Localized Depletion of Three Alaska Rockfish Species

Dana Hanselman
NOAA Fisheries, Alaska Fisheries Science Center, Auke Bay Laboratory, Juneau, Alaska

Paul Spencer
NOAA Fisheries, Alaska Fisheries Science Center, Resource Ecology and Fisheries Management (REFM) Division, Seattle, Washington

Kalei Shotwell
NOAA Fisheries, Alaska Fisheries Science Center, Auke Bay Laboratory, Juneau, Alaska

Rebecca Reuter
NOAA Fisheries, Alaska Fisheries Science Center, REFM Division, Seattle, Washington

Abstract

The distributions of some rockfish species in Alaska are clustered. Their distribution and relatively sedentary movement patterns could make localized depletion of rockfish an ecological or conservation concern. Alaska rockfish have varying and little-known genetic stock structures. Rockfish fishing seasons are short and intense and usually confined to small areas. If allowable catches are set for large management areas, the genetic, age, and size structures of the population could change if the majority of catch is harvested from small concentrated areas. In this study, we analyzed data collected by the North Pacific Observer Program from 1991 to 2004 to assess localized depletion of Pacific ocean perch (Sebastes alutus), northern rockfish (S. polyspinis), and dusky rockfish (S. variabilis). The data were divided into blocks with areas of approximately 10,000 km\(^2\) and 5,000 km\(^2\) of consistent, intense fishing. We used two different block sizes to consider the size for which localized depletion could be detected. For each year, the Leslie depletion estimator was used to determine whether catch-per-unit-effort (CPUE) values in each
block declined as a function of cumulative catch. We examined trends in CPUE over time using NMFS survey data for depleted areas. The results showed significant depletions among all species in several areas and years. Pacific ocean perch exhibited localized depletion most often, but not continuing into the next year, possibly indicating more migration than expected. Northern and dusky rockfish showed depletions less often, and occasional significant increases also occurred. Northern rockfish showed significant longer-term fishery depletion in one area. Results could be affected by hyperstability, migration, or target switching. The importance of the results depends on genetic stock structure, and importance of an area for reproductive success.

**Introduction**

Many deepwater rockfish (*Sebastes* spp.) in Alaska waters have a patchy or contagious distribution and are thought to move little from year to year (Love et al. 2002). This patchy distribution could be caused by several factors including a specific preference for a narrow depth range on the continental slope (Hanselman et al. 2001), the patchiness of habitats they are associated with (Krieger and Wing 2002), and oceanographic conditions that affect prey availability (Scott 1995). Species with this type of distribution may be subject to localized depletion, which is a reduction of population size over a relatively small spatial area as a result of intensive fishing.

For rockfish, localized depletion is a potential conservation issue because several species have been observed to be patchily distributed and their stock structure could occur at relatively small spatial scales. For example, Withler et al. (2001) observed two genetically distinct stocks of Pacific ocean perch (*S. alutus*) in a small area of the Queen Charlotte Islands off of British Columbia. Other genetic studies for species such as rougheye (*S. aleutianus*) and shortraker rockfish (*S. borealis*), which are relatively sedentary and associated with rugged benthic habitats indicate broadscale genetic structure similar to management areas in the Gulf of Alaska (Matala et al. 2004). However, apart from genetic information for some species, little is known about the spatial structure of Alaska rockfish populations. Local depletions could affect local spawning populations to a greater degree than the overall population.

Detectable localized depletion is dependent upon fishing intensity of sufficient strength to reduce the population size. Species that may be susceptible to localized depletions include both targeted rockfish such as Pacific ocean perch, northern rockfish (*S. polystpinis*), and dusky rockfish (*S. variabilis*) and incidentally caught rockfish such as rougheye rockfish, and shortraker rockfish. In Alaska, fisheries target only Pacific ocean perch, northern rockfish, and dusky rockfish. High catches have occurred in localized areas for some other rockfish species,
such as rougheye rockfish in the Seguam area in the Aleutian Islands. However, both the lack of a target fishery, and the relatively few hauls where rougheye dominate the catch, impede a quantitative approach to estimation of depletion. For these reasons, Pacific ocean perch in the Aleutian Islands and Pacific ocean perch, northern rockfish, and dusky rockfish in the Gulf of Alaska are the only species that have sufficient data available for an analysis of short-term localized depletion.

Typically, localized depletion is analyzed using the catch-per-unit-effort (CPUE) from directed fishing as an index of abundance. In the absence of directed fishing, changes in CPUE may not directly reflect changes in abundance (Hilborn and Walters 1992). For example, the catch of northern rockfish in the Aleutian Islands is obtained predominantly in the Atka mackerel fishery, and declines in CPUE of northern rockfish could either reflect declines of northern rockfish biomass or the increased use of areas where northern rockfish incidental catch is minimized. Surveys could potentially detect localized depletion of bycatch species, but the sampling intensity of trawl surveys in Alaska is likely insufficient to detect population declines within short time periods. However, we can use trawl survey CPUEs to examine longer-term changes in CPUE for both target and non-target species.

The Leslie model was first utilized in estimating populations of rats (Leslie and Davis 1939) and was first applied to fisheries problems by DeLury (DeLury 1947, 1951). Recently, the technique was used to assess local depletion on relatively sedentary species in well-defined, heavily fished areas (Iribarne et al. 1991; Lowe and Fritz 1997; Ito 1999; Battaile 2004; P. Spencer and R. Reuter, pers. comm., 2004, Alaska Fisheries Science Center, Seattle; Fritz and Brown 2005). The purpose of this study is to assess the extent to which localized depletion has occurred for Pacific ocean perch, northern rockfish, and dusky rockfish in Alaska waters. We consider the geographic scale at which localized depletion is detectable and important. We also differentiate two types of localized depletion. Serial depletion, or depletion that persists year after year, is a conservation concern because it may reduce spawning biomass to levels that are unsustainable for a distinct stock. Conversely, ecological depletion, or depletion that only occurs during a short fishing season, is an ecological concern because it may disturb predator-prey dynamics or alter schooling behavior. In addition, we examine longer-term trends in local densities by utilizing trawl survey CPUEs.

**Methods**

**Data selection**

To identify potential areas of study, we selected trawl hauls from the rockfish fishery sampled for species composition by the North Pacific Groundfish Observer Program. Data from this program were not con-
consistent in sampling methodologies until 1991. We displayed retrieval positions of these data in a geographic information system (GIS) to locate areas of intense fishing from 1991 to 2004. The resulting maps indicated that 18 areas of approximately 10,000 km$^2$ blocks while the horizontal line splits them into ~5,000 km$^2$ blocks. Smaller blocks are designated as #.1 and #.2 for the western and eastern sides respectively (e.g., area 5.1 is the western half of area 5).

Figure 1. Map of selected blocks for Leslie depletion analysis for Alaska rockfish. The whole rectangles are the ~10,000 km$^2$ blocks while the horizontal line splits them into ~5,000 km$^2$ blocks. Smaller blocks are designated as #.1 and #.2 for the western and eastern sides respectively (e.g., area 5.1 is the western half of area 5).
From a larger pool of hauls with potential for inclusion in the analysis, the number of hauls was reduced through a series of restrictions to select for hauls that targeted rockfish. The commercial rockfish fishery typically occurs in the summer months; therefore, only hauls between June 1 and September 30 were used. An individual haul was considered to be targeting rockfish if the sum of the three target species’ catch was greater than 35% of the total catch (Fritz 1996). Fritz and Brown (2005) used different target percentages for Pacific cod between 20% to 60% and found that regressions generally fit better with lower percentages. Different percentages were attempted for rockfish, ranging from 20% to 60%, and 35% seemed to best identify coherent targeted fishing. The remaining 65% of the catch in the hauls near the 35% level consisted mainly of non-target rockfish such as sharpchin (S. zacentrus) and redstripe (S. proriger) rockfish or arrowtooth flounder (Atheresthes stomias) and skates (Bathyraja spp. and Raja spp.). Few hauls had relatively high catches of pollock (Theragra chalcogramma) which would likely be unintentional, while others had sablefish (Anoplopoma fimbria) which could represent “topping off” of valuable bycatch species. Of all included hauls, 84% contained at least 60% of the three target rockfish species.

We implemented additional restrictions on the data that accounted for specifics of the Leslie estimation procedures. In two depletion experiments, Ito (1999) and Battaile (2004) found that shortraker/rougheye rockfish and pollock were replenished after seven days. Data were considered acceptable for Leslie estimation when there were at least 10 hauls that were not separated by more than three days. Additionally, some amount of catch goes unobserved because catcher boats under 125 feet in length do not require 100% coverage. Therefore, to account for unobserved catch, cumulative catches (not CPUE) were expanded to expected catch by the percentage unobserved by year and area, to give reasonable estimates of initial biomass (Fritz and Brown 2005).

This restriction process considerably narrowed available hauls for each species (Table 1) and resulted in a total of 249 data sets to use for Leslie estimation for both block sizes. Data from the biennial groundfish surveys conducted by the National Marine Fisheries Service were selected for these same areas from 1983 to 2004 to examine areas where depletion was detected.

**Statistical methods for depletion estimation**

The Leslie method assesses population depletion by a fishery via a linear decline in the CPUE as a function of cumulative fish catch since the start of the fishery:

\[ \frac{C_t}{f_t} = qB_0 - qK_t \]

Here, \( C_t \) and \( f_t \) are an observation of catch and effort, respectively, for a daily time period \( t \), \( B_0 \) is the initial biomass prior to the start of the
fishery, \( q \) is the catchability coefficient defining the proportion of \( B_0 \) that is taken with one minute of trawling, and \( K_t \) is the cumulative total catch taken prior to period \( t \) plus one half of the catch during period \( t \) (Braaten 1969). Catchability estimates were the negative of the slope of regressions and estimates of initial biomass were the regression intercepts divided by the catchability.

Assumptions of the Leslie model include (1) the population is closed to immigration and emigration, and the period of study is short enough where natural mortality was negligible; (2) the catchability of the fishing gear remains constant; (3) changes in CPUE are directly related to abundance; (4) catch is measured with little error; and (5) the quality of fishing effort does not change over the time of fishing (Miller and Mohn 1993). These assumptions are more likely met if directed fishing occurs within a well-defined area within a relatively short time. Violations of these assumptions for rockfish might include fishing gear disaggregating schools of rockfish or vessels “targeting” rockfish, but “topping off” on valuable bycatch species such as sablefish.

### Table 1. Number of hauls containing one of the three targeted rockfish species before filtering by year and number of hauls with each species after filtering.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Before filtering</th>
<th>POP After filtering</th>
<th>Northern After filtering</th>
<th>Dusky After filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>705</td>
<td>33</td>
<td>233</td>
<td>180</td>
</tr>
<tr>
<td>1992</td>
<td>420</td>
<td>94</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
<td>1993</td>
<td>837</td>
<td>67</td>
<td>71</td>
<td>83</td>
</tr>
<tr>
<td>1994</td>
<td>984</td>
<td>33</td>
<td>133</td>
<td>133</td>
</tr>
<tr>
<td>1995</td>
<td>656</td>
<td>12</td>
<td>103</td>
<td>94</td>
</tr>
<tr>
<td>1996</td>
<td>1021</td>
<td>80</td>
<td>71</td>
<td>84</td>
</tr>
<tr>
<td>1997</td>
<td>394</td>
<td>60</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>1998</td>
<td>676</td>
<td>101</td>
<td>57</td>
<td>21</td>
</tr>
<tr>
<td>1999</td>
<td>736</td>
<td>117</td>
<td>102</td>
<td>88</td>
</tr>
<tr>
<td>2000</td>
<td>632</td>
<td>124</td>
<td>26</td>
<td>31</td>
</tr>
<tr>
<td>2001</td>
<td>793</td>
<td>100</td>
<td>38</td>
<td>30</td>
</tr>
<tr>
<td>2002</td>
<td>955</td>
<td>176</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>2003</td>
<td>1,061</td>
<td>152</td>
<td>55</td>
<td>23</td>
</tr>
<tr>
<td>2004</td>
<td>1,025</td>
<td>165</td>
<td>89</td>
<td>41</td>
</tr>
<tr>
<td>Total</td>
<td>10,895</td>
<td>1,314</td>
<td>1,055</td>
<td>891</td>
</tr>
</tbody>
</table>

POP = Pacific ocean perch.
Results

Of the 249 area, year, and size combinations analyzed, 43 produced significant depletions (negative slopes), which was many more than the approximately six negative results that would be expected by chance at the $\alpha = 0.05$ significance level. Only eight regressions had significantly positive slopes, which was approximately what was expected at the $\alpha = 0.05$ significance level (Table 2). Comparisons of estimated initial biomasses with catches in some areas with significant results showed high exploitation rates, with some catches exceeding the estimated initial biomass (Table 3). It should be recognized that the estimates of initial biomass are not very precise. One example was in area 7 for Pacific ocean perch in 1999; the point estimate was 1,053 t, but when a 95% confidence interval was calculated using methods from DeLury (1951), the range was from 791 t to 2,402 t. Confidence intervals were always asymmetrical, indicating that many of the exploitation rates over 100% may have been due to the imprecise and skewed distribution of initial biomass. Important results for each species are described below.

Pacific ocean perch

Pacific ocean perch is the dominant commercial rockfish species and had the most data available for analysis. A total of 113 regressions were performed across 14 of the 18 selected areas. In both block sizes, regression slopes were mainly negative (Table 2) and on average 24% of these negative slopes were significant for both block sizes ($p < 0.05$). Only one regression had a significant positive slope. Depletions were detectable at both scales of block sizes and significant results occurred in similar areas and years between block sizes (Table 3). Areas with the
### Table 3. Significant results from Leslie depletion analysis of Pacific ocean perch for two block sizes.

<table>
<thead>
<tr>
<th>Block</th>
<th>Year</th>
<th>Intercept</th>
<th>Slope ((-q))</th>
<th>(p)-value</th>
<th>(B_0(t))</th>
<th>Catch</th>
<th>% Caught</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5,000 km(^2) blocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>2003</td>
<td>720</td>
<td>-0.00028</td>
<td>0.011</td>
<td>2,589</td>
<td>2,289</td>
<td>88%</td>
</tr>
<tr>
<td>4.1</td>
<td>1993</td>
<td>331</td>
<td>-0.00016</td>
<td>0.006</td>
<td>2,089</td>
<td>1,022</td>
<td>49%</td>
</tr>
<tr>
<td>4.2</td>
<td>1991</td>
<td>202</td>
<td>-0.00031</td>
<td>0.009</td>
<td>651</td>
<td>447</td>
<td>69%</td>
</tr>
<tr>
<td>6.1</td>
<td>1994</td>
<td>276</td>
<td>-0.00028</td>
<td>0.011</td>
<td>984</td>
<td>625</td>
<td>64%</td>
</tr>
<tr>
<td>6.1</td>
<td>2002</td>
<td>397</td>
<td>-0.00039</td>
<td>0.016</td>
<td>1,032</td>
<td>737</td>
<td>71%</td>
</tr>
<tr>
<td>6.1</td>
<td>2004</td>
<td>538</td>
<td>-0.00032</td>
<td>0.011</td>
<td>1,675</td>
<td>1,236</td>
<td>74%</td>
</tr>
<tr>
<td>6.2</td>
<td>2003</td>
<td>597</td>
<td>-0.00082</td>
<td>0.002</td>
<td>730</td>
<td>747</td>
<td>102%</td>
</tr>
<tr>
<td>7.1</td>
<td>1993</td>
<td>400</td>
<td>-0.00047</td>
<td>0.003</td>
<td>846</td>
<td>756</td>
<td>89%</td>
</tr>
<tr>
<td>7.1</td>
<td>1994</td>
<td>303</td>
<td>-0.00019</td>
<td>0.010</td>
<td>1,580</td>
<td>1,061</td>
<td>67%</td>
</tr>
<tr>
<td>12.2</td>
<td>1997</td>
<td>361</td>
<td>-0.00027</td>
<td>0.039</td>
<td>1,361</td>
<td>1,073</td>
<td>79%</td>
</tr>
<tr>
<td>18.2</td>
<td>1992</td>
<td>191</td>
<td>-0.00024</td>
<td>0.013</td>
<td>809</td>
<td>676</td>
<td>83%</td>
</tr>
<tr>
<td>18.2</td>
<td>1996</td>
<td>311</td>
<td>-0.00100</td>
<td>0.002</td>
<td>311</td>
<td>301</td>
<td>97%</td>
</tr>
<tr>
<td><strong>10,000 km(^2) blocks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1999</td>
<td>309</td>
<td>0.000109</td>
<td>0.013</td>
<td>-2,829</td>
<td>4,306</td>
<td>-152%</td>
</tr>
<tr>
<td>1</td>
<td>2003</td>
<td>705</td>
<td>-0.00025</td>
<td>0.011</td>
<td>2,779</td>
<td>2,414</td>
<td>87%</td>
</tr>
<tr>
<td>2</td>
<td>1998</td>
<td>411</td>
<td>-0.00017</td>
<td>0.043</td>
<td>2,447</td>
<td>1,436</td>
<td>59%</td>
</tr>
<tr>
<td>4</td>
<td>1993</td>
<td>336</td>
<td>-0.00017</td>
<td>0.004</td>
<td>1,957</td>
<td>996</td>
<td>51%</td>
</tr>
<tr>
<td>5</td>
<td>2001</td>
<td>307</td>
<td>-0.00045</td>
<td>0.040</td>
<td>680</td>
<td>438</td>
<td>64%</td>
</tr>
<tr>
<td>6</td>
<td>1994</td>
<td>276</td>
<td>-0.00028</td>
<td>0.011</td>
<td>984</td>
<td>625</td>
<td>64%</td>
</tr>
<tr>
<td>6</td>
<td>2002</td>
<td>300</td>
<td>-0.00014</td>
<td>0.041</td>
<td>2,149</td>
<td>1,194</td>
<td>56%</td>
</tr>
<tr>
<td>6</td>
<td>2003</td>
<td>437</td>
<td>-0.00019</td>
<td>0.001</td>
<td>2,249</td>
<td>2,042</td>
<td>91%</td>
</tr>
<tr>
<td>6</td>
<td>2004</td>
<td>514</td>
<td>-0.00023</td>
<td>0.004</td>
<td>2,234</td>
<td>1,632</td>
<td>73%</td>
</tr>
<tr>
<td>7</td>
<td>1993</td>
<td>382</td>
<td>-0.00043</td>
<td>0.000</td>
<td>887</td>
<td>835</td>
<td>94%</td>
</tr>
<tr>
<td>7</td>
<td>1994</td>
<td>303</td>
<td>-0.00019</td>
<td>0.010</td>
<td>1,580</td>
<td>1,061</td>
<td>67%</td>
</tr>
<tr>
<td>7</td>
<td>1999</td>
<td>1537</td>
<td>-0.00146</td>
<td>0.018</td>
<td>1,053</td>
<td>1,231</td>
<td>117%</td>
</tr>
<tr>
<td>7</td>
<td>2003</td>
<td>491</td>
<td>-0.00020</td>
<td>0.030</td>
<td>2,486</td>
<td>1,671</td>
<td>67%</td>
</tr>
<tr>
<td>12</td>
<td>1997</td>
<td>356</td>
<td>-0.00026</td>
<td>0.033</td>
<td>1,374</td>
<td>1,120</td>
<td>82%</td>
</tr>
<tr>
<td>16</td>
<td>2002</td>
<td>397</td>
<td>-0.00022</td>
<td>0.021</td>
<td>1,815</td>
<td>1,348</td>
<td>74%</td>
</tr>
<tr>
<td>18</td>
<td>1992</td>
<td>197</td>
<td>-0.00026</td>
<td>0.001</td>
<td>749</td>
<td>683</td>
<td>91%</td>
</tr>
<tr>
<td>18</td>
<td>1996</td>
<td>294</td>
<td>-0.00086</td>
<td>0.003</td>
<td>342</td>
<td>320</td>
<td>94%</td>
</tr>
</tbody>
</table>
most consistent depletion were in the eastern Aleutian Islands between Seguam Island and Yunaska Island (areas 6 and 7). Regressions in area 6 showed depletions in the last three consecutive fishing seasons (2002-2004, Fig. 2). The estimates of initial biomass suggested that much of the Pacific ocean perch biomass in area 6 was being depleted over the fishing season, but was likely replenished by the next year. Area 7 also had four significant depletions, but not in consecutive years. Several depletion events in the 1990s were found in area 18, around Yakutat; however, this area is no longer fished for rockfish, mainly due to the eastern Gulf of Alaska bottom trawling closure.

Northern rockfish

Northern rockfish are the next most abundant rockfish in Alaska waters following Pacific ocean perch. A total of 78 regressions were performed across 12 of the 18 selected areas (Table 2). Under both block sizes, 13% of the regressions had significant \( p < 0.05 \) negative slopes. Only two
Table 4. Significant results from Leslie depletion analysis of northern rockfish for two block sizes.

<table>
<thead>
<tr>
<th>Block</th>
<th>Year</th>
<th>Intercept</th>
<th>Slope (-q)</th>
<th>p-value</th>
<th>Bₒ (t)</th>
<th>Catch</th>
<th>% Caught</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000 km² blocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>1991</td>
<td>7</td>
<td>-0.00047</td>
<td>0.021</td>
<td>15</td>
<td>14</td>
<td>94%</td>
</tr>
<tr>
<td>11.1</td>
<td>1994</td>
<td>232</td>
<td>-0.00038</td>
<td>0.000</td>
<td>609</td>
<td>432</td>
<td>71%</td>
</tr>
<tr>
<td>13.2</td>
<td>1994</td>
<td>267</td>
<td>-7.1E-05</td>
<td>0.001</td>
<td>3,731</td>
<td>2,236</td>
<td>60%</td>
</tr>
<tr>
<td>14.1</td>
<td>1996</td>
<td>213</td>
<td>-0.00204</td>
<td>0.012</td>
<td>104</td>
<td>103</td>
<td>98%</td>
</tr>
<tr>
<td>17.2</td>
<td>1999-2</td>
<td>211</td>
<td>-0.00073</td>
<td>0.001</td>
<td>288</td>
<td>278</td>
<td>96%</td>
</tr>
<tr>
<td>10,000 km² blocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1998</td>
<td>41</td>
<td>-0.00101</td>
<td>0.002</td>
<td>41</td>
<td>41</td>
<td>101%</td>
</tr>
<tr>
<td>11</td>
<td>1994</td>
<td>232</td>
<td>-0.00038</td>
<td>0.000</td>
<td>609</td>
<td>432</td>
<td>71%</td>
</tr>
<tr>
<td>13</td>
<td>1994</td>
<td>270</td>
<td>-5.5E-05</td>
<td>0.002</td>
<td>4,944</td>
<td>2,720</td>
<td>55%</td>
</tr>
<tr>
<td>14</td>
<td>1996</td>
<td>168</td>
<td>-0.00107</td>
<td>0.023</td>
<td>156</td>
<td>159</td>
<td>102%</td>
</tr>
<tr>
<td>16</td>
<td>2004</td>
<td>17</td>
<td>0.000549</td>
<td>0.041</td>
<td>-31</td>
<td>102</td>
<td>-328%</td>
</tr>
<tr>
<td>17</td>
<td>2001</td>
<td>59</td>
<td>0.000515</td>
<td>0.048</td>
<td>-114</td>
<td>303</td>
<td>-266%</td>
</tr>
<tr>
<td>17</td>
<td>1999-2</td>
<td>211</td>
<td>-0.00073</td>
<td>0.001</td>
<td>288</td>
<td>278</td>
<td>96%</td>
</tr>
</tbody>
</table>

1999 was split into two “seasons” because of a large break in consecutive fishing.

Figure 3. Two significant depletion regressions using fishery CPUE versus cumulative catch in areas 11 and 13 for northern rockfish.
regressions had significant positive slopes. Significant results were dispersed without a discernable pattern between years, areas, and block sizes (Table 4). No area had more than one significant depletion event. Areas 11 and 13 had significant depletion in 1994 over both block sizes, which may suggest the only legitimate depletions for northern rockfish (Fig. 3). Area 13 contains the “Snakehead” area, a known high intensity fishing area off of Kodiak Island, where much of the recent northern rockfish catch has been harvested. When annual CPUEs from the fishery and survey were examined for northern rockfish in area 13, there was a strong and significant downward trend for fishery CPUE ($p < 0.001$, $n = 14$) and a similar but weaker downward trend for the survey CPUE, indicating potential serial depletion (Fig. 4). Aside from area 13, estimates of initial biomass suggested that other significant results were located in areas with small populations.

**Dusky rockfish**

Dusky rockfish are the third most abundant rockfish in Alaska waters. A total of 58 regressions were performed across 7 of the 18 selected areas (Table 2). Approximately 10% of the regressions had significant ($p < 0.05$) negative slopes with an equal number of significant positive slopes. Significant results were only in areas 13, 17, and 18 with negative
results only in 13 and 17 (Table 5). Again, area 13 seemed to be the only location with results suggesting likely depletion (Fig. 5). Like northern rockfish, dusky rockfish exhibited a long-term decreasing trend in both survey and fishery CPUE in area 13 (Fig. 6). In area 17, there was a significant positive result early in the 1999 season that contrasts with a significant negative result later in that year (Fig. 5).

### Table 5. Significant results from Leslie depletion analysis of dusky rockfish for two block sizes.

<table>
<thead>
<tr>
<th>Block</th>
<th>Year</th>
<th>Intercept</th>
<th>Slope (-q)</th>
<th>p-value</th>
<th>( B_0(t) )</th>
<th>Catch</th>
<th>% Caught</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000 km² blocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.2</td>
<td>1994</td>
<td>33</td>
<td>-4.7E-05</td>
<td>0.019</td>
<td>698</td>
<td>418</td>
<td>60%</td>
</tr>
<tr>
<td>13.2</td>
<td>1996</td>
<td>85</td>
<td>-0.00236</td>
<td>0.057</td>
<td>36</td>
<td>35</td>
<td>98%</td>
</tr>
<tr>
<td>17.2</td>
<td>1996</td>
<td>15</td>
<td>9.86E-05</td>
<td>0.000</td>
<td>-153</td>
<td>412</td>
<td>-268%</td>
</tr>
<tr>
<td>10,000 km² blocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1994</td>
<td>34</td>
<td>-3.5E-05</td>
<td>0.041</td>
<td>956</td>
<td>502</td>
<td>52%</td>
</tr>
<tr>
<td>13</td>
<td>1996</td>
<td>85</td>
<td>-0.00238</td>
<td>0.034</td>
<td>36</td>
<td>36</td>
<td>101%</td>
</tr>
<tr>
<td>17</td>
<td>1996</td>
<td>15</td>
<td>0.0001</td>
<td>0.000</td>
<td>-145</td>
<td>412</td>
<td>-284%</td>
</tr>
<tr>
<td>17</td>
<td>1999-1</td>
<td>66</td>
<td>0.000283</td>
<td>0.021</td>
<td>-234</td>
<td>896</td>
<td>-383%</td>
</tr>
<tr>
<td>17</td>
<td>1999-2</td>
<td>206</td>
<td>-0.00028</td>
<td>0.010</td>
<td>736</td>
<td>598</td>
<td>81%</td>
</tr>
<tr>
<td>18</td>
<td>1992</td>
<td>7</td>
<td>0.000744</td>
<td>0.001</td>
<td>-9</td>
<td>124</td>
<td>-1392%</td>
</tr>
</tbody>
</table>

1999 was split into two “seasons” because of a large break in consecutive fishing.

Discussion

**Fishery depletions**

When intensive fishing occurs such that the CPUE is markedly reduced over the length of the fishing season, the Leslie depletion estimator reasonably estimates catchability, initial population size, and exploitation rate. For this study, we were more interested in the ability to detect localized depletion in a targeted fish population, and at what scales depletion could be detected.

Overall, Pacific ocean perch exhibited the most significant depletions in consistent areas. Some depletions occurred over consecutive years, such as in area 6 in 2002-2004. However, these depletions did not appear to proceed where they left off in the previous year. The areas seemed to be replenished by new fish or the fishery shifted to an aggregation nearby in the same area because the CPUEs at the start of the fishery each year were similar (Fig. 2) and the estimate of initial biomass was also similar. This replenishment may indicate a higher degree of migratory behavior then previously thought. Area 7 was locally depleted
Biology, Assessment, and Management of North Pacific Rockfishes

in the 1990s and was lightly fished until 2003 when CPUE increased rapidly as the area was fished again. Pacific ocean perch may have shown the most depletion because this species had the most data available and was the most intensely fished in the commercial rockfish fishery.

Localized depletion in a concentration of northern rockfish only seemed to occur in one year in the “Snakehead” area of the Gulf of Alaska (area 13) in 1994. Some depletion of dusky rockfish appeared to occur in the same area and year. This area was fished heavily for northern rockfish in the 1990s, but is now only lightly fished. The long-term downward trend in the fishery and survey CPUE for northern rockfish (Fig. 4) and dusky rockfish (Fig. 6) suggests the area has been slow to recover. Clausen and Heifetz (2002) also noted that 46% of the catch of northern rockfish was taken from this area during 1990-1998. However, northern rockfish and dusky rockfish did not show substantial intra-annual depletions since 1991. Several explanations of this may exist: (1) local populations may be large enough compared to the

Figure 5. Four significant depletion regressions using fishery CPUE versus cumulative catch in areas 13 and 17 for dusky rockfish. 1999-1 and 1999-2 were the same year but had a large break in fishing.
existing catch limits that significant depletions do not occur; (2) there may be insufficient data to detect real depletions that have happened; or (3) the detectability of localized depletion may be affected by target switching. If the fishery begins targeting Pacific ocean perch until the catch limit is reached, then targets northern rockfish, and finally dusky rockfish, depletion would be exaggerated for the first target and then underestimated for the final target. This is parallel to Polovina’s (1986) result showing an increase in CPUE for one of three species of snapper throughout a controlled longline experiment. As a more competitive species was removed, the CPUE of the less competitive species increased.

**Scale and comparison to other studies**

In this study we analyzed relatively large areas at two scales. We used two block sizes to see if localized depletion was detectable at different block sizes to help determine what “localized” means for rockfish, and at what scale there are sufficient data to perform an effective analysis. We showed that in most cases, localized depletions were detectable at
both scales. However, in a few instances, depletions were significant at one scale and not the other.

Controlled studies have demonstrated depletion on small scales for sedentary and immobile populations. Iribarne et al. (1991) conducted an intensive depletion experiment on a very small area (0.36 km$^2$) for scallops. In their study, they used both the Leslie (CPUE vs. cumulative catch) and the DeLury estimator (log of CPUE vs. cumulative effort) and showed a 50% decrease in CPUE over a 31-day period with similar results for each estimator. Joll and Penn (1990) also used two areas of 0.36 km$^2$ for scallops. They swept each experimental area three times over three nights and determined that they captured 93-96% of the scallops from their estimates of initial biomass using the Leslie estimator. Their reductions in CPUE were rapid, as scallops are sedentary and vulnerable to capture. These studies differed from our study because those studies were planned experiments with restricted areas and planned fishing effort.

Similar to this study, Lowe and Fritz (1997) used medium-sized areas (200-1,200 km$^2$) of observed fishery data for a depletion study on Atka mackerel. Like the rockfish analyzed in this study, Atka mackerel are highly aggregated and the fishery had been locally concentrated in space and time. In this analysis, they found that eight of nine area-year combinations yielded significant depletions of Atka mackerel. Since then, a regulatory amendment was instituted to spread the fishery out spatially and temporally (Lowe et al. 2005).

Fritz and Brown (2005) estimated depletion of Pacific cod in the southeastern Bering Sea for two larger areas (8,000 and 12,000 km$^2$) using trawl data from the fishery observers. Their study on the smaller of the two areas had “high observer sampling” and had a data set of 47 fishing days and a cumulative catch of over 11,000 t. Their results showed highly significant depletion and showed the strongest results when the target percentage was the lowest of three different thresholds (when catch was >20% cod). However, results were similar and nearly as strong at the other two targeting thresholds (40% and 60%). They also examined data from the longline fishery, which also showed strong and significant depletion over a 27 day study period.

Several specific and small areas (1,000 km$^2$) in the Aleutian Islands were analyzed for Pacific ocean perch depletions in an unpublished manuscript presented to the North Pacific Fishery Management Council (P. Spencer and R. Reuter, pers. comm., 2004, Alaska Fisheries Science Center, Seattle). Significant depletion was detected in the Northwest Buldir reef area in 2003, which was located inside of area 1 in this study. Data were more limited for that study at the smaller spatial scale.

From these four studies, it appears that depletion may be detectable with targeted fishery data at a number of different spatial scales and targeting thresholds. Large changes in CPUE appear to suppress noisy
data and reveal actual depletions. Rockfish and Atka mackerel fishery data resulted from fairly short and intense localized fisheries. In the Pacific cod study, the fishing was more spread out temporally, but was quite locally intense with 11,000 tons of fish being removed from one small block. Other fisheries such as sablefish that are more spread out over the year, or have higher migration rates, would be less likely to exhibit signals of localized depletion. The appropriate spatial and temporal scale at which localized depletion becomes important for rockfish is a subject for future research.

Conclusions and management implications
Several caveats to this study exist. First, it is well known that CPUE is not necessarily proportional to abundance (Harley et al. 2001). The CPUE for fish species that have contagious distributions like rockfish often exhibits “hyperstability” (Hilborn and Walters 1992). This means that CPUE decreases slower than abundance, because fishers are able to locate dense schools until there are too few schools to target. One way to compensate for this characteristic of the fishery is to record search time between hauls. Search time is currently not recorded on vessels targeting Alaska groundfish. Hyperstability could result in an underestimate of total depletion events in Alaska rockfish. Another result of a hyperstable distribution is an overestimate of the initial biomass of the area examined. Conversely, if hauls are included at the end of the time series that have low CPUE because they are not actually target hauls, then initial biomass would be underestimated. Additionally, downward changes in catchability throughout the study period due to behavioral changes in rockfish schools or other factors would result in underestimates of initial biomass (Miller and Mohn 1993). Confidence intervals around initial biomass estimates were highly imprecise and skewed. These reasons may help explain some exploitation estimates that were over 100% (Table 3).

The extent to which localized fishing becomes problematic for rockfish is dependent upon the ability of rockfish to replenish fished areas such that local spawning populations are not eliminated. Pacific ocean perch have not been shown to have fine-scale stock structure in Alaska, but have shown fine-scale structure in British Columbia. Pacific ocean perch showed depletions that would be important on an ecological scale. That is, if they were an important prey item for another species during the time the population was being depleted, this would be a potential concern. Additionally, removing a large quantity of fish during a specific time may allow another competitive species to thrive. Northern rockfish have not yet been shown to have much stock structure, which would imply that depletions will eventually be replenished by migration. However, in one area we found a serial decline in fishery CPUE, perhaps indicating little movement. Little is known about dusky rockfish stock
structure. If either of these two species was shown to have fine-scale stock structure or area 13 was shown to be an important source of reproductive capabilities, then this type of type of longer-term depletion would be a conservation concern.

Considerations regarding localized depletion for rockfish should reflect the spatial scale characterizing fish movement within a year and the location and spatial extent of spawning populations. As more information becomes known about these characteristics of rockfish, Leslie depletion estimation will be a useful tool to identify areas where problems may arise. Future work on localized depletion might use variograms or other spatial analyses in a GIS environment to identify the exact scale and location of depletion events.

Acknowledgments
We thank two anonymous reviewers, Jon Heifetz and Jeff Fujioka, for their constructive criticisms and comments on earlier versions of this manuscript. We also thank the North Pacific Observer Program and the individual observers, skippers, and vessel crews that facilitated the collection of the data used in this study. In addition, we thank the Restoration and Assessment of Coral Ecosystems (RACE) program for survey data and the managers of the databases from which the data were obtained.

References


The Effect of Maternal Age of Spawning on Estimation of $F_{\text{msy}}$ for Alaska Pacific Ocean Perch

Paul Spencer  
NOAA Fisheries, Alaska Fisheries Science Center, Resource Ecology and Fisheries Management (REFM) Division, Seattle, Washington

Dana Hanselman  
NOAA Fisheries, Alaska Fisheries Science Center, Auke Bay Laboratory, Juneau, Alaska

Martin Dorn  
NOAA Fisheries, Alaska Fisheries Science Center, REFM Division, Seattle, Washington

Abstract
Recent laboratory research suggests that rockfish larval survival rates increase with the age of the spawner, thus potentially necessitating more conservative harvest policies that explicitly consider the age structure of the spawning stock biomass. In this study, we use simple deterministic population dynamic equations to examine the effect of reduced survival of larvae from younger females on commonly used fishing rate reference points such as $F_{\text{msy}}$ and $F_{\text{xx%}}$, the fishing rates corresponding to the maximum sustained yield and conservation of $\text{xx}\%$ of the reproductive potential per recruit relative to an unfished population, respectively. Reduced survival of larvae from younger females results in reduced reproductive potential per recruit for a given level of fishing mortality and also increased estimated resiliency, which results from the estimated recruitments being associated with a reduced measure of reproductive potential. For Bering Sea/Aleutian Islands and Gulf of Alaska Pacific ocean perch, these two effects nearly counteract each other, producing $F_{\text{msy}}$ estimates that were relatively insensitive but decreased slightly as maternal effects were considered. Estimates of $F_{\text{xx%}}$ rates that correspond to $F_{\text{msy}}$ proxies are more conservative (i.e., cor-
respond to reduced fishing intensity) when uncertainty in the degree to which maternal age affects reproductive potential is considered, as compared to analyses using spawning stock biomass as reproductive potential. These results indicate that estimated stock resiliency is not necessarily independent of the life-history parameters describing production of reproductive potential.

**Introduction**

Declines in rockfish populations off the U.S. West Coast (California, Oregon, and Washington) have occurred during the past two decades, resulting in the development of rebuilding plans for several species and the declaration of the U.S. West Coast fishery as a “failure” by the U.S. Secretary of Commerce (Parker et al. 2000, Dorn 2002). The collapse of several West Coast rockfish populations has drawn increased attention to rockfish fishery management policies, which, historically, were based on the principle of conserving 40% of the estimated spawning stock biomass per recruit (SPR) obtained from an unfished population. The fishing mortality reference point of $F_{40\%}$ which conserves this level of SPR originated from Clark (1993), who used stochastic simulations to show that $F_{40\%}$ produces a large fraction of the equilibrium maximum sustainable yield (MSY) and reduces the likelihood of low biomass for stocks described with a plausible range of stock-recruitment curves and levels of recruitment autocorrelation. Based on these results, Alaska groundfish are managed by using $F_{35\%}$ as limiting harvest rate and proxy to $F_{MSY}$ (the harvest rate associated with MSY) in cases where MSY cannot be reasonably estimated, and $F_{40\%}$ is used as a target harvest rate. Criticisms of the $F_{40\%}$ policy have primarily focused on two issues: (1) stock-recruitment curves typical for rockfish may be less productive than the range considered by Clark (1993), suggesting that policies that conserve more than 40% of the unfished SPR may be appropriate; and (2) harvest policies for rockfish must recognize the reduction of reproductive potential (defined as the output of the spawning process (e.g., eggs or larvae) which provides the basis for stock replacement) associated with the truncated age compositions of exploited populations (Leaman 1991, Berkeley et al. 2004b).

For West Coast rockfish, analyses of stock-recruitment data suggest that fishing mortality rates more conservative than $F_{40\%}$ are appropriate. Dorn (2002) conducted a Bayesian meta-analysis of rockfish stock-recruitment data and found West Coast rockfish stocks to be generally less productive than stocks considered by Clark (1993), and suggested that a risk-neutral harvest rate policy of $F_{50\%}$ is appropriate for these stocks. Additionally, Clark (2002) recommended that for stocks with low resiliency, SPR rates of $F_{50\%}$ or $F_{60\%}$ may be required to maintain an adequate balance of maximizing yield while preserving stock size.
Research on the reproductive biology of rockfish suggests that the reproductive potential of the stock may be a function of the age structure, in particular the proportion of old fish in the population. Leaman (1987, 1991) noted that rockfish are long-lived with little somatic growth in older fish, allowing older fish to allocate a large proportion of available energy to reproduction. The removal of older females by fishing thus disproportionately reduces spawning output such that reproductive value (the lifetime expected number of offspring from a female of a particular age in a stable age distribution) is highly sensitive to increases in fishing mortality. Additionally, Berkeley et al. (2004a) found in laboratory studies that older black rockfish (*Sebastes melanops*) produced larvae with increased survival rates; thus, exploitation can be expected to disproportionately remove the most effective spawners. The implication from these studies is that simply conserving spawning biomass is not sufficient, and managers should aim to preserve spawning biomass with a desirable age structure.

Given the collapse of several West Coast rockfish species, considerable interest exists in determining whether management policies for Alaska rockfish are sufficiently conservative. A panel charged with evaluating the $F_{40\%}$ policy for Alaska groundfish (Goodman et al. 2002) suggested that the currently used $F_{40\%}$ policy may not provide sufficient conservation for Alaska rockfish. Dorn’s (2002) meta-analysis is the only study that simultaneously considered the productivity of both West Coast and Alaska rockfish, evaluating eight West Coast stocks, one British Columbia Pacific ocean perch (POP) stock, and three Alaska POP stocks (at that time, Bering Sea and Aleutian Islands POP were assessed as separate stocks). The Alaska POP stocks show greater resiliency (increased slope of the stock-recruitment curve at the origin) than the West Coast stocks, with MSY occurring at SPR rates of approximately $F_{30\%}$. The finding of observed greater resiliency in the Bering Sea/Aleutian Islands (BSAI) POP and Gulf of Alaska (GOA) POP has been repeated in recent stock-recruitment analyses, which have found that estimated $F_{msy}$ reference points are greater than the proxies of $F_{40\%}$ (i.e., $F_{msy} > F_{40\%}$; Spencer and Dorn 2003, Hanselman et al. 2004). However, these studies did not consider how changes in age structure may affect estimates of stock productivity and estimation of harvest reference points such as $F_{msy}$. For example, the analyses of Clark (1991,1993) evaluate the correspondence of $F_{msy}$ and $F_{xx\%}$ (the fishing rate corresponding to conservation of $xx\%$ of the reproductive potential per recruit relative to an unfished population) when spawning stock biomass (SSB) is used as a measure of stock reproductive potential. How would expressing reproductive potential in units that reflect differential spawning effectiveness between age groups change the results of Clark’s (1991,1993) analyses, and what would be the effect on the estimate of $F_{msy}$ for a particular stock?
The purpose of this study is to consider the effect of the maternal age of spawning on $F_{\text{msy}}$ and proxies to $F_{\text{msy}}$. The analysis consists of converting measurements of reproductive potential from spawning stock biomass to “viable larvae,” the per-unit production of which is a function of spawner age. First, we consider under what conditions this redefinition may be expected to affect estimates of fishing reference points. Second, we use deterministic population dynamics equations to illustrate the effect on estimation of $F_{\text{msy}}$, assuming that stock-recruitment parameters are well estimated. Third, we estimate $F_{\text{msy}}$ for BSAI and GOA POP using a variety of measures of reproductive potential, and compare these estimates to currently used fishing mortality reference points. Finally, we illustrate how common fishing rate proxies to $F_{\text{msy}}$ that aim to conserve a specified proportion of the reproductive potential per recruit are affected by maternal effects on larval viability.

Methods

Standard population dynamics equations were used to estimate yield-per-recruit and spawning biomass-per-recruit as a function of fishing mortality for a population with life history characteristics equivalent to those estimated for BSAI POP. These life history parameters describe a stock with relatively low natural mortality ($M = 0.05$), moderate von Bertalanffy $K$ parameter ($K = 0.17$), and age at 50% selection in the fishery less than age at 50% maturity (Fig. 1a), and are viewed as broadly representing common life-history characteristics of exploited rockfish in the North Pacific. Little information is available regarding fecundity of Alaska POP, although studies in other areas indicate that larger females attain fecundities of 305,000 (Hart 1973) and 350,000 (Leaman 1991). A fecundity-at-age relationship for Alaska POP was obtained from fitting an asymptotic curve to Vancouver Island POP data (Dr. Bruce Leaman, International Pacific Halibut Commission, pers. comm.).

Viable larvae are introduced as a measure of reproductive potential that discounts the output from younger spawners via a larval survival curve. Viable larvae were estimated as

$$\text{Viable larvae} = \sum_a s_a f_a m_a p_a N$$

where $N$ is total number of female fish, $p_a$ is the proportion at age, $m_a$ is the proportion mature at age, $f_a$ is fecundity at age, and $s_a$ is proportion of larvae surviving to two weeks.

Two separate larval survival curves were considered: (1) a proxy curve adapted from the black rockfish laboratory data of Berkeley et al. (2004a); and (2) a knife-edged curve in which no larvae produced from a female younger than 20 years would survive. Berkeley et al. (2004a) develop an asymptotically increasing relationship between maternal age and the time required for 50% mortality of black rockfish larvae, and
Figure 1. (a) Selectivity, maturity, weight, and fecundity at age used to model BSAI POP, all shown on a relative scale. (b) Days to 50% survival for black rockfish larvae (dashed line; from Berkeley et al. 2004a) as a function of spawner age, and modified curve used for POP (solid line); the estimated proportion of POP surviving to two weeks (shown for ages 3-25+) is shown in the dotted line.
this relationship was modified to model larval mortality rate for POP (Fig. 1b). Relative to black rockfish, POP have both a longer generation time and older age at maturity. The curve describing time to 50% larval mortality for POP thus had a higher x-intercept and lower slope to reflect these considerations and was used to calculate the proportion of larvae surviving two weeks, a period arbitrarily chosen to provide some contrast in the larval survival rates by age. The knife-edged survival curve provides a scenario of extreme maternal effects on reproductive potential, thus creating contrast between measures of reproductive potential that consider intermediate and no effects on larval survival, represented by the larvae produced with the proxy curve and SSB, respectively.

A Beverton-Holt recruitment curve was used for computation of equilibrium yield and was re-parameterized using $R_0$, the expected recruitment consistent with the reproductive potential of an unfished stock $S_0$, and a parameter that measures the resiliency of the stock, $h$, defined as the proportion of $R_0$ that recruits when the reproductive potential of the stock is reduced to 20% of $S_0$ (i.e., the steepness parameter of Mace and Doonan 1988). The reparameterized Beverton-Holt curve is given by

$$ R = \frac{0.8 R_0 h S}{0.2 \Phi_0 R_0 (1-h) + (h-0.2)S}, $$

where $S$ is reproductive potential (either SSB or viable larvae), $\Phi$ is either SSB or viable larvae-per-recruit (defined as SPR and LPR, respectively), and $S_0 = \Phi_0 R_0$ for an unfished stock. Steepness ranges between 0.2 (recruits related linearly to reproductive potential) to 1.0 (recruits independent of reproductive potential). Equilibrium recruitment and yield were obtained for a sequence of harvest rates where LPR and SPR is reduced to a fraction $p$ of unfished LPR or SPR ($p = 1.00, 0.99, \ldots, 0.01$), and $F_{msy}$ was estimated as the instantaneous fishing mortality rate associated with the level of $p$ at which equilibrium yield is maximized.

**Application to Alaska POP**

Estimates of $F_{msy}$ for GOA and BSAI POP using larvae (produced with either the proxy or knife-edged survival curve) and SSB as measures of reproductive potential were made with a Bayesian estimation procedure. Time series of numbers at age, including recruits, for each stock were obtained from age-structured stock assessments (Spencer et al. 2004, Hanselman et al. 2003), and estimates of viable larvae were made from Eq. 1 using the appropriate life-history parameters from each region. There are three parameters for which priors need to be developed, $h$, $R_0$, and $\sigma^2$, the variance of expected recruitment. The prior for steepness was modeled by assuming that $\beta$, the logit of $h$, was normally distributed (after rescaling $h$ into the interval $(0,1)$, $(h-0.2) / 0.8$, and simplifying),
For $h$ in the interval $(0.2, 1.0)$ the logit $\beta$ ranges from $-\infty$ to $+\infty$, allowing straightforward specification of a mean and variance. A normal prior was used for $R_0$, and a locally uniform prior for $\sigma$ on a log scale was used. The log joint posterior distribution is the sum of the log-likelihood and the log prior, and the mode of the joint posterior distribution was obtained using the AD Model Builder nonlinear optimization software (Otter Research 1996).

The prior for $\beta$ was based on levels of reproductive success (defined as $R/S$ at the origin divided by $R_0/S_0$) considered plausible for rockfish. Dorn et al. (2003) generated a prior distribution by using a level of reproductive success of 8 ($\beta = 0.34$) as the midpoint of the distribution (corresponding to the middle of the range of stock-recruitment curves considered by Clark 1991), and set the prior variance so that reproductive success values of 4 and 16 were located at the 10th and 90th percentiles of the distribution. For Alaska POP, the same variance was used but the midpoint of the distribution was lowered to reflect a level of reproductive success of 4 ($\beta = -0.51$), thus reflecting the perceived lower productivity of rockfish relative to the values considered by Clark (1991). The midpoint of this distribution corresponds to a steepness of 0.50, closer to the value of 0.39 found for five rockfish stocks in a meta-analysis by Myers et al. (1999). Prior estimates of $R_0$ were derived from estimates of recruits consistent with the stock size in the first year of the age-structured stock assessment model, and a relatively large coefficient of variation of 0.22 was assigned.

**Estimation of fishing rate proxies to $F_{msy}$**

The relationship between equilibrium yield and fishing mortality requires knowledge of the stock-recruitment parameters $h$ and $R_0$, and for cases where these parameters are unknown Clark (1991, 1993) proposed examining yield curves for a range of potential stock-recruitment relationships in which the level of reproductive success ranged from 4 to 16. The “maximin” criteria, defined as the maximum of the minimum equilibrium yield for each level of fishing mortality, was used to identify the optimal fishing rate, expressed as $F_{xx\%}$, to be used as a proxy to $F_{msy}$. In this study, the same methodology is applied to examine how the index of reproductive potential may affect the harvest rate proxies. Consistent with Clark (1991,1993), yield curves corresponding to the levels of reproductive success of 4 and 16 (corresponding to steepness values of 0.5 and 0.8, respectively) were produced for each of the three measures of reproductive potential (intermediate levels of reproductive success did not affect the maximin fishing mortality rate), and the optimal fishing rate proxy was then identified explicitly considering
uncertainty not only in stock-recruitment relationships, but also the
degree to which spawner age affects larval viability.

**Results**

Spawning stock biomass is commonly used as a proxy for reproduc-
tive potential (i.e., eggs produced) in stock-recruitment analyses, and
under the assumption of a linear (density-independent) relationship this
substitution does not affect the stock-recruitment analyses (Rothschild
and Fogarty 1989). Similarly, recasting reproductive potential from SSB
to viable larvae will not change the stock-recruitment analysis unless
there is a nonlinear relationship between these measures, and this can
be evaluated by examining whether the ratio of viable larvae to SSB
changes with stock size. Spawning stock biomass can be expressed as
the sum over all ages of the product of numbers at age, weight at age,
and maturity at age, and the ratio of viable larvae (Eq. 1) to SSB is

\[
\frac{\text{Larvae}}{\text{SSB}} = \frac{\sum_a s_a f_m m ap_a}{\sum_a w_ap_a}
\]

where \(w_a\) is the weight at age. Although density-dependent changes in
fecundity, proportion mature at age, and growth may occur for rockfish
(Leaman 1991, Gunderson 1997), attention on the production of viable
larvae has largely focused on the reduction of the age structure associ-
ated with exploited populations (Berkeley et al. 2004b). Thus, the major
factor expected to affect the per unit production of viable larvae in the
presence of age-dependent maternal effects is \(p_a\), and Eq. 3 provides
a framework for assessing how several factors may affect the ratio of
viable larvae to SSB.

The relationships between SSB, viable larvae (produced with the
proxy curve) and mean age for an equilibrium population with con-
stant recruitment are shown in Fig. 2a. As fishing mortality increases
the mean age decreases, resulting in the production of viable larvae
decreasing at a greater rate than SSB due to the age-dependant mater-
nal influence on larval survival. Thus, the proportion of viable larvae
per recruit conserved, relative to an unfished stock, at any given fish-
ing mortality rate is lower than the proportion of SSB conserved. For
example, a fishing rate of 0.049 would conserve 40% of the SSB but only
35% of the viable larvae per recruit (proxy survival curve), and 27% of
the viable larvae per recruit (knife-edged survival curve).

Conversely, a reduction in mean age combined with defining repro-
ductive potential as viable larvae rather than SSB results in increased
estimated steepness in the stock-recruitment curve. This occurs because
although reproductive potential is reduced, the definition of recruits has
not been altered. Thus, an identical level of recruits would be associated
Figure 2. (a) The proportion of SSB per recruit (lower solid line) and larvae per recruit produced with the proxy (dashed line) and knife-edged (dotted line) survival curves, relative to an unfished stock, with increasing fishing mortality; the relative mean age is shown with the upper solid line. (b) Stock-recruitment curves and replacement lines for three measures of reproductive potential, plotted on relative scales: SSB (solid lines), larvae from proxy survival curve (dashed lines), and larvae from knife-edged survival curve (dotted lines). The replacement lines correspond to an $F$ of 0.145.
with diminished reproductive potential, resulting in an interpretation of increased steepness $h$ and resiliency. Consider a case where the number of recruits is defined as a function of SSB via the Beverton-Holt curve with a steepness parameter $h$ of 0.7, and increased fishing results in reduced equilibrium SSB and the truncated equilibrium age structure as in Fig. 2a. Relating the number of equilibrium recruits derived from this curve to equilibrium viable larvae (as produced from the proxy curve) results in an estimated steepness of 0.75, whereas relating the same recruits to equilibrium viable larvae (as produced from the knife-edged curve) results in an estimated steepness of 0.85 (Fig. 2b).

The effect of using viable larvae as a measure of reproductive potential on $F_{msy}$ will involve a tradeoff between the greater conservatism implied by the reduced reproductive potential per recruit and the greater resiliency implied by an increased steepness in the stock-recruitment curve. Thus, while the slope of the spawner-recruit curve at the origin becomes steeper with maternal effects, the replacement lines (the recruits per unit of reproductive output) also become steeper for a given level of fishing mortality, and the effect on equilibrium recruitment, yield, and $F_{msy}$ depends on the relative relationship of these two lines. For example, for the stock-recruitment curve with viable larvae (knife-edged curve) the rate of fishing producing equilibrium recruitment of zero ($F_{crash}$) was 0.145, whereas applying the same $F$ to the stock-recruitment curves for the other two measures of reproductive output produces positive equilibrium recruitment. The estimated $F_{msy}$ also increases from 0.057 to 0.06 when reproductive potential changes from SSB to viable larvae with the knife-edged curve (Fig. 3).

Application to the BSAI and GOA POP data provided contrasting results in which the estimates of $F_{msy}$ decreased slightly as maternal effects are considered. Changes in the definition of reproductive potential noticeably changes the scatterplot of stock-recruitment data; the individual data points are shifted by varying degrees to the left as the recruitment data are associated with diminished measures of reproductive potential (Fig. 4). The stock-recruitment curves derived from these data are shown in Fig. 5, along with the replacement lines corresponding to extinction when reproductive potential is measured as viable larvae with the knife-edged survival curve. The fishing rate associated with this replacement line leads to positive sustained yields when reproductive output is measured as viable larvae (proxy survival curve) or SSB. For the BSAI POP, the estimates of steepness ranged from 0.86 (SSB) to 0.91 (larvae with knife-edged survival curve), whereas the estimates of $F_{40\%}$ decreased from 0.049 (SSB) to 0.033 (larvae with knife-edged survival curve) (Table 1, Fig. 5). Estimated $F_{msy}$ decreased from 0.087 (SSB) to 0.070 (larvae with knife-edged survival curve), and $F_{crash}$ decreased dramatically from 0.35 (SSB) to 0.17 (larvae with knife-edged survival curve) (Table 1, Fig. 6). A similar pattern was seen for
Figure 3. Relative yield as a function of fishing mortality for the stock-recruitment curves presented in Fig. 2b, with reproductive potential defined as SSB (solid line), larvae (proxy survival curve; dashed line), and larvae (knife-edged survival curve; dotted line).

Incorporation of uncertainty in the degree to which spawner age affects larval survival resulted in estimated proxy fishing mortality reference points being more conservative than those attained from consideration of stock-recruitment uncertainty alone. The yield curves for each of the three measures of reproductive potential are shown in Fig. 7(a-c), and correspond to stock recruitment curves with levels of reproductive success of 4 or 16, spanning the range considered by Clark (1991). With reproductive potential measured in SSB, the proxy fishing mortality rate resulting from the maximin criterion occurs at an $F_{spr}$ rate of $F_{43\%}$, identical to the results of Clark (2002) for Beverton-Holt curves. With reproductive potential defined as larvae (either from the proxy or knife-edged survival curves), the proxy fishing reference points would conserve a similar amount of the reproductive potential, but the fishing mortality reference point would decrease from 0.044 (SSB) to 0.032 (lar-
Figure 4. Stock recruitment data for (a) BSAI POP and (b) GOA POP with scaled reproductive potential measured as SSB (circles), larvae from proxy survival curve (triangles), and larvae from knife-edged survival curve (crosses).
Figure 5. Estimated stock-recruitment curves for (a) BSAI POP and (b) GOA POP with scaled reproductive potential measured as SSB (solid lines), larvae from proxy survival curve (dashed lines), and larvae from knife-edged survival curve (dotted lines). The replacement lines correspond to $F$ levels of 0.17 and 0.20 for BSAI and GOA POP, respectively.
vae with the knife-edged curve). The yield curves for all three measures of reproductive potential are plotted against $F$ in Fig. 7d, as incorporation of uncertainty in the degree of maternal effects on larval survival in precludes presenting yield curves in terms of relative reproductive potential per recruit. Here, the identified proxy fishing mortality is $F = 0.035$, more conservative than the value of 0.044 that only considers reproductive potential as SSB.

**Discussion**

Effective reproductive potential of rockfish may be expected to decline at a greater rate than SSB with increased fishing due to a reduced mean age and age-dependent spawner effectiveness (Berkeley et al. 2004a). However, in order to incorporate this observation in operational management advice, it becomes necessary to examine its effect on commonly used reference points such as $F_{\text{msy}}$. It is important to note that although the reproductive potential may be diminished, relative to SSB, the measure of recruits has not been altered. Ideally, one would obtain recruitment estimates from juvenile surveys, although in practice they are typically obtained from stock assessment models utilizing age-composition data from fisheries and surveys. In either case, recruits are simply defined as the number of young fish entering the population. Thus, relating an identical number of recruits with a diminished measure of reproductive potential implies greater estimated resilience, and illustrates that our perception of resilience and stock productivity are not independent of the life-history parameters governing reproductive potential (Morgan and Brattey 2005). The extent to which this estimated increased resilience affects $F_{\text{msy}}$ depends on the relative

<table>
<thead>
<tr>
<th>Stock</th>
<th>Units of reproductive potential</th>
<th>Steepness</th>
<th>$F_{40%}$</th>
<th>$F_{\text{msy}}$</th>
<th>$F_{\text{crash}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSAI POP</td>
<td>SSB</td>
<td>0.86</td>
<td>0.049</td>
<td>0.25</td>
<td>0.087</td>
</tr>
<tr>
<td></td>
<td>Larvae (proxy mortality)</td>
<td>0.89</td>
<td>0.042</td>
<td>0.21</td>
<td>0.084</td>
</tr>
<tr>
<td></td>
<td>Larvae (knife-edged mortality)</td>
<td>0.91</td>
<td>0.033</td>
<td>0.17</td>
<td>0.070</td>
</tr>
<tr>
<td>GOA POP</td>
<td>SSB</td>
<td>0.81</td>
<td>0.060</td>
<td>0.24</td>
<td>0.111</td>
</tr>
<tr>
<td></td>
<td>Larvae (proxy mortality)</td>
<td>0.85</td>
<td>0.049</td>
<td>0.20</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>Larvae (knife-edged mortality)</td>
<td>0.93</td>
<td>0.036</td>
<td>0.12</td>
<td>0.095</td>
</tr>
</tbody>
</table>

Table 1. Estimates of steepness, $F_{40\%}$, $F_{\text{msy}}$, $F_{\text{crash}}$, and proportion unfished SSB or larvae at $F_{\text{msy}}$ for BSAI POP and GOA POP with three units of reproductive potential.
Figure 6. Relative yield as a function of fishing mortality for (a) BSAI POP and (b) GOA POP with reproductive potential defined as SSB (solid line), larvae (proxy survival curve; dashed line), and larvae (knife-edged survival curve; dotted line).
Figure 7. (a-c) Relative yield as a function of either relative spawner per recruit or larvae per recruit for three measures of reproductive potential with reproductive success of 4 (dashed line) and 16 (solid line); the maximin $F_{spr}$ or $F_{lpr}$ are denoted by the vertical lines. (d) Relative yield for all three measures of reproductive potential and two levels of reproductive success plotted against $F$. 
relationship between the stock-recruitment curve and the replacement lines, which are a direct function of the reproductive output per recruit; thus, age-dependent maternal effects on spawning effectiveness may either increase or decrease $F_{\text{msy}}$. For the theoretical example presented here, the estimated increased resilience was the dominant effect and produced increased $F_{\text{msy}}$ with maternal effects. However, for Alaska POP the two opposing processes nearly compensated each other and produced $F_{\text{msy}}$ estimates that were relatively insensitive but decreased slightly with maternal effects, whereas $F_{\text{crash}}$ decreased sharply. These results are similar to those found for Georges Bank Atlantic cod by Murawski et al. (2001), who found that $F_{\text{med}}$ (based on the median level of recruits/spawner) decreased slightly from 0.61 to 0.57 as reproductive potential was converted from SSB to viable larvae, whereas $F_{\text{crash}}$ decreased from 1.4 to 0.88.

Consideration of uncertainty in stock-recruitment relationships led to the development of $F_{35\%}$ as a proxy for $F_{\text{msy}}$ and additional uncertainty regarding the extent to which spawner age structure affects reproductive potential would produce more conservative proxy reference points. Similar to the results found by Clark (2002) for Beverton-Holt recruitment curves, the results presented here indicate that conserving approximately 40% of the reproductive potential per recruit is desirable even if the definition of reproductive potential changes from SSB to viable larvae (produced with either the proxy or knife-edged mortality curves). However, the level of fishing mortality associated with these reference points decreases as reproductive potential changes from SSB to viable larvae (produced with the knife-edged curve). For example, if viable larvae (produced from the knife-edged mortality curve) rather than SSB was known to be the appropriate measure of reproductive potential, the $F$ rate used as a proxy for $F_{\text{msy}}$ would decrease substantially in this example from 0.044 to 0.032. In practice, there is likely to be uncertainty in the extent to which spawner size/age affects larval viability in addition to the stock-recruitment parameters. Because expressing reproductive potential as SSB represents one bound where these maternal effects are assumed to not occur, any consideration of the maternal effects on reproductive potential were found to produce relatively more conservative harvest rate proxies (Fig. 7).

Given the uncertainty in stock-recruitment relationships for Alaska POP, perhaps the best use of $F_{\text{msy}}$ estimates is as a qualitative indicator to assess the need for any directional changes in current harvest rate proxies. The currently used $F_{40\%}$ estimates for BSAI and GOA POP (0.048 and 0.062, respectively) are more conservative than estimates of $F_{\text{msy}}$ based on any of the three measures of reproductive potential, suggesting that the current harvest policy is not unduly aggressive given available data on stock productivity. As with much stock-recruitment data, it can be difficult to parse out how much of the recruitment signal
is attributable to spawner output and how much is attributable to environmental conditions. The estimates of high resiliency for Alaska POP derive from a few strong recruitments during favorable environmental conditions in the 1980s, and these results may not be repeated in different environmental conditions. Similarly, much of what we perceive as the low productivity of rockfish recruitment derives from West Coast data collected during a period of unproductive environmental conditions (McGowen et al. 1998), and this interaction between environmental and stock effects, in part, prompted Dorn (2002) to advise cautious interpretation of his meta-analysis results. What is desired is knowledge of how species with rockfish life-history characteristics respond to a variety of environmental regimes, and development of robust management strategies appropriate for this range of environmental variation. For example, low-frequency trends in recruitment can affect the mean age of the stock and thus the indices of reproductive potential and estimation of $F_{msy}$. Additionally, recruitment variability may be related to longevity (Longhurst 2002), and stochastic simulations can allow examination of the effects of truncated age classes for stocks showing episodic recruitment patterns. Management strategy evaluations (Stokes et al. 1999) appear to be one promising approach for addressing these questions and will be pursued in future research.

Field and laboratory research aimed at documenting the reproductive biology of specific rockfish stocks will greatly assist the interpretation of management importance of maternal effects. Even basic information such as fecundity is absent for many Alaska rockfish stocks, and shows differences between areas for those species where data are available. Although one may never expect to obtain complete knowledge of the influence of spawner age on larval mortality rates in situ, laboratory and field studies that document, for example, the relationship between larval oil globule volume and spawner age can reduce uncertainty for specific stocks and provide a more realistic range of potential maternal effects. A realistic range of the potential influence of maternal effects on larval viability is desired for fisheries management, as this will have a large influence on the harvest rate proxies that will be obtained.

The declines in reproductive potential when maternal age affects larvae viability have also been noted by many other researchers (Scott et al. 1999, Murawski et al. 2001), prompting Berkeley et al. (2004b) to emphasize the importance of older fish in the replenishment of fish stocks and concluding that standard management practices generally do not adequately conserve older fish. However, a complete evaluation of the role of older fish in stock replenishment must not only look at the indices of reproductive potential (i.e., the x-axis of the stock-recruitment plot), but also estimates of stock productivity and management implications resulting from these improved estimates of reproductive potential.
The results of this study are consistent with those of Morgan and Brattey (2005), who found that different measures of reproductive potential can markedly affect perceived stock productivity for Atlantic cod, and demonstrate how information on maternal effects could be addressed within an $F_{spr}$ framework. For future studies, more refined information on rockfish reproductive biology of the type conducted by Berkeley et al. (2004a) would greatly refine our estimates of reproductive potential and the resulting implications for stock productivity.

**Acknowledgments**

We thank Anne Hollowed, Dan Kimura, Bernie Megrey, Rick Stanley, and two anonymous reviewers for their helpful comments on earlier drafts.

**References**


Otter Research. 1996. An introduction to AD Model Builder. Otter Research, P.O. Box 2040, Sidney, B.C. V8L 3S3 Canada.


Index
Italic page numbers indicate illustrations.

A
ABC. See acceptable biological catch (ABC)
Aboriginal Fisheries Commission (British Columbia), 354
Abramov, Alexei A., 207-221
abundance, 168, 169, 175, 334-335, 474, 490, 495. See also biomass; catch statistics; stock assessment larval abundance, 252, 254, 255, 455-456
of Ophiodon elongatus, 224
of predators, 406, 457, 467
relationship to CPUE, 495, 498, 508
of Sebastes aleutianus, 60, 131, 133, 266, 412, 413, 415, 424, 431
of Sebastes alutus, 60, 252, 266, 392-393, 473
of Sebastes borealis, 60, 207, 217, 266, 412, 413, 415, 424
of Sebastes caurinus, 223-224, 234
of Sebastes emphaeus, 224-225, 226, 233-235
of Sebastes glaucus, 62, 66
of Sebastes iracundus, 66
of Sebastes jordani, 451, 454, 458, 461, 463, 464-465, 467
of Sebastes polyspinis, 66, 69, 252, 266
of stable isotopes in Prince William Sound, 21
Age and Growth Program of Alaska Fisheries Science Center, 238
AI. See Aleutian Islands
Alaska. See also Aleutian Islands; Gulf of Alaska; Prince William Sound, Alaska
distribution and genetic structure of Sebastes aleutianus, 121-140
localized depletions of Sebastes alutus, Sebastes polyspinis, and Sebastes variabilis, 493-511
site map, 318
Alaska Board of Fisheries (BOF), 316, 321
Alaska Coastal Current (ACC), 256-258, 257
Alaska Department of Fish and Game (ADFG), 123, 315-316, 319, 320-321, 322, 323, 324
Alaska Fisheries Science Center (AFSC), 159, 412, 413
Age and Growth Program, 238
Resource Assessment and Conservation Engineering Division, 385
Alaskan Stream, 256, 257, 257, 258, 266
Aleutian Islands. See also Bering Sea
characterizing aspects of rockfish, 383-409
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
age (continued)
age determination strategy, 241
age-modulated variation in reproductive development of Sebastes alutus, 1-20
age-structured assessment model for Gulf of Alaska, 429-449
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
timing of ovarian development, 14, 14-15
use of radiometric ages to develop conventional ageing methods for Sebastes borealis, 237-249
Age and Growth Program of Alaska Fisheries Science Center, 238
Al. See Aleutian Islands
ACC. See Alaska Coastal Current (ACC)
acceptable biological catch (ABC), 122, 320, 321, 454
acoustics. See hydroacoustics
Acrosiphonia spp., 380
ADFG. See Alaska Department of Fish and Game (ADFG)
ADMB software, 430, 431, 434
AFA. See American Fisheries Act (AFA)
AFSC. See Alaska Fisheries Science Center (AFSC)
age
and abortive maturation, 11, 12
age composition and growth rates of Sebastes emphaeus, 223, 227, 229-232
Aleutian Islands
localized depletion of Sebastes alutus, 493-511
modeling larval dispersion as a tool, 251-273
site map, 256-258, 386, 398-399
larval releases, 262-265
Aleutian North Slope Current, 257, 257-258, 266
algae, 173
Acrosiphonia spp., 380
Callophyllis spp., 372, 373, 380
Desmarestia viridis, 380
drift algae, 368
Fucus gardneri, 380
habitats of young-of-year, Sebastes caurinus and Sebastes maliger, 380
alleles
allele variation in Sebastes borealis, 217-218
diversity of, 168
frequencies of, 105, 107, 125, 127, 128-129, 143, 144, 452
and genotyping, 105-106
heterozygosity and, 125, 137-140, 167, 169-170, 171, 172, 173
microsatellite data, 137-140, 141, 142, 167
number and ranges of, 176-183
American Fisheries Act (AFA), 310-311
American Fisheries Society (AFS), 316
Ammodytes hexapterus, 318
angry rockfish. See Sebastes iracundus
Animal Movement Analysis Extension, 43
Anoplopoma fimbria, 299, 300, 304, 307, 312, 383, 384, 386, 392, 497
ArcGIS software, 43-44
ArcMap software, 393
ArcView software, 43
Atheresthes stomias (arrowtooth flounder), 497
Atka mackerel. See Pleurogrammus monopterigius
Auke Bay Laboratory, Ocean Carrying Capacity Program (OCC), 154
aurora rockfish. See Sebastes aurora

B
bank rockfish. See Sebastes rufus
Banks, Michael A., 141-152
bathymetry
of Gadus macrocephalus, 401
of Sebastes alutus, 401
of Sebastes glaucus, 67, 69-70
bathymetry (continued)
of Sebastes iracundus, 69-70
of Sebastes polypinis, 69-70
Bathyraja spp., 497
Bellman, Marlene A., 275-294
Bering Sea. See also Aleutian Islands
distribution and genetic structure of Sebastes aleutianus, 121-140
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
pollock fishery, 310-311
site map, 124
biological characteristics
of Sebastes glaucus, 59-85
of Sebastes iracundus, 59-85
of Sebastes polypinis, 59-85
biomass, 168, 315, 380, 431, 440, 460, 476. See also abundance; catch statistics; spawning, spawning stock biomass (SSB); stock assessment
as fish management technique, 384
of Sebastes aleutianus, 122
of Sebastes alutus, 412-413, 415, 419, 435, 501, 504
of Sebastes ciliatus/variabilis, 315, 320, 435
of Sebastes jordani, 455, 460-461, 462, 467
of Sebastes melanops, 317
of Sebastes paucispinis, 176
of Sebastes polypinis, 495, 503
total catch biomass, 433-434
use of Leslie depletion analysis, 497, 498, 499, 507
birds, predatory. See seabirds
black-and-yellow rockfish. See Sebastes chrysomelas
black bass. See Sebastes melanostomus
blackgill rockfish. See Sebastes melanops
blackmouth rockfish. See Sebastes melanostomus
blackrockfish. See Sebastes sinensis
body length
and abortive maturation, 11, 12
and otolith size of Sebastes borealis, 210
of Sebastes glaucus, 76-79
of Sebastes iracundus, 76-79
of Sebastes polypinis, 76-80
timing of ovarian development, 14, 14-15

Index
body length (continued)
and timing of parturition, 4
body weight
of *Sebastes glaucus*, 78-80
of *Sebastes iracundus*, 78-80
of *Sebastes polyspinis*, 78-80
BOF. See Alaska Board of Fisheries (BOF)
Bray-Curtis dissimilarity measure, 388-389
British Columbia, 234, 309, 474
developing an integrated commercial fishing strategy for, 353-366
and *Sebastes aleutianus*, 131, 256
and *Sebastes alutus*, 203, 254, 494, 508, 515
and *Sebastes borealis*, 217, 256
and *Sebastes caurinus*, 183
and *Sebastes ciliatus/variabilis*, 203
and *Sebastes jordani*, 452
and *Sebastes maliger*, 183
and *Sebastes mentella*, 183
and *Sebastes polyspinis*, 203
and *Sebastes reedi*, 203
and *Sebastes ruberrimus*, 183
British Columbia Aboriginal Fisheries Commission, 354
broadbanded thornyhead rockfish. See *Sebastolobus macrochir*
bronzespotted rockfish. See *Sebastes gilli*
brown rockfish. See *Sebastes auriculatus*
BSAI. See Aleutian Islands; Bering Sea
Buckley, Raymond M., 87-98, 99-119
bycatch rates
of *Anoplopoma fimbria*, 495
maximum retainable allowance (MRA), 300, 307
reducing, 354, 357, 358
of *Sebastes jordani*, 454, 455
of *Sebastes polyspinis*, 495
C
calico rockfish. See *Sebastes dalli*
California Cooperative Oceanic and Fisheries Investigations (CalCOFI), 455-456, 460, 461, 465
California Current population dynamics of *Sebastes jordani*, 451-472
Triennial Trawl Survey in, 456, 460, 464
California Department of Fish and Game, 278
*Callophyllis* spp., 373, 380
Canadian Species at Risk Act, 355
canary rockfish. See *Sebastes pinniger*
Cancer magister, 318
canopy kelp. See *Nereocystis luetkeana*
carbon isotope values, 21, 23, 24, 27-28, 29-30, 31, 33
catch limits, 279, 283, 297, 354, 506
catch restrictions. See quotas; total allowable catch (TAC)
catch statistics
catch-per-unit effort (CPUE), 386, 388, 455, 456
vs. cumulative catch, 502, 507
in large-scale trawl surveys of Gulf of Alaska, 423, 423
localized depletions of *Sebastes alutus*, *Sebastes polyspinis*, and *Sebastes ciliatus/variabilis*, 493-494
relationship to abundance, 495, 498, 504-505, 508. See also abundance; biomass; spawning, spawning stock biomass (SSB); stock assessment and Unimak surveys, 415-416, 416-417, 418
catch rate for *Sebastes glaucus*, 74-76
catch rate for *Sebastes iracundus*, 74-76
catch rate for *Sebastes polyspinis*, 74-76
for *Sebastes aleutianus*, 415
for *Sebastes borealis*, 415
Cephus columba, 318
*Cerorhinca monocerata*, 457-458
CGIAC. See Commercial Groundfish Integrated Advisory Committee (CGIAC)
chameleon rockfish. See *Sebastes phillipsi*
Chamissocephalus gunnari, 474
chilipepper rockfish. See *Sebastes goodei*
China rockfish. See *Sebastes nebulosus*
chinook salmon. See *Oncorhynchus tshawytscha*
CIC. See Commercial Groundfish Integrated Advisory Committee (CGIAC), Commercial Industry Caucus
Clausen, David M., 153-183, 411-428, 473-492
*Clupea pallasi*, 318
Coates, Julia, 223-236
coho salmon. See *Oncorhynchus kisutch*
commercial fisheries
developing an integrated strategy for British Columbia, 353-366
management of *Sebastes melanops* in Kodiak Management Area, 315-327
commercial fisheries (continued)
management strategies of rebuilding rockfish stocks, 329-351
minimizing impact of fishing on habitat, 275-294
and Sebastes jordani, 451, 454
Commercial Groundfish Integrated Advisory Committee (CGIAC), 354
Commercial Industry Caucus (CIC), 353, 354-355, 357-358, 359, 360-364, 365
EM Working Group, 359
conservation, 133, 142, 175-176, 354, 367
depletion as an issue, 252-253, 493, 494, 495, 509
management strategy evaluation of rebuilding revision rules for overfished stocks, 329-351
Marine Conservation Caucus, 354
Marine protected areas (MPAs), 40, 54, 99, 100, 115, 168, 235, 324, 368, 378, 384, 401
modeling larval dispersion as a tool for marine reserve design, 251-273
trawl effort distribution—regulatory shifts and seafloor habitat conservation, 275-294
copepod. See Neocalanus cristatus
copper rockfish. See Sebastes caurinus
coral reef damselfish. See Pomacentrus amboinensis
Cortez rockfish. See Sebastes cortesi
Courtney, Dean L., 429-449
cowcod. See Sebastes levis
currents. See Alaska Coastal Current (ACC); Alaskan Stream; Aleutian North Slope Current; California Current; West Wind Drift

dark rockfish. See Sebastes ciliatus
darkblotched rockfish. See Sebastes crameri
Darkblotted Rockfish Conservation Area (DBCA), 288-289
Department of Fisheries and Oceans Canada (DFO), 357-359, 361
depletion. See also overfishing: stock assessment
protection from, 252
rebuilding revision rules for overfished stocks, 239-351
of Sebastes aleutianus, 122
of Sebastes alutus, 493-511
of Sebastes ciliatus/variabilis, 493-511
depression (continued)
of Sebastes jordani, 461
of Sebastes melanops, 39, 322-323
of Sebastes polypinai, 493-511
Desmarestia viridis, 380
DFO. See Department of Fisheries and Oceans Canada (DFO)
Dick, E.J., 451-472
distribution. See also stock assessment
of Sebastes aleutianus, 121-140, 386, 411, 416, 424
of Sebastes alutus, 386, 412, 416, 421, 424, 493-511
of Sebastes auriculatus, 93, 101, 112, 114
of Sebastes borealis, 217, 386, 411, 416, 424
of Sebastes ciliatus/variabilis, 493-511
of Sebastes entomelas, 164
of Sebastes glaucus, 59-85, 71
of Sebastes iracundus, 59-85, 71
of Sebastes melanops, 50, 53
of Sebastes mystinus, 164
of Sebastes polypinai, 59-85, 71, 493-511
trawl effort distribution—regulatory shifts and seafloor habitat conservation, 275-294
of young-of-year rockfish, 154, 164, 165, 376, 377, 380
DNA analysis, 103-105, 169, 187
of juvenile rockfish, 158-159, 160
mtDNA, 123-124, 126, 154, 158, 185-206
dockside monitoring programs (DMP), 359
Dorn, Martin, 513-533
Dungeness crab. See Cancer magister
dusky rockfish. See Sebastes ciliatus/variabilis
dwarf-red rockfish. See Sebastes rufinanus

echosounder signals. See hydroacoustics
ecological depletion. See depletion
eelgrass. See Zostera marina
EEZ. See Exclusive Economic Zone (EEZ)
EFH. See essential fish habitat (EFH)
EFH-EIS. See Groundfish Essential Fish Habitat Environmental Impact Statement (NOAA Fisheries)
EFP. See exempted fishing permits (EFP)
eggs
atresia of oocytes, 10, 11, 14
developing eggs, 13, 16, 18, 89
egg abundance used for stock assessment, 455-456
eggs (continued)

marking of, 101
maximum oocyte diameter (MMOD), 4, 5, 8, 8-9
oocyte resorption, 4, 10, 16
planktonic egg stage, 254

Electronic Monitoring Working Group of the CIC, 359
El Niño, impact of, 223, 226, 233-234, 235, 455, 461
Embiotochidae, 87, 95
environmental factors. See El Niño, impact of; water depth; water temperature

Environmental Systems Research Institute, Inc. (ESRI), 43, 278, 393
essential fish habitat (EFH), 252
minimizing impact of trawl fishing on habitat, 275-294
Excel software, 105, 209, 227
Exclusive Economic Zone (EEZ), 278, 315, 320, 321
exempted fishing permits (EFP), 279-280

false jacopever. See Sebastes capensis
feeding dynamics. See food supply
Field, J.C., 451-472
Fina, Mark, 295-313
fins, morphological description of, 161-164
First Nations, 353, 357, 358
fisheries management, 142-143, 207-208.

See also stock assessment
catch limitations. See total allowable catch (TAC)
developing an integrated commercial fishing strategy for British Columbia, 353-366
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
minimizing impact of trawl fishing on habitat, 275-294
population decline of rockfish, 167-183 of Sebastes melanops in Kodiak Management Area, 315-327
share-based management program for in central Gulf of Alaska, 295-313
strategies for rebuilding overfished rockfish stocks, 329-351
Fishery Conservation and Management Act 1996 (U.S.), 276
fishing industry. See commercial fisheries
flag rockfish. See Sebastes rubrivinctus
food supply. See also prey; zooplankton
food webs, 176, 223
in Prince William Sound, Alaska, 23, 31
in Puget Sound, 223, 225
seabirds, food habits of, 457, 458, 464, 464-465
of Sebastes caurinus, 31
of Sebastes emphaeus, 234-235
of Sebastes iracundus, 81
of Sebastes maliger, 31
of Sebastes melanops, 53, 317
of Sebastes polypinio, 82
of Sebastes ruberrimus, 31
Zalophus californianus, food habits of, 458, 465
freckled rockfish. See Sebastes lentiginosus
FSTAT software, 105
Fucus gardneri, 380
Fujioka, Jeffrey T., 411-428, 473-492

G

Gadus macrocephalus, 299, 300, 304, 307, 312, 383, 384, 386, 393-393, 400
GENEPOP software, 105

genetics. See also DNA analysis
genetic divergence. See also DNA analysis
genetic divergences of 2 types of Sebastes aleutianus, 121-140
genetic identification of Sebastes auriculatus progeny, 91, 93, 95, 99-119
microsatellite analysis, 123-125, 217-218
allele frequencies, 137-140, 141
spatial genetic analysis of Sebastes crameri, 141-152
subgeneric relations within Sebastes, 185-206
used to estimate population and genetic diversity, 167-183

Gharrett, Anthony J., 121-140, 153-183, 185-206

GHLs. See guideline harvest levels (GHLs)
Global Ocean Ecosystem Dynamics (GLOBEC), 155
GLOBEC, 155

GOA. See Gulf of Alaska
Goetz, Betty, 223-236
goma-soi. See Sebastes nivosus
Gomez-Uchida, Daniel, 141-152
gopher rockfish. See Sebastes carnatus
Goto, A., 185-206
gill rockfish. See Sebastes rastrelliger
Gray, Andrew K., 121-140, 185-206
gray rockfish. See *Sebastes glaucus*
greenblotched rockfish. See *Sebastes rosenblatti*
green filamentous algae. See *Acrosiphonia* spp.
greenspotted rockfish. See *Sebastes chlorostictus*

Groundfish Essential Fish Habitat
Environmental Impact Statement (NOAA Fisheries), 292

developing an integrated strategy for British Columbia, 353-366
licenses for in British Columbia, 356
rebuilding revision rules for overfished stocks, 329-351

Groundfish Fishery Management Plan, 330
Groundfish Hook-and-line Advisory Committee (GHLAC), 358
growth rate, 17, 244, 467. See also otoliths changes in growth and recruitment of *Sebastes emphaeus*, 223-236
guideline harvest levels (GHLs), 315, 320, 321-322, 324, 330, 334, 349

Gulf of Alaska. See also Alaska
age-structured assessment model, 429-449
carbon source and rockfish, 21, 23, 27, 31, 34
central Gulf share-based management program for, 295-313
site map, 298-299
distribution and genetic structure of *Sebastes aleutianus*, 121-140
echosounder signals for improving trawl survey precision for *Sebastes alutus* survey, 473-492
effect of maternal age of spawning of *Sebastes alutus* on fishing rate reference points, 513-533
fishery management plan, 321
juvenile rockfish in, 153-183
localized depletion of *Sebastes polypsis* and *Sebastes ciliatus/varibiulis*, 493-511
management of commercial fisheries for *Sebastes melanops*, 315-327
modeling larval dispersion as a tool, 251-273
site map, 124, 155, 256-258, 414-415
larval releases, 262-265

Gulf of Alaska (continued)

variability in trawl survey catches of *Sebastes alutus*, *Sebastes borealis*, and *Sebastes aleutianus*, 411-428
gulf rockfish. See *Sebastes exsul*

Gunderson, Donald R., 223-236, 237-249, 367-382

H

habitat
minimizing impact of trawl fishing on habitat, 275-294
nearshore habitat associations of young-of-year *Sebastes caurinus* and *Sebastes maliger*, 367-382

halfbanded rockfish. See *Sebastes semicinctus*

Hannah, Robert W., 1-20, 39-57
Hanselman, Dana, 429-449, 493-511, 513-533

Hardy Weinberg, 99-119
Hayden-Spear, Jessica, 367-382

Heifetz, Jonathan, 121-140, 429-449, 473-492

Heppell, Scott A., 275-294
Hermann, Albert J., 251-273
herring. See *Clupea pallasii*

Heterozygosity. See alleles

Hexagrammos decagrammus, 234, 377

Hippoglossus stenolepis, 296, 307, 310

honeycomb rockfish. See *Sebastes umbrosus*

Hutchinson, Charles E., 237-249

hydroacoustics
acoustic telemetry, 40-41
echosounder signals for improving trawl survey precision for *Sebastes alutus* survey, 473-492

I

Ianelli, James N., 429-449

incidental catch species, 295-296, 299, 300, 304-305, 307, 308, 310, 312

rockfish as, 238, 283, 299, 305, 307, 312, 384, 495

individual transferable quotas (ITQs), 355, 358-359

individual vessel quotas (IVQs), 355, 357-358, 359, 365
Insightful Corporation, 388
isotopes, 238
blood isotope data, 21, 34-35
carbon isotope values, 21, 23, 24, 27-28, 29-30, 31, 33
lipid isotope data, 21, 24, 29-30, 33
nitrogen isotope values, 21, 23, 24, 29-30, 31, 33
rockfish trophic relationships in Prince William Sound, 21-37

J
juveniles
in the Gulf of Alaska, 153-183
juvenile survey of Sebastes jordani, 456-457
migration of, 96, 122, 207, 208, 266, 267, 317
and otolith samples, 87, 88, 90, 91, 95-96, 207

K
Kamchatka Fisheries and Oceanography Research Institute (KamchatNIRO), 61
Kastelle, Craig R., 237-249
kelp. See algae
ekelp greenling. See Hexagrammos decagrammus
kelp rockfish. See Sebastes atrovirens
Kendall Jr., Arthur W., 153-183
Key, M., 451-472
Kimura, Daniel K., 237-249
king salmon. See Oncorhynchus tshawytscha
Kline Jr., Thomas C., 21-37
Kodiak Management Area
management of commercial fisheries for Sebastes melanops, 315-327
site map, 325
Kondzela, Christine M., 153-183
Koolman, John, 353-366

L
LaFrance, Laura, 223-236
Laminaria spp. and young-of-year, Sebastes caurinus and Sebastes maliger, 367-382
larvae
larval abundance of Sebastes jordani, 463
larval dispersion of rockfish, 88-89, 122, 251-273
larvae (continued)
larval retention, 40, 89, 96, 253, 261, 267-268
and dispersal of Sebastes auriculatus, 99-119
mortality of, 95, 101, 516-517, 518, 526, 529, 530
of Sebastes alutus, 518-519, 520-526
trans-generational markings of larval otoliths, 87-98
LeClair, Larry L., 87-98, 99-119
length. See body length
Leslie depletion analysis, 500, 502, 504
site map for, 496
summary results, 499
Li, Zhuozhuo, 121-140, 153-183, 185-206
lingcod. See Ophiodon elongatus
lipid isotope data, 21, 24, 29-30, 33
localized depletion, 322-323, 495
of Sebastes alutus, 493-511
of Sebastes ciliatus/variabilis, 493-511
of Sebastes polylepis, 493-511
Love, M.S., 185-206
Lowry, M., 451-472
Lucero, Y., 451-472
Lunsford, Chris R., 473-492

M
MacCall, A., 451-472
mackerel icefish. See Champsocephalus gunnari
macroscopic maturity stage, 7, 9, 9
management strategies
developing an integrated commercial fishing strategy for British Columbia, 353-366
for rebuilding rockfish stocks, 329-351, 385
Marine Conservation Caucus, 354
Marine protected areas (MPAs), 40, 54, 99, 100, 115, 168, 235, 324, 368, 378, 384, 401
marine reserve design, modeling larval dispersion as a tool, 251-273
Markov Chain Monte Carlo (MCMC) integration technique, 431, 434-435, 440
Matala, Andrew P., 121-140
Mattes, Lynn A., 315-327
maturation
of Sebastes alutus, 1-20
of Sebastes borealis, 243-244
maximum oocyte diameter (MMOD), 5, 8, 8-9
maximum retainable allowance (MRA), 300, 307
Index

maximum sustainable yield (MSY), 322, 330, 384, 514, 515
MCMC. See Markov Chain Monte Carlo (MCMC) integration technique
*Merluccius productus*, 452, 457, 474
methodologies
field trial, 89-90
genetic analysis, 143, 144
DNA analysis, 103-105, 169, 187
microsatellite analysis, 123-125
mtDNA, 123-124, 126, 158
phylogenetic analysis, 187
Leslie depletion analysis, 496, 497-498
logbook data, 278
modeling
larval individual-based model (IBM), 252
operating model, 334-335
Monte Carlo simulation techniques, 333-334
performance measures, 339-340
population dynamics equations, 515
rebuilding analysis, 336
regression analysis, 215
restriction site analysis, 187
sampling, 3-4, 103, 144, 226
adaptive sampling, 474, 485, 488, 489
Sound Ecosystem Assessment program (SEA), 25
spatial analysis, 278-280
stock assessment, 335-336
surveys
acoustic surveys, 40-41, 455
bottom trawl surveys, 59, 60-61, 209, 385-386, 401, 406
experimental surveys, 413-415
juvenile surveys, 456-457
large scale trawl surveys, 418-421
salmonid research surveys, 153
trawl surveys, 3-4, 126-127, 432, 456, 495-497
use of echosounder, 475-476
tagging, 41, 43
Mexican rockfish. See *Sebastes macdonaldi*
Micro-Checker software, 105, 106
microsatellite analysis, 123-125
allele frequencies, 137-140, 141
population decline of rockfish in northeastern Pacific Ocean, 167-183
microscopic determination of maturity, 9, 9
migration
of juveniles, 96, 122, 207, 208, 266, 267, 317
migration (continued)
ontogenetic, 268
reverse migration, 207, 208
of *Sebastes aleutianus*, 122-123, 132
of *Sebastes alutus*, 489, 494, 504-505
of *Sebastes auriculatus*, 100
of *Sebastes borealis*, 208
of *Sebastes crameri*, 141, 144-148
of *Sebastes glaucus*, 65, 75, 76-77
of *Sebastes iracundus*, 69
of *Sebastes polygynus*, 67, 76, 508
stepping-stone model, 143, 146, 147
vertical migration, 101, 112, 251, 253-254, 255, 261, 262-265, 268
Miller, Bruce S., 223-236
minimum stock size threshold (MSST), 330, 331
mitochondrial DNA analysis, 123-124, 126, 154
for assigning subgenera to *Sebastes*, 185-206
of juvenile rockfish, 156-158, 160
models and modeling
age and size structured statistical model, 454-455
age-structured assessment models, 429-449
stock assessment models, 429-449
MONTE module, 126
morphological analysis of Gulf of Alaska juvenile rockfish, 159-160, 161-164
mortality, 55, 89, 359, 360
natural mortality, 227-228, 228, 276, 331, 332, 334, 335, 431-432, 434, 436, 437, 440
of *Sebastes jordani*, 452, 455, 460, 461, 465, 467
of rockfish larvae, 95, 101, 516-517, 518, 526, 529, 530
Mose, Brian, 353-366
movement patterns of *Sebastes melanops*, 39-57
MPAs. See marine protected areas (MPAs)
MRA. See maximum retainable allowance (MRA)
M ratio, 176-183
MSST. See minimum stock size threshold (MSST)
MSY. See maximum sustainable yield (MSY)
mtDNA. See mitochondrial DNA analysis
Multifan CL software, 430
murre. See Uria aalge
mutation rate and population size, 169-176

N
Narum, Shawn R., 167-183
National Marine Fisheries Service (NMFS), 2, 315, 320, 321, 431, 435, 497
National Oceanic and Atmospheric Administration (NOAA). See NOAA Fisheries
Neocalanus cristatus, 28
Nereocystis luetkeana, 373, 380
Newton, Lyndsay, 99-119
nitrogen isotope values, 21, 23, 24, 29-30, 31, 33
NMFS. See National Marine Fisheries Service (NMFS)
NOAA Fisheries, 292, 331, 337
northern rockfish. See Sebastes polynspis
North Pacific Fishery Management Council (NPFMC), 122, 315
pilot share-based program for fishery management in central Gulf of Alaska, 295-313
North Pacific Groundfish Observer Program, 495-496
North Pacific Observer Program, 493
nucleotide divergences, 187, 191, 192, 200, 201
nutrition. See food supply

O
Ocean Carrying Capacity Program (OCC), Auke Bay Laboratory, 154
olive rockfish. See Sebastes serranoides
Olson, Jean M., 39-57
Oncorhynchus kisutch, 27
Oncorhynchus tshawytscha, 27, 142, 318, 452
ovaries. See eggs
Ophiodon elongatus, 223, 234, 318, 377-378
Oregon coast
age and reproductive development of Sebastes alutus, 1-20
Sebastes melanops movement patterns, 39-57
and Sebastes pinniger, 183
site map, 42
Oregon Department of Fish and Wildlife, 278
Orlov, Alexei M., 59-85, 207-221
otoliths, 101. See also growth rate
otolith study of population structure of Sebastes borealis, 207-221
size of otoliths, 210-213, 216-217
trans-generational markings of larval marine fish, 87-98
used to determine sea lion prey, 458-459
use of radiometric ages to develop conventional ageing methods for Sebastes borealis, 237-249
Otter Research Ltd., 430

P
Pacific cod. See Gadus macrocephalus
Pacific Fishery Management Council (PFMC), 2, 454
Rebuilding Plans for overfished rockfish stocks, 329-351
Pacific hake. See Merluccius productus
Pacific halibut. See Hippoglossus stenolepis
Pacific Ocean
Northeast Pacific, regional ocean modeling of, 258-260
North Pacific, 10
distribution and biology of rockfish in the western North Pacific, 59-85
Sebastes borealis, otolith study of ageing, 237-249
Sebastes borealis, otolith study of population structure, 207-221
site map, 209
Oregon coast, 1-20
and Sebastes alutus, 1-20
and Sebastes melanops, 39-57
and Sebastes pinniger, 183
site map, 42
population decline of rockfish in northeastern Pacific Ocean, 167-183
Pacific ocean perch. See *Sebastes alutus*
Palsson, Wayne A., 223-236
parental assignment, 108-113
Parker, Steven J., 1-20, 39-57
Pearson, D., 451-472
Peterson, Eric L., 121-140
PFMC. See Pacific Fishery Management Council (PFMC)
phylogenetic analysis, 190, 191, 193, 199-204
pigeon guillemots. See *Cepphus columba*
pink rockfish. See *Sebastes similor*
*Pleurogrammus monopterygius*, 383, 384, 386, 389-393, 399, 400, 406, 508
pollock. See *Theragra chalcogramma*
*Pomacentrus amboinensis*, 101
POP (Pacific ocean perch). See *Sebastes alutus*
population assignment of *Sebastes crameri* using spatial genetic structure, 141-152
population dynamics
  effect of maternal age of spawning of *Sebastes alutus* on fishing rate reference points, 513-533
  otolith study of population structure of *Sebastes borealis*, 207-221
  population decline of rockfish, 167-183
  population size and $M$ ratio, 176-183
  of *Sebastes jordani* in the California Current, 451-472
predators and predation, 377-378
  *Cepphus columba*, 318
  *Laminaria* spp. as optimal habitat for young-of-year, 377
  *Oncorhynchus tshawytscha*, 318, 452
  *Ophiodon elongatus*, 318
  predator-prey dynamics, 495
  seabirds, 452, 457-458, 464, 464-465
  of young-of-year *Sebastes caurinus* and *Sebastes maliger*, 377-378, 379-380
  *Zalophus californianus*, 452, 458-459, 463, 465, 466, 467
prey, 406-407. See also food supply
  *Ammodites hexapterus*, 318
  *Cancer magister*, 318
  *Clupea pallasi*, 318
euphausiids, 452
Prince William Sound, Alaska, 123, 126, 170, 175. See also Alaska
trophic relationships of rockfish, 21-37
prohibited species catch (PSC), 296, 298
*Pteropodus*, 185
Puget Sound, 53, 149, 175
*Sebastes auriculatus*
genic identification of progeny, 99-119
trans-generational markings of otoliths, 87-98
*Sebastes emphaeus*, changes in growth and recruitment of, 223-236
young-of-year rockfish in the San Juan Channel, 367-382
Puget Sound rockfish. See *Sebastes emphaeus*
Punt, André E., 329-351
PWS. See Prince William Sound, Alaska
pygmy rockfish. See *Sebastes wilsoni*
Q
quillback rockfish. See *Sebastes maliger*
quotas, 360, 363, 384, 430. See also catch restrictions; total allowable catch (TAC)
individual transferable quotas (ITQs), 355, 358-359
individual vessel quotas (IVQs), 355, 357-358, 359, 365
R
radiometric ageing to develop conventional ageing methods for *Sebastes borealis*, 237-249
*Raja* spp., 497
Ralston, Stephen, 329-351, 451-472
Rankin, Polly S., 39-57
RCA. See Rockfish Conservation Areas (RCA)
Rebuilding Plans for overfished rockfish stocks, 329-351
recruitment, 101, 268, 343, 347, 349, 430, 437-439
changes in growth and recruitment of *Sebastes emphaeus*, 223-236
equilibrium recruitment, 460, 461, 518, 522
larval recruitment, 88-89, 96
outside recruitment, 252, 253, 255, 261, 267
of *Sebastes alutus*, 513, 515, 518, 520
of *Sebastes caurinus*, 368
of *Sebastes jordani*, 454, 456-457, 460-461, 462, 465
of *Sebastes polyspinis*, 432-433
self-recruitment, 96, 97, 98, 99-103, 111-113, 261, 267
recruitment (continued)
stock recruitment, 330, 332, 334-336, 350, 431-434, 440-441, 442, 460, 514-516, 519-520, 521, 522-523, 523, 525, 529
redbanded rockfish. See Sebastes babcocki
red branched algae. See Callophyllis spp.
redfish. See Sebastes mentella
redstripe rockfish. See Sebastes proriger
Regional Ocean Modeling System (ROMS), 256-260
reproduction. See also eggs; spawning
reproductive biology of Sebastes alutus, 515
reproductive development of Sebastes alutus, 1-20
timing of, 4-5, 13
restrictions, 277, 291, 311, 324, 360, 365, 497. See also quotas; total allowable catch (TAC)
restriction site analysis, 185, 190-191, 193, 200, 203
DNA restriction analysis, 123, 124, 158, 159, 185, 186, 187, 190-191, 204
intraspecific variations in neighbor-joining trees, 194-198, 199
retention of larvae, 40, 89, 96, 253, 261, 267-268
and dispersal of Sebastes auriculatus, 99-119
Reuter, Rebecca F., 383-409, 493-511
rhinoceros auklet. See Cerorhinca monocerata
rockfish. See names of individual species; Sebastes spp.
Rockfish Conservation Areas (RCA), 283, 284-285, 286-287, 290
ROMS. See Regional Ocean Modeling System (ROMS)
rosethorn rockfish. See Sebastes helvomaculatus
rosy rockfish. See Sebastes rosaceus
roughey rockfish. See Sebastes aleutianus
Russian Federal Research Institute for Fisheries and Oceanography, 61
sablefish. See Anoplopoma fimbria
Sagalkin, Nicholas H., 315-327
Sakhalin Research Institute of Fishery and Oceanography (SakhNIRO), 61
salmon
chinook. See Oncorhynchus tshawytscha
salmon (continued)
coho salmon. See Oncorhynchus kisutch
salmonid research surveys, 155
sandlance. See Ammodytes hexapterus
San Juan Channel, 224, 226, 228, 234
nearshore habitat associations of young-of-year Sebastes caurinus and Sebastes maliiger, 367-382
site map, 225, 369
SARA. See Species at Risk Act (SARA) of Canada
SAS Institute, Inc., 28
Schroder, Steve L., 87-98
SEA. See Sound Ecosystem Assessment program (SEA)
seabirds, 452
Sebastes jordani as prey, 457-458
seafloor habitat conservation, minimizing impact of trawl fishing on habitat, 275-294
seagrass. See Zostera marina
sea lettuce. See Ulva spp.
sea lions. See Zalophus californianus
Sebastes spp.
characterizing aspects of rockfish in the Aleutian Islands, 383-409
population decline of rockfish, 167-183
in Prince William Sound, Alaska, 21-37
Rebuilding Plans for overfished rockfish stocks, 329-351
subgeneric relations within Sebastes, 185-206
Sebastes aleutianus, 203
abundance of, 60, 131, 133, 266, 412, 413, 415, 424, 431
age-structured assessment model for Gulf of Alaska, 429-449
distribution and genetic structure of, 121-140, 386, 411, 416, 424
distribution of, 121-140, 386, 411, 416, 424
in the Gulf of Alaska, 153-183
as incidental catch, 307, 312, 494-495
migration of, 122-123, 132
morphological description of, 163
spatial management of, 149
as survey haul group, 299, 383-384, 385, 393, 399
total allowable catch (TAC) of, 363
variability in trawl survey catches in Gulf of Alaska, 411-428
Sebastes alutus, 201, 203, 389-393, 399
abundance of, 60, 252, 266, 392-393, 473
Sebastes alutus (continued)
age-structured assessment model for
Gulf of Alaska, 429-449
biomass of, 412-413, 415, 419, 435,
501, 504
in British Columbia, 203, 254, 494,
508, 515
designated as overfished off the U.S.
West Coast, 331
distribution of, 386, 412, 416, 421, 424,
493-511
effect of maternal age of spawning on
fishing rate reference points,
513-533
in the Gulf of Alaska, 153-183
heterozygosity and, 170, 175
improving trawl survey precision,
473-492
larvae of, 518-519, 520-526
localized depletion of, 493-511
migration of, 489, 494, 504-505
morphological description of, 163-164
overharvesting of, 175
pilot program for management of,
295-313
radiometric ageing of, 238
recruitment of, 513, 515, 518, 520
reproductive development of, 1-20
spatial management of, 148
spawning, 2
effect of maternal age of spawning
on fishing rate reference
points, 513-533
synchronous spawning of, 10, 13
spawning stock biomass (SSB), 513,
514, 515, 516, 520-524, 526-
527
as survey haul group, 383, 384, 385,
386, 393-394, 401, 406
variability in trawl survey catches in
Gulf of Alaska, 411-428
Sebastes atrovirens, 185, 200, 201
Sebastes auriculatus, 148-149, 185-186,
200, 201
distribution of, 93, 101, 112
genetic identification of progeny of, 91,
93, 95, 99-119
trans-generational markings of larval
otoliths, 87-98
Sebastes aurora, 203
Sebastes babcocki, 22, 200, 384
Sebastes baramenuke, 201
Sebastes borealis, 31, 148, 153-183, 203,
299, 399
abundance of, 60, 207, 217, 266, 412,
413, 415, 424
Sebastes borealis (continued)
in British Columbia, 217, 256
distribution of, 217, 386, 411, 416, 424
in the Gulf of Alaska, 153-183
as incidental catch, 307, 312, 494
maturation of, 243-244
morphological description of, 161
mutation rate of, 170, 175
otolith study of population structure,
207-221
reproductive and life history, 168
as survey haul group, 383-384, 385,
393
total allowable catch (TAC), 363
use of radiometric ages to develop
conventional ageing methods,
237-249
variability in trawl survey catches in
Gulf of Alaska, 411-428
Sebastes brevispinis, 201
Sebastes capensis, 200
Sebastes carnatus, 170, 200
Sebastes caurinus, 21, 200
abundance of, 223-224, 234
blood samples of, 25, 27, 28, 34
in British Columbia, 183
food supply for, 31
heterozygosity and, 170, 175
nearshore habitat associations of
young-of-year, 367-382
reproductive and life history, 168
spatial management of, 148
Sebastes chlorostictus, 190, 200
Sebastes chrysomelas, 170, 174, 200
Sebastes ciliatus/variabilis, 21-34, 154, 160,
186, 201, 203, 252, 384, 385
age-structured assessment model for
Gulf of Alaska, 429-449
biomass of, 315, 320, 435
distribution of, 493-511
localized depletion of, 493-511
morphological description of, 161, 163
pilot program for management of,
295-313
Sebastes constellatus, 200
Sebastes cortezi, 202
Sebastes crameri, 4, 16, 186, 201, 202-203,
283
designated as overfished off the U.S.
West Coast, 331
in the Gulf of Alaska, 153, 160
morphological description of, 161, 163
population differentiation and spatial
genetic analysis, 141-152
Sebastes dalli, 185-186, 200, 201, 202
Sebastes diploproa, 202, 238
Sebastes elongatus, 201
Sebastes emphaeus, 202
abundance of, 224-225, 226, 233-235
growth and recruitment, changes in, 223-236
Sebastes ensifer, 200
Sebastes entomelas, 154, 160, 170, 201,
203, 315, 320, 456, 457
designated as overfished off the U.S.
West Coast, 331
distribution of, 164
morphological description of, 163-164
pilot program for management of, 295-313
Sebastes eos, 200
Sebastes exsul, 200
Sebastes flavidus, 4, 202, 224, 315, 320
pilot program for management of, 295-313
Sebastes gilli, 186, 200, 203
Sebastes glaucus, 59-85, 71
Sebastes goodei, 203, 457
Sebastes helvomaculatus, 200
Sebastes hopkinsi, 201
Sebastes hubbsi, 200
Sebastes iracundus, 201
distribution of, 59-85, 71
Sebastes jordani, 203
biological characteristics, 452
biomass of, 455, 460-461, 462, 467
population dynamics in the California
Current, 451-472
spawning stock biomass (SSB), 155,
455, 461, 495
Sebastes lentiginosus, 188, 200
Sebastes levis, 203
designated as overfished off the U.S.
West Coast, 331
Sebastes macdonaldi, 201, 203
Sebastes maliger, 21, 34, 175, 200, 223-224
food supply of, 31
nearshore habitat associations of
young-of-year, 367-382
Sebastes melanops, 4, 25, 148, 202, 223-
224, 307, 518
biological characteristics, 316-318
depletion of, 39, 322-323
distribution of, 50, 53
food supply of, 53, 317
in Kodiak Management Area, 315-327
movement patterns of, 39-57
tagging of, 41, 43, 53, 318
Sebastes melanostomus, 201, 203
Sebastes mentella, 170, 183
Sebastes miniatus, 149, 203
Sebastes mystinus, 160, 164, 201, 202, 203,
307
Sebastes nebulosus, 200
Sebastes nigrocinctus, 200
Sebastes nivosus, 200
Sebastes notius, 200
Sebastes ovalis, 201
Sebastes paucispinis, 148, 168, 170, 175,
176, 202, 203, 291, 331
Sebastes peduncularis, 202
Sebastes phillipsi, 203
Sebastes pinniger, 148, 183, 203, 291
designated as overfished off the U.S.
West Coast, 331
Sebastes polyspinis, 154, 160, 186, 201, 203
abundance of, 66, 69, 252, 266
age-structured assessment model for
Gulf of Alaska, 429-449
biomass of, 495, 503
distribution of, 59-85, 71, 493-511
as incidental catch, 384
localized depletion of, 493-511
maximum sustainable yield (MSY), 384
migration of, 67, 76, 508
morphological description of, 161, 163
pilot program for management of, 295-313
radiometric ageing of, 238
as survey group haul, 385, 392, 399
Sebastes proriger, 201, 202, 384
as incidental catch, 497
Sebastes rastrelliger, 148, 200
Sebastes reedi, 186, 201
in British Columbia, 203
in the Gulf of Alaska, 153-183
morphological description of, 163
Sebastes rosaceus, 200
Sebastes rosenblatti, 200
Sebastes ruberrimus, 21, 174, 203, 238, 384
designated as overfished off the U.S.
West Coast, 331
food supply of, 31
Sebastes rubrivinctus, 200
Sebastes rufinanus, 202
Sebastes rufus, 201
Sebastes saxicola, 201, 202
Sebastes scyphthorus, 201, 202
Sebastes semicinctus, 201, 202
Sebastes serranoides, 202
Sebastes serriceps, 201
Sebastes simulator, 200
Sebastes sinensis, 202
Sebastes spinorbis, 200
Sebastes thompsoni, 168, 174
Sebastes trivittatus, 200
Sebastes umbrosus, 200
Sebastes variabilis. See Sebastes ciliatus/
variabilis
Sebastes variegatus, 202, 384, 385
Sebastes varispinis, 202
Sebastes wilsoni, 202
Sebastes zacentrus, 202, 384
as incidental catch, 497
Sebastolobus alascanus, 22, 60, 187, 189-191, 299, 383-384
Sebastolobus macrochir, 60, 387
self-recruitment rates. See recruitment
sex ratio of Sebastes glaucus, Sebastes iracundus, and Sebastes polyspinis, 80-82
sharpchin rockfish. See Sebastes zacentrus
shima-zoi. See Sebastes trivittatus
shortbelly rockfish. See Sebastes jordani
shortraker rockfish. See Sebastes borealis
shortspine thornyhead rockfish. See Sebastolobus alascanus
Shotwell, Kalei, 493-511
Sierra Club of British Columbia, 357
SIF. See Stable Isotope Facility of University of Alaska (SIF)
silvergray rockfish. See Sebastes brevispinis
size. See body length; body weight
skates. See Bathyraja spp.; Raja spp.
software
ADMB software, 430, 431, 434
ArcGIS software, 43-44, 278
ArcMap software, 393
ArcView software, 43
Excel software, 105, 209, 227
FSTAT software, 105
GENEPOP software, 105
Micro-Checker software, 105, 106
MONTE module, 126
Multifan CL software, 430
S-PLUS software, 388
Statview, 28
Stock Synthesis software, 430-431
Sound Ecosystem Assessment program (SEA), 25
spawning (continued)
synchronous spawning of, 10, 13
spawning potential ratio (SPR), 330-331
spawning stock biomass (SSB), 2, 88, 115, 435, 439, 442. See also abundance; biomass; stock assessment
and Sebastes alutus, 513, 514, 515, 516, 520-524, 526-527
of Sebastes jordani, 155, 455, 461, 495
Species at Risk Act (SARA) of Canada, 355
speckled rockfish. See Sebastes ovalis
Spencer, Paul D., 383-409, 493-511, 513-533
spiny-eye rockfish. See Sebastes spinorbis
splitnose rockfish. See Sebastes diploproa
S-PLUS software, 388
Sports Fish Advisory Board, 354
squarespot rockfish. See Sebastes hopkinsi
SrCl₂. See strontium chloride
stable isotope analysis, 21-37
Stable Isotope Facility of University of Alaska (SIF), 25
Stanley, Richard D., 353-366
starry rockfish. See Sebastes constellatus
Statview software, 28
stock assessment. See also depletion; distribution
age and length of maturity of Sebastes alutus, 3
age-structured assessment model for Gulf of Alaska, 429-449
characterizing aspects of rockfish in the Aleutian Islands, 383-409
echosounder signals for improving trawl survey precision for Sebastes alutus survey, 473-492
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
localized depletions of Sebastes alutus, Sebastes polyspinis, and Sebastes ciliatus/variabilis, 493-511
population dynamics of Sebastes jordani in the California Current, 451-472
stock recruitment, 330, 332, 334-336, 350, 431-434, 440-441, 442, 460, 514-516, 519-520, 521, 522-523, 523, 525, 529
stocks. See specific stock names
Stock Synthesis software, 430-431
spawning
Sebastes alutus, 2
effect of maternal age of spawning on fishing rate reference points, 513-533
spawning (continued)
synchronous spawning of, 10, 13
spawning potential ratio (SPR), 330-331
spawning stock biomass (SSB), 2, 88, 115, 435, 439, 442. See also abundance; biomass; stock assessment
and Sebastes alutus, 513, 514, 515, 516, 520-524, 526-527
of Sebastes jordani, 155, 455, 461, 495
Species at Risk Act (SARA) of Canada, 355
speckled rockfish. See Sebastes ovalis
Spencer, Paul D., 383-409, 493-511, 513-533
spiny-eye rockfish. See Sebastes spinorbis
splitnose rockfish. See Sebastes diploproa
S-PLUS software, 388
Sports Fish Advisory Board, 354
squarespot rockfish. See Sebastes hopkinsi
SrCl₂. See strontium chloride
stable isotope analysis, 21-37
Stable Isotope Facility of University of Alaska (SIF), 25
Stanley, Richard D., 353-366
starry rockfish. See Sebastes constellatus
Statview software, 28
stock assessment. See also depletion; distribution
age and length of maturity of Sebastes alutus, 3
age-structured assessment model for Gulf of Alaska, 429-449
characterizing aspects of rockfish in the Aleutian Islands, 383-409
echosounder signals for improving trawl survey precision for Sebastes alutus survey, 473-492
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
localized depletions of Sebastes alutus, Sebastes polyspinis, and Sebastes ciliatus/variabilis, 493-511
population dynamics of Sebastes jordani in the California Current, 451-472
stock recruitment, 330, 332, 334-336, 350, 431-434, 440-441, 442, 460, 514-516, 519-520, 521, 522-523, 523, 525, 529
stocks. See specific stock names
Stock Synthesis software, 430-431
spawning
Sebastes alutus, 2
effect of maternal age of spawning on fishing rate reference points, 513-533
spawning (continued)
synchronous spawning of, 10, 13
spawning potential ratio (SPR), 330-331
spawning stock biomass (SSB), 2, 88, 115, 435, 439, 442. See also abundance; biomass; stock assessment
and Sebastes alutus, 513, 514, 515, 516, 520-524, 526-527
of Sebastes jordani, 155, 455, 461, 495
Species at Risk Act (SARA) of Canada, 355
speckled rockfish. See Sebastes ovalis
Spencer, Paul D., 383-409, 493-511, 513-533
spiny-eye rockfish. See Sebastes spinorbis
splitnose rockfish. See Sebastes diploproa
S-PLUS software, 388
Sports Fish Advisory Board, 354
squarespot rockfish. See Sebastes hopkinsi
SrCl₂. See strontium chloride
stable isotope analysis, 21-37
Stable Isotope Facility of University of Alaska (SIF), 25
Stanley, Richard D., 353-366
starry rockfish. See Sebastes constellatus
Statview software, 28
stock assessment. See also depletion; distribution
age and length of maturity of Sebastes alutus, 3
age-structured assessment model for Gulf of Alaska, 429-449
characterizing aspects of rockfish in the Aleutian Islands, 383-409
echosounder signals for improving trawl survey precision for Sebastes alutus survey, 473-492
effect of maternal age of spawning of Sebastes alutus on fishing rate reference points, 513-533
localized depletions of Sebastes alutus, Sebastes polyspinis, and Sebastes ciliatus/variabilis, 493-511
population dynamics of Sebastes jordani in the California Current, 451-472
stock recruitment, 330, 332, 334-336, 350, 431-434, 440-441, 442, 460, 514-516, 519-520, 521, 522-523, 523, 525, 529
stocks. See specific stock names
Stock Synthesis software, 430-431
Stolyarova, Elena V., 207-221
Strait of Georgia and young-of-year (YOY) and eelgrass beds, 381
strontium chloride, 89-96, 111
surficial lithology, 277, 278, 281-282
surfperches. See Embiotocidae surveys. See hydroacoustics; methodologies; trawl surveys
Sustainable Fisheries Act (U.S.), 330
Rebuilding Plans, 329
swordspine rockfish. See Sebastes ensifer
Sydeman, W., 451-472
TAC. See total allowable catch (TAC) tagging, 40, 41, 43, 55
otolith tagging, 102
of Sebastes melanops, 41, 43, 53, 318
TAPAS. See Trawl and Acoustic Presence/Absence Survey (TAPAS)
temperature. See water temperature
Thayer, J., 451-472
Theragra chalcogramma, 474, 497
tiger rockfish. See Sebastes nigrocinclus
Tokranov, Alexei M., 59-85
total allowable catch (TAC), 295, 296, 298, 304, 305, 307, 312, 358, 361, 363, 368
tracking. See tagging
Trager, Diana, 353-366
Trawl and Acoustic Presence/Absence Survey (TAPAS), 474-475, 485, 488, 489
trawl fishing
distribution of over habitat types, 281
limited entry (LE) trawl fishing, 283
minimizing impact of fishing on habitat, 275-294
share-based management program for in central Gulf of Alaska, 295-313
trawl surveys
bottom trawl surveys, 59, 60-61, 209, 385-386
variability in catches of Sebastes alutus, Sebastes borealis, and Sebastes aleutianus in Gulf of Alaska, 411-428
improving precision for Sebastes alutus survey, 473-492
large scale trawl surveys of the Gulf of Alaska, 418-419
Trawl and Acoustic Presence/Absence Survey (TAPAS), 474-475, 485, 488, 489
trawl surveys (continued)
Triennial Trawl Survey, 456, 460, 464
Unimak surveys, 413-414, 414, 415, 416, 416, 417, 421, 423-424, 425-426
treefish. See Sebastes serriceps
Triennial Trawl Survey in the California Current, 456, 460, 464

U
Ulva spp., 373, 380
understory kelp. See Laminaria spp.
Unimak surveys, 413-414, 414, 415, 416, 416, 417, 421, 423-424, 425-426
United States Pacific coast, minimizing impact of trawl fishing on habitat, 275-294
University of Alaska, Stable Isotope Facility, 25
Uria aalge
food habits of, 464
Sebastes jordani as prey, 457-458
U.S. Fishery Conservation and Management Act 1996, 276
U.S. Sustainable Fisheries Act, 330
Rebuilding Plans, 329
usu-mebaru. See Sebastes thompsoni

V
vermillion rockfish. See Sebastes miniatus
vertical migration, 101, 112, 251, 253-254, 255, 261, 262-265, 268
vessel monitoring systems (VMS), 359
vessels. See commercial fisheries
VNIRO. See Russian Federal Research Institute for Fisheries and Oceanography
Volk, Eric C., 87-98

W
walleye pollock. See Theragra chalcogramma
water depth
impact on haul groups in Aleutian Islands, 392, 394-397, 402-405, 406
and Sebastes aleutianus, 412, 419
and Sebastes alutus, 412, 419
and Sebastes borealis, 412, 419
and Sebastes caurinus young-of-year, 367-382
and Sebastes maliger young-of-year, 367-382
water temperature
  effects on rockfish population in Aleutian Islands, 393
  El Niño and, 223, 233-234, 235
  impact on haul groups in Aleutian Islands, 393, 396-397, 400, 404-405, 406
  and Sebastes glaucus, 72, 74
  and Sebastes iracundus, 72, 74
  and Sebastes polyspinis, 72, 74
  West Wind Drift, 256, 257
widow rockfish. See Sebastes entomelas

Y
yelloweye rockfish. See Sebastes ruberrimus
yellowmouth rockfish. See Sebastes reedi
yellowtail rockfish. See Sebastes flavidus
yoroi-mebaru. See Sebastes hubbsi
young-of-year (YOY), nearshore habitat associations of Sebastes caurinus and Sebastes maliger, 367-382

Z
Zalophus californianus
  frequency of occurrence, 463, 466
  Sebastes jordani as prey, 458-459, 465, 467
zooplankton. See food supply; prey
Zostera marina, 380-381