12. Assessment of the Dusky Rockfish stock in the Gulf of Alaska

Chris R. Lunsford, Peter-John F. Hulson, S. Kalei Shotwell, and Dana H. Hanselman
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Executive Summary

Rockfish are assessed on a biennial stock assessment schedule to coincide with the availability of new survey data. For Gulf of Alaska rockfish in on-cycle (odd) years, we present a full stock assessment document with updated assessment and projection model results.

We use a statistical age-structured model as the primary assessment tool for Gulf of Alaska dusky rockfish which qualifies as a Tier 3 stock. This assessment consists of a population model, which uses survey and fishery data to generate a historical time series of population estimates, and a projection model, which uses results from the population model to predict future population estimates and recommended harvest levels. For this on-cycle year, we update the 2013 assessment model estimates with new data collected since the last full assessment, present three new model improvements, and recommend an alternative bottom trawl survey biomass estimator.

Summary of Changes in Assessment Inputs

Relative to last year's assessment, we made the following substantive changes in the current assessment.

Changes in input data: The input data were updated to include survey age compositions for 2013, final catch for 2014 and preliminary catch for 2015, fishery age compositions from 2012, and fishery size compositions for 2013.

Additionally, updated survey biomass estimates are available. In this assessment we have traditionally used bottom trawl survey biomass estimates derived from a design-based stratified-random estimator. For this year's assessment, we are recommending using a geostatistical generalized linear mixed model (GLMM) to compute the time series of trawl survey biomass estimates from survey catch data (Appendix 12B). This methodology was informally presented to the September 2015 Plan Team as an option for modeling the West Coast stocks (Thorson et al. 2015). We chose this model based estimate because 1) the model-based trawl survey biomass index reduces variability both across and within years compared to the design-based trawl survey biomass index, and 2) using the model-based trawl survey index improves the retrospective pattern found within this assessment. Updated input data includes geostatistical model based trawl survey biomass estimates for the years 1984-2015.

Changes in the assessment methodology: The assessment methodology has changed since the 2013 assessment and incorporates the following changes:

1. In the past these trawl survey age samples were treated as if they were randomly collected. Growth is now estimated taking into account that ages are collected under a length-stratified sampling design.
2. The ageing error matrix was extended to more appropriately model the ages at or near the plus age group. An ageing error matrix was constructed that extends the modeled ages compared to the ages fit in the data until >99.9% were in the plus age group of the data.
3. The plus age group has been set to 25+ (previously was set to 21+) to 1) ensure the plus age group proportion is <10% and, 2) ensure the plus age group proportion is less than the maximum proportion in the remainder of the age composition data.
4. Apportionment is determined using the recommended random effects smoothing model applied to

the design-based survey biomass estimates.

Summary of Results

Substantive changes were made to both input data and assessment methodologies. The three major model changes generally improved model fits to the data. When growth estimates are computed using a length-stratified design rather than a random design for mean weight and the size-age transition matrix the overall data likelihood decreases. Extending the ageing error matrix resulted in improvements to the fit of age compositions and greatly improved the issue of overestimating those age classes adjacent to the plus group. Setting the plus age group from 21+ to 25+ did not have a major effect on likelihoods yet is balanced by minimizing the number of age bins that have zero samples.

The substantive change made to the input data is to recommend using the geostatistical estimator for determining survey biomass in favor of the traditional design-based estimator. The 2015 design-based survey estimate (32,786 t) was the second lowest on record behind the 1984 estimate, 53% lower than the average (69,721 t), and 67% lower than the 2013 biomass (99,170 t). Consistent with other previously low biomass estimates, the variance and associated CV are very low (CV=24%). A 67% decrease in biomass in two years is unlikely for a long-lived species with fairly low exploitation rates. The survey biomass time series for dusky rockfish is characterized by high variability because the survey does a poor job at sampling untrawlable habitat where dusky rockfish are encountered. The geostatistical estimator described by Thorson et al. (2015) is a preferred method to the design-based methodology for estimating biomass as it uses the available survey catch data more efficiently than conventional estimators and reduces the inter-annual variability in the biomass estimates by over 63% compared to the design-based estimates. We present the geostatistical model and evaluate the results as a preferred alternative survey biomass estimator for dusky rockfish in Appendix 12B. Based on these results, we recommend using the geostatistical model estimates for trawl survey biomass in this assessment.

For 2015, we recommend using the 2013 base model updated with:

1. Using a length-stratified design to model growth
2. An extended ageing error matrix be used to fit the age compositions
3. The plus age group set at 25
4. A new time series of trawl survey biomass estimates based on a geostatistical GLMM estimator

The following results are based on the author recommended model. The maximum allowable ABC for 2016 is 4,681 t based on the Tier 3 harvest control rule for dusky rockfish. This ABC is 8% less than last year's ABC of 5,109 t. The decrease in ABC is supported by a decline in the trawl survey biomass estimate in 2015 from 2013. The 2016 Gulf-wide OFL for dusky rockfish is 5,733 t. Area apportionments of ABC are based on the recommended random effects smoothing model applied to the design-based survey biomass estimates. The 2016 recommended area apportionments of ABC are 173 t for the Western area, 4,147 t for the Central area, 275 t for the West Yakutat area, and 91 t for the Southeast/Outside area. This represents a shift in ABC to the Central Gulf area and a substantial decrease in the West Yakutat region for 2016. This shift in apportionment is attributable to the highest ever biomass recorded in the West Yakutat area in the 2013 survey which encountered large numbers of dusky rockfish in two hauls resulting in an increase to the West Yakutat apportionment for 2014 and 2015. The corresponding reference values for dusky rockfish are summarized in the following table, with the recommended ABC and OFL values in bold. Overfishing is not occurring, the stock is not overfished, and it is not approaching an overfished condition.

Quantity	As estimated or *specified last* year for: 2015	2016	As estimated or *recommended this* year for: 2016[1]	2017[1]
M (natural mortality rate)	0.07	0.07	0.07	0.07
Tier	3a	3a	3a	3a
Projected total (age 4+) biomass (t)	66,629	64,295	60,072	57,492
Female spawning biomass (t)	27,345	25,344	25,238	23,245
$B_{100\%}$	52,264	52,264	49,268	49,268
$B_{40\%}$	20,906	20,906	19,707	19,707
$B_{35\%}$	18,292	18,292	17,244	17,244
F_{OFL}	0.122	0.122	0.121	0.121
$maxF_{ABC}$	0.098	0.098	0.098	0.098
F_{ABC}	0.098	0.098	0.098	0.098
OFL (t)	**6,246**	5,759	**5,733**	5,253
maxABC (t)	5,109	4,711	4,686	4,284
ABC (t)	**5,109**	4,711	**4,686**	4,284
Status	As determined *last* year for: 2013	2014	As determined *this* year for: 2014	2015
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

[1] Projections are based on estimated catches of 3,145 t and 2,792 t used in place of maximum permissible ABC for 2016 and 2017.

The following table shows the recommended apportionment for 2016.

	Western	Central	Eastern	Total
Area Apportionment	3.7%	88.5%	7.8%	100%
Area ABC (t)	**173**	**4,147**	**366**	**4,686**
OFL (t)				**5,733**

Amendment 41 prohibited trawling in the Eastern area east of 140° W longitude. The ratio of biomass still obtainable in the W. Yakutat area (between 147° W and 140° W) is 0.75. This results in the following apportionment to the W. Yakutat area:

	W. Yakutat	E. Yakutat/Southeast
Area ABC (t)	**275**	**91**

Plan Team Summaries

Stock	Year	Biomass[1]	OFL	ABC	TAC	Catch[2]
Dusky Rockfish	2014	69,371	6,708	5,486	5,486	3,034
	2015	66,629	6,246	5,109	5,109	2,709[2]
	2016	60,072	5,733	4,686		
	2017	57,492	5,253	4,284		

Stock	Area	2015 OFL	ABC	TAC	Catch[2]	2016 OFL	ABC	2017 OFL	ABC
Dusky Rockfish	W		296	296	182		173		159
	C		3,336	3,336	2,519		4,147		3,791
	WYAK		1,288	1,288	1		275		251
	EYAK/SEO		189	189	6		91		83
	Total	6,246	5,109	5,109	2,708	5,733	4,686	5,253	4,284

[1]Total biomass (age 4+) estimates from age-structured model
[2]Current as of October 1, 2015

Responses to SSC and Plan Team Comments on Assessments in General

"For the GOA age-structured rockfish assessments, if length composition data are withheld, the Team recommends exploratory model runs to test sensitivity. This should include any year of fishery or survey length composition data which could serve as a proxy for the age composition, not simply the most recent survey year." (Plan Team, November 2013)

The GOA rockfish models do not utilize length frequency composition data from the trawl survey as an additional set of compositional data because it used in constructing the age composition data and the size-age conversion matrix. Other assessment authors use only the last year of survey size composition because ages are not yet available, and then remove them in the following assessment. An analysis including only the most recent year of the bottom trawl survey length composition data into the GOA rockfish assessment models was presented as Appendix 9B in the 2014 POP assessment (Hulson et al., 2014) and reviewed by the PT and SSC. Overall, the results of this analysis suggest that the usefulness of including the most recent year's bottom trawl survey length composition is case specific but does not significantly influence model performance. Unless we were to fit the entire series of survey length composition data in the model, we continue to support excluding the last year's length composition in isolation in the interest of model stability and consistency. Therefore, we recommend that the status quo assessment model that does not include the most recent year's survey length composition continue to be used for dusky rockfish.

"*The SSC requests that stock assessment authors utilize the following model naming conventions in SAFE chapters:*
- *Model 0: last years' model with no new data,*
- *Model 1: last years' model with updated data, and*
- *Model numbers higher than 1 are for proposed new models.*" SSC, December 2014

"*For this year's final assessments, the Teams recommend that each author of an age-structured assessment use one of the following model naming conventions ("TPA" represents the alternative described in the Team procedures document)…*" Joint Plan Team, September, 2015

"*Of the options presented in the Joint Plan Teams minutes, the SSC agrees that Option 4 has several advantages and recommends that this Option be advanced next year.*" SSC, October 2015

For this assessment, we will use the simplified convention suggested in the December SSC minutes and will investigate further detailed naming for the next full assessment cycle.

"The Team recommends using the random effects model, rather than the weighted survey average approach to the extent practical for POP and for rockfish in general [for apportionment]." (Plan Team, September 2014)

The SSC also requests that stock assessment authors utilize the random effects model for area apportionment of ABCs": SSC, December 2014

"*The Teams recommend that the random effects survey smoothing model be used as a default for determining current survey biomass and apportionment among areas.*" Joint Plan Teams, September 2015

For dusky rockfish we are proposing using a new survey biomass estimator for this year's assessment. However, area-specific biomass estimates using this estimator haven't been developed for dusky rockfish at this time. Instead, we are computing area apportionments following the recommended methodology of using the random effects smoothing model applied to the design-based survey biomass estimates. See the 'Area Apportionment of Harvests' section below for further details.

SSC and Plan Team Comments Specific to this Assessment

"For assessments involving age-structured models, this year's CIE review of BSAI and GOA rockfish assessments included three main recommendations for future research: Authors should consider: (1) development of alternative survey estimators, (2) evaluating selectivity and fits to the plus group, and (3) re-evaluating natural mortality rates. The SSC recommends that authors address the CIE review during full assessment updates scheduled in 2014." (SSC, December 2013)

An AFSC response to the rockfish CIE review was prepared that addresses some of their concerns. Please refer to the "Summary and response to the 2013 CIE review of the AFSC rockfish" document presented to the September 2013 Plan Team for further details (http://www.afsc.noaa.gov/REFM/stocks/Plan_Team/2013/Sept/2013_Rockfish_CIE_Response.pdf). Specifically, in response to SSC comments above:

1. In this assessment we propose using an alternative methodology for computing survey biomass estimates based on a geostatistical generalized linear mixed model presented in Appendix 12B. This approach provides an alternative methodology for estimating biomass from catch data and for dusky rockfish outperforms the traditional design-based estimates. This alternative estimator generates biomass estimates that are more reasonable for a slow growing long lived species such as dusky rockfish and results in improved model fits to this time series.
2. In September, 2015, three GOA rockfish modeling updates were presented: using a length stratified design rather than random design for growth estimation, extending the ageing error matrix to more appropriately model the plus age group, and examining the best age for the plus group age bin. In this assessment we present alternative model runs incorporating all of these changes.
3. In 2007 the natural mortality rate used in this assessment was changed from 0.09 to 0.07 based on the most recent available data. We will continue to assess to appropriateness of this natural mortality based on available data and literature.

"The Team asks the [rockfish] *authors to investigate whether the conversion matrix has changed over time. Additionally, the Team requests that the criteria for omitting data in stock assessment models be based upon the quality of the data (e.g. bias, sampling methods, information content, redundancy with other data, etc.) rather than the effect of the data on modeled quantities."* (Plan Team, November 2011)

In September, 2015, three GOA rockfish modeling updates were presented: using a length stratified design rather than random design for growth estimation, extending the ageing error matrix to more appropriately model the plus age group, and examining the best age for the plus group age bin. In this assessment we present alternative model runs incorporating all of these changes.

"The Team recommends exploration of extending the modeled ages beyond the plus group in the data in order to improve the fits to the age composition data." (Plan Team, November 2013)

In this year's assessment, the ageing error matrix was extended to more appropriately model the plus age group. An ageing error matrix was constructed that extends the modeled ages compared to the ages fit in the data until >99.9% were in plus age group of data. Additionally, the plus age group was changed to 25 from 21. Model statistics including likelihood components and standard deviation in normalized residuals (SDNR) were examined but were generally uninformative. The plus age of 25 was chosen because the proportion of ages in the plus group is smaller than the maximum proportion of any one given age proportion, yet is balanced by minimizing the number of age bins that have zero samples.

"In order to evaluate the relative precision of area-specific biomass estimates, the Team recommends that the authors include the survey CVs by region when presenting apportionment estimates." (Plan Team, November 2013)

In this year's assessment we provide area-specific CVs along with recommended apportionments in Table 12-17. These CVs are based on the design-based biomass estimates which are used for determining apportionment. At this time we do not have area-specific biomass estimates for this estimator and therefore cannot provide biomass CVs by region. We plan to have area-specific biomass estimates and CVs based on the geostatistical estimator for the next full assessment.

"The SSC concurs with the Plan Team that exploration of the impacts of extending the plus-group in the assessment, and trying the random effects models for spatial allocation, would be potentially useful enhancements to the assessment. The SSC notes that the CIE reviewers provided comments on the use of survey data in stock assessments and encourages the author to evaluate comments relevant to the dusky assessment." (SSC, December 2013)

As mentioned above the plus-group has been changed to 25. Additionally, for this year we computed area apportionments using the random effects model (Table 12-17). Finally, in response to SSC and CIE comments, in this assessment we present an alternative biomass estimator as an alternative to the traditional design based survey estimator. We believe this method provides a reasonable alternative to computing survey biomass estimates for dusky rockfish.

Introduction

Biology and Distribution

Dusky rockfish (*Sebastes variabilis*) have one of the most northerly distributions of all rockfish species in the Pacific. They range from southern British Columbia north to the Bering Sea and west to Hokkaido Is., Japan, but appear to be abundant only in the Gulf of Alaska (GOA). The forms of dusky rockfish commonly recognized as "light dusky rockfish" and "dark dusky rockfish" are now officially recognized as two species (Orr and Blackburn 2004). *S. ciliatus* applies to the dark shallow-water species with a common name dark rockfish, and *S. variabilis* applies to variably colored usually deeper-water species with the common name dusky rockfish.

Adult dusky rockfish are concentrated on offshore banks and near gullies on the outer continental shelf at depths of 100 to 200 m (Reuter 1999). Anecdotal evidence from fishermen and from biologists on trawl surveys suggests that dusky rockfish are often caught in association with a hard, rocky bottom on these banks or gullies. Also, during submersible dives on the outer shelf of the eastern GOA, dusky rockfish were observed in association with rocky habitats and in areas with extensive sponge beds, where adults were seen resting in large vase sponges[1]. A separate study counted eighty-two juvenile rockfish closely associated with boulders that had attached sponges. No rockfish were observed near boulders without sponges (Freese and Wing 2003). Another study using a submersible in the eastern GOA observed small dusky rockfish associated with *Primnoa* spp. corals (Krieger and Wing 2002). Research focusing on untrawlable habitats found rockfish species often associate with biogenic structure (Du Preez et al., 2011, Laman et al., 2015), and that dusky rockfish in particular are often found in both trawlable and untrawlable habitats (Rooper and Martin, 2012, Rooper et al., 2012). Several of these studies are notable as results indicate further research is needed to address if there are differences in adult dusky rockfish density between trawlable and untrawlable habitats because currently survey catch estimates are extrapolated to untrawlable habitat (Jones et al., 2012; Rooper et al. 2012).

Management Units
Dusky rockfish are managed as a separate stock in the GOA Federal Management Plan (FMP). There are three management areas in the GOA: Western, Central, and Eastern. The Eastern area is further divided into West Yakutat and East Yakutat/Southeast Outside management units. This is done to account for the trawl prohibition in the East Yakutat/Southeast Outside area (east of 140 degree W. longitude) created by Amendment 41.

Stock structure
A review of dusky rockfish stock structure was presented to the GOA Plan Team in September, 2011, and was presented as an Appendix to the 2012 assessment document. In summary, available data suggests lack of significant stock structure; therefore, the current resolution of spatial management is likely adequate and consistent with management goals (Lunsford et al. 2012). It is evident from this evaluation that life history focused research is warranted and will help in evaluating dusky rockfish stock structure in the GOA.

Life history
Parturition is believed to occur in the spring, based on observation of ripe females sampled on a research cruise in April 2001 in the central GOA. Similar to all other species of *Sebastes*, dusky rockfish are ovoviviparous with fertilization, embryonic development, and larval hatching occurring inside the mother. After extrusion, larvae are pelagic, but larval studies are hindered because they can only be positively identified by genetic analysis. Post-larval dusky rockfish have not been identified; however, the post-larval stage for other *Sebastes* is pelagic, so it is also likely to be pelagic for dusky rockfish. The habitat of young juveniles is completely unknown. At some point they are assumed to migrate to the bottom and take up a demersal existence, juveniles less than 25 cm fork length are infrequently caught in bottom trawl surveys (Clausen et al. 2002) or with other sampling gear. Older juveniles have been taken only infrequently in the trawl surveys, but when caught are often found at more inshore and shallower locations that adults. Laman et al. (2015) found juvenile Pacific ocean perch utilize the vertical habitat that biogenic structures provide in otherwise low-relief, trawlable habitats, indicating these biogenic structures may represent refugia to juvenile rockfish. The major prey of adult dusky rockfish appears to be euphausiids, based on the limited food information available for this species (Yang 1993). In a more recent study, Yang et al. (2006) found that Pacific sandlance along with euphausiids were the most common prey item of dusky rockfish, comprising 82% and 17% , respectively, of total stomach contents by weight.

The evolutionary strategy of spreading reproductive output over many years is a way of ensuring some reproductive success through long periods of poor larval survival (Leaman and Beamish 1984). Fishing generally selectively removes the older and faster-growing portion of the population. If there is a distinct

[1]V.M. O'Connell, Alaska Dept. of Fish and Game, 304 Lake St., Sitka, AK 99835. Pers. commun. July 1997.

evolutionary advantage of retaining the oldest fish in the population, either because of higher fecundity or because of different spawning times, age-truncation could be deleterious to a population with highly episodic recruitment like rockfish (Longhurst 2002). Work on black rockfish (*S. melanops*) has shown that larval survival may be dramatically higher from older female spawners (Berkeley et al. 2004, Bobko and Berkeley 2004). De Bruin et al. (2004) examined Pacific ocean perch (*S. alutus*) and rougheye rockfish (*S. aleutianus*) for senescence in reproductive activity of older fish and found that oogenesis continues at advanced ages. Leaman (1991) showed that older individuals have slightly higher egg dry weight than their middle-aged counterparts. Such relationships have not yet been determined to exist for dusky rockfish in Alaska but maternal age effects on reproduction are an important consideration for assessing population status. Some literature suggests that environmental factors may affect the condition of female rockfish that contributes to reproductive success (Hannah and Parker, 2007; Rodgveller et al. 2012; Beyer et al. 2015). No specific studies have addressed if abortive maturation occurs in dusky rockfish in Alaska or if spawning success is variable over time. Stock assessments for Alaska groundfish have assumed that the reproductive success of mature fish is independent of age and that all mature females will spawn annually.

Fishery

Description of Directed Fishery

Dusky rockfish are caught almost exclusively with bottom trawls in the central and western areas of the GOA. Catches of dusky rockfish are concentrated at a number of relatively shallow, offshore banks of the outer continental shelf, especially the “W” grounds west of Yakutat, Portlock Bank northeast of Kodiak Island, and around Albatross Bank south of Kodiak Island. Highest catch-per-unit-effort in the commercial fishery is generally at depths of 100-149 m (Reuter 1999). During the period 1988-95, almost all the catch of dusky rockfish (>95%) was taken by large factory trawlers that processed the fish at sea. This changed starting in 1996, when smaller shore-based trawlers also began taking a sizeable portion of the catch in the Central Gulf area for delivery to processing plants in Kodiak.

The Rockfish Program in the Central GOA initiated in 2007 allocated the rockfish quota by sector so the percentage of 2007-present catches by shore-based catcher vessels differs in comparison to previous years. One benefit realized from the Rockfish Program is increased observer coverage and sampled catch for trips that target dusky rockfish (Lunsford et al. 2009). Since the majority of dusky rockfish catch comes from the Central GOA, the effects of the Rockfish Program has implications on the spatial distribution of dusky rockfish catch. In a study on localized depletion of Alaskan rockfish, Hanselman et al. (2007) found that dusky rockfish were rarely depleted in areas 5,000-10,000 km^2, except during 1994 in one area known as the “Snakehead” outside Kodiak Island in the Gulf of Alaska. This area was heavily fished for northern and dusky rockfish in the 1990s and both fishery and survey catch-per-unit-effort have consistently declined in this area since 1994. Comparison of spatial distribution of the dusky rockfish catch before and after the Rockfish Program began did not show major changes in catch distribution (Lunsford et al. 2013). Interpreting this data is confounded, however, as it’s unclear if results are attributable to changes in effort or observer coverage. To further complicate data interpretation, in 2013 the North Pacific Groundfish and Halibut Observer Program was restructured with the objective to create a more rigorous scientific method for deploying observers onto more vessels in Federal fisheries. Because many of the vessels targeting rockfish fall in the partial coverage category we expect this restructuring effort will change the extent of data collected from the rockfish fishery and will monitor.

