular to the x-axis. The dotted light blue line represents the supply curve of wild sablefish if harvests were unconstrained by the TAC. At the point where the TAC constrains the commercial harvest of sablefish, the supply curve turns vertical, as shown by the solid light blue line. The market clearing wholesale price (P_1) is the point where the TAC-constrained commercial supply curve meets the initial demand curve (dark gold line) for sablefish.

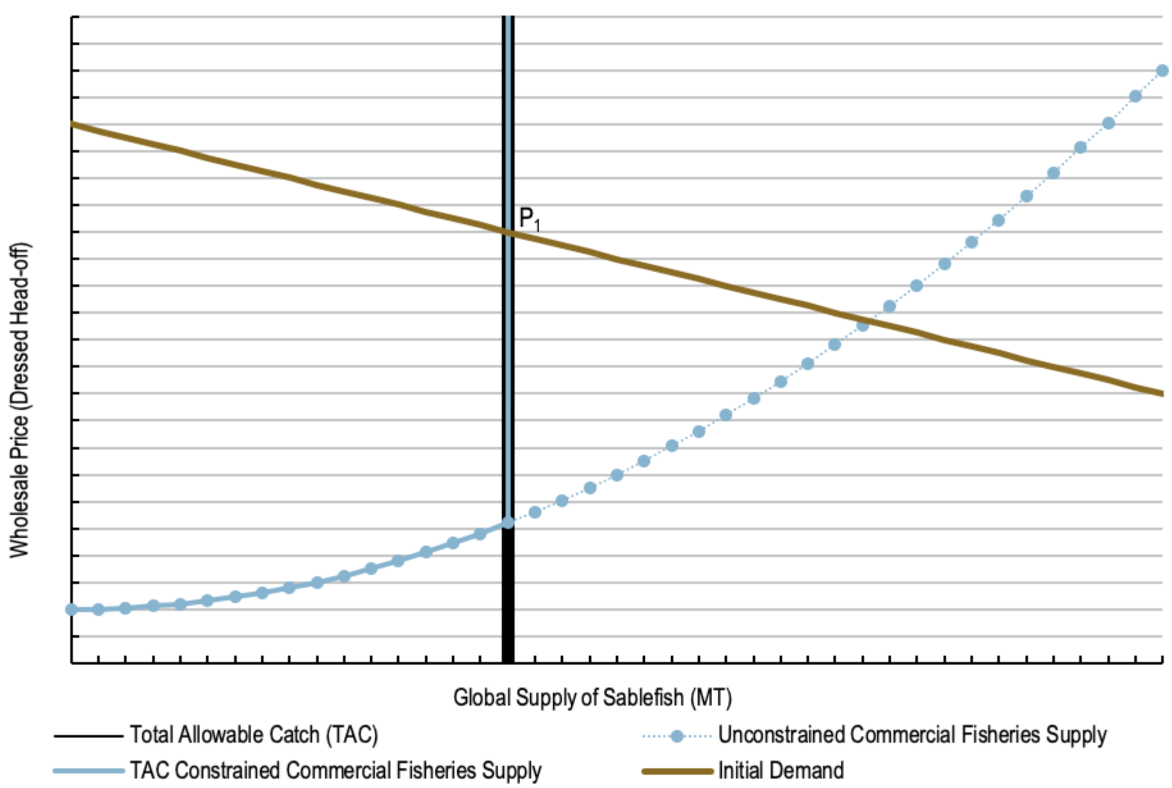

Figure 17. Theoretical sablefish supply and demand without aquaculture.

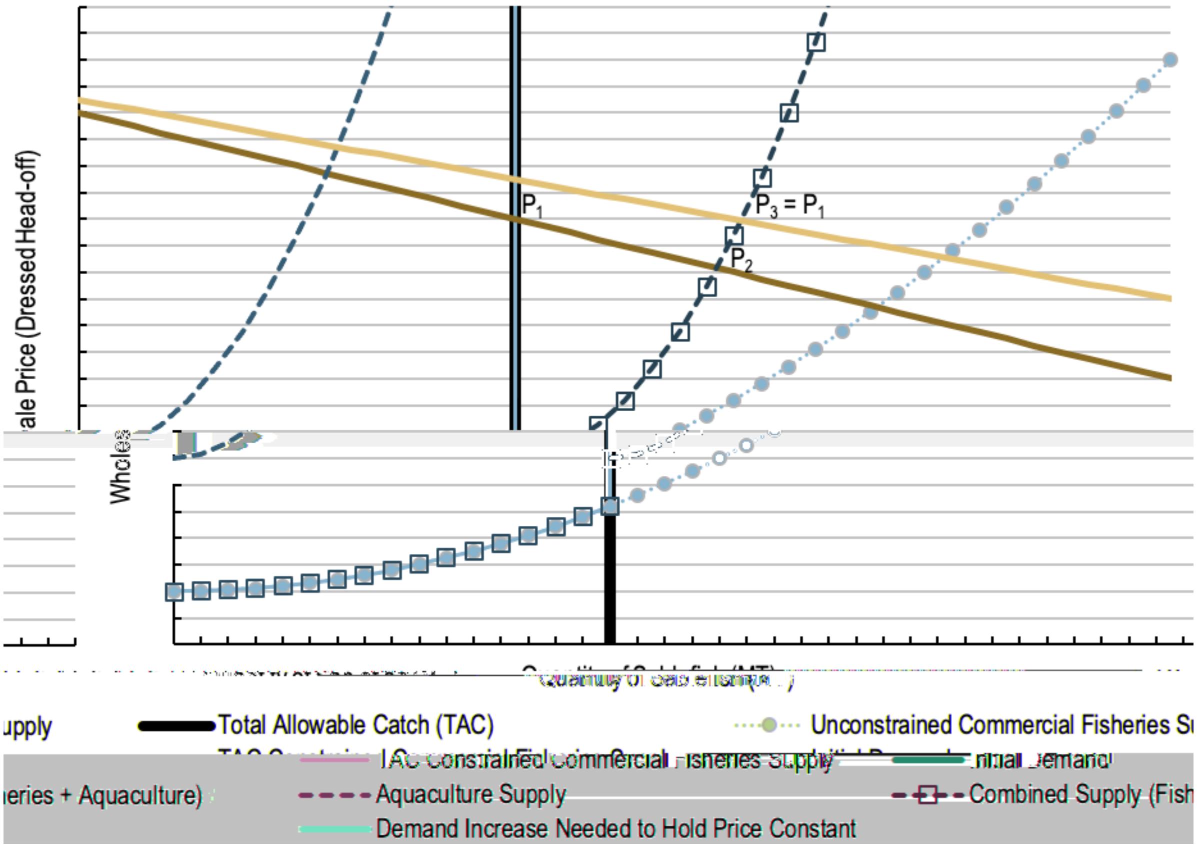

Figure 18. Theoretical sablefish supply and demand with aquaculture.

Figure 18 demonstrates the impact on total sablefish supply and the market clearing price with the addition of sablefish aquaculture. The figure assumes a relatively stable aquaculture supply represented by the dashed dark blue line. The Combined Supply (Fisheries + Aquaculture) curve is represented by the line with the hollow squares and dark blue dashes to the right of the TAC line. If the overall demand for sablefish is unaffected by the increase in supply, the market clearing wholesale price for sablefish would slide to the right along the initial demand curve from P_1 to P_2.

The factors that affect movement along the demand curve and those that cause a shift in the curve are different. Movements along the demand curve are strictly a function of changes in supply. If the supply of sablefish goes down because the TAC is reduced, the price goes up; if supply is increased, the price goes down. In contrast, an increase in the willingness or ability of consumers to buy sablefish will shift the demand curve up and to the right (as shown by the light gold line in Figure 18), while a reduction in consumers' willingness to buy will shift it down and to the left. A number of factors can cause a change in the willingness or ability of consumers to purchase sablefish, including:

- **Price of substitute goods:** A substitute good is a good that is similar to the original good and that a consumer may purchase in place of the original. If the price of a substitute good increases, the consumer would demand more of the original good. For example, the color, oil content, and flesh quality of Patagonian toothfish are similar enough to those of sablefish that some seafood experts expect an increase in the demand for sablefish should the price of toothfish increase due to a decrease in supply caused by overfishing (Huppert and Best 2004, Sonu 2014). There are many premium fish competing with sablefish in the same center-of-the-plate market, and changes in supply of these species in the aggregate may factor into sablefish prices as much as the supply of sablefish itself.

- **Real disposable income:** Disposable income is the amount of money that households have available for spending after taxes and other mandatory charges have been accounted for. A higher real income means a higher purchasing power, since real income refers to the income adjusted for inflation. The demand for sablefish would be expected to change as consumers' incomes change. The demand for sablefish in Japan is very sensitive to changes in per-capita Japanese income (Huppert and Best 2004, Warpinski et al. 2016), which suggests that sablefish is a luxury good (i.e., a good for which demand increases more than proportionally as income rises).
- **Number of buyers:** Changes in market size have an effect on demand. For example, the development of new markets for sablefish in North America, Europe, and other Asian countries besides Japan has increased the demand for sablefish.
- **Consumer tastes and preferences:** Consumers' tastes are constantly changing, which, in turn, can cause a change in the demand for a given good. For instance, sablefish has gained popularity in the growing number of U.S. restaurants that feature Asian or Pan-Asian cuisine.
- **Expectations:** Expectations about future quantities and prices can cause demand to change in the present. In the case of commercial sablefish fisheries, the expectation that a future decrease in supply will occur due to a lower annual TAC can increase current demand by consumers. Cold storage has reduced this effect to some extent, as it allows commercial seafood buyers to build up inventories of sablefish products that allow supplies to be carried over from year to year.[54]

These factors, alone or in combination, could at least partially offset a decrease in price caused by an increase in the supply of sablefish on the market due to sablefish farming. The light gold line in Figure 18 represents the demand increase that would be needed to keep the market price of sablefish at pre-aquaculture levels. Sellers of sablefish products must figure out which of these factors are in play when analyzing the changes in the markets for their products.

6.2 Sablefish Demand Analysis

6.2.1 Previous studies of sablefish market demand

The structure of the market for sablefish, together with the likely effects of sablefish aquaculture on the price commanded in the market, has been studied previously. In chronological order, this section summarizes the findings of these earlier studies.

[54] The volumes of frozen supplies sitting in cold storage holdings at any moment dictate the price point at which the fish move from freezers and through retail outlets. Sablefish distributors overseas know the clock is ticking against U.S. processors, who incur increased costs of keeping the fish frozen each day that product doesn't move (Ess 2018).

Jacobson (1982) examined the effects of the foreign vessel reduction and increased consumer demand for sablefish. As summarized by Warpinski et al. (2016), he used annual data from 1971–80 to estimate a single equation model of the Tokyo wholesale sablefish price as a function of the quantity of sablefish traded in the Tokyo central wholesale market, nominal Japan gross state product (GSP), and the real price of chum salmon (*Oncorhynchus keta*). Chum salmon was chosen as a substitute because, like sablefish, it was used by consumers in fish stews. Jacobson predicted that increased production of chum salmon by hatcheries in Japan and the Pacific Northwest would have a negative impact on export prices for sablefish. However, Warpinski et al. (2016) note that there is no evidence that this actually happened, probably because of changes in how Japanese consumers use sablefish.

Squires et al. (1988) examined the relationship between U.S. sablefish production and the Japanese market. They noted that if the U.S. ex-vessel market becomes more tightly interwoven with Japanese markets, U.S. sablefish fisheries could become more vulnerable to changes in Japanese market conditions and government policies. To assess the relationship, the authors examined the price integration of the U.S. West Coast and Alaska fixed gear, ex-vessel markets for sablefish and the Tokyo wholesale market for sablefish from 1981–86. The U.S. West Coast ex-vessel market was found to be segmented from the Tokyo market, implying that changes in Tokyo market prices had no effect on the ex-vessel prices of the U.S. West Coast market. Squires et al. felt this was due to the fact that most of the U.S. West Coast's production of sablefish is consumed in the United States. However, the Tokyo wholesale and Alaska ex-vessel markets were shown to be well integrated by prices, and the authors concluded that changes in Japanese trade policies, the yen–dollar exchange rate, and Japanese consumer preferences are all likely to affect the prices received by fishers in Alaska.

Hastie (1989) expanded on Jacobson's (1982) model. As summarized by Warpinski et al. (2016), Hastie substituted real Japan GSP for nominal GSP and used quarterly data from 1972–87. In Hastie's model, the quantity of sablefish sold in the Japanese wholesale market became significant, and the responsiveness of price to changes in quantity was estimated to have increased between the 1972–80 and 1980–87 periods. In addition, Hastie reported the results of an export market model based on monthly U.S. export data from 1981–87. Sablefish export price was modeled as a function of the Tokyo wholesale price, yen–dollar exchange rate, and inflation, and separate models were estimated for ex-vessel prices in Alaska and U.S. West Coast sablefish fisheries as functions of lagged ex-vessel prices, Tokyo wholesale prices, and exchange rates. Hastie concluded that the Japanese market largely sets Alaska sablefish ex-vessel prices and, in contrast to Squires et al. (1988), that this influence extends to U.S. West Coast ex-vessel prices.

Gislason et al. (2001) suggested that there should potentially be a strong market demand for farmed sablefish, because 1) sablefish aquaculture can fill the void in the Japanese market created by declining wild sablefish and Patagonian toothfish catches; 2) demand for sablefish in North America and other parts of the world beside Japan would be increasing in the long run; and 3) sablefish aquaculture can target specialty or "niche" markets, e.g., ethnic live-fish markets. However, Gislason et al. (2001) estimated that increasing the supply of sablefish by 8,000 mt (about a 30% increase over 2003 production in the B.C. sablefish fishery) from aquaculture would drive the B.C. sablefish ex-vessel price down by 40%.

Huppert and Best (2004) developed two price forecasting models to help predict the price effects of expanded sablefish supply, whether from growing TAC limits in the fisheries or from expansion of aquaculture production. The first model estimated demand in Japan using a standard demand specification that included the price of a substitute (in this case, sockeye salmon [*O. nerka*]) and per-capita income. The second model was an extension of the first, incorporating Japanese macroeconomic variables, including the yen–dollar exchange rate and economic conditions in Japan as reflected by changes in GSP. In order to estimate the models, the study made two assumptions: 1) sablefish products would be sold mainly in the Japanese markets, implying that there would be no change in sablefish demand in other countries; and 2) any increase in supply from aquaculture would provide identical fish products and would compete directly with wild sablefish.

The 2004 model results of Huppert and Best indicated that the sablefish wholesale price in Japan would drop linearly as the overall quantity supplied increased. Their first model forecasted that 1) the ex-vessel price in the Alaska sablefish fishery would drop $0.064/kg ($0.029/lb) for each 1,000-mt increase in supply of sablefish; 2) the ex-vessel price in B.C. would drop $0.077/kg ($0.035/lb) for each 1,000-mt supply increase; and 3) the U.S. West Coast ex-vessel price would drop $0.033/kg ($0.015/lb) for each 1,000-mt supply increase. The authors' second model, which incorporated the effects of income volatility and exchange rates on the Japanese market, forecasted more severe price changes. For a 1,000-mt increase in overall sablefish supply, the model predicted price reductions of $0.086/kg ($0.039/lb), $0.104/kg ($0.047/lb), and $0.04/kg ($0.020/lb) for Alaska, B.C., and U.S. West Coast sablefish fisheries, respectively. The authors concluded that the actual effects of prospective sablefish supply increases would likely fall in the range of estimates provided by the two models.

Huppert and Best noted that a number of factors could mitigate the price reductions caused by increases in sablefish supply. For example, the price effects of expanded sablefish supply would be less than predicted by the models if: 1) Japan became less important to the sablefish market due to increasing North American demand or the emergence of other Asian markets, and/or 2) production of sablefish in aquaculture operations focused on smaller fish or niche markets which differed from the main Japanese markets. In addition, if the economy of Japan experiences a significant expansion relative to recent experience, the demand for sablefish there would grow more than the models estimate, and the Japanese wholesale prices would rise relative to the price predictions. These changes would translate back to higher U.S. ex-vessel prices as indicated by the price linkage functions estimated in the models.

Sumaila et al. (2007) examined how the ecological impacts of sablefish aquaculture could alter the price effects of aquaculture production. According to the authors, while the ecological effects of sablefish aquaculture on wild sablefish are currently not known with any certainty, potential negative effects include the spread of pathogens and parasites originating from farms, and genetic interactions between farm escapees and wild stocks. Sumaila et al. (2007) predicted that sablefish prices would drop less precipitously due to aquaculture production if ecological externalities reduce landings of wild sablefish.

Warpinski et al. (2016) used a simultaneous equation market model for sablefish to examine linkages between landings volume and ex-vessel price and revenue, including the sensitivity of Alaska ex-vessel price and revenue to changes in landings, to changes resulting from the implementation of an ITQ program, and to changes in the Japanese economy. Model simulations indicate that markets could absorb substantially more sablefish than can be sustainably harvested from the current stock of Alaska sablefish. However, sluggishness in the Japanese economy has resulted in overall downward pressure on ex-vessel prices in the Alaska sablefish fishery. Model simulations indicate that ITQ program implementation in the Alaska sablefish fishery significantly increased ex-vessel revenue as a consequence of longer seasons. In addition, Warpinski et al. (2016) found that the ITQ program helped buffer the fishery against revenue losses associated with reduced TAC limits triggered by the decline of sablefish biomass in the Alaska fishery.

6.2.2 Updated sablefish demand analysis

This section updates the sablefish demand analysis of Huppert and Best (2004). As described above, Huppert and Best presented two price forecasting models to help predict the price effects of expanded sablefish supply: one model estimated demand in Japan using a standard demand specification that included the price of a substitute (sockeye salmon) and per-capita income, and the other model incorporated the yen–dollar exchange rate and economic conditions in Japan as reflected by changes in GSP. The updated analysis chose to focus on the first model, estimating the Japanese sablefish market price as a function of per-capita consumption, a per-capita income proxy variable (GSP per capita), and the price of a substitute good (sockeye salmon). The exchange rate is important for determining the earnings of fishers in the short run, but economic theory suggests that the nominal exchange rate would not affect sablefish supply or demand in the long run. Nominal exchange rates implicitly assume that equivalent goods fetch the same price regardless of the units of currency used to purchase them. For example, if one metric ton of sablefish could be purchased in U.S. dollars and resold in yen at a profit, there is an opportunity for arbitrage in the market. Given that annual data covering a 28-year period were available for the updated analysis, this long-run assumption should hold. Therefore, we used a standard demand model which includes the price of a substitute and per-capita income.

Where possible, the data series used by Huppert and Best were expanded with more-recent estimates. These data series include ex-vessel prices in the Alaska, B.C., and U.S. West Coast sablefish fisheries, Japanese wholesale market prices, Japanese import quantities, and Japanese GSP (Sonu 2014, DFO 2018a; Government of Japan 2018, NMFS 2018c, 2018d, PacFIN 2018). In some cases, the reporting methods for data have changed. For example, data on Japanese GSP are now only available from 1994 to 2015, and the estimation method has changed since Huppert and Best (2004) completed their analyses. Similarly, Japanese population numbers (used to calculate per-capita measures) using the same data source are available for 2000–15. In each case, the original data series published by Huppert and Best (2004) was combined with the current series to generate a continuous estimate of per-capita GSP and per-capita sablefish consumption.

Huppert and Best (2004) estimated Japanese sablefish supply as a function of TAC limits in the three North American fisheries, to capture the effect of expectations about future sablefish supply. The current analysis substitutes actual annual catches for TAC limits, as actual catch reflects unforeseen changes in market supply that affect price changes along the demand curve.

The aggregate levels of sablefish imports, exports, and prices used in both the Huppert and Best (2004) model and the updated model make no distinction between farm-raised versus wild-caught sablefish, or sablefish of different size or quality. Therefore, both models assume that sablefish is a homogenous product.

Figure 19 shows the historical sablefish prices (dashed lines) and linear trends (solid lines) for average annual ex-vessel prices in the Alaska, B.C., and U.S. West Coast sablefish fisheries, and the Tokyo central wholesale market price. The historical data show that Alaska ex-vessel prices have increased more dramatically (steepest slope) than either of the other fisheries. From 2007 onward, the B.C. and U.S. West Coast fishery prices track closely, while the Alaska price is subject to greater variation.

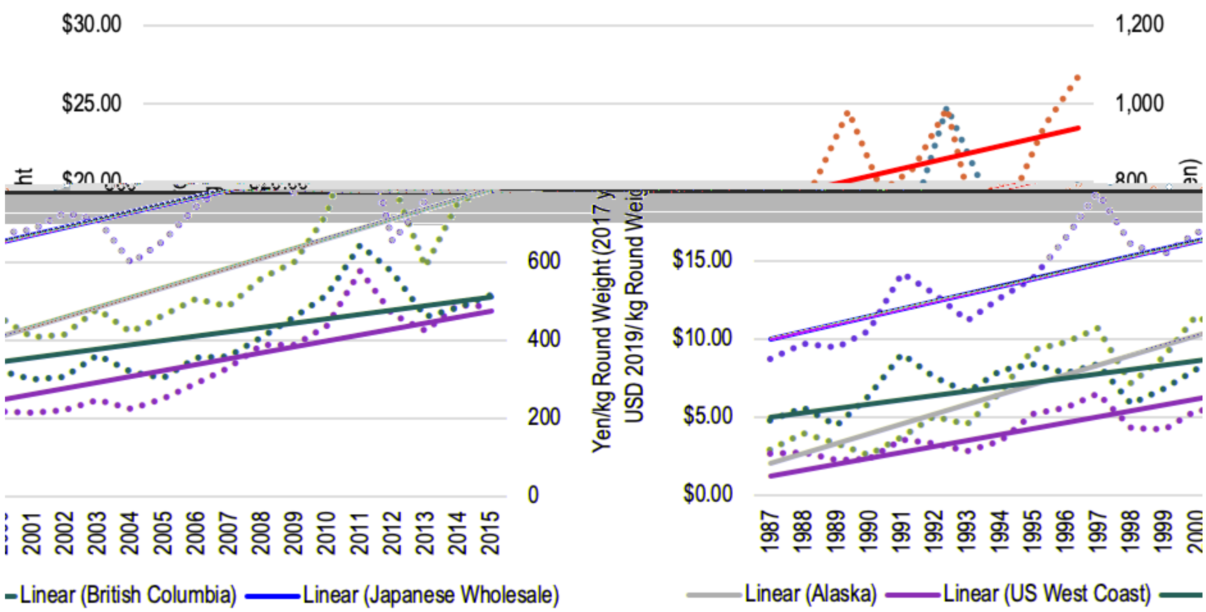

Figure 19. Historic average annual sablefish ex-vessel and Tokyo central wholesale market prices, 1987–2015. Note: Dotted lines represent historical data, solid lines represent linear trendlines for visualization. Sources: NMFS (2018a, 2018c), DFO (2018a), PacFIN (2018).

The currency data in the newly constructed regression models are converted into year-2000 dollars for consistency and to generate straightforward comparisons with the results reported by Huppert and Best (2004). The original specifications from the Huppert and Best (2004) model[55] were used to construct a preliminary demand model. An analysis of the errors (residuals) from this preliminary model indicated that there was some bias present in the output. The model generally underestimated price during the period of 2007–15, and overestimated price in years prior to 2007 (Figure 20). To adjust for the bias, an indicator variable for years 2007 and later was added to each of the three ex-vessel price equations in the updated model and to the Tokyo central wholesale market price equation as an exogenous variable. The updated model shows improvement by evenly distributing

[55] Both the Huppert and Best (2004) model and the updated model used a three-stage least squares regression methodology that combines seemingly unrelated regression (SUR) with two-stage least squares to simultaneously estimate the system of equations.

the errors across the period (Figure 21). The significance of the indicator variable and its positive coefficient in the model suggest that an increase in aggregate sablefish demand occurred in or near 2007, perhaps as a result of heightened consumer awareness of sablefish through social media and the internet.

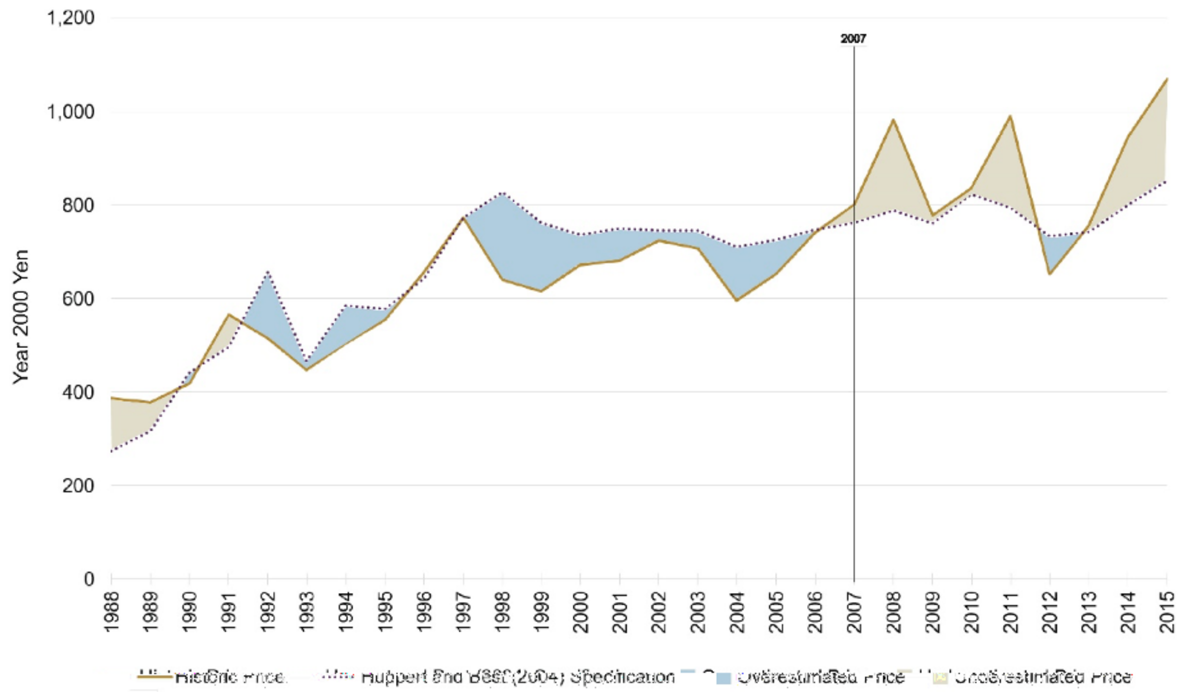

Figure 20. Preliminary demand model prediction and Tokyo central wholesale market price.

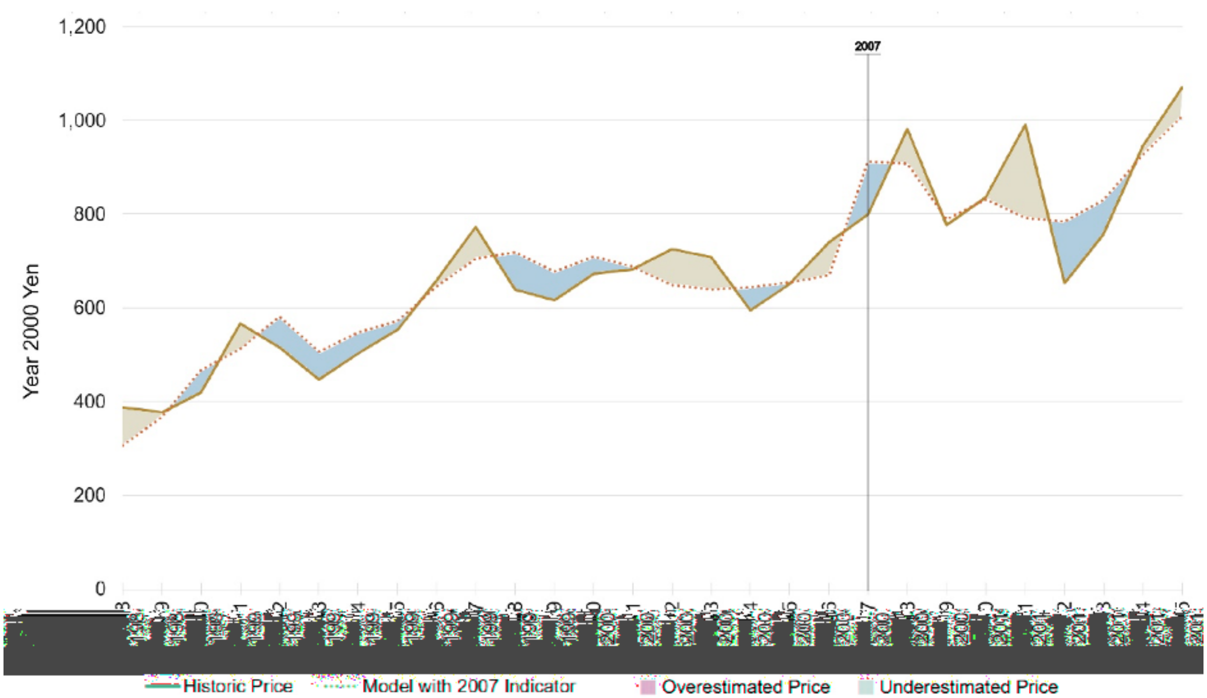

Figure 21. Model prediction with year-2007 indicator variable and Tokyo central wholesale market price.

The coefficient for the indicator was positive in each equation and statistically significant at the 1% level in the wholesale market price and U.S. West Coast ex-vessel price equations. The term was included in the Alaska and B.C. ex-vessel equations despite statistical insignificance. The model was further improved by interacting the year-2007 indicator variable with Japanese market price. Huppert and Best (2004) used the same methodology to account for changes due to the implementation of ITQ programs in the early 1990s. They included indicator variable–price interaction terms in their model to capture changes in ex-vessel price that occurred due to the new fishery management regimes. Similarly, the updated model includes indicator variable–price interaction terms as a substitute for the year-2007 indicator variable, within the ex-vessel price equations. Table 21 compares the regression output coefficients for the Huppert and Best (2004) and updated models, where the units of each coefficient represent year-2000 currencies for each respective country. The interaction term is statistically significant in the U.S. West Coast fishery equation, and slightly outside of the 10% confidence interval for the B.C. fishery equation. These results suggest that the events in years 2007 and later have more effect on the U.S. West Coast and B.C. fisheries than on the Alaska fishery.

Table 21. Comparison of regression outputs for Huppert and Best (2004) model and updated model. Note: Coefficients for each country are shown in year-2000 values in that country's currency.

		Coefficients	
Equation	**Variable**	**Huppert and Best model**[a]	**Updated model**
Japanese quanitity of imported sablefish	TAC (Huppert and Best 2004); landings, in mt (updated model)	0.734	0.585[b]
	intercept	−6,504	−338.925
Tokyo central wholesale market price	per-capita Japanese consumption (kg/person)	−2.130	-0.899[c]
	per-capita gross state product (million yen/person)	344	414.254[b]
	price of sockeye salmon (yen/kg)	0.162	0.273[d]
	2007 indicator	n/a	214.459[b]
	intercept	n/a	−1004.140[c]
Alaska ex-vessel price	Japanese wholesale price (year-2000 USD/kg)	0.292	0.797[b]
	Alaska ITQ indicator × Price	0.353	0.527[b]
	2007 indicator × Price	n/a	0.048
	intercept	n/a	−0.653
U.S. West Coast ex-vessel price	Japanese wholesale price (year-2000 USD/kg)	0.231	0.218
	Alaska ITQ indicator × price	0.098	0.275[b]
	2007 indicator × price	n/a	0.223[b]
	intercept	n/a	0.962[d]
B.C. ex-vessel price	Japanese wholesale price (year-2000 CAD/kg)	0.458	0.239
	B.C. ITQ indicator × price	0.056	0.334[b]
	2007 indicator × price	n/a	0.059
	intercept	n/a	3.133[b]

[a] Huppert and Best (2004) do not report statistically insignificant intercept values.
[b] $P < 1\%$.
[c] $P < 5\%$.
[d] $P < 10\%$.

Table 22. Comparison of R-squared values for Huppert and Best (2004) model and updated model.

	R-squared value	
Equation	**Huppert and Best model**	**Updated model**
Japanese quanitity of imported sablefish	0.85	0.85
Tokyo central wholesale market price	0.71	0.88
Alaska ex-vessel price	0.98	0.92
U.S. West Coast ex-vessel price	0.95	0.95
B.C. ex-vessel price	0.94	0.82

Table 22 compares the R-squared values of the Huppert and Best (2004) model and the updated model.[56] Overall, the results are similar. About 88% of the variation in the Tokyo central wholesale market price is explained by the exogenous variables in the updated model, compared to 71% in the Huppert and Best model. However, the updated model explains less of the variation in ex-vessel prices than does the Huppert and Best model, even though the additional 10 years of data used by the updated model were expected to result in a relatively higher explanatory power. It is possible that sablefish market interactions have increased in complexity since the Huppert and Best model was developed.

The indicator variable–price interaction terms allow the updated model to estimate changes to ex-vessel prices on a per-dollar basis of changes in Japanese wholesale price. In other words, the interaction terms capture differences in price-point between fisheries. Input values for the forecast were based on an average of the latest three years of data used in the updated model (2013–15). The analyses presented here and by Huppert and Best (2004) apply only to marginal changes in the market supply of sablefish. The effect of a sudden and unexpected increase or decrease in supply cannot be accurately predicted with either model.

Table 23 compares Huppert and Best's ex-vessel price forecast with the updated model forecast, with both sets of estimates specified in terms of 2019 dollars per kg. Prices for Alaska and the U.S. West Coast are represented in USD and prices in British Columbia are represented in CAD.[57] Both models predict linear decreases in ex-vessel prices as sablefish supply increases. The results of the updated model indicate that for each 1,000-mt increase in supply, Alaska sablefish ex-vessel price would decrease $0.077/kg. The effect is much smaller in the U.S. West Coast and B.C. sablefish fisheries, with a decrease of $0.040/kg and $0.039/kg, respectively. Note: the higher prices in Alaska mean that the price changes as a percentage of the estimated ex-vessel prices in the three regions vary within a relatively smaller range (–0.24% to –0.39%) than in the original model.

In general, these price impacts are small relative to total prices, and they are very small relative to the annual variations in prices in the three regions. During the years 1987–2015, ex-vessel prices in Alaska and the West Coast had a coefficient of variation (CV)[58] of 53%, while the CV for ex-vessel prices in British Columbia was 23% of the mean price.

[56] The R-squared value is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). It provides a measure of how well observed outcomes are replicated by a model, based on the proportion of total variation of outcomes explained by the model.
[57] Prices in British Columbia are converted into 2019 CAD using the consumer price index for Canada (Statistics Canada 2020).
[58] The coefficient of variation is a measure of interannual variation relative to the mean price, and is calculated as the standard deviation of prices ÷ the average price.

Table 23. Estimated ex-vessel price responses per 1,000-mt increase in supply. Note: Values in the row for British Columbia have been adjusted to 2019 CAD using the Canadian Consumer Price Index (Statistics Canada 2020). Values in red parentheses are negative.

	Huppert and Best (2004) model			Updated model		
Fishery	**Price response (PR)**	**2004 price**	**PR as a % of 2004 price**	**Price response (PR)**	**2015 price**	**PR as a % of 2015 price**
Alaska	($0.113)	$10.51	–1.07%	($0.077)	$19.83	–0.39%
U.S. West Coast	($0.061)	$5.58	–1.09%	($0.040)	$12.16	–0.33%
B.C.	($0.080)	$10.44	–0.77%	($0.039)	$16.63	–0.24%

A comparison of the results from the original and the updated models indicates that model estimates of price responses as a percentage of ex-vessel prices current at the time of the analysis are noticeably lower in the updated model than in the original model. This is an indication that in the 14 years between estimation of the two models, sablefish prices have become less sensitive to supply changes.

The results of any analysis of market interactions between wild-caught and farm-raised sablefish is sensitive to the period investigated, as fish markets are dynamic and changing continuously (Bjørndal and Guillen 2016). As Huppert and Best (2004) note, there are a number of potential future circumstances that would reduce the effect of increased supply from aquaculture on demand for wild-caught fish, and prices would fall less than the demand models predict. These circumstances include:

- Expansion of markets for sablefish outside of the traditional Japanese market, such as increasing domestic demand or the emergence of other overseas markets.
- Production of sablefish in aquaculture operations focused on niche markets that differ from the main Japanese market.
- Growth in the economy of Japan relative to recent experience, which causes the demand for sablefish to increase. Japanese wholesale prices would rise, and this increase would translate back to higher ex-vessel prices in North America as indicated by the price linkage functions estimated in the models.

In addition, it is possible that future prices for sablefish are not dictated by sablefish supply and demand but by the supply of a basket of similar species competing for premium markets.

The results of the updated sablefish econometric model, along with the findings from the market research summarized in Chapter 4, clearly indicate that the global and domestic markets for sablefish have expanded.

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Appendix: Seafood Restaurant Survey

The survey instrument as it appeared on SurveyMonkey is attached on the following pages.[1]

Sablefish Markets

Background: Researchers at NOAA's Northwest Fisheries Science Center have developed the ability to produce all-female stocks of sablefish (also known as black cod) through a completely non-GMO approach. This breakthrough capitalizes on the more rapid growth of females compared to males and allows for the production of faster growing, similar sized fish for [illegible]

Purpose: Northern Economics, Inc., through a grant-funded project, is working to better understand the demand for sablefish in the U.S. The purpose of this survey is to determine if there is sufficient United States demand for cultured sablefish by restaurant owners, chefs, and retail markets to turn this experiment into a viable business opportunity.

Many thanks in advance for your assistance.

1. Contact Information

Your Name

Your Restaurant or Business

Your Email Address

2. Have you ever served sablefish at your establishment?

- Yes
- No

3. Do you currently serve sablefish?

- Yes
- No

4. If you serve (or would like to serve) sablefish, what would be your typical preparation?

[1] https://www.surveymonkey.com/

5 How much do you charge (or would you charge) for a sablefish meal?

6 Sablefish has historically been very limited in quantity and mostly exported. Where have you made wholesale purchases of sablefish in the past? (Please choose all that apply)

- ☐ N/A
- ☐ Locally
- ☐ From national markets
- ☐ From international markets
- ☐ Other (please specify)

7 Have you ever made wholesale purchases of farmed Sablefish in the past? (Please choose all that apply)

- ☐ Sable Fish Canada
- ☐ Global Blue Technologies
- ☐ Other (please specify)

8 What is the average price per pound that you pay for Sablefish?

9 If you do not purchase or prepare sablefish, why not?

- ☐ Lack of demand
- ☐ Lack of supply
- ☐ **I do** purchase/prepare sablefish
- ☐ Other reasons (please explain)

10 Do you see high demand for sablefish from your customers?

- ◯ Yes
- ◯ No

11 Do any of your customers specifically ask for sablefish?

- ◯ Yes
- ◯ No

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12 Does the size of the fish that you purchase matter to you or your customers?

- ◯ Yes
- ◯ No

13 Do you ever prepare and serve fish (of any species) that has been farmed (e.g., tilapia, Atlantic salmon, oysters)?

- ◯ Yes
- ◯ No

14 Would you be interested in a consistent supply of farmed sablefish if it were available?

- ◯ Yes
- ◯ No

15 Would it matter to you if the fish were sustainably produced (i.e. the fish had Best Aquaculture Practices (BAP) certification)?

- ◯ Yes
- ◯ No

16 What would you be willing to pay for a pound of sablefish that you know will be of a consistent size and quality?

[ ]

17 Is this a higher price than you are currently willing to pay for commercially harvested sablefish?

- ◯ Yes
- ◯ No

18 Do you have any additional thoughts about the potential demand for sablefish?

19 Other Comments?

20 While individual responses will be kept confidential and only reported in aggregate, we might want to use some of your comments as quotes in the report. May we (anonymously) quote your comments?

- ◯ Yes
- ◯ No
- ◯ Contact me first

Thank you for your input!

For questions or clarifications, please contact Katharine F. Wellman at 206.618.4814,
or by email at: katharine.wellman@norecon.com

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