Catch History

Catch reconstruction for dusky rockfish is difficult because in past years dusky rockfish were managed as part of the pelagic shelf rockfish assemblage (Table 12-1). Fishery catch statistics specific to dusky rockfish in the Gulf of Alaska are available for the years 1977-2015 (Table 12-2). Generally, annual catches increased from 1988 to 1992, and have fluctuated in the years following. This pattern is largely explained by management actions that have affected rockfish during this period. In the years before 1991, TACs were relatively large for more abundant slope rockfish species such as Pacific ocean perch, and there was less reason for fishermen to target dusky rockfish. However, as TACs for slope rockfish became more restrictive in the early 1990's and markets changed, there was a greater economic incentive for taking dusky rockfish. As a result, catches of the pelagic shelf assemblage increased, reaching 3,605 t Gulf-wide in 1992. However, a substantial amount of unharvested TAC generally remains each year in this fishery. This is largely due to in-season management regulations which close the rockfish fishery to ensure other species such as Pacific ocean perch do not exceed TAC, or to prevent excess bycatch of Pacific halibut.

In response to Annual Catch Limits (ACLs) requirements, assessments now document all removals including catch that is not associated with a directed fishery and reported in the Catch Accounting System. These types of removals may include sport fishery harvest, research catches, or subsistence catch. Research catches of pelagic shelf rockfish have been reported in previous stock assessments (Lunsford et al. 2009). For this year, estimates of all removals not associated with a directed fishery including research catches are available and are presented in Appendix 12.A. In summary, research removals have typically been less than 10 t and some harvest occurs in the recreational fishery. These levels likely do not pose a significant risk to the dusky rockfish stock in the GOA.

Bycatch
Bycatch of other species caught in dusky rockfish targeted hauls has historically been dominated by northern rockfish and Pacific ocean perch (Ackley and Heifetz 2001). Similarly, dusky rockfish was the major bycatch species for hauls targeting northern rockfish. These observations are supported by another study (Reuter 1999), in which catch data from the observer program showed dusky rockfish were most commonly associated with northern rockfish, Pacific ocean perch, and harlequin rockfish.

Total FMP groundfish catch estimates in the GOA rockfish fishery from 2011-2015 are shown in Table 12-3. For the GOA rockfish fishery during 2011-2015, the largest non-rockfish bycatch groups are Atka mackerel (1,032 t/year), walleye pollock (915 t/year), arrowtooth flounder (933 t/year), and Pacific cod (587 t/year). Non-FMP species catch in the rockfish target fisheries is dominated by giant grenadier and miscellaneous fish (Table 12-4). However, the amounts from dusky only targeted hauls are likely much lower as this includes all rockfish target hauls.

Prohibited species catch in the GOA rockfish fishery is generally low for most species. Catch of prohibitted and non-target species generally decreased with implementation of the Central GOA Rockfish Program (Lunsford et al. 2013). The only increase of prohibited species catch observed in 2015 was in halibut catch, which was nearly 20 tons greater than the 2014 catch (Table 12-5). Chinook salmon catch was lower than the five year average in both 2014 and 2015.

In summary, dusky rockfish are most likely to be associated with other rockfish species in fisheries and the bycatch of non-rockfish species in the dusky fishery are likely low but the only data available is for all rockfish targeted hauls. Bycatch estimates decreased for the majority of species in the Central GOA following the implementation of the Rockfish Pilot Program. The significant prohibited species that are encountered are Pacific halibut and chinook salmon.

Discards
Gulf-wide discard rates (percent of the total catch discarded within management categories) of dusky rockfish are available from 1991-2015. Rates are listed in the following table and have ranged from less than one to ten percent of the total dusky catch over time. The significant drop in discards rates in 1998-current can be attributed to a change in management category. The lowest rates were near one percent

during 2007 – 2011 and have since increased to 3-5% in recent years. These rates are considered to be low and are consistent with other GOA rockfish species.

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
% Discard	9.8	5.6	10.5	9.2	6.1	5.0	6.1	1.8	1.3	0.9
Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
% Discard	1.7	4.3	1.7	1.8	0.9	5.0	0.7	0.7	1.5	1.0
Year	2011	2012	2013	2014	2015					
% Discard	1.8	3.9	5.2	3.1	3.8					

Management History

Sebastes rockfish species in Federal waters of the Gulf of Alaska (GOA) were first split into three broad management assemblages by the North Pacific Fishery Management Council (NPFMC) in 1988: slope rockfish, pelagic shelf rockfish, and demersal shelf rockfish. Species in each group were thought to share a somewhat similar habitat as adults, and separate "Stock Assessment and Fishery Evaluation" (SAFE) reports were prepared for each assemblage. Dusky rockfish were included in the pelagic shelf rockfish complex, defined as those species of *Sebastes* that inhabit waters of the continental shelf of the Gulf of Alaska, and that typically exhibit midwater, schooling behavior. In 1998 a GOA FMP amendment went into effect that removed black rockfish (*S. melanops*) and blue rockfish (*S. mystinus*) from the assemblage. In 2009 a similar amendment removed dark rockfish from the assemblage. Management authority of these three species was transferred to the State of Alaska.

Beginning in 2009 the pelagic shelf rockfish assemblage consisted of just three species, dusky, widow, and yellowtail rockfish. The validity of this management group became questionable as the group was dominated by dusky rockfish, which has a large biomass in the GOA and supports a valuable directed fishery, especially in the central GOA. In contrast, yellowtail and widow rockfish have a relatively low abundance in the GOA and are only taken commercially in very small amounts as bycatch. Moreover, since 2003, dusky rockfish has been assessed by an age-structured model and is considered a "Tier 3" species in the North Pacific Fishery Management Council's (NPFMC) harvest policy definitions, while yellowtail and widow rockfish remained "Tier 5" species in which the assessment is based on simple estimates of biomass and natural mortality.

Following recommendations by the authors, the GOA Groundfish Plan Team, and the NPFMC's Science and Statistical Committee, dusky rockfish were assessed separately starting in 2012 and are now presented as a stand-alone species in this document; widow and yellowtail rockfish have been included in the *Other Rockfish* stock assessment (see Appendix 12B, Lunsford et al 2011). Beginning in 2012 ABCs, TACs, and OFLs specific to dusky rockfish have been assigned.

Management Measures

In 1998, trawling in the Eastern Gulf east of 140 degrees W. longitude was prohibited through Amendment 41 (officially recognized in 2000). This had important management concerns for most rockfish species, including the pelagic shelf management assemblage, because the majority of the quota is caught by the trawl fishery. In response to this action, since 1999 the NPFMC has divided the Eastern Gulf management area into two smaller areas: West Yakutat (area between 140 and 147 degrees W. longitude) and East Yakutat/Southeast Outside (area east of 140 degrees W. longitude). ABC and TAC recommendations for dusky rockfish are generated for both West Yakutat and East Yakutat/Southeast Outside areas to account for the trawling ban in the Eastern area.

In 2007 the Central Gulf of Alaska Rockfish Program was implemented to enhance resource conservation and improve economic efficiency for harvesters and processors who participate in the Central Gulf of Alaska rockfish fishery. This rationalization program establishes cooperatives among trawl vessels and processors which receive exclusive harvest privileges for rockfish species. The primary rockfish management groups are northern, Pacific ocean perch, and pelagic shelf rockfish (changed to dusky rockfish only in 2012). Potential effects of this program on the dusky rockfish fishery include: 1) Extended fishing season lasting from May 1 – November 15, 2) changes in spatial distribution of fishing effort within the Central GOA, 3) improved at-sea and plant observer coverage for vessels participating in the rockfish fishery, and 4) a higher potential to harvest 100% of the TAC in the Central GOA region. We continue to monitor available fishery data to help understand effects the Rockfish Project may have on the dusky rockfish stock in the Central GOA.

Within the GOA, separate ABCs and TACs for dusky rockfish are assigned to smaller geographical areas that correspond to NMFS management areas. These include the Western GOA, Central GOA, and Eastern GOA. In response to Amendment 41 which prohibited bottom trawling east of 140 degrees W. longitude, the Eastern GOA management area was further divided into two smaller areas. These areas, West Yakutat and East Yakutat/Southeast Outside, are now assigned separate ABCs and TACs. OFLs for dusky rockfish are defined on a GOA-wide basis.

A summary of key management measures, a time series of catch, ABC, and TAC are provided in Table 12-1.

Data

Data Summary

The following table summarizes the data available for this assessment (bold denotes new data for this assessment):

Source	Data	Years
Fisheries	Catch	1977-**2015**
NMFS bottom trawl surveys	Biomass index	1984, 1987, 1990, 1993, 1996, 1999, 2001, 2003, 2005, 2007, 2009, 2011, 2013, **2015**
NMFS bottom trawl surveys	Age	1984, 1987, 1990, 1993, 1996, 1999, 2001, 2003, 2005, 2007, 2009, 2011, **2013**
U.S. trawl fisheries	Age	2000, 2001, 2002, 2003, 2004, 2005, 2006, 2008, 2012, **2014**
U.S. trawl fisheries	Length	1990-1999, 2007, 2009, 2011, **2013**

Fishery Data

Catch

Catch estimates are a combination of foreign observer data, joint venture catch data, and NMFS Regional Office blend data. Catch estimates for dusky rockfish are available 1977-2015 (Table 12-2, Figure 12-1). Catches range from 17 t in 1986 to 4,538 t in 1999. We are skeptical of the low catches that occurred prior to 1988 and believe the catches for years 1985-1987 are likely underestimated. These catches occurred during the end of the joint venture years and prior to accurate catch accounting of the newly formed domestic fishery.

Age and Size Composition

Length frequency data for dusky rockfish in the commercial fishery are available for the years 1991-2015 but are only used in the model when age compositions are not expected to be available for that year (Table 12-6). These data are the raw length frequencies for all dusky rockfish measured by observers in a given year. Generally, these lengths were taken from hauls in which dusky rockfish were either the target or a dominant species, and they provide an indication of the trend in size composition for the fishery. Some years (1995, 1996) had relatively small sample sizes and should be treated with caution as all years regardless of sample size are included. Size of fish taken by the fishery generally appears to have increased after 1992; in particular, the mode increased from 42 cm in 1991-92 to 44-47 cm in 1993-97. The mode then decreased to 42 cm in 1998, and rose back to 45 cm in 1999-2002. Fish smaller than 40 cm are seen in moderate numbers in certain years (1991-92 and 1996-98), but it is unknown if this is an artifact of observer sampling patterns, or if it shows true influxes of younger fish or a decrease in older fish.

Age samples for dusky rockfish have been collected by observers in the 1999-2015 commercial fisheries. Aging has been completed for the 2000-2012 samples (Table 12-7). Similar to the fishery length data discussed in the preceding paragraph, the data in Table 12-7 depicts the raw age distribution of the samples, and we did not attempt any further analysis to estimate a more comprehensive age composition. However, the samples were randomly collected from fish in over 100 hauls that had large catches of dusky rockfish, so the raw distribution is probably representative of the true age composition of the fishery. Fish ranged in age from 4 to 76 years. Several large and relatively steady year classes are evident through the time series including 1986, 1992, 1995, and 1999 (Figure 12-2).

Survey Data

Trawl Survey Biomass Estimates

Comprehensive trawl surveys were conducted on a triennial basis in the Gulf of Alaska in 1984, 1987, 1990, 1993, 1996, and 1999, and biennially in 2001, 2003, 2005, 2007, 2009, 201, 2013 and 2015. Dusky rockfish were separated into “light” and “dark” varieties in surveys since 1996 and in starting in 2004 labeled as dusky and dark rockfish. Each of these surveys has shown that dusky rockfish (light dusky) overwhelmingly predominate and that dark rockfish (dark dusky) are caught in only small quantities. Presumably, the dusky rockfish biomass in surveys previous to 1996 consisted of nearly all dusky rockfish.

The 1984 and 1987 survey results should be treated with some caution. A different survey design was used in the eastern Gulf of Alaska in 1984; furthermore, much of the survey effort in the western and central Gulf of Alaska in 1984 and 1987 was by Japanese vessels that used a very different net design than what has been the standard used by U.S. vessels throughout the surveys. Also, the 2001 survey biomass is a weighted average of 1993-1999 biomass estimates, since the Eastern Gulf was not surveyed in 2001.

The traditional design-based estimates of biomass are based on a systematic random sampling design with Neyman allocation of effort allocated to strata based on habitat and depth. Comparative biomass estimates for the trawl surveys show wide fluctuations for dusky rockfish (Table 12-8, Table 12-9A). Total estimated biomass increased substantially between 1984 and 1987, dropped by over 50% in 1990, rebounded in 1993 and 1996, and decreased again in 1999 and 2001 (in areas that were sampled in 2001), increased in 2003, increased 2.5 fold in 2005 to 170,484 t, decreased in 2007 and 2009 to estimates similar to 2003, increased again in 2011 and 2013, and then decreased drastically in 2015 to 32,786 t. Large confidence intervals are associated with all these biomass estimates, particularly in 1987, 1996, 2003, 2005, 2007, and 2011. This is an indication of the generally patchy and highly aggregated distribution of this species. The 2015 design-based survey estimate (32,786 t) was the second lowest on record behind the 1984 estimate and 67% lower than the 2013 biomass (99,170 t) and 53% lower than the average (69,721 t). The variance associated with this year’s estimate is very low which is consistent with previous low biomass estimates and results in a coefficient of variation (CV) of 24%, the second lowest CV in the time series. The spatial distribution of the catches of dusky rockfish in the 2011, 2013, and 2015 surveys are shown in Figure 12-3. The magnitude of catch varies greatly with several large tows typically occurring in each survey. It is unknown whether these fluctuations indicate true changes in abundance, temporal changes in the availability of dusky rockfish to the survey gear, or are an artifact of the imprecision of the survey for this species.

In this year's assessment we propose using an alternative trawl survey biomass estimator based on a geostatistical generalized linear mixed model (GLMM) presented in Thorson et al. (2015). Application of this biomass estimator for five GOA rockfish species is presented in Appendix 12B. We believe this estimator is preferred to the design-based estimator for estimating dusky rockfish biomass. The geostatistical GLMM appears to work well in smoothing out the dramatic and unlikely swings in abundance that occur in some of the more patchily distributed GOA rockfish. The model also increases the precision relative to the design-based estimators by incorporating spatial and temporal covariation. For dusky rockfish, these biomass estimates are much smoother than the design-based estimates and have a realistic trend not discernable in the design-based estimates (Table 12-9B, Figure 12-4). Variance estimates for the geostatistical estimator are lower and CVs are relatively stable over the time series ranging from 14-25 percent. Biomass estimates range from a minimum 20,633 t in 1984 to a maximum of 63,604 t in 2005. Overall, biomass estimates have been relatively stable with a slight increase over time. The 2015 biomass estimate of 52,304 t is just a three percent decrease from the 2013 estimate.

Survey Size Compositions

Gulf-wide survey size compositions are available from 1984-2015 (Table 12-10). Survey size compositions suggest that strong recruitment of dusky rockfish is a relatively infrequent event, as only three surveys, 1993, 2001, and 2003, showed evidence of substantial recruitment. Mean population length increased from 39.8 cm in 1987 to 43.1 cm in 1990. In 1993, however, a large number of small fish (~27-35 cm long) appeared which formed a sizeable percentage of the population, and this recruitment decreased the mean length to 38.3 cm. In the 1996 and 1999 surveys, the length frequency distribution was similar to that of 1990, with very few small fish, and both years had a mean population length of 43.9 cm. The 2001 size composition, although not directly comparable to previous years because the eastern Gulf of Alaska was not sampled, shows modest recruitment of fish <40 cm. In 2003, a distinct mode of fish is seen at ~30 cm that suggests relatively strong recruitment may have occurred. No evidence of recruitment of small fish has been seen in recent surveys. Average length has increased each survey year since 2009 and is more comparable to fishery lengths in recent years (Tables 12-6, Table 12-10). Sample sizes have remained stable varying from 1,410 lengths taken in 2011 to 1,820 in 2015. Survey length compositions are used in estimating the length-age conversion matrix and in estimating the population age composition, but are not used as an additional compositional time series, because survey ages are available from those same years and are used in the model except for the most recent year.

Survey Age Compositions

Gulf-wide age composition data for dusky rockfish are available for the 1984 through 2013 trawl surveys (Table 12-11). Similar to the length data, these age data also indicate that strong recruitment is infrequent. For each survey, ages were determined using the "break-and-burn" method of aging otoliths, and a Gulf-wide age-length key was developed. The key was then used to estimate age composition of the dusky rockfish population in the Gulf of Alaska. The 1976 year class appeared to be abundant in the early surveys, especially 1984 (Figure 12-5). The 1986 year class appeared strong in the 1993, 1996, and perhaps the 1999 surveys. Because rockfish are difficult to age, especially as the fish grow older, one possibility is that some of the fish aged 12 in 1999 were actually age 13 (members of the 1986 year class), which would agree more with the 1993 and 1996 age results. Little recruitment occurred in the years following until the 1992 and 1995 year classes appeared. The only prominent year class since then is the 1998 year class, which had the highest proportion of ages sampled in the 2013 survey.

Analytical Approach

Model Structure

We present model results for dusky rockfish based on an age-structured model using AD Model Builder software (Fournier et al. 2012). The assessment model is based on a generic rockfish model developed in a workshop held in February 2001 (Courtney et al. 2007) and follows closely the GOA Pacific ocean perch and northern rockfish models (Hanselman et al. 2007, Courtney et al. 1999). In 2003, biomass estimates from an age-structured assessment model were first accepted as an alternative to trawl survey biomass estimates. As with other rockfish age-structured models, this model does not attempt to fit a stock-recruitment relationship but estimates a mean recruitment, which is adjusted by estimated recruitment deviations for each year. We do this because there does not appear to be an obvious stock-recruitment relationship in the model estimates, and there have been very high recruitments at low stock size (Figure 12-6). The parameters, population dynamics, and equations of the model are in Box 1.

Model Selection

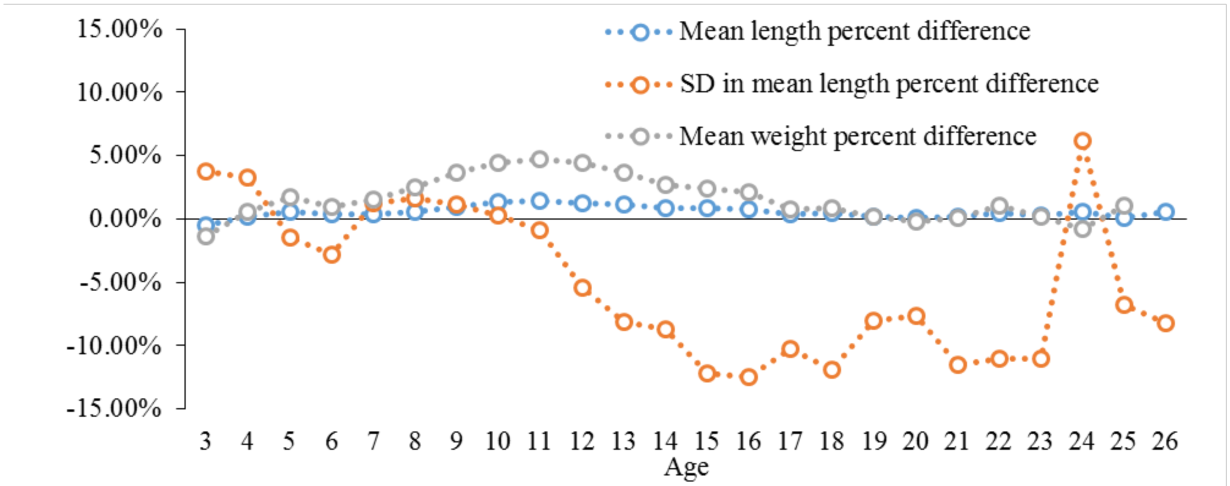
In total, four changes were made to input data and model configuration in this year's assessment compared to the 2013 assessment. We present these changes in a step-wise manner, building upon each previous model change to arrive at the preferred model for this year's assessment. The following table provides the model case name and description of the changes made to the model.

Model case	**Description**
M0	2013 model
M1	Same model as 2013, but with updated data
M2	Model M1, with length-stratified estimates of growth parameters for weight-at-age and size-age transition matrix
M3	Model M2, with extension of the number of ages in the model compared to the number of ages in data within the ageing error matrix
M4	Model M3, with extension the plus age group
M5	Model M4, with alternative bottom trawl survey index

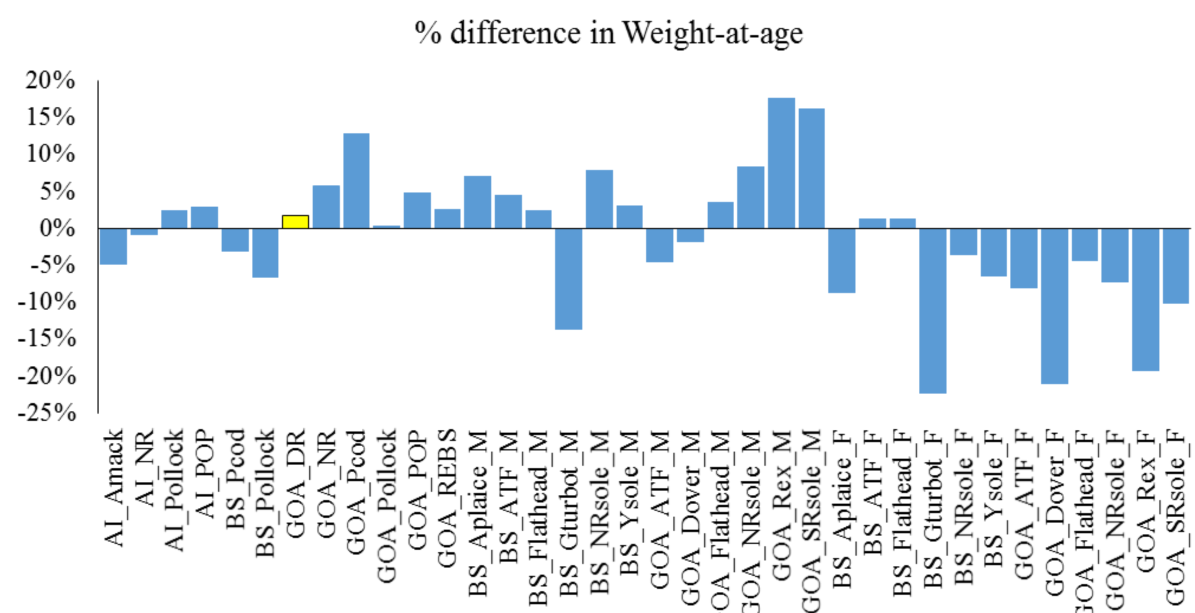
Note, each additional model case includes the changes made to the model in the previous model case. For example, model case M2 would also include length-stratified estimates of growth in addition to the extension of the ageing error matrix. A brief description of each model changed is provided below.

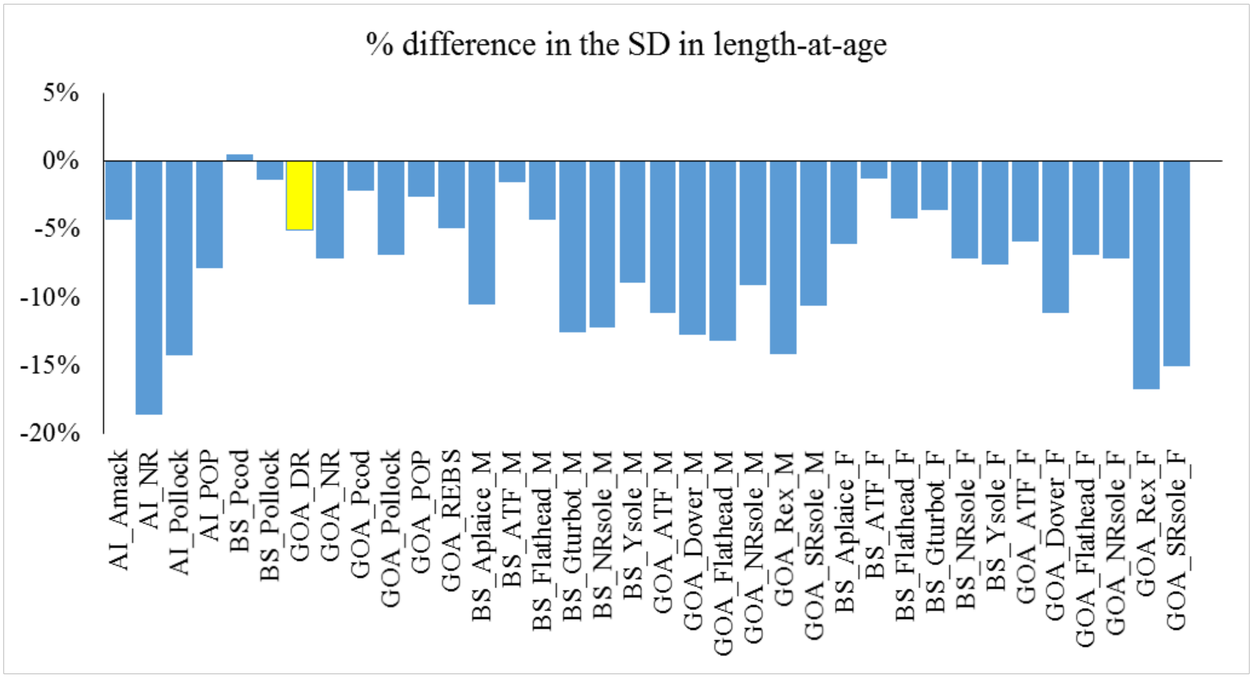
M2 – Length-stratified growth

Otolith collections for rockfish in the AFSC bottom trawl survey are done following a length-stratified design (i.e., a specified number of otoliths are collected for each length category). Corresponding growth estimates are then derived using these samples. In previous rockfish assessments growth observations have been treated as if they were collected randomly, rather than following the length-stratified sampling design of the survey. In this year's assessment we use new estimates of growth, for weight-at-age and the size-age conversion matrix used in the assessment model, based on length-stratified methods rather than random methods (Quinn and Deriso 1999, Bettoli and Miranda 2001). The following figure compares the percent difference between random and length-stratified mean length, standard deviation (SD) in mean length, and mean weight (positive values indicate that the mean value from random methods is larger than the mean value from length-stratified methods).



Overall, the differences in mean length were small between length-stratified and random methods. However, the SD in mean length was, on average, about 5% smaller from length-stratified methods compared to random and had the largest differences for ages greater than around ten. Mean weight was, on average, about 2% larger from length-stratified methods compared to random methods. These differences between length-stratified methods and random methods in weight-at-age and the SD in length-at-age are not uncommon when investigating the differences for other species, however. The following plots show the average percent difference (across age) in weight-at-age and the SD in length-at-age across a number of the Tier 3 species at AFSC (GOA dusky rockfish is highlighted in yellow).

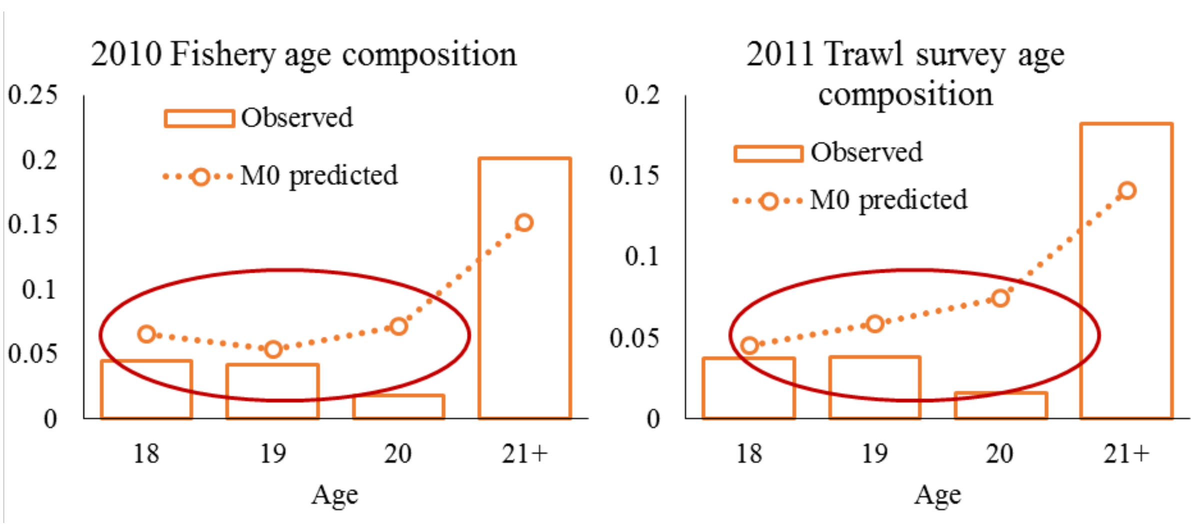




Compared with other species assessed at AFSC, the average percent difference in weight-at-age for dusky rockfish is smaller than most species with positive weight-at-age differences. The percent differences in the SD in mean length-at-age between length-stratified and random methods for dusky rockfish is also comparable to other species differences. In the following section, ‘Parameters Estimated Outside the Assessment Model’, the parameter estimates from the von Bertalanffy growth curve that are shown were obtained from length-stratified methods to determine mean length and weight. This data change is reflected in model case M2 and is used in all the following model cases M3 – M5.

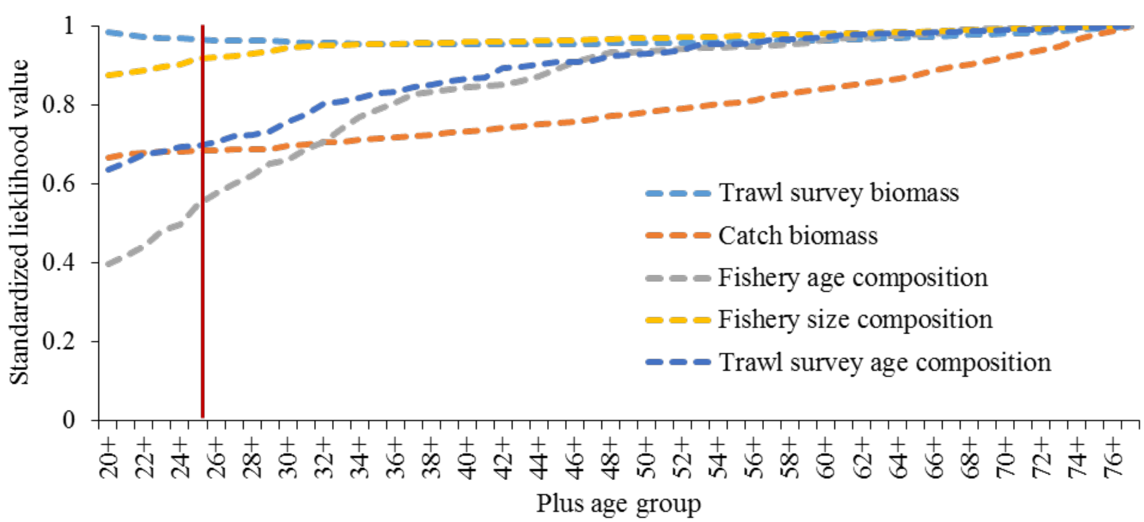
M3 – Extension of ageing error matrix

Previous assessments have noted that the model consistently over-estimated the proportions-at-age in the age classes adjacent to the plus age group in the bottom trawl survey and fishery age composition datasets. An example of the 2013 model fit to the most recent fishery and trawl survey age compositions in that assessment is shown in the following figure (shown are the last 4 age classes for presentation, with circles identifying the ages with lack of fit from the model).



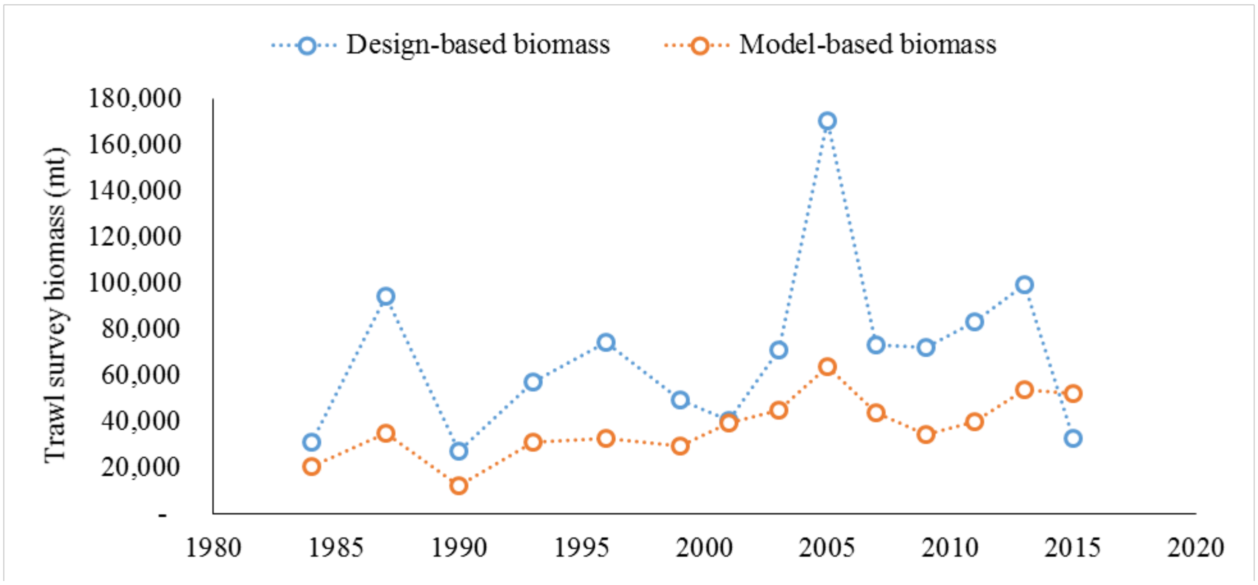
Further investigations revealed that this over estimation was due to the construction of the ageing error matrix. In its current form, the ageing error matrix distributes the fish in the plus age group based on the ageing error of the first age in the plus age group. For example, in the 2013 dusky rockfish assessment the plus age group was started at age 21, thus, the distribution of fish in the plus age group into age classes younger than the plus age group were based on the ageing error of age 21, rather than based on the ageing error of all the fish age 21 and older. This translates into a greater probability of fish in the plus age group being in the adjacent age classes that are younger than the plus age group than would be present for all fish older than the plus age group. This explains the consistent over estimation shown in the figures above. In model case M3 we provide an alternative ageing error matrix that extends the plus age group in the model compared to the plus age group in the data until 99.9% of the fish in the model's plus age group are within the plus age group of the data. Using this improved ageing error matrix vastly improves model fit to the age classes adjacent to the plus age group for both fishery and survey age compositions. This form of the ageing error matrix is also used in the following model cases M4 and M5.

M4 – Setting the plus age group
In both the GOA and BSAI rockfish assessments investigations have been devoted to determining the appropriate plus age group for the data fit by the assessment model (e.g., Hulson et al. 2011, Spencer and Ianelli 2012). These investigations evaluated the changes to the likelihood values of the fitted data in the model to determine the appropriate age group. Unfortunately, these investigations have not given clear guidance as to where to set the plus age group. Following SSC and Plan Team guidance, in model case M4 we extend the plus age group of the data until (1) <10% of the age composition is within the plus age group and (2) the proportion in the plus age group is less than the maximum proportion within the remainder of the age composition. For GOA dusky rockfish this results in a plus age group starting at age-25. The following figure shows where this plus age group of 25+ is in relation to the standardized negative log-likelihood values for the fitted datasets when changing the plus age group from age 20+ to age-77+.

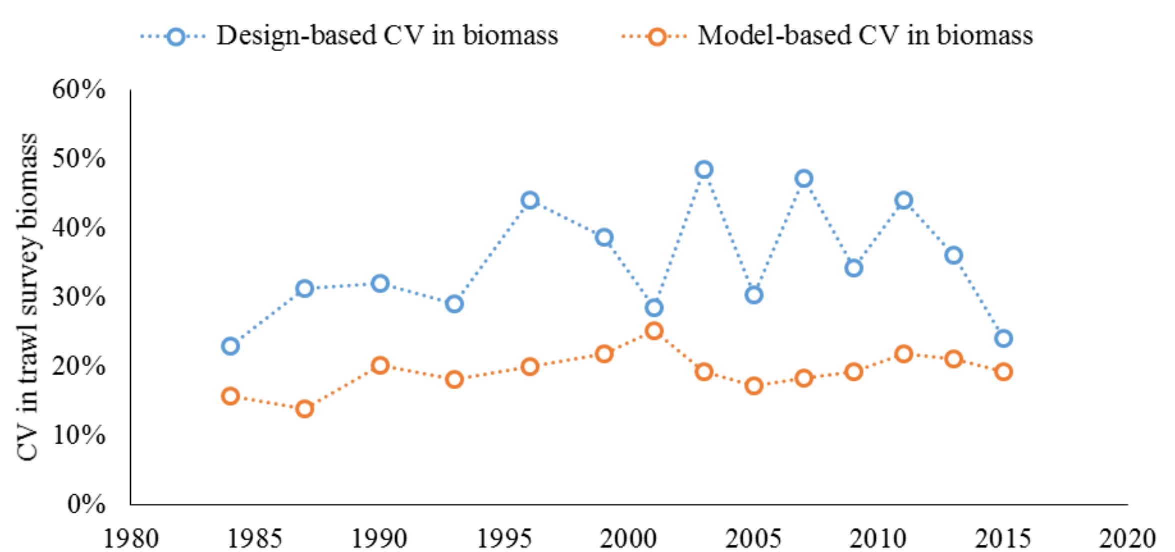


At a plus group of age 25+ the negative log-likelihoods for trawl survey biomass and fishery size have nearly plateaued, indicating further changes to the plus age group to these objective function components is negligible. At the plus age the catch negative log-likelihood is slowly increasing. The age composition negative log-likelihoods for both the fishery and survey at this plus age are also increasing with additional data being modeled. In model case M4 we set the plus age at age 25+, and use this plus age group (along with the changes made in model cases M2 and M3) in model case M5.

M4 – Alternative model-based trawl survey biomass
As described in Appendix 12B, an alternative method to estimate the trawl survey biomass has been constructed based on a geostatistical estimator (Thorson et al. 2015). The following figure compares the biomass estimates from the design-based survey biomass, which is currently used in the dusky rockfish assessment, and the alternative model-based biomass index.



The alternative model-based biomass largely reduces the inter-annual variability in the biomass from the trawl survey compared to the design-based values by over 63%. Note that the years with larger than average biomass from the design-based method (e.g., 2005, 2013) are in years where a small number of large catches in the trawl survey are extremely influential. However, the influence of these large catches is reduced in the model-based trawl survey biomass index, resulting in a more consistent time series of trawl survey biomass. The following figure presents the CVs in the design-based and model-based trawl survey biomass.



The average CV in trawl survey biomass from the design-based method across years is ~35% and can reach upwards of 45% in some years, whereas the average CV in biomass from the modeled index is 19%, ranging from 14-25%. This results in a decrease of nearly 45% in the average trawl survey biomass CV. In previous assessments the weight in the objective function for the design-based survey biomass index had been set at 5 in order to get an adequate model fit to the survey biomass time series. The ratio of the mean weighted inverse variance between the design-based and model-based trawl survey biomass (1.66) was used as the relative weighting for the model-based trawl survey biomass. This approach ensured that the relative weighting between the model-based index and the remaining datasets fit by the model were consistent. In model case M4 we use this alternative bottom trawl survey biomass index within the assessment model.

Parameters Estimated Outside the Assessment Model

Parameters fit outside the assessment model include the life-history parameters for weight-at-age, age error matrices, and natural mortality. For dusky rockfish, these values were previously taken from the 2001 Pelagic Shelf Rockfish SAFE Document (Clausen and Heifetz 2001). In this year's assessment growth information was updated with length-stratified methods (as described above in model case M2). Length-weight information for dusky rockfish is derived from data collected from GOA trawl surveys from 1990-2013, with a total sample size of 4,248. The length weight relationship for combined sexes, using the formula $W = aL^b$, where W is weight in grams and L is fork length in mm, $a = 6.56 \times 10^{-6}$ and $b = 3.16$.

The size-age conversion matrix was constructed from the Von Bertalanffy growth curve fit to length and age data collected from GOA trawl surveys from 1990-2013. The conversion matrix was constructed by adding normal error with a standard deviation equal to the standard deviation of survey lengths for each age class. Estimated parameters are: $L_\infty = 47.8$ cm, $\kappa = 0.19$, and $t_0 = 0.48$.

Ageing error matrices were constructed by assuming that the break-and-burn ages were unbiased but had a given amount of normal error around each age based on between-reader percent agreement tests conducted at the AFSC Age and Growth lab for dusky rockfish. In past assessments the ageing error matrix was constructed by assuming the same age determination error used for northern rockfish (Courtney et al. 1999).

Prior to 2007 the natural mortality rate used for dusky rockfish was 0.09. Questions about the validity of the high natural mortality rate of dusky rockfish versus other similarly aged rockfish were raised in previous stock assessments (Lunsford et al. 2007). In 2007, the natural mortality rate was changed to 0.07 based on an estimate calculated by Malecha et al. (2004) using updated data. This method used the Hoenig (1983) empirical estimator for natural mortality based on maximum lifespan. Based on the highest age recorded in the trawl survey of 59 this estimate is 0.08. The highest recorded age in the fishery ages was 76, which equates to a Hoenig estimate of 0.06. The current natural morality estimate used in this assessment (0.07) is comparable to other similarly aged rockfish in the GOA.

Parameters Estimated Inside the Assessment Model

Maturity-at-age is modeled with the logistic function which estimates logistic parameters for maturity-at-age conditionally. Parameter estimates for maturity-at-age are obtained by combining data collected on female dusky rockfish maturity from Lunsford (pers. comm. July 1997) and Chilton (2010). The binomial likelihood is used in the assessment model as an additional component to the joint likelihood function to fit the combined observations of female dusky rockfish maturity (e.g., Quinn and Deriso, 1999). The binomial likelihood was selected because (1) the sample sizes for maturity are small and assuming convergence to the normal distribution may not be appropriate in this case, (2) the binomial likelihood inherently includes sample size as a weighting component, and, (3) resulting maturity-at-age from the normal likelihood (weighted by sample size) was very similar to maturity-at-age obtained with the binomial likelihood.

The fit to the combined observations of maturity-at-age obtained in the preferred assessment model is shown in Figure 12-7. Parameters for the logistic function describing maturity-at-age estimated conditionally in the model, as well as all other parameters estimated conditionally, were identical to estimating maturity-at-age independently. Estimating maturity-at-age parameters conditionally influences the model only through the evaluation of uncertainty, as the MCMC procedure includes variability in the maturity parameters in conjunction with variability in all other parameters, rather than assuming the maturity parameters are fixed. Thus, estimation of maturity-at-age within the assessment model allows for uncertainty in maturation to be incorporated into uncertainty for key model results (e.g., ABC) (described below in the *Uncertainty approach* section).

Other parameters estimated conditionally in the current model include, but are not limited to: logistic parameters for selectivity for survey and fishery, mean recruitment, fishing mortality, spawner per recruit levels, and logistic parameters for maturity. The numbers of estimated parameters are shown below. Other derived parameters are described in Box 1.

Parameter name	Symbol	Number
Catchability	q	1
Log-mean-recruitment	μ_r	1
Recruitment variability	σ_r	1
Spawners-per-recruit levels	$F_{35\%}, F_{40\%}, F_{50\%}$	3
Recruitment deviations	τ_y	62
Average fishing mortality	μ_f	1
Fishing mortality deviations	ϕ_y	39
Logistic fishery selectivity	$a_{f50\%}, \delta_f$	2
Logistic survey selectivity	$a_{s50\%}, \delta_s$	2
Logistic maturity-at-age	$a_{m50\%}, \delta_m$	2
Total		114

Uncertainty approach

Evaluation of model uncertainty has recently become an integral part of the “precautionary approach” in fisheries management. In complex stock assessment models such as this model, evaluating the level of uncertainty is difficult. One way is to examine the standard errors of parameter estimates from the Maximum Likelihood approach derived from the Hessian matrix. While these standard errors give some measure of variability of individual parameters, they often underestimate their variance and assume that the joint distribution is multivariate normal. An alternative approach is to examine parameter distributions through Markov Chain Monte Carlo (MCMC) methods (Gelman et al. 1995). When treated this way, our stock assessment is a large Bayesian model, which includes informative (e.g., lognormal natural mortality with a small CV) and non-informative (or nearly so, such as a parameter bounded between 0 and 10) prior distributions. In the model presented in this SAFE report, the number of parameters estimated is 114. In a low-dimensional model, an analytical solution might be possible, but in one with this many parameters, an analytical solution is intractable. Therefore, we use MCMC methods to estimate the Bayesian posterior distribution for these parameters. The basic premise is to use a Markov chain to simulate a random walk through the parameter space which will eventually converge to a stationary distribution which approximates the posterior distribution. Determining whether a particular chain has converged to this stationary distribution can be complicated, but generally if allowed to run long enough, the chain will converge (Jones and Hobert 2001). The "burn-in" is a set of iterations removed at the beginning of the chain. This method is not strictly necessary but we use it as a precautionary measure. In our simulations we removed the first 1,000,000 iterations out of 10,000,000 and "thinned" the chain to one value out of every two thousand, leaving a sample distribution of 4,500. Further assurance that the chain had converged was attained by comparing the mean of the first half of the chain with the second half after removing the "burn-in" and "thinning". Because these two values were similar we concluded that convergence had been attained. We use these MCMC methods to provide further evaluation of uncertainty of the parameters presented here, including 95% credible intervals for some parameters.

BOX 1. AD Model Builder Model Description

Parameter definitions	
Y	Year
A	Age classes
L	Length classes
w_a	Vector of estimated weight at age, $a_0 \rightarrow a_+$
m_a	Vector of estimated maturity at age, $a_0 \rightarrow a_+$
a_0	Age at first recruitment
a_+	Age when age classes are pooled
μ_r	Average annual recruitment, log-scale estimation
μ_f	Average fishing mortality
σ_r	Annual recruitment deviation
ϕ_y	Annual fishing mortality deviation
fs_a	Vector of selectivities at age for fishery, $a_0 \rightarrow a_+$
ss_a	Vector of selectivities at age for survey, $a_0 \rightarrow a_+$
M	Natural mortality, fixed
$F_{y,a}$	Fishing mortality for year y and age class a ($fs_a \mu_f e^{\varepsilon}$)
$Z_{y,a}$	Total mortality for year y and age class a ($=F_{y,a}+M$)
$\varepsilon_{y,a}$	Residuals from year to year mortality fluctuations
$T_{a,a'}$	Aging error matrix
$T_{a,l}$	Age to length transition matrix
q	Survey catchability coefficient
SB_y	Spawning biomass in year y, ($=m_a w_a N_{y,a}$)
q_{prior}	Prior mean for catchability coefficient
$\sigma_{r(prior)}$	Prior mean for recruitment deviations
σ_q^2	Prior CV for catchability coefficient
$\sigma_{\sigma_r}^2$	Prior CV for recruitment deviations

BOX 1 (Continued)

Equations describing the observed data

$$\hat{C}_y = \sum_a \frac{N_{y,a} * F_{y,a} * \left(1 - e^{-Z_{y,a}}\right)}{Z_{y,a}} * w_a$$

Catch equation

$$\hat{I}_y = q * \sum_a N_{y,a} * \frac{s_a}{\max(s_a)} * w_a$$

Survey biomass index (t)

$$\hat{P}_{y,a'} = \sum_a \left(\frac{N_{y,a} * s_a}{\sum_a N_{y,a} * s_a} \right) * T_{a,a'}$$

Survey age distribution
Proportion at age

$$\hat{P}_{y,l} = \sum_a \left(\frac{N_{y,a} * s_a}{\sum_a N_{y,a} * s_a} \right) * T_{a,l}$$

Survey length distribution
Proportion at length

$$\hat{P}_{y,a'} = \sum_a \left(\frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,a'}$$

Fishery age composition
Proportion at age

$$\hat{P}_{y,l} = \sum_a \left(\frac{\hat{C}_{y,a}}{\sum_a \hat{C}_{y,a}} \right) * T_{a,l}$$

Fishery length composition
Proportion at length

Equations describing population dynamics

Start year

$$N_a = \begin{cases} e^{\left(\mu_r + \tau_{styr-a_0-a-1}\right)}, & a = a_0 \\ e^{\left(\mu_r + \tau_{styr-a_0-a-1}\right)} e^{-(a-a_0)M}, & a_0 < a < a_+ \\ \dfrac{e^{(\mu_r)} e^{-(a-a_0)M}}{\left(1 - e^{-M}\right)}, & a = a_+ \end{cases}$$

Number at age of recruitment

Number at ages between recruitment and pooled age class

Number in pooled age class

Subsequent years

$$N_{y,a} = \begin{cases} e^{\left(\mu_r + \tau_y\right)}, & a = a_0 \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}}, & a_0 < a < a_+ \\ N_{y-1,a-1} * e^{-Z_{y-1,a-1}} + N_{y-1,a} * e^{-Z_{y-1,a}}, & a = a_+ \end{cases}$$

Number at age of recruitment

Number at ages between recruitment and pooled age class

Number in pooled age class

Formulae for likelihood components **BOX 1 (Continued)**

$L_1 = \lambda_1 \sum_y \left(\ln \left[\frac{C_y + 0.01}{\hat{C}_y + 0.01} \right] \right)^2$	Catch likelihood
$L_2 = \lambda_2 \sum_y \frac{\left(I_y - \hat{I}_y \right)^2}{2 * \hat{\sigma}^2 \left(I_y \right)}$	Survey biomass index likelihood
$L_3 = \lambda_3 \sum_{styr}^{endyr} -n^*{}_y \sum_a^{a+} \left(P_{y,a} + 0.001 \right) * \ln \left(\hat{P}_{y,a} + 0.001 \right)$	Fishery age composition likelihood ($n^*{}_y$ =square root of sample size, with the largest set to one hundred)
$L_4 = \lambda_4 \sum_{styr}^{endyr} -n^*{}_y \sum_l^{l+} \left(P_{y,l} + 0.001 \right) * \ln \left(\hat{P}_{y,l} + 0.001 \right)$	Fishery length composition likelihood
$L_5 = \lambda_5 \sum_{styr}^{endyr} -n^*{}_y \sum_a^{a+} \left(P_{y,a} + 0.001 \right) * \ln \left(\hat{P}_{y,a} + 0.001 \right)$	Survey age composition likelihood
$L_6 = \lambda_6 \sum_{styr}^{endyr} -n^*{}_y \sum_l^{l+} \left(P_{y,l} + 0.001 \right) * \ln \left(\hat{P}_{y,l} + 0.001 \right)$	Survey size composition likelihood
$L_7 = \frac{1}{2\sigma_q^2} \left(\ln \frac{q}{q_{prior}} \right)^2$	Penalty on deviation from prior distribution of catchability coefficient
$L_8 = \frac{1}{2\sigma_{\sigma_r}^2} \left(\ln \frac{\sigma_r}{\sigma_{r(prior)}} \right)^2$	Penalty on deviation from prior distribution of recruitment deviations
$L_9 = \lambda_9 \left[\frac{1}{2 * \sigma_r^2} \sum_y \tau_y^2 + n_y * \ln \left(\sigma_r \right) \right]$	Penalty on recruitment deviations
$L_{10} = \lambda_{10} \sum_y \phi_y^2$	Fishing mortality regularity penalty
$L_{11} = \lambda_{11} \bar{s}^2$	Average selectivity penalty (attempts to keep average selectivity near 1)
$L_{12} = \lambda_{12} \sum_{a_0}^{a_+} \left(s_i - s_{i+1} \right)^2$	Selectivity dome-shapedness penalty – only penalizes when the next age's selectivity is lower than the previous (penalizes a downward selectivity curve at older ages)
$L_{13} = \lambda_{13} \sum_{a_0}^{a_+} \left(FD(FD(s_i - s_{i+1}) \right)^2$	Selectivity regularity penalty (penalizes large deviations from adjacent selectivities by adding the square of second differences)
$L_{total} = \sum_{i=1}^{13} L_i$	Total objective function value

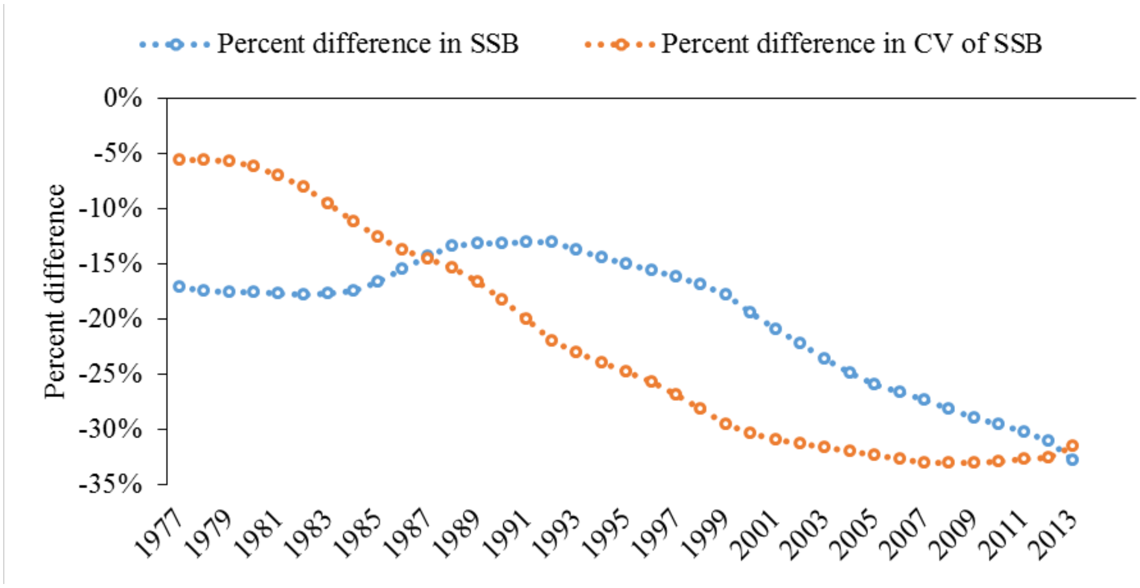
Results

Model Selection

Before presenting the standard model results, in this section we will present the results of each of the alternative model cases investigated in this year's assessment in a stepwise manner, ultimately arriving at the recommended assessment model for this year. Results investigated include the changes in model results for each model case as well as the model output uncertainty and objective function values.

M1 – 2013 model with updated data

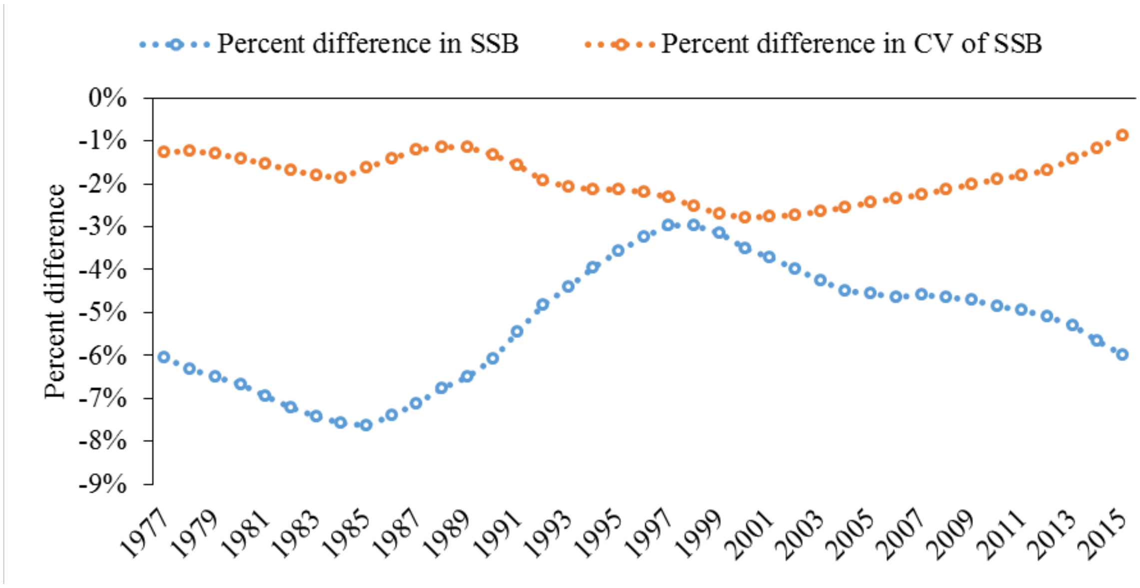
Updating the 2013 model with data current through 2015 increases the overall objective function, as would be expected with the additional data being fit by the model (Table 12-12). The catchability parameter increases from the 2013 value of 0.896 to 1.055 with the inclusion of the 2015 design-based survey biomass estimate, and mean recruitment decreases from 7.08 in 2013 to 5.36 in 2015. The following figure shows the percent difference in spawning biomass and the CV in spawning biomass for model case M1 compared to M0 (negative values indicate estimates that are smaller in model case M1 compared to M0).



The average decrease in spawning biomass from the 2013 assessment (model case M0) and the same model with updated data to 2015 (model case M1) was 20%, reaching a maximum decrease of 33% by 2013. The CV in spawning biomass also decreased compared to the 2013 assessment. This decrease in estimated spawning biomass can be attributed to the model fitting the design-based trawl survey biomass decrease that occurred in the 2015 survey compared to the 2013 survey.

M2 – Length-stratified growth

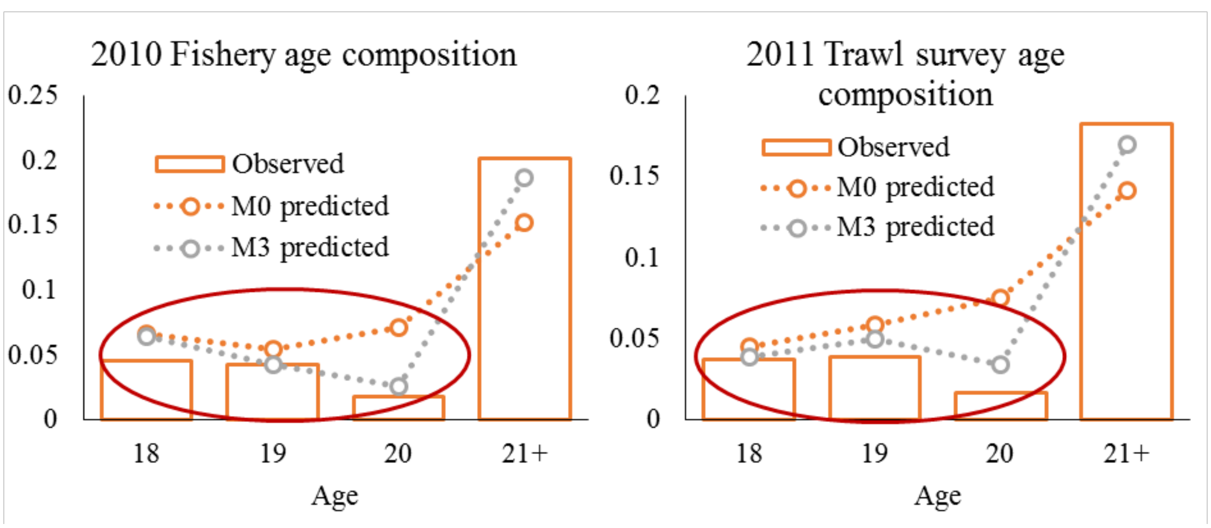
When length-stratified growth estimates are used in the assessment model for mean weight and the age-size transition matrix the overall data negative log-likelihood decreases (Table 12-12). Decreases in negative log-likelihood values resulted for the catch, fishery age composition, and fishery size composition. Increases in negative log-likelihood values occurred for the trawl survey biomass index (by 1%) and the trawl survey age composition (by 2%). The following figure shows the percent difference in spawning biomass and the CV in spawning biomass for model case M2 compared to M1 (negative values indicate estimates that are smaller in model case M2 compared to M1).



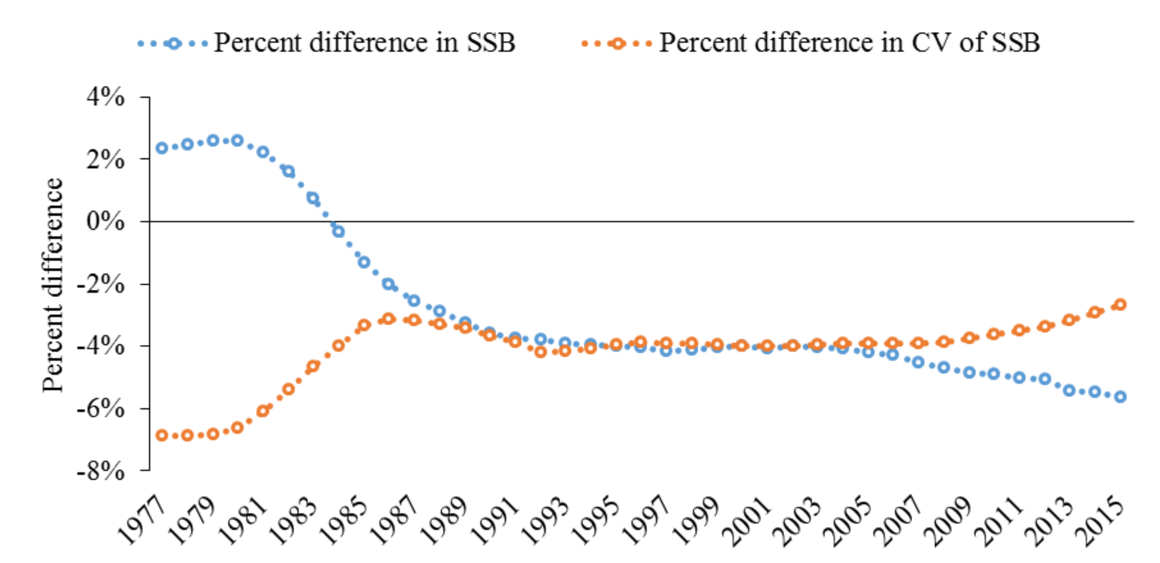
Overall, the spawning biomass in model case M2 compared to M1 decreases by about 5% across the time series, and the CV in spawning biomass is also smaller in model case M2 than model case M1 by around 2%. As it is more appropriate to model growth using the same methods as those used when collecting the data (length-stratified), we recommend that in this year's assessment and in future assessments growth be modeled using length-stratified methods. The results from the following model cases (M3 – M5) all use length-stratified estimates of growth.

M3 – Extension of the ageing error matrix

When the extended ageing error matrix is utilized in model case M3 to more properly model the plus age group and the adjacent age classes the data negative log-likelihood decreases by around 7% in model case M3 compared to model case M2 (Table 12-12). This decrease is attributed to large decreases in the negative log-likelihoods of the age composition datasets, the fishery age composition negative log-likelihood decreases by 38% and the trawl survey age composition negative log-likelihood decreases by 12%. The following figures use the example age composition years for the fishery and trawl survey age composition shown above, with comparison to results from model case M3.



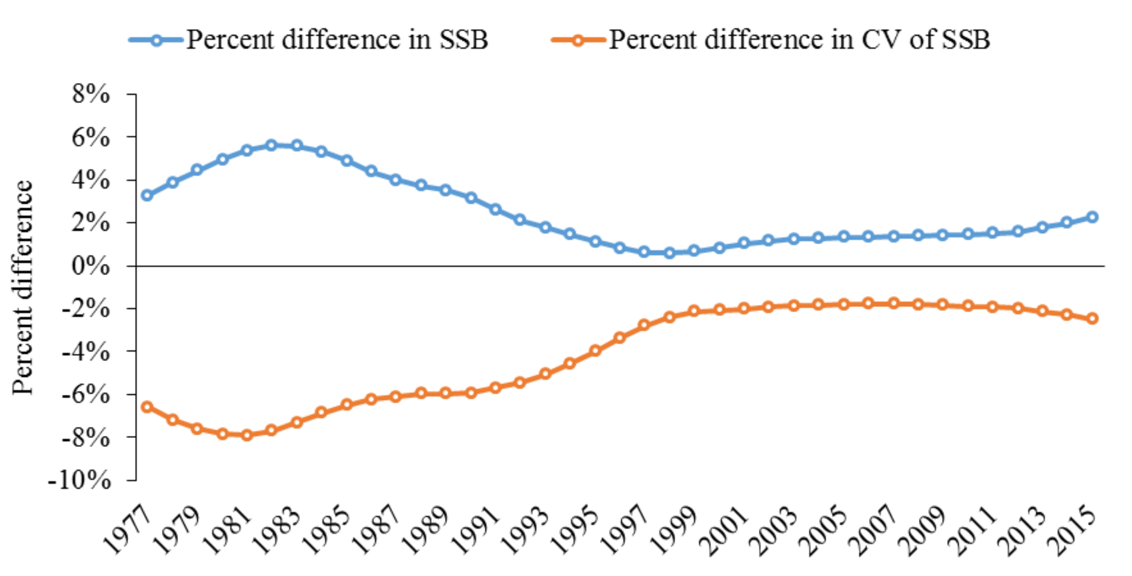
The large improvement in fit to the age composition data in model case M3 compared to M2 and M1 is due, in large part, to fitting the adjacent age classes to the plus age group more precisely, it also improves the fit to the plus age group itself. The following figure shows the percent difference in spawning biomass and the CV in spawning biomass for model case M3 compared to M2 (negative values indicate estimates that are smaller in model case M3 compared to M2).



Overall, the spawning biomass in model case M3 compared to M2 is larger at the beginning of the time series, then decreases to about 6% at the end of the time series, and the CV in spawning biomass is also smaller in model case M3 than model case M2 by around 4%. Due to the large improvement in fit to the age composition datasets, we recommend that in this year's assessment and in future assessments the extended ageing error matrix be utilized to fit the age composition datasets. The results from the following model cases (M4 – M5) all use the extended ageing error matrix presented in model case M3.

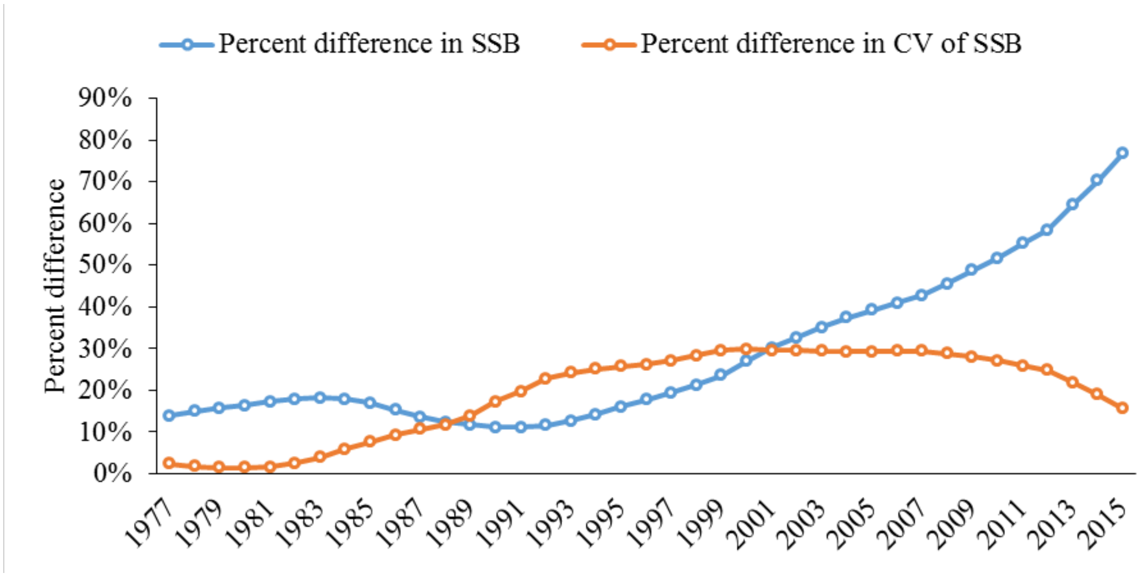
M4 – Setting the plus age group

Upon setting the plus age group to age-25+ in model case M4 to (1) ensure the plus age group proportion is <10% and (2) the plus age group proportion is less than the maximum proportion in the remainder of the age composition data, there was an overall increase in the data negative log-likelihood value (Table 12-12). This increase is attributed to increases in the negative log-likelihood values for the fishery and survey age composition, which is expected given the larger number of ages modeled. The negative log-likelihood values for the remaining datasets also increased for catch (by 2%) and fishery size composition (by 3%). The negative log-likelihood value for survey biomass decreased by 1%. The following figure shows the percent difference in spawning biomass and the CV in spawning biomass for model case M4 compared to M3 (negative values indicate estimates that are smaller in model case M4 compared to M3).

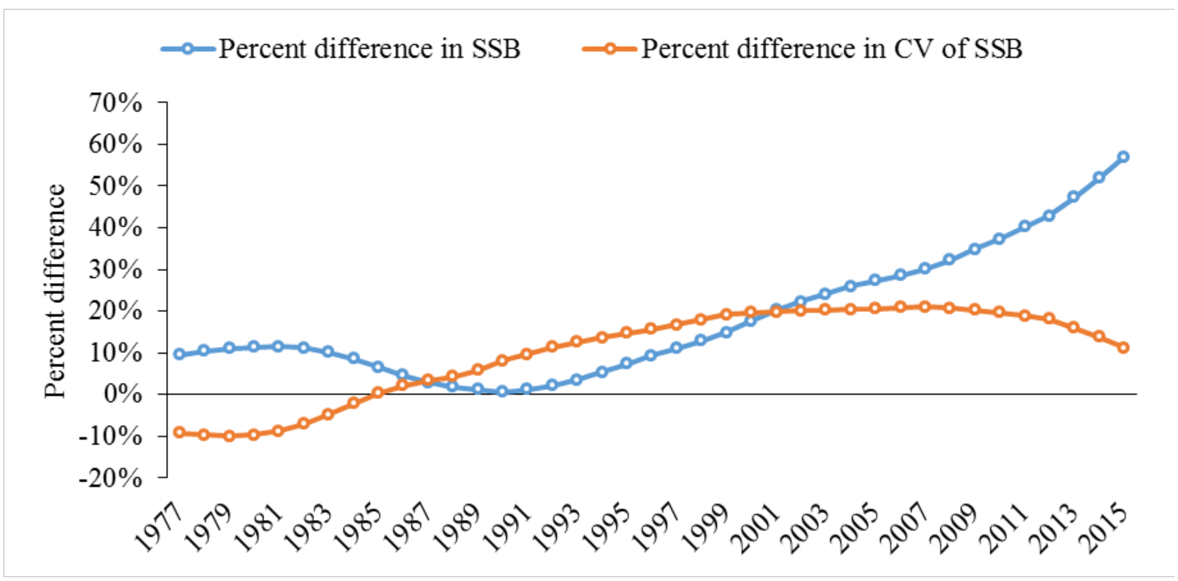


Overall, model case M4 results in about a 2% increase in the spawning biomass and a 4% decrease in the CV in spawning biomass compared to model case M3. To ensure that the proportion of fish in the plus age group remains manageable in both the fishery and trawl survey age composition we recommend that in this year's assessment and in future assessments a plus age group of age-25+ be used. This plus age group, as well as all the changes recommended in model cases M2 and M3 is used in model case M5.

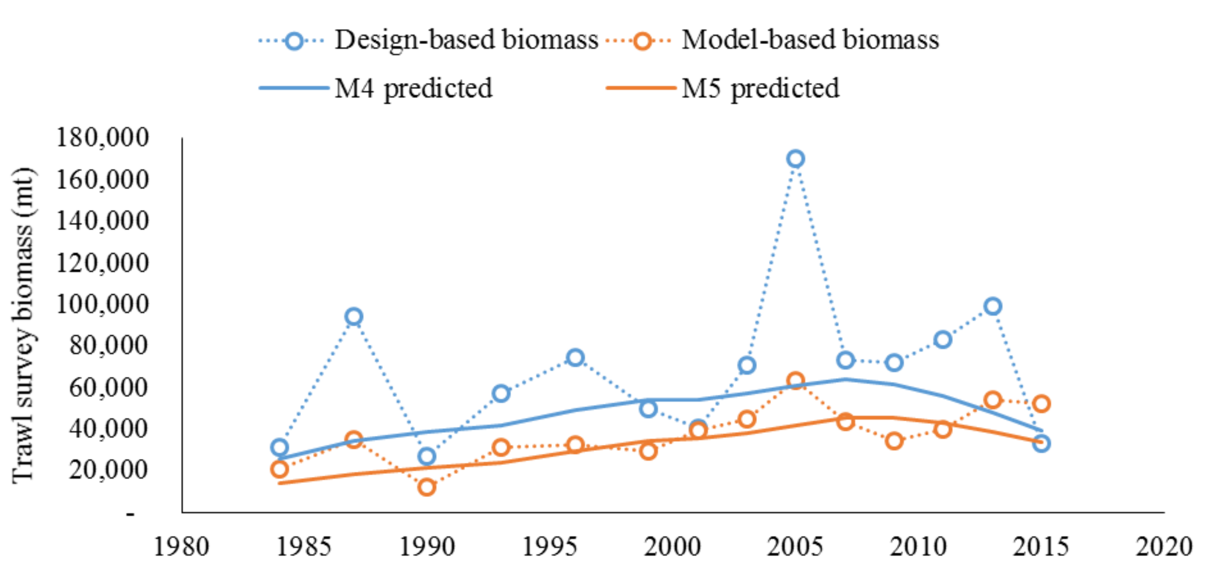
M5 – Alternative model-based trawl survey biomass
Using the alternative model-based trawl survey biomass index in the assessment resulted in an overall decrease in the data negative log-likelihood (Table 12-12). Besides the survey biomass negative log-likelihood decrease the largest decrease was in the fit to the catch time series, with a decrease of around 8%. There were no large increases in the negative log-likelihoods of the other data sources from model case M5 compared to model case M4 indicating that there were no conflicts with the new model-based survey biomass index. As large increases in the negative-log likelihood values did not result, it seems that the new model-based survey biomass index is consistent with the other data sources used in the assessment model. The following figure shows the percent difference in spawning biomass and the CV in spawning biomass for model case M5 compared to M4 (negative values indicate estimates that are smaller in model case M5 compared to M4).



Overall, the spawning biomass estimated in model case M5 is larger compared to the spawning biomass estimated in model case M4, which is attributed to a decrease in the catchability parameter for the bottom trawl survey with the new model-based trawl survey biomass index (Table 12-12). The CV in estimated spawning biomass from model case M5 was also larger than the CV in model case M4. The following figure shows the percent difference in spawning biomass and the CV in spawning biomass for model case M5 compared to M1, the base case model that is the same as the model used in 2013 but with updated data (negative values indicate estimates that are smaller in model case M5 compared to M1).



For much of the time series the spawning biomass estimated from model case M5 is larger than the estimated spawning biomass from case M1. The estimated CV in spawning biomass also follows this trend and is larger from model case M5 compared to model case M1 for most of the time series. It should be noted that absolute values for the 2015 SSB CVs are 15% and 16% for M1 and M5, respectively. The following figure shows the fit of model case M4 to the design-based survey biomass index, and the fit from model case M5 to the alternative survey biomass index.



The estimated survey biomass from model M3 tends to fit the low survey biomass values from the design-based index well but fails to fit the larger biomass values. A run of positive residuals from 2003-2013 occurs in the fit to the survey biomass in M4 which is greatly diminished in M5. The estimated survey biomass from model case M5 tends to fit the alternative model-based survey biomass index more precisely than M4 does the design-based survey biomass index.

According to the Retrospective Working Group report (Hanselman et al. 2013) the retrospective pattern from the dusky rockfish assessment was one of the worst among all the assessments conducted at AFSC. The following table shows the results of several retrospective statistics for each model case M1 – M5.

Statistic	M1	M2	M3	M4	M5
Mohn's revised ρ	0.55	0.51	0.41	0.30	0.10
Wood's Hole ρ	0.74	0.71	0.57	0.45	0.39
RMSE	0.32	0.30	0.21	0.14	0.13

For each of these retrospective parameters, the magnitude of retrospective patterns decreases for each sequential model case. Comparing between model case M1 and model case M5, Mohn's revised ρ decreased by over 80%, the Wood's Hole ρ decreased by over 47%, and the Root Mean Squared Error (RMSE) decreased by nearly 60%.

In summary, we recommend model case M5 as the preferred model for the 2015 dusky rockfish assessment for the following reasons: (1) growth should be modeled based on the manner in which the observations were collected, (2) extending the ageing error matrix results in improvements to the fit of the age composition datasets, (3) setting the plus age group to 25+ allows for a manageable proportion of fish within the plus age group to be modeled, (4) the model-based trawl survey biomass index reduces variability both across and within years compared to the design-based trawl survey biomass index, and (5) using the model-based trawl survey index improves the retrospective pattern found within this assessment. In the following sections results from the author's preferred model (model case M5) are presented.

Model Evaluation

The recommended changes to the model for this year's assessment were described in the previous section and our recommended model for this year is model case M5. When we present alternative model configurations, our usual criteria for choosing a superior model are: (1) the best overall fit to the data (in terms of negative log-likelihood), (2) biologically reasonable patterns of estimated recruitment, catchabilities, and selectivities, (3) a good visual fit to length and age compositions, and (4) parsimony.

The model generally produces good visual fits to the data, and biologically reasonable patterns of recruitment, abundance, and selectivities. Therefore, the recommended 2015 model is utilizing the new information effectively, and we use it to recommend 2016 ABC and OFL.

Time Series Results

Key results have been summarized in Tables 12-12 – 12-15. In general, model predictions continue to fit the data well (Figures 12-1 – 12-2, and 12-4).

Definitions

Spawning biomass is the biomass estimate of mature females. Total biomass is the biomass estimate of all dusky rockfish age four and greater. Recruitment is measured as number of age four dusky rockfish. Fishing mortality is fully-selected F, meaning the mortality at the age the fishery has fully selected the fish.

Biomass and Exploitation Trends

In general, model predictions continue to fit the data well (Figures 12-1 – 12-2, and 12-4)). The predicted survey biomass estimate from the model is lower than the 2013 and 2015 observed values (geostatistical model estimates) despite a modest increase in the observed 2013 and 2015 survey biomass compared to 2011. The model tracks most of the survey biomass estimates well from 1993 on, although the 2005 the model estimates are lower than the observed values (Figure 12-3). Total biomass estimates (age 4+) indicate a moderately increasing trend over time with a slight dome shape in the years surrounding the exceptionally high 2005 survey biomass estimate and a decrease thereafter, while spawning biomass estimates show a continuous linear increase throughout the time series and is also slightly dome shaped in recent years after 2010 (Figure 12-9). MCMC credible intervals indicate that the historic low was more certain than the more recent increases, particularly when looking at the upper credible interval.

The estimated selectivity curve for the fishery and survey data suggested a pattern similar to what we expect for dusky rockfish (Figure 12-10). The commercial fishery should target larger and subsequently older fish and the survey should sample a larger range of ages. Fish are fully selected by the survey by age 13, while fish are fully selected by the fishery at age 15.

The fully-selected fishing mortality time series indicates a rise in fishing mortality from late 1980's through the late 1990's and has declined since with a small increase in 2007 and 2008 and an increase in 2012 (Figure 12-11). This rise may be due to harvest exceeding TAC in the Western GOA in 2012, which occurred in all rockfish fisheries in response to a delayed closing of the fishery. Goodman et al. (2002) suggested that stock assessment authors use a "management path" graph as a way to evaluate management and assessment performance over time. We use a phase-plane plot of the ratio of fishing mortality to F_{OFL} ($F_{35\%}$) and the estimated spawning biomass relative to the target level ($B_{35\%}$). Harvest control rules based on $F_{35\%}$ and $F_{40\%}$ and the tier 3b adjustment are provided for reference. The historical management path for dusky rockfish has been above the FOFL adjusted limit for only a few years in the early 1980's and early 1990's. Since 2000, dusky rockfish have been above $B_{40\%}$ and well below $F_{40\%}$ (Figure 12-12).

Recruitment

There is some lack of fit to the plus group in the fishery size compositions for 1991-1993 (Figure 12-8).

This may be due to the increase in size of fish taken by the fishery in those years as mentioned in the Fishery data section. In general, the model fits the fishery age compositions well, likely due to the addition of data and the especially strong 1992 and 1995 year classes which are prevalent throughout the fishery age compositions (Figure 12-2). The survey age compositions also track the 1992 year class well and try to fit the 1995 year class, which appears strong in recent surveys (Figure 12-5); in 2013 the model predicted a larger proportion of fish to be in the plus age group than what was observed in the survey. Recruitment estimates have not been strong since several above average events in mid to late 1990's.

Recruitment (age 4) is highly variable throughout the time series (Figure 12-13), particularly the most recent years, where typically very little information is known about the strength of incoming year classes. There also does not seem to be a clear spawner recruit relationship for dusky rockfish as recruitment appears unrelated to spawning stock biomass (Figure 12-6). MCMC credible bars for recruitment are fairly narrow in some years; however, the credible bands nearly contain zero for many years which indicates considerable uncertainty, particularly for the most recent years (Figure 12-13).

Retrospective Analysis

A within-model retrospective analysis of the recommended model was conducted for the last 10 years of the time-series by dropping data one year at a time. The revised Mohn's "rho" statistic (Hanselman et al. 2013) in female spawning biomass was 0.10, indicating that the model decreases the estimate of female spawning biomass in recent years as data is added to the assessment. This is a major improvement in retrospective pattern compared to past assessments that used the design-based biomass estimates. The retrospective female spawning biomass and the relative difference in female spawning biomass from the model in the terminal year are shown in Figure 12-14 (with 95% credible intervals from MCMC). In general, the relative difference in female spawning biomass ranges from around 0% to 80%.

Uncertainty Results

From the MCMC chains described in the *Uncertainty approach* section, we summarize the posterior densities of key parameters for the recommended model using histograms (Figure 12-15) and credible intervals (Table 12-15). We also use these posterior distributions to show uncertainty around time series estimates such as total biomass, spawning biomass and recruitment (Figures 12-9, 12-13, Figure 12-16).

Table 12-13 shows the maximum likelihood estimate (MLE) of key parameters with their corresponding standard deviations derived from the Hessian matrix compared to the standard deviations derived from MCMC methods. The Hessian and MCMC standard deviations are similar for q, but the MCMC standard deviations are larger for the estimates of $F_{40\%}$, ABC, and female spawning biomass. These larger standard deviations indicate that these parameters are more uncertain than indicated by the standard estimates. However, all estimates fall within the Bayesian credible intervals.

Harvest Recommendations

Amendment 56 Reference Points

Amendment 56 to the GOA Groundfish Fishery Management Plan defines the "overfishing level" (OFL), the fishing mortality rate used to set OFL (F_{OFL}), the maximum permissible ABC, and the fishing mortality rate used to set the maximum permissible ABC. The fishing mortality rate used to set ABC (F_{ABC}) may be less than this maximum permissible level, but not greater. Because reliable estimates of reference points related to maximum sustainable yield (MSY) are currently not available, but reliable estimates of reference points related to spawning per recruit are available, dusky rockfish in the GOA are managed under Tier 3 of Amendment 56. Tier 3 uses the following reference points: $B_{40\%}$, which is equal to 40% of the equilibrium spawning biomass that would be obtained in the absence of fishing, $F_{35\%}$ which is ,equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 35% of the level that would be obtained in the absence of fishing, and $F_{40\%}$, which is equal to the fishing mortality rate that reduces the equilibrium level of spawning per recruit to 40% of the level that would be obtained in the absence of fishing.

Estimation of the $B_{40\%}$ reference point requires an assumption regarding the equilibrium level of recruitment. In this assessment, it is assumed that the equilibrium level of recruitment is equal to the average of age 4 recruits from 1981-2011 (year classes between 1977 and 2007). Because of uncertainty in very recent recruitment estimates, we lag 4 years behind model estimates in our projection. Other useful biomass reference points which can be calculated using this assumption are $B_{100\%}$ and $B_{35\%}$, defined analogously to $B_{40\%}$. The 2015 estimates of these female spawning biomass reference points are:

$B_{100\%}$	$B_{40\%}$	$B_{35\%}$	$F_{40\%}$	$F_{35\%}$
49,268	19,707	17,244	0.098	0.121

Specification of OFL and Maximum Permissible ABC
Female spawning biomass for 2016 is estimated at 25,239 t. This is above the $B_{40\%}$ value of 19,707 t. Under Amendment 56, Tier 3, the maximum permissible fishing mortality for ABC is $F_{40\%}$ and fishing mortality for OFL is $F_{35\%}$. Applying these fishing mortality rates for 2016, yields the following ABC and OFL:

$F_{40\%}$	0.098
ABC	4,686
$F_{35\%}$	0.121
OFL	5,733

Population Projections
A standard set of projections is required for each stock managed under Tiers 1, 2, or 3 of Amendment 56. This set of projections encompasses seven harvest scenarios designed to satisfy the requirements of Amendment 56, the National Environmental Policy Act, and the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA).

For each scenario, the projections begin with the vector of 2015 numbers at age as estimated in the assessment. This vector is then projected forward to the beginning of 2016 using the schedules of natural mortality and selectivity described in the assessment and the best available estimate of total (year-end) catch for 2015. In each subsequent year, the fishing mortality rate is prescribed on the basis of the spawning biomass in that year and the respective harvest scenario. In each year, recruitment is drawn from an inverse Gaussian distribution whose parameters consist of maximum likelihood estimates determined from recruitments estimated in the assessment. Spawning biomass is computed in each year based on the time of peak spawning and the maturity and weight schedules described in the assessment. Total catch after 2015 is assumed to equal the catch associated with the respective harvest scenario in all years. This projection scheme is run 1,000 times to obtain distributions of possible future stock sizes, fishing mortality rates, and catches.

Five of the seven standard scenarios will be used in an Environmental Assessment prepared in conjunction with the final SAFE. These five scenarios, which are designed to provide a range of harvest alternatives that are likely to bracket the final TAC for 2016, are as follow ("*max* F_{ABC}" refers to the maximum permissible value of F_{ABC} under Amendment 56):

Scenario 1: In all future years, F is set equal to *max* F_{ABC}. (Rationale: Historically, TAC has been constrained by ABC, so this scenario provides a likely upper limit on future TACs.)

Scenario 2: In 2016 and 2017, F is set equal to a constant fraction of *max* F_{ABC}, where this fraction is equal to the ratio of the realized catches in 2012-2014 to the ABC recommended in the assessment for each of those years. For the remainder of the future years, maximum permissible ABC is used. (Rationale: In many fisheries the ABC is routinely not fully utilized, so assuming

an average ratio catch to ABC will yield more realistic projections.)
Scenario 3: In all future years, F is set equal to 50% of max F_{ABC}. (Rationale: This scenario provides a likely lower bound on F_{ABC} that still allows future harvest rates to be adjusted downward when stocks fall below reference levels.)
Scenario 4: In all future years, F is set equal to the 2010-2014 average F. (Rationale: For some stocks, TAC can be well below ABC, and recent average F may provide a better indicator of F_{TAC} than F_{ABC}.)
Scenario 5: In all future years, F is set equal to zero. (Rationale: In extreme cases, TAC may be set at a level close to zero.)

Two other scenarios are needed to satisfy the MSFCMA's requirement to determine whether a stock is currently in an overfished condition or is approaching an overfished condition. These two scenarios are as follow (for Tier 3 stocks, the MSY level is defined as $B_{35\%}$):
Scenario 6: In all future years, F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is overfished. If the stock is expected to be above 1) above its MSY level in 2015 or 2) above ½ of its MSY level in 2015 and above its MSY level in 2025 under this scenario, then the stock is not overfished.)
Scenario 7: In 2016 and 2017, F is set equal to *max* F_{ABC}, and in all subsequent years F is set equal to F_{OFL}. (Rationale: This scenario determines whether a stock is approaching an overfished condition. If the stock is expected to be above its MSY level in 2027 under this scenario, then the stock is not approaching an overfished condition.)

Spawning biomass, fishing mortality, and yield are tabulated for the seven standard projection scenarios (Table 12-16). The difference for this assessment for projections is in Scenario 2 (Author's F); we use pre-specified catches to increase accuracy of short-term projections in fisheries where the catch is usually less than the ABC. This was suggested to help management with setting preliminary ABCs and OFLs for two year ahead specifications.

Status Determination
In addition to the seven standard harvest scenarios, Amendments 48/48 to the BSAI and GOA Groundfish Fishery Management Plans require projections of the likely OFL two years into the future. While Scenario 6 gives the best estimate of OFL for 2016, it does not provide the best estimate of OFL for 2017, because the mean 2016 catch under Scenario 6 is predicated on the 2016 catch being equal to the 2016 OFL, whereas the actual 2016 catch will likely be less than the 2016 OFL. The executive summary contains the appropriate one- and two-year ahead projections for both ABC and OFL.

Under the MSFCMA, the Secretary of Commerce is required to report on the status of each U.S. fishery with respect to overfishing. This report involves the answers to three questions: 1) Is the stock being subjected to overfishing? 2) Is the stock currently overfished? 3) Is the stock approaching an overfished condition?

Is the stock being subjected to overfishing? The official catch estimate for the most recent complete year (2014) is 3,034 t. This is less than the 2014 OFL of 6,708 t. Therefore, the stock is not being subjected to overfishing.

Harvest Scenarios #6 and #7 are intended to permit determination of the status of a stock with respect to its minimum stock size threshold (MSST). Any stock that is below its MSST is defined to be *overfished*. Any stock that is expected to fall below its MSST in the next two years is defined to be *approaching* an overfished condition. Harvest Scenarios #6 and #7 are used in these determinations as follows:

Is the stock currently overfished? This depends on the stock's estimated spawning biomass in 2015:

a. If spawning biomass for 2015 is estimated to be below ½ $B_{35\%}$, the stock is below its MSST.
b. If spawning biomass for 2015 is estimated to be above $B_{35\%}$ the stock is above its MSST.
c. If spawning biomass for 2015 is estimated to be above ½ $B_{35\%}$ but below $B_{35\%}$, the stock's status relative to MSST is determined by referring to harvest Scenario #6 (Table 12-16). If the mean spawning biomass for 2025 is below $B_{35\%}$, the stock is below its MSST. Otherwise, the stock is above its MSST.

Is the stock approaching an overfished condition? This is determined by referring to harvest Scenario #7:
a. If the mean spawning biomass for 2017 is below 1/2 $B_{35\%}$, the stock is approaching an overfished condition.
b. If the mean spawning biomass for 2017 is above $B_{35\%}$, the stock is not approaching an overfished condition.
c. If the mean spawning biomass for 2017 is above 1/2 $B_{35\%}$ but below $B_{35\%}$, the determination depends on the mean spawning biomass for 2027. If the mean spawning biomass for 2027 is below $B_{35\%}$, the stock is approaching an overfished condition. Otherwise, the stock is not approaching an overfished condition.

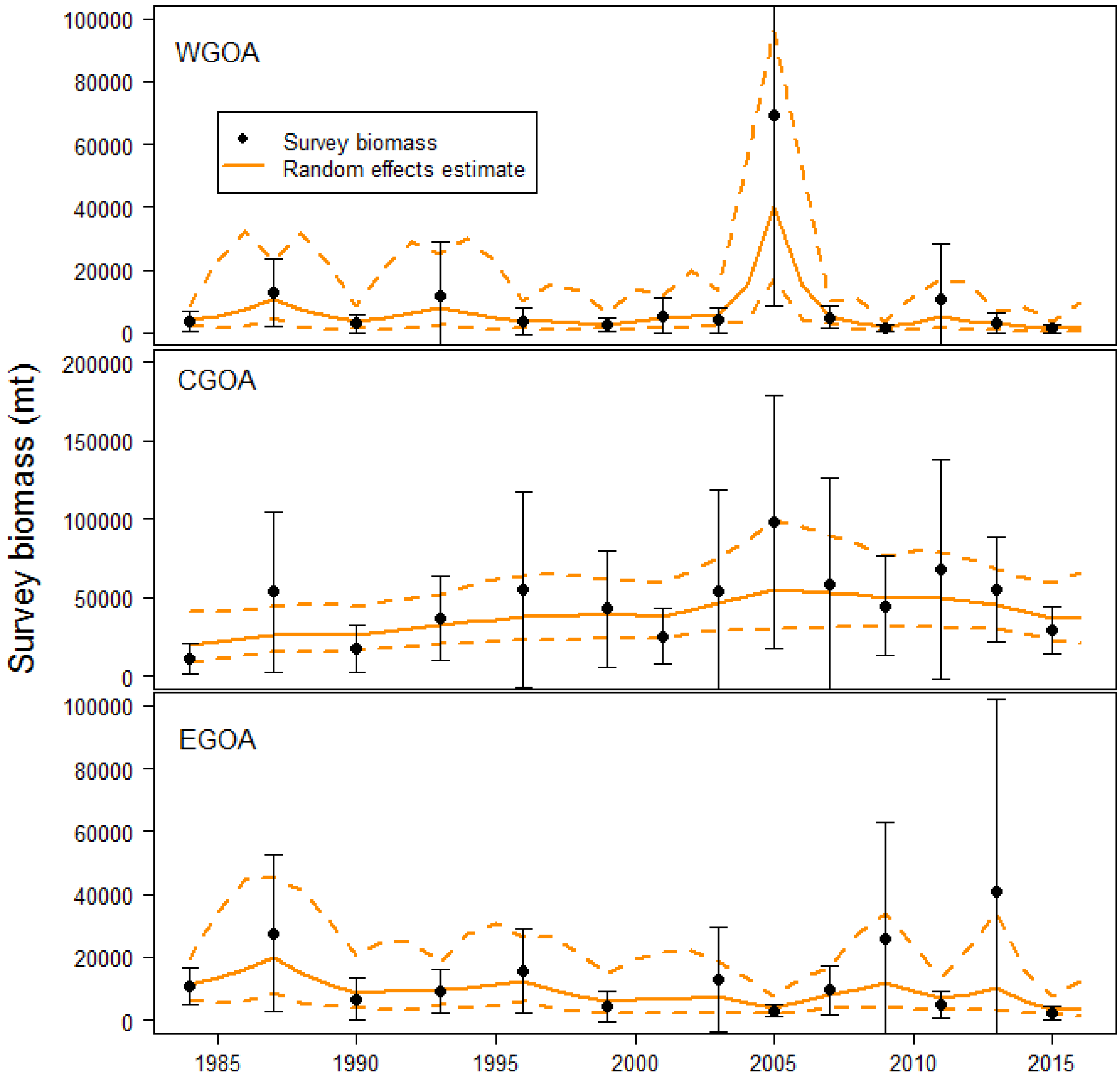
Based on the above criteria and Table 12-16, the stock is not overfished and is not approaching an overfished condition.

Alternate Projection

During the 2006 CIE review, it was suggested that projections should account for uncertainty in the entire assessment, not just recruitment from the endpoint of the assessment. We continue to present an alternative projection scenario using the uncertainty of the full assessment model harvesting at the same estimated yield ratio (0.67) as Scenario 2, except for all years instead of the next two. This projection propagates uncertainty throughout the entire assessment procedure and is based on an MCMC chain of 10,000,000. The projection shows wide credibility intervals on future spawning biomass (Figure 12-16). The $B_{35\%}$ and $B_{40\%}$ reference points are based on the 1981-2011 age-4 recruitments, and this projection predicts that the median spawning biomass will decrease quickly until average recruitment is attained.

Area Allocation of Harvests

For this assessment the Plan Team and SSC requested that the random effects model proposed by the survey averaging working group be utilized for apportionment. The random effects model was fit to the survey design-based biomass estimates (with associated variance) for the Western, Central, and Eastern Gulf of Alaska. Geostatistical model-based area-specific biomass estimates are not yet available but will be investigated for determining apportionment in future assessments. The random effects model estimates a process error parameter (constraining the variability of the modeled estimates among years) and random effects parameters in each year modeled. The fit of the random effects model to survey biomass in each area is shown in the following figure. For illustration the 95% confidence intervals are shown for the survey biomass (error bars) and the random effects estimates of survey biomass (dashed lines).



In general the random effects model fits the area-specific survey biomass reasonably well. For comparison, following the 4:6:9 weight scheme used to determine apportionment that has been used in previous assessments would result in a 2015 apportionment scheme of 5.6% in the Western area, 77.0% in the Central area, and 17.4% in the Eastern area. Using the random effects model estimates of survey biomass the apportionment results in 3.7% for the Western area (down from 5.8% in 2013), 88.5% for the Central area (up from 65.3% in 2013), and 7.8% for the Eastern area (down from 28.9% in 2013). This results in recommended ABC's of **173** t for the Western area, **4,147** t for the Central area, and **366** t for the Eastern area.

Because the Eastern area is now divided into two management areas dusky rockfish, i.e., the West Yakutat area (area between 147 degrees W. longitude and 140 degrees W. longitude) and the East Yakutat/Southeast Outside area (area east of 140 degrees W. longitude), the ABC for this management group in the Eastern area must be further apportioned between these two smaller areas. The weighted average method described above results in a point estimate with considerable uncertainty. In an effort to balance this uncertainty with associated costs to the fishing industry, the Gulf of Alaska Plan Team has recommended that apportionment to the two smaller areas in the eastern Gulf be based on the upper 95% confidence limit of the weighted average of the estimates of the eastern Gulf biomass proportion that is in the West Yakutat area. The upper 95% confidence interval of this proportion is 0.75 (down from 0.87 in 2013), so that the dusky rockfish ABC for West Yakutat would be 275 t, and the ABC for East Yakutat/Southeast Outside would be 91 t (Table 12-17).

Overfishing Definition
Based on the definitions for overfishing in Amendment 44 in Tier 3a (i.e., $F_{OFL} = F_{35\%}$=0.121), the 2016 overfishing (OFL) is set equal to 5,733 t for dusky rockfish in the GOA (Table 12-17).

Ecosystem Considerations

In general, a determination of ecosystem considerations is hampered by the lack of biological and habitat information for dusky rockfish. A summary of the ecosystem considerations presented in this section is listed in Table 12-18. Additionally, we provide information regarding the FMP, non-FMP, and prohibited species caught in rockfish target fisheries to help understand ecosystem impacts by the dusky fishery (Tables 12-3, 12-4, 12-5).

Ecosystem Effects on the Stock

Prey availability/abundance trends: similar to many other rockfish species, stock condition of dusky rockfish appears to be greatly influenced by periodic abundant year classes. Availability of suitable zooplankton prey items in sufficient quantity for larval or post-larval dusky rockfish may be an important determining factor of year class strength. Unfortunately, there is no information on the food habits of larval or post-larval rockfish to help determine possible relationships between prey availability and year class strength; moreover, field-collected larval dusky rockfish at present cannot even be visually identified to species. Yang (1993) reported that adult dusky rockfish consume mostly euphausiids. Yang et al. (2006) reports Pacific sandlance *Ammodytes hexapterus* and euphausiids as the most common prey item of dusky rockfish with Pacific sandlance comprising 82% of stomach content weight. Euphausiids are also a major item in the diet of walleye pollock, Pacific ocean perch, and northern rockfish. Changes in the abundance of these three species could lead to a corollary change in the availability of euphausiids, which would then have an impact on dusky rockfish.

Predator population trends: there is no documentation of predation on dusky rockfish. Larger fish such as Pacific halibut that are known to prey on other rockfish may also prey on adult dusky rockfish, but such predation probably does not have a substantial impact on stock condition. Predator effects would likely be more important on larval, post-larval, and small juvenile dusky rockfish, but information on these life stages and their predators is nil.

Changes in physical environment: strong year classes corresponding to the period 1976-77 have been reported for many species of groundfish in the Gulf of Alaska, including walleye pollock, Pacific ocean perch, northern rockfish, sablefish, and Pacific cod. As discussed in the *survey data* section, age data for dusky rockfish indicates that the 1976 and/or 1977 year classes were also unusually strong for this species. Therefore, it appears that environmental conditions may have changed during this period in such a way that survival of young-of-the-year fish increased for many groundfish species, including dusky rockfish. The environmental mechanism for this increased survival of dusky rockfish, however, remains unknown. Pacific ocean perch and dusky rockfish both appeared to have strong 1986 year classes, and this may be another year when environmental conditions were especially favorable for rockfish species.

Changes in bottom habitat due to natural or anthropogenic causes could alter survival rates by altering available shelter, prey, or other functions. Associations of juvenile rockfish with biotic and abiotic structure have been noted by Carlson and Straty (1981), Pearcy et al. (1989), and Love et al. (1991). However, the Essential Fish Habitat Environmental Impact Statement (EFH EIS) (NMFS 2005) concluded that the effects of commercial fishing on the habitat of groundfish are minimal or temporary. The long-term upward trend in abundance suggests that at current levels of abundance and exploitation, habitat effects from fishing is not limiting this stock.

Fishery Effects on the Ecosystem

Fishery-specific contribution to bycatch of HAPC biota: there is limited habitat information on adult dusky rockfish, especially regarding the habitat of the major fishing grounds for this species in the Gulf of Alaska. Nearly all the catch of dusky rockfish, however, is taken by bottom trawls, so the fishery potentially could affect HAPC biota such as corals or sponges if it occurred in localities inhabited by that biota. Corals and sponges are usually found on hard, rocky substrates, and there is some evidence that dusky rockfish may be found in such habitats. On submersible dives on the outer continental shelf of the eastern Gulf of Alaska, light dusky rockfish were observed in association with rocky habitats and in areas with extensive sponge beds, where the fish were observed resting in large vase-type sponges.[2] Also, dusky rockfish often co-occur and are caught with northern rockfish in the commercial fishery and in trawl surveys (Reuter 1999) and catches of northern rockfish have been associated with a rocky or rough bottom habitat (Clausen and Heifetz 2002). Based on this indirect evidence, it can be surmised that dusky rockfish are likely also associated with a rocky substrate. An analysis of bycatch of HAPC biota in commercial fisheries in the Gulf of Alaska in 1997-99 indicated that the dusky rockfish trawl fishery ranked fourth among all fisheries in the amount of corals taken as bycatch and sixth in the amount of sponges taken (National Marine Fisheries Service 2001). Little is known, however, about the extent of these HAPC biota and whether the bycatch is detrimental.

Fishery-specific concentration of target catch in space and time relative to predator needs in space and time (if known) and relative to spawning components: the dusky rockfish trawl fishery in the Gulf of Alaska previously started in July and usually lasted only a few weeks. As mentioned previously in the *fishery* section, the fishery is concentrated at a number of offshore banks on the outer continental shelf. Beginning in 2007 the Rockfish Program began which allowed fishing in the Central Gulf from May 1 – November 15. There is no published information on time of year of insemination or parturition (larval release), but insemination is likely in the fall or winter, and anecdotal observations indicate parturition is mostly in the spring. Hence, reproductive activities are probably not directly affected by the commercial fishery. However, there may be some interaction in the Central Gulf if parturition is delayed until May 1.

Fishery-specific effects on amount of large size target fish: a comparison between Table 12-6 (length frequency in the commercial fishery) and Table 12-10 (size composition in the trawl surveys) suggests that although the fishery does not catch many small fish <40 cm length the fishery also does not target on very large fish.

Fishery contribution to discards and offal production: fishery discard rates of dusky rockfish have been quite low in recent years, especially after formation of the Rockfish Program. The discard rate of in the dusky rockfish fishery is unknown as discards are grouped as rockfish fishery target and are not available for just the dusky fishery.

Fishery-specific effects on age-at-maturity and fecundity of the target fishery: the fishery effects on age-at-maturity and fecundity are unknown, but based on the size of 50% maturity of female dusky rockfish

[2]V.M. O=Connell, Alaska Dept. of Fish and Game, 304 Lake St., Sitka, AK 99835. Pers. commun. July 1997.

reported in this document (42.8 cm), the fishery length frequency distributions in Figure 12-10 suggest that in the 1990's the fishery may have caught a sizeable number of immature fish.

Fishery-specific effects on EFH living and non-living substrate: effects of the dusky rockfish fishery on non-living substrate is unknown, but the heavy-duty rockhopper trawl gear commonly used in the fishery can move around rocks and boulders on the bottom. Table 12-4 shows the estimated bycatch of living structure such as benthic urochordates, corals, sponges, sea pens, and sea anemones by the GOA rockfish fisheries.

Data Gaps and Research Priorities

There is no information on larval, post-larval, or early stage juvenile dusky rockfish. Larval dusky rockfish can only be identified with genetic techniques, which are very high in cost and manpower. Analysis of stock structure through the stock structure template illustrates the need for a large scale genetic study to investigate stock structure of dusky rockfish in the GOA. Habitat requirements for larval, post-larval, and early stage juvenile dusky rockfish are unknown. Habitat requirements for later stage juvenile and adult fish are anecdotal or conjectural. Research needs to be done to identify the HAPC biota on the bottom habitat of the major fishing grounds and what impact bottom trawling has on these biota. Several different techniques are used by stock assessors to weight length and age sample sizes in models. Research is currently being conducted to determine the best technique for weighting sample sizes and results should help us in choosing appropriate rationale for weighting. Additional analysis of using the model-based approach for estimating biomass is needed and will be presented in the next assessment.

Summary

A summary of biomass levels, exploitation rates and recommended ABCs and OFLs for dusky rockfish is in the following table:

Quantity	As estimated or *specified last* year for:		As estimated or *recommended this* year for:	
	2015	2016	2016[1]	2017[1]
M (natural mortality rate)	0.07	0.07	0.07	0.07
Tier	3a	3a	3a	3a
Projected total (age 4+) biomass (t)	66,629	64,295	60,072	57,492
Female spawning biomass (t)	27,345	25,344	25,238	23,245
$B_{100\%}$	52,264	52,264	49,268	49,268
$B_{40\%}$	20,906	20,906	19,707	19,707
$B_{35\%}$	18,292	18,292	17,244	17,244
F_{OFL}	0.122	0.122	0.121	0.121
$maxF_{ABC}$	0.098	0.098	0.098	0.098
F_{ABC}	0.098	0.098	0.098	0.098
OFL (t)	**6,246**	5,759	**5,733**	5,253
maxABC (t)	5,109	4,711	4,686	4,284
ABC (t)	**5,109**	4,711	**4,686**	4,284
	As determined *last* year for:		As determined *this* year for:	
Status	2013	2014	2014	2015
Overfishing	No	n/a	No	n/a
Overfished	n/a	No	n/a	No
Approaching overfished	n/a	No	n/a	No

[1] Projections are based on estimated catches of 3,145 t and 2,792 t used in place of maximum permissible ABC for 2016 and 2017.

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Table 12-1. A summary of key management measures and the time series of catch, ABC and TAC for pelagic shelf rockfish and dusky rockfish in the Gulf of Alaska.

Year	Catch[1] (t)	ABC	TAC		Management Measures
1988	1,086	3,300	3,300		Pelagic shelf rockfish assemblage was one of three management groups for *Sebastes* implemented by the North Pacific Management Council. Previously, *Sebastes* in Alaska were managed as "Pacific ocean perch complex" or "other rockfish" which included PSR species. Apportionment and biomass determined from average percent biomass of most recent trawl surveys
1989	1,738	6,600	3,300		No reported foreign or joint venture catches of PSR
1990	1,647	8,200	8,200		
1991	2,187	4,800	4,800		
1992	3,532	6,886	6,886		
1993	3,182	6,740	6,740		
1994	2,980	6,890	6,890		
1995	2,882	5,190	5,190		
1996	2,290	5,190	5,190		Area apportionment based on 4:6:9 weighting scheme of 3 most recent survey biomass estimates rather than average percent biomass
1997	2,467	5,140	5,140		
1998	3,109	4,880	4,880		Black and blue rockfish removed from PSR assemblage and federal management plan Trawling prohibited in Eastern Gulf east of 140 degrees W.
1999	4,658	4,880	4,880		Eastern Gulf divided into West Yakutat and East Yakutat/Southeast Outside and separate ABCs and TACs assigned
2000	3,728	5,980	5,980		Amendment 41 became effective which prohibited trawling in the Eastern Gulf east of 140 degrees W.
2001	3,006	5,980	5,980		Dusky rockfish treated as tier 4 species whereas dark, widow, and yellowtail broken out as tier 5 species
2002	3,321	5,490	5,490		
2003	3,056	5,490	5,490		Age structured model for dusky rockfish accepted to determine ABC and moved to Tier 3 status
2004	2,688	4,470	4,470		
2005	2,236	4,553	4,553		
2006	2,452	5,436	5,436		
2007	3,383	5,542	5,542		Amendment 68 created the Central Gulf Rockfish Pilot Project
2008	3,657	5,227	5,227		
2009	3,075	4,781	4,781		Dark rockfish removed from PSR assemblage and federal management plan
2010	3,119	5,059	5,509		
2011	2,538	4,754	4,754		Dusky rockfish broken out as stand-alone species for 2012. Widow and yellowtail rockfish included in other rockfish assemblage.
2012	4,012	5,118	5,118		
2013	3,133	4,700	4,700		
2014	3,034	5,486	5,486		
2015	2,709[2]	5,109	5,109		

[1] Catch is for entire pelagic shelf rockfish assemblage
[2] Catch is for dusky rockfish only, updated through October 1, 2015. Source: AKFIN.

Table 12-2. Commercial catch (t) of dusky rockfish in the Gulf of Alaska, with Gulf-wide values of acceptable biological catch (ABC), total allowable catch (TAC), and percent TAC harvested (% TAC). Values are a combination of foreign observer data, joint venture catch data, and NMFS Regional Office Catch Accounting System data.

Year	Catch	ABC[1]	TAC[1]	% TAC
1977	388	-	-	-
1978	162	-	-	-
1979	224	-	-	-
1980	597	-	-	-
1981	845	-	-	-
1982	852	-	-	-
1983	1,017	-	-	-
1984	540	-	-	-
1985	34	-	-	-
1986	17	-	-	-
1987	19	-	-	-
1988	1,067	3,300	3,300	32%
1989	1,707	6,600	3,300	52%
1990	1,612	8,200	8,200	20%
1991	2,035	4,800	4,800	41%
1992	3,443	6,886	6,886	50%
1993	3,119	6,740	6,740	46%
1994	2,913	6,890	6,890	42%
1995	2,836	5,190	5,190	55%
1996	2,275	5,190	5,190	44%
1997	2,464	5,140	5,140	48%
1998	3,107	4,880	4,880	64%
1999	4,535	4,880	4,880	93%
2000	3,699	5,980	5,980	62%
2001	2,997	5,980	5,980	50%
2002	3,301	5,490	5,490	60%
2003	3,020	5,490	5,490	55%
2004	2,557	4,470	4,470	57%
2005	2,209	4,553	4,553	49%
2006	2,436	5,436	5,436	45%
2007	3,372	5,542	5,542	61%
2008	3,631	5,227	5,227	69%
2009	3,069	4,781	4,781	64%
2010	3,109	5,059	5,059	61%
2011	2,529	4,754	4,754	53%
2012	4,012	5,118	5,118	78%
2013	3,159	4,700	4,700	67%
2014	3,061	5,486	5,486	56%
2015[a]	2,709	5,109	5,109	53%

[1] ABC and TAC are for the pelagic shelf rockfish assemblage which dusky rockfish was a member of until 2011. Individual ABCs and TACs were assigned to dusky rockfish starting in 2012.
[a] Catch updated through October 1, 2015. Source: AKFIN.

Table 12-3. FMP groundfish species caught in rockfish targeted fisheries in the Gulf of Alaska from 2011-2015. Conf. = Confidential because of less than three vessels. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 10/15/2015.

Group Name	2011	2012	2013	2014	2015	Average
Pacific Ocean Perch	13,120	13,953	11,555	15,283	15,895	13,961
Northern Rockfish	3,164	4,883	4,527	3,650	3,600	3,965
Dusky Rockfish	2,315	3,642	2,870	2,752	2,480	2,812
Arrowtooth Flounder	340	764	766	1,425	1,370	933
Walleye Pollock	813	574	829	1,339	1,022	915
Atka Mackerel	1,404	1,173	1,162	446	973	1,032
Pacific cod	560	404	584	624	763	587
Harlequin Rockfish	350	603	305	437	565	452
Sablefish	440	470	495	527	410	468
Shortraker Rockfish	239	303	290	243	237	262
Rougheye Rockfish	286	219	274	359	223	272
Thornyhead Rockfish	161	130	104	243	216	171
Rex Sole	51	72	89	84	115	82
Yelloweye Rockfish	69	188	179	86	113	127
Sharpchin Rockfish	112	82	45	93	96	86
Flathead Sole	13	16	25	30	44	26
Sculpin	39	55	70	33	43	48
Redstripe Rockfish	67	54	22	70	42	51
Dover Sole	15	37	24	30	33	28
Longnose Skate	25	23	23	26	31	26
Silvergray Rockfish	57	28	14	25	30	31
Rock Sole	44	61	26	28	26	37
Redbanded Rockfish	25	14	14	31	24	22
Majestic Squid	12	15	10	19	23	16
Skate, Other	14	14	18	36	22	21

Table 12-4. Non-FMP species bycatch estimates in tons for Gulf of Alaska rockfish targeted fisheries 2011-2015. Conf. = Confidential because of less than three vessels. Source: NMFS AKRO Blend/Catch Accounting System via AKFIN 10/15/15.

Group Name	2011	2012	2013	2014	2015
Benthic urochordata	Conf.	Conf.	Conf.	Conf.	Conf.
Birds	27	60.	Conf.	20	Conf.
Bivalves	0.01	0.01	Conf.	0.01	Conf.
Brittle star unidentified	0.01	0.04	0.02	0.05	0.06
Capelin	-	-	0.02	-	-
Corals Bryozoans	0.11	Conf.	Conf.	Conf.	Conf.
Dark Rockfish	12.82	55.38	42.16	47.91	45.12
Eelpouts	Conf.	.30	.04	.13	Conf.
Eulachon	Conf.	Conf.	0.07	0.02	0.03
Giant Grenadier	449.33	310.82	889.11	512.50	727.33
Greenlings	7.67	8.76	6.99	4.16	8.14
Pacific Grenadier	-	-	-	-	-
Hermit crab unidentified	0.02	Conf.	0.03	.04	0.03
Invertebrate unidentified	0.35	3.85	0.18	Conf.	0.19
Lanternfishes	-	-	Conf.	-	0.04
Misc crabs	0.04	0.04	0.01	0.04	Conf.
Misc crustaceans	Conf.	-	Conf.	Conf.	Conf.
Misc deep fish	-	-	Conf.	-	-
Misc fish	129.52	151.71	159.64	124.55	142.73
Misc inverts (worms etc)	Conf.	-	-	-	-
Other osmerids	-	Conf.	0.02	Conf.	-
Pacific Sand lance	Conf.	-	-	-	-
Pandalid shrimp	0.06	0.06	0.06	0.10	0.05
Polychaete unidentified	-	-	Conf.	-	-
Scypho jellies	0.02	0.16	0.39	5.13	1.23
Sea anemone unidentified	4.07	6.27	4.02	2.15	1.12
Sea pens whips	0.04	-	0.04	0.06	-
Sea star	1.46	0.92	0.89	1.60	3.46
Snails	0.23	1.26	0.15	0.12	0.26
Sponge unidentified	3.95	1.37	1.28	1.81	5.45
Stichaeidae	-	-	Conf.	Conf.	Conf.
Urchins, dollars cucumbers	0.44	0.30	0.28	0.21	0.98

Table 12-5. Prohibited Species Catch (PSC) estimates reported in tons for halibut and herring, and counts of animals for crab and salmon, by year, for the GOA rockfish fishery. Source: NMFS AKRO Blend/Catch Accounting System PSCNQ via AKFIN 10/15/2015.

Group Name	2011	2012	2013	2014	2015	Average
Bairdi Crab	25	87	69	173	49	81
Blue King Crab	0	0	0	0	0	0
Chinook Salmon	1,013	1,580	2,319	1,247	878	1,407
Golden K. Crab	129	111	102	34	19	79
Halibut	122	109	113	127	144	123
Herring	0	0	0	0	0	0
Other Salmon	210	308	2020	555	336	686
Opilio Crab	0	0	0	0	28	6
Red King Crab	0	0	0	0	0	0

Table 12-6. Fishery size compositions and sample size by year used in the model for dusky rockfish in the Gulf of Alaska. Lengths below 21 are pooled and lengths greater than 47 are pooled.

Length (cm)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2007
≤21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
26	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
27	0.000	0.002	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000
28	0.000	0.002	0.000	0.002	0.000	0.002	0.000	0.000	0.000	0.001
29	0.000	0.003	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000
30	0.002	0.005	0.000	0.002	0.000	0.012	0.000	0.000	0.000	0.000
31	0.002	0.011	0.000	0.000	0.001	0.006	0.001	0.000	0.000	0.000
32	0.003	0.012	0.000	0.000	0.000	0.004	0.001	0.000	0.000	0.000
33	0.004	0.015	0.000	0.002	0.000	0.014	0.004	0.001	0.000	0.002
34	0.007	0.019	0.000	0.001	0.001	0.008	0.008	0.001	0.000	0.003
35	0.025	0.019	0.000	0.004	0.002	0.004	0.019	0.000	0.002	0.003
36	0.029	0.015	0.000	0.004	0.005	0.010	0.026	0.001	0.002	0.005
37	0.019	0.017	0.001	0.003	0.004	0.008	0.042	0.003	0.001	0.010
38	0.024	0.027	0.001	0.009	0.007	0.002	0.041	0.006	0.004	0.014
39	0.069	0.036	0.006	0.004	0.020	0.010	0.034	0.012	0.006	0.019
40	0.084	0.108	0.020	0.019	0.028	0.033	0.041	0.027	0.011	0.035
41	0.134	0.117	0.046	0.041	0.045	0.052	0.060	0.059	0.028	0.057
42	0.145	0.125	0.103	0.074	0.059	0.082	0.088	0.099	0.079	0.075
43	0.140	0.114	0.145	0.076	0.084	0.093	0.106	0.147	0.116	0.103
44	0.136	0.117	0.200	0.146	0.098	0.120	0.112	0.170	0.164	0.115
45	0.085	0.100	0.197	0.171	0.124	0.128	0.119	0.163	0.182	0.131
46	0.057	0.073	0.151	0.176	0.126	0.126	0.097	0.126	0.148	0.132
47+	0.034	0.060	0.131	0.266	0.397	0.278	0.199	0.185	0.257	0.295
Sample size	2012	5495	3659	2117	1794	515	3090	2565	1684	4599

Table 12-6. (continued) Fishery size compositions and sample size by year for dusky rockfish in the Gulf of Alaska. Lengths below 21 are pooled and lengths greater than 47 are pooled.

Length (cm)	2009	2011	2013
≤21	0.000	0.000	0.000
22	0.000	0.000	0.000
23	0.000	0.000	0.000
24	0.000	0.000	0.000
25	0.000	0.000	0.000
26	0.000	0.000	0.000
27	0.000	0.000	0.000
28	0.000	0.000	0.000
29	0.000	0.000	0.000
30	0.000	0.000	0.000
31	0.001	0.000	0.000
32	0.000	0.001	0.001
33	0.002	0.001	0.001
34	0.004	0.001	0.004
35	0.006	0.001	0.004
36	0.010	0.001	0.004
37	0.013	0.002	0.005
38	0.021	0.007	0.009
39	0.027	0.014	0.012
40	0.043	0.026	0.018
41	0.049	0.044	0.031
42	0.070	0.077	0.053
43	0.086	0.107	0.081
44	0.104	0.121	0.120
45	0.121	0.137	0.132
46	0.123	0.128	0.120
47+	0.319	0.332	0.405
Sample size	4843	3550	4792

Table 12-7. Fishery age compositions for dusky rockfish in the Gulf of Alaska. Pooled age 25+ includes all fish 25 and older.

Age(yr)	2000	2001	2002	2003	2004	2005	2006	2008	2010	2012
4	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.002	0.002	0.000	0.002	0.005	0.000	0.000	0.000	0.000	0.000
7	0.000	0.004	0.007	0.000	0.007	0.002	0.006	0.007	0.000	0.002
8	0.012	0.004	0.009	0.019	0.002	0.005	0.026	0.007	0.006	0.003
9	0.007	0.043	0.011	0.030	0.055	0.014	0.036	0.038	0.033	0.003
10	0.034	0.035	0.104	0.046	0.069	0.092	0.078	0.086	0.054	0.025
11	0.049	0.068	0.109	0.177	0.066	0.104	0.146	0.109	0.069	0.090
12	0.141	0.077	0.095	0.102	0.182	0.079	0.097	0.065	0.151	0.095
13	0.207	0.132	0.063	0.091	0.114	0.191	0.074	0.164	0.105	0.116
14	0.212	0.170	0.154	0.038	0.083	0.099	0.113	0.076	0.048	0.139
15	0.100	0.161	0.134	0.073	0.040	0.061	0.071	0.060	0.133	0.085
16	0.051	0.089	0.120	0.127	0.076	0.038	0.052	0.058	0.066	0.062
17	0.027	0.060	0.052	0.097	0.104	0.061	0.039	0.045	0.027	0.075
18	0.015	0.031	0.025	0.062	0.055	0.061	0.071	0.041	0.045	0.033
19	0.015	0.012	0.011	0.018	0.019	0.063	0.036	0.043	0.042	0.021
20	0.012	0.017	0.007	0.014	0.021	0.038	0.049	0.050	0.018	0.029
21	0.029	0.012	0.016	0.008	0.017	0.023	0.023	0.036	0.009	0.034
22	0.022	0.010	0.005	0.008	0.012	0.023	0.019	0.030	0.051	0.036
23	0.019	0.010	0.007	0.010	0.007	0.002	0.010	0.013	0.051	0.021
24	0.015	0.019	0.014	0.002	0.000	0.000	0.006	0.010	0.021	0.031
25+	0.032	0.046	0.057	0.076	0.064	0.045	0.049	0.063	0.069	0.100
Sample size	411	517	441	628	422	444	309	604	332	612

Table 12-8. Biomass estimates (t) for dusky rockfish in the Gulf of Alaska by statistical area, based on results of NMFS bottom trawl surveys.

Year	Species[1]	Statistical Areas					Total
		Shumagin	Chirikof	Kodiak	Yakutat	Southeastern	
1984	Dusky Unident.	3,843	7,462	4,329	15,126	307	31,068
1987	Dusky Unident.	12,753	4,222	49,560	26,562	1,115	94,212
1990	Dusky Unident.	2,854	1,189	16,153	5,664	967	26,827
	Dusky	-	-	-	-	68	68
1993	Dusky Unident.	11,450	12,880	23,780	7,481	1,626	57,217
1996	Dusky	3,553	19,217	36,037	14,193	1,480	74,480
1999	Dusky	2,538	9,157	33,729	2,097	2,108	49,628
2001[a]	Dusky	5,351	2,062	23,590	7,924	1,738	40,665
2003	Dusky	4,039	46,729	7,192	11,519	1,377	70,856
2005	Dusky	69,295	38,216	60,097	2,488	418	170,513
2007	Dusky	4,985	38,350	20,303	5,579	3,857	73,074
2009	Dusky	1,404	4,075	40,836	25,082	726	72,123
2011	Dusky	10,473	5,169	62,893	4,103	768	83,407
2013	Dusky	2,950	19,123	36,238	40,685	174	99,170
2015	Dusky	1,395	12,877	16,306	1,682	526	32,786

[a]Note: The Yakutat and Southeastern areas were not sampled in the 2001 survey. Estimates of biomass for these two areas in 2001 were obtained by averaging the corresponding area biomasses in the 1993, 1996, and 1999 surveys.

[1] Dusky rockfish included in dusky unidentified rockfish, which included “light” and “dark” dusky combined, until 1996. In 1990 the first instance of dusky rockfish as a separate species occurred.

Table 12-9A. GOA dusky rockfish biomass estimates, standard errors, lower confidence intervals, and upper confidence intervals, based on results of NMFS bottom trawl surveys.

Year	Biomass	Standard Error	Lower CI	Upper CI	Coefficient of Variation (CV)
1984	31,068	7,147	17,060	45,076	23%
1987	94,212	29,391	36,606	151,818	31%
1990	26,895	8,635	9,970	43,820	32%
1993	57,217	16,590	24,701	89,733	29%
1996	74,480	32,851	10,092	138,868	44%
1999	49,628	19,194	12,008	87,248	39%
2001	40,665	11,628	17,874	63,456	29%
2003	70,856	34,352	3,526	138,186	48%
2005	170,513	51,658	69,234	271,734	30%
2007	73,074	34,498	4,890	139,616	47%
2009	72,123	24,687	23,736	120,510	34%
2011	83,407	36,806	11,267	155,547	44%
2013	99,170	35,767	29,067	169,273	36%
2015	32,786	7,870	17,361	48,211	24%

Table 12-9B. GOA dusky rockfish biomass estimates, standard errors, lower confidence intervals, and upper confidence intervals, based on results of NMFS bottom trawl surveys using a geostatistical general linear mixed model estimator.

Year	Biomass	Standard Error	Lower CI	Upper CI	Coefficient of Variation (CV)
1984	20,633	3,246	14,271	26,995	16%
1987	34,846	4,849	25,341	44,350	14%
1990	11,919	2,395	7,224	16,613	20%
1993	31,008	5,615	20,003	42,013	18%
1996	32,524	6,493	19,798	45,250	20%
1999	29,221	6,409	16,660	41,782	22%
2001	39,115	9,828	19,851	58,378	25%
2003	44,795	8,639	27,863	61,728	19%
2005	63,604	10,934	42,173	85,036	17%
2007	43,638	7,992	27,974	59,301	18%
2009	34,310	6,636	21,303	47,318	19%
2011	39,800	8,672	22,803	56,797	22%
2013	53,927	11,416	31,552	76,302	21%
2015	52,304	10,045	32,616	71,993	19%

Table 12-10. NMFS trawl survey length compositions for dusky rockfish in the Gulf of Alaska. Lengths below 22 are pooled and lengths greater than 47 are pooled. Survey size compositions are not used in model.

Length (cm)	1984	1987	1990	1993	1996	1999	2001	2003	2005
≤21	0.000	0.000	0.000	0.001	0.003	0.001	0.003	0.000	0.001
22	0.000	0.001	0.008	0.002	0.001	0.001	0.002	0.004	0.001
23	0.000	0.001	0.004	0.004	0.004	0.001	0.003	0.000	0.001
24	0.000	0.000	0.002	0.007	0.003	0.000	0.005	0.001	0.002
25	0.000	0.000	0.006	0.002	0.003	0.002	0.003	0.000	0.002
26	0.000	0.001	0.000	0.015	0.001	0.000	0.004	0.004	0.001
27	0.000	0.000	0.006	0.018	0.001	0.001	0.006	0.017	0.001
28	0.002	0.000	0.006	0.023	0.001	0.000	0.002	0.024	0.001
29	0.001	0.000	0.007	0.021	0.005	0.001	0.022	0.027	0.004
30	0.004	0.001	0.000	0.030	0.002	0.002	0.024	0.044	0.005
31	0.009	0.001	0.001	0.039	0.002	0.006	0.029	0.027	0.010
32	0.015	0.004	0.007	0.051	0.002	0.008	0.033	0.031	0.014
33	0.014	0.002	0.001	0.043	0.007	0.008	0.026	0.053	0.016
34	0.036	0.018	0.003	0.040	0.003	0.013	0.030	0.008	0.019
35	0.048	0.039	0.001	0.046	0.006	0.015	0.026	0.011	0.021
36	0.061	0.061	0.002	0.053	0.001	0.015	0.042	0.013	0.046
37	0.066	0.093	0.004	0.037	0.009	0.016	0.039	0.043	0.027
38	0.090	0.084	0.006	0.049	0.009	0.019	0.040	0.077	0.053
39	0.131	0.080	0.019	0.051	0.016	0.016	0.059	0.072	0.031
40	0.139	0.109	0.017	0.051	0.036	0.031	0.061	0.066	0.042
41	0.134	0.142	0.077	0.035	0.080	0.035	0.071	0.050	0.046
42	0.105	0.121	0.125	0.044	0.065	0.072	0.061	0.050	0.072
43	0.061	0.112	0.115	0.061	0.127	0.104	0.064	0.065	0.092
44	0.037	0.062	0.153	0.064	0.133	0.115	0.058	0.070	0.101
45	0.022	0.028	0.175	0.073	0.111	0.150	0.083	0.065	0.100
46	0.013	0.019	0.151	0.065	0.113	0.141	0.076	0.062	0.101
47+	0.014	0.020	0.104	0.076	0.256	0.231	0.127	0.114	0.190
Sample Size	1881	2818	1113	2299	1478	1340	1255	1780	3383

Table 12-10 (continued). NMFS trawl survey length compositions for dusky rockfish in the Gulf of Alaska. Lengths below 22 are pooled and lengths greater than 47 are pooled. Survey size compositions are not used in model.

Length (cm)	2007	2009	2011	2013	2015
≤21	0.000	0.003	0.001	0.000	0.000
22	0.000	0.006	0.000	0.001	0.000
23	0.000	0.011	0.000	0.000	0.000
24	0.000	0.012	0.000	0.000	0.001
25	0.001	0.005	0.000	0.001	0.002
26	0.001	0.009	0.000	0.002	0.003
27	0.001	0.005	0.000	0.001	0.001
28	0.001	0.006	0.000	0.001	0.002
29	0.001	0.007	0.000	0.002	0.001
30	0.003	0.010	0.002	0.003	0.003
31	0.001	0.008	0.002	0.004	0.007
32	0.004	0.010	0.002	0.003	0.005
33	0.003	0.005	0.003	0.005	0.006
34	0.010	0.007	0.005	0.003	0.010
35	0.013	0.007	0.006	0.005	0.010
36	0.013	0.008	0.015	0.007	0.014
37	0.017	0.006	0.019	0.011	0.017
38	0.024	0.011	0.017	0.012	0.024
39	0.049	0.011	0.036	0.011	0.027
40	0.070	0.020	0.042	0.009	0.029
41	0.077	0.031	0.058	0.021	0.039
42	0.110	0.036	0.091	0.043	0.050
43	0.106	0.073	0.135	0.101	0.051
44	0.115	0.069	0.114	0.112	0.083
45	0.098	0.105	0.109	0.179	0.106
46	0.099	0.154	0.103	0.153	0.114
47+	0.185	0.363	0.238	0.307	0.395
Sample Size	1818	2024	1410	1889	1820

Table 12-11. NMFS trawl survey age compositions for dusky rockfish in the Gulf of Alaska. Pooled age 25+ includes all fish 25 and older.

Age (yr)	1984	1987	1990	1993	1996	1999	2001	2003	2005	2007
4	0.000	0.000	0.007	0.004	0.013	0.001	0.014	0.002	0.006	0.000
5	0.000	0.000	0.005	0.058	0.007	0.001	0.006	0.072	0.008	0.003
6	0.000	0.000	0.003	0.094	0.013	0.001	0.081	0.114	0.029	0.005
7	0.075	0.192	0.001	0.193	0.004	0.056	0.074	0.011	0.060	0.021
8	0.284	0.003	0.001	0.088	0.025	0.013	0.052	0.288	0.063	0.023
9	0.115	0.047	0.007	0.118	0.049	0.047	0.188	0.073	0.038	0.116
10	0.142	0.155	0.115	0.031	0.188	0.033	0.095	0.019	0.100	0.092
11	0.145	0.213	0.134	0.032	0.111	0.113	0.093	0.064	0.089	0.046
12	0.121	0.109	0.086	0.020	0.148	0.270	0.037	0.037	0.058	0.165
13	0.052	0.057	0.113	0.048	0.045	0.121	0.066	0.035	0.150	0.126
14	0.011	0.034	0.171	0.022	0.029	0.064	0.099	0.019	0.064	0.066
15	0.040	0.043	0.139	0.039	0.033	0.025	0.061	0.044	0.034	0.061
16	0.006	0.014	0.042	0.045	0.015	0.015	0.034	0.066	0.037	0.041
17	0.000	0.027	0.015	0.042	0.018	0.001	0.013	0.033	0.034	0.009
18	0.000	0.012	0.055	0.016	0.052	0.020	0.009	0.016	0.035	0.035
19	0.000	0.018	0.035	0.016	0.041	0.025	0.007	0.020	0.055	0.036
20	0.002	0.010	0.009	0.010	0.045	0.048	0.008	0.004	0.038	0.022
21	0.000	0.014	0.020	0.011	0.019	0.040	0.005	0.015	0.019	0.021
22	0.000	0.002	0.007	0.009	0.016	0.023	0.005	0.000	0.008	0.020
23	0.000	0.000	0.000	0.009	0.023	0.020	0.015	0.008	0.003	0.010
24	0.000	0.004	0.001	0.015	0.011	0.005	0.003	0.004	0.006	0.007
25+	0.008	0.045	0.033	0.079	0.097	0.056	0.033	0.056	0.067	0.075
Sample size	161	446	94	445	554	174	676	195	461	490

Table 12-11. (continued) NMFS trawl survey age compositions for dusky rockfish in the Gulf of Alaska. Pooled age 25+ includes all fish 25 and older.

Age (yr)	2009	2011	2013
4	0.004	0.000	0.000
5	0.022	0.000	0.000
6	0.009	0.005	0.002
7	0.026	0.004	0.004
8	0.013	0.023	0.010
9	0.022	0.018	0.009
10	0.036	0.095	0.017
11	0.067	0.092	0.027
12	0.058	0.072	0.084
13	0.051	0.119	0.099
14	0.134	0.112	0.103
15	0.059	0.066	0.178
16	0.069	0.080	0.086
17	0.074	0.040	0.080
18	0.024	0.037	0.083
19	0.024	0.039	0.050
20	0.055	0.016	0.016
21	0.032	0.022	0.012
22	0.039	0.024	0.029
23	0.074	0.031	0.025
24	0.017	0.023	0.035
25+	0.091	0.082	0.052
Sample size	495	427	434

Table 12-12. Likelihood values and estimates of key parameters for 2013 model and this year's 2015 model cases for GOA dusky rockfish.

Likelihoods	*2013 M0*	*2015 M1*	*2015 M2*	*2015 M3*	*2015 M4*	*2015 M5*
Catch	27.14	28.84	28.68	29.84	30.35	27.86
Survey Biomass	38.84	44.16	44.74	44.65	44.34	37.36
Fishery Ages	30.23	33.12	31.79	19.81	25.01	24.50
Survey Ages	85.83	96.26	97.97	85.92	94.74	95.62
Fishery Sizes	49.93	52.57	47.67	47.84	49.26	50.46
Maturity Likelihood	65.00	65.00	65.00	65.00	65.00	65.00
Data-Likelihood	**296.97**	**319.95**	**315.85**	**293.06**	**308.7**	**300.80**
Penalties/Priors						
Recruitment Devs	25.83	26.57	27.51	23.73	20.85	24.58
F Regularity	33.75	34.13	33.37	33.80	34.32	32.70
σ_r prior	0.40	0.41	0.38	0.57	0.75	0.60
q prior	0.03	0.01	0.03	0.06	0.05	0.70
Objective Fun. Total	**356.98**	**381.07**	**377.14**	**351.22**	**364.67**	**359.38**
Parameter Estimates						
Number parameters estimated	103	107	107	110	114	114
Q	0.896	1.055	1.11	1.17	1.14	0.59
σ_r	1.006	1.001	1.02	0.93	0.87	0.92
Mean recruitment (millions)	7.08	5.39	5.02	4.94	4.97	6.30
$F_{40\%}$	0.098	0.099	0.099	0.099	0.098	0.098
Total Biomass	69,371	37,111	35,193	33,768	34,875	60,072
Spawning biomass	31,574	15,551	14,590	13,742	14,097	25,238
$B_{100\%}$ (t)	52,264	39,775	39,081	38,624	38,910	49,268
$B_{40\%}$ (t)	20,906	15,910	15,632	15,450	15,564	19,707
ABC ($F_{40\%}$) (t)	**5,486**	**2,849**	**2,543**	**2,279**	**2,371**	**4,686**

Table 12-13. Estimates of key parameters (μ) with Hessian estimates of standard deviation (σ), MCMC standard deviations (σ (MCMC)) and 95% Bayesian credible intervals (BCI) derived from MCMC simulations.

Parameter	μ	μ MCMC	σ	σ MCMC	Median MCMC	BCI Lower	BCI Upper
Q	0.588	0.588	0.585	0.073	0.075	0.450	0.745
$F_{40\%}$	0.098	0.120	0.112	0.029	0.047	0.062	0.224
2016 Female SSB	25,238	25,896	25,477	4,324	4,540	18,101	36,124
ABC	4,686	5,776	5,378	1,536	2,301	2,725	11,004

Table 12-14. Estimated time series of female spawning biomass, 6+ biomass (age 6 and greater), catch/6 + biomass, and number of age four recruits for dusky rockfish in the Gulf of Alaska. Estimates are shown for the current assessment and from the previous SAFE.

	Spawning biomass (t)		6+ Biomass (t)		Catch/6+ biomass		Age 4 recruits (1000's)	
Year	Previous	Current	Previous	Current	Previous	Current	Previous	Current
1977	12,365	10,489	28,423	24,661	0.024	0.028	2,277	1,894
1978	11,775	9,997	28,018	24,187	0.015	0.017	2,492	2,105
1979	11,395	9,710	27,885	24,093	0.017	0.020	3,113	2,449
1980	11,093	9,474	27,914	24,141	0.028	0.034	11,614	7,850
1981	10,778	9,181	28,042	24,144	0.033	0.040	6,132	5,736
1982	10,567	8,945	31,953	26,789	0.029	0.036	3,612	4,268
1983	10,571	8,880	34,493	29,125	0.029	0.036	1,926	1,843
1984	10,802	8,992	36,085	30,965	0.021	0.024	11,097	8,999
1985	11,456	9,499	37,073	31,956	0.005	0.005	1,577	1,732
1986	12,665	10,532	42,327	36,748	0.003	0.004	2,267	2,750
1987	14,083	11,780	44,057	38,514	0.003	0.004	1,548	1,877
1988	15,531	13,104	45,551	40,314	0.027	0.031	9,911	8,181
1989	16,398	13,913	45,233	40,298	0.036	0.040	3,341	4,976
1990	16,973	14,471	47,828	42,673	0.030	0.032	20,420	15,874
1991	17,523	15,079	48,299	44,223	0.033	0.034	11,557	11,008
1992	17,936	15,594	55,912	50,994	0.059	0.064	10,430	9,499
1993	17,643	15,409	59,558	54,855	0.050	0.054	1,552	2,563
1994	17,802	15,673	63,429	58,732	0.044	0.047	8,381	6,972
1995	18,542	16,476	63,699	59,462	0.043	0.046	3,586	5,006
1996	19,835	17,770	66,109	61,614	0.034	0.037	20,675	15,135
1997	21,647	19,533	66,786	63,070	0.037	0.039	1,515	2,876
1998	23,353	21,191	74,148	68,892	0.042	0.045	10,452	8,435
1999	24,534	22,344	73,708	68,846	0.061	0.064	21,771	17,348
2000	24,817	22,618	74,872	69,437	0.049	0.052	1,188	2,200
2001	25,404	23,143	82,013	75,267	0.036	0.039	11,799	10,219
2002	26,468	24,056	82,122	75,360	0.039	0.043	15,478	13,685
2003	27,603	24,961	85,477	78,173	0.034	0.038	2,969	5,576
2004	29,013	26,102	90,817	83,065	0.028	0.031	6,394	6,539
2005	30,702	27,520	91,513	84,841	0.024	0.026	5,619	6,502
2006	32,483	29,092	93,003	86,799	0.026	0.028	2,431	2,149
2007	33,975	30,470	93,404	88,068	0.036	0.038	2,412	1,802
2008	34,717	31,253	90,952	85,912	0.039	0.042	3,228	2,132
2009	34,918	31,632	87,539	82,587	0.035	0.037	2,015	1,788
2010	34,844	31,835	84,485	79,350	0.037	0.039	1,771	1,356
2011	34,240	31,509	80,591	75,480	0.031	0.034	1,936	1,495
2012	33,428	30,943	76,840	71,685	0.051	0.055	2,189	1,575
2013	31,574	29,252	71,561	66,341	0.042	0.047	2,173	1,699
2014		27,590		61,794		0.049		2,029
2015		25,750		57,431		0.049		2,018

Table 12-15. Estimated time series of recruitment, female spawning biomass, and total biomass (4+) for dusky rockfish in the Gulf of Alaska. Columns headed with 2.5% and 97.5% represent the lower and upper 95% credible intervals from the MCMC estimated posterior distribution.

	Recruits (Age 4)			Total Biomass			Spawning Biomass		
Year	Mean	2.50%	97.50%	Mean	2.50%	97.50%	Mean	2.50%	97.50%
1977	2,004	401	4,929	27,610	22,282	35,160	11,226	8,816	14,435
1978	2,204	523	4,950	27,140	21,850	34,671	10,723	8,394	13,837
1979	2,554	535	6,049	27,198	22,083	34,693	10,426	8,150	13,462
1980	7,926	3,774	13,560	28,577	23,535	36,216	10,183	8,002	13,132
1981	5,691	1,637	11,456	30,022	24,926	38,028	9,886	7,763	12,857
1982	4,124	897	8,458	31,498	26,305	39,757	9,646	7,542	12,563
1983	1,865	310	5,454	32,688	27,396	40,983	9,578	7,513	12,547
1984	8,661	4,814	12,910	35,100	29,595	43,478	9,684	7,596	12,659
1985	1,799	333	4,945	36,911	31,298	45,480	10,172	8,073	13,233
1986	2,798	666	5,601	39,201	33,506	48,028	11,189	9,049	14,405
1987	1,951	381	4,715	41,054	35,325	50,162	12,408	10,141	15,788
1988	8,389	5,199	12,478	43,916	38,062	53,173	13,690	11,297	17,290
1989	5,154	1,710	9,069	45,356	39,250	54,688	14,404	11,901	18,137
1990	16,381	11,967	22,378	48,955	42,542	58,770	14,832	12,325	18,416
1991	11,383	6,996	16,258	53,535	46,535	63,941	15,414	12,911	19,083
1992	9,812	6,281	14,434	58,441	50,963	69,768	15,928	13,434	19,555
1993	2,674	625	5,241	60,380	52,378	72,405	15,755	13,177	19,566
1994	7,230	4,646	10,643	62,932	54,462	75,854	16,054	13,367	20,040
1995	5,215	2,343	8,164	64,992	55,890	78,508	16,918	14,065	21,163
1996	15,773	12,085	21,406	68,972	59,109	84,023	18,294	15,152	22,922
1997	3,014	818	5,503	71,530	60,987	87,394	20,151	16,679	25,240
1998	8,809	5,722	12,864	74,398	63,089	91,570	21,906	18,128	27,440
1999	18,128	13,574	24,960	78,680	66,360	97,506	23,154	19,148	29,030
2000	2,314	458	4,839	79,325	66,303	99,293	23,522	19,343	29,708
2001	10,664	7,185	15,455	81,752	67,762	103,220	24,140	19,629	30,847
2002	14,295	10,019	20,731	85,822	70,754	109,238	25,149	20,349	32,358
2003	5,839	2,515	9,851	88,312	72,393	113,027	26,157	21,045	33,922
2004	6,866	3,652	11,267	90,721	74,049	117,010	27,405	21,915	35,722
2005	6,869	3,817	11,139	93,053	75,621	120,686	28,934	23,071	37,875
2006	2,291	593	4,931	94,168	76,073	122,330	30,616	24,324	40,228
2007	1,935	522	4,484	93,884	75,361	122,588	32,099	25,375	42,173
2008	2,302	611	5,519	91,737	72,948	120,312	32,976	25,918	43,565
2009	1,946	409	5,255	88,477	69,735	117,139	33,438	26,022	44,562
2010	1,487	279	4,830	85,018	66,443	113,631	33,711	26,028	45,228
2011	1,636	298	5,767	80,998	62,896	109,186	33,435	25,709	45,302
2012	1,715	285	7,325	77,226	59,617	105,008	32,897	25,044	44,831
2013	1,837	279	8,144	71,884	54,767	98,843	31,214	23,380	43,062
2014	2,166	319	13,351	67,384	50,934	94,550	29,541	21,886	41,290
2015	2,148	329	12,836	63,058	47,056	90,221	27,678	20,233	39,341
2016	6,364	580	25,629	60,016	44,121	88,014	25,239	18,101	36,124
2017	6,364	605	25,722	57,335	41,510	84,939	23,214	16,321	32,917

Table 12-16. Set of projections of spawning biomass (SB) and yield for dusky rockfish in the Gulf of Alaska. Six harvest scenarios designed to satisfy the requirements of Amendment 56, NEPA, and MSFCMA. For a description of scenarios see section *Harvest Recommendations*. All units are in t. $B_{40\%}$ = 19,707 t, $B_{35\%}$ = 17,244 t, $F_{40\%}$ = 0.098, and $F_{35\%}$ = 0.121.

Year	Maximum permissible F	Author's F (pre-specified catch)[1]	Half maximum F	5-year average F	No fishing	Overfished	Approaching overfished
			Spawning Biomass (t)				
2015	27,121	27,121	27,121	27,121	27,121	27,121	27,121
2016	25,103	25,238	25,298	25,289	25,502	25,009	25,103
2017	22,396	23,245	23,639	23,567	24,968	21,828	22,396
2018	20,048	21,367	22,113	21,997	24,445	19,144	19,974
2019	18,124	19,247	20,790	20,650	24,007	17,047	17,689
2020	16,764	17,647	19,733	19,603	23,743	15,631	16,123
2021	15,946	16,648	19,013	18,917	23,731	14,803	15,184
2022	15,637	16,198	18,664	18,647	24,046	14,504	14,802
2023	15,748	16,197	18,710	18,767	24,698	14,629	14,862
2024	16,127	16,486	19,006	19,171	25,613	15,014	15,195
2025	16,635	16,920	19,524	19,750	26,712	15,510	15,650
2026	17,167	17,392	20,297	20,402	27,902	16,014	16,121
2027	17,668	17,846	21,026	21,066	29,117	16,472	16,553
2028	18,121	18,261	21,599	21,715	30,329	16,875	16,935
			Fishing Mortality				
2015	0.054	0.054	0.054	0.054	0.054	0.054	0.054
2016	0.098	0.065	0.049	0.052	-	0.121	0.121
2017	0.098	0.063	0.049	0.052	-	0.121	0.121
2018	0.098	0.098	0.049	0.052	-	0.118	0.118
2019	0.090	0.096	0.049	0.052	-	0.104	0.104
2020	0.083	0.087	0.049	0.052	-	0.095	0.095
2021	0.078	0.082	0.047	0.052	-	0.089	0.089
2022	0.077	0.080	0.046	0.052	-	0.087	0.087
2023	0.077	0.079	0.046	0.052	-	0.088	0.088
2024	0.079	0.081	0.047	0.052	-	0.091	0.091
2025	0.081	0.082	0.048	0.052	-	0.093	0.093
2026	0.083	0.084	0.049	0.052	-	0.096	0.096
2027	0.085	0.086	0.049	0.052	-	0.099	0.099
2028	0.086	0.087	0.049	0.052	-	0.101	0.101
			Yield (t)				
2015	2,828	2,828	2,828	2,828	2,828	2,828	2,828
2016	4,686	4,686	2,398	2,542	-	5,733	4,686
2017	4,160	4,284	2,231	2,358	-	4,977	4,160
2018	3,700	3,947	2,077	2,189	-	4,210	4,526
2019	3,042	3,440	1,940	2,039	-	3,298	3,557
2020	2,565	2,851	1,812	1,916	-	2,728	2,909
2021	2,287	2,501	1,679	1,828	-	2,408	2,539
2022	2,191	2,356	1,628	1,794	-	2,305	2,404
2023	2,249	2,381	1,655	1,818	-	2,380	2,458
2024	2,395	2,499	1,725	1,878	-	2,554	2,616
2025	2,568	2,651	1,813	1,950	-	2,759	2,806
2026	2,732	2,797	1,902	2,024	-	2,952	2,989
2027	2,878	2,928	1,983	2,094	-	3,115	3,143
2028	3,005	3,044	2,057	2,160	-	3,255	3,276

[1]Projected ABCs and OFLs for 2016 and 2017 are derived using estimated catch of 2,828 for 2015, and projected catches of 3,145 t and 2,792 t for 2016 and 2017 based on realized catches from 2012-2014.

Table 12-17. Allocation of 2016 ABC for dusky rockfish in the Gulf of Alaska. Apportionment is based on the random effects model fit to dusky rockfish biomass estimates. Allocation for West Yakutat and SE/Outside is equal to the upper 95% confidence interval of the ratio of biomass in West Yakutat area to SE/Outside area. All units are in t.

Year	Western	Central	Eastern Yakutat	Eastern Southeast	Total
Area	3.7%	88.5%	7.8%		100%
Apportionment			75.0%	25.0%	
2015 design-based survey biomass CV	49%	27%	45%		24%
Area ABC (t)	**173**	**4,147**	**366**		**4,686**
Yak/SE ABC (t)			**275**	**91**	
OFL (t)					**5,733**

Table 12-18. Analysis of ecosystem considerations for pelagic shelf rockfish and the dusky rockfish fishery.

Ecosystem effects on *GOA pelagic shelf rockfish*			
Indicator	Observation	Interpretation	Evaluation
Prey availability or abundance trends			
Phytoplankton and Zooplankton	Important for larval and post-larval survival but no information known	May help determine year class strength, no time series	Possible concern if some information available
Predator population trends			
Marine mammals	Not commonly eaten by marine mammals	No effect	No concern
Birds	Stable, some increasing some decreasing	Affects young-of-year mortality	Probably no concern
Fish (Halibut, arrowtooth, lingcod)	Arrowtooth have increased, others stable	More predation on juvenile rockfish	Possible concern
Changes in habitat quality			
Temperature regime	Higher recruitment after 1977 regime shift	Contributed to rapid stock recovery	No concern
Winter-spring environmental conditions	Affects pre-recruit survival	Different phytoplankton bloom timing	Causes natural variability, rockfish have varying larval release to compensate
Production	Relaxed downwelling in summer brings in nutrients to Gulf shelf	Some years are highly variable, like El Nino 1998	Probably no concern, contributes to high variability of rockfish recruitment
GOA pelagic rockfish fishery effects on ecosystem			
Indicator	Observation	Interpretation	Evaluation
Fishery contribution to bycatch			
Prohibited species	Stable, heavily monitored	Minor contribution to mortality	No concern
Forage (including herring, Atka mackerel, cod, and pollock)	Stable, heavily monitored (P. cod most common)	Bycatch levels small relative to forage biomass	No concern
HAPC biota	Medium bycatch levels of sponge and corals	Bycatch levels small relative to total HAPC biota, but can be large in specific areas	Probably no concern
Marine mammals and birds	Very minor take of marine mammals, trawlers overall cause some bird mortality	Rockfish fishery is short compared to other fisheries	No concern
Sensitive non-target species	Likely minor impact on non-target rockfish	Data limited, likely to be harvested in proportion to their abundance	Probably no concern
Fishery concentration in space and time	Duration is short and in patchy areas	Not a major prey species for marine mammals	No concern, fishery is being extended for several months starting 2006
Fishery effects on amount of large size target fish	Depends on highly variable year-class strength	Natural fluctuation	Probably no concern
Fishery contribution to discards and offal production	Decreasing	Improving, but data limited	Possible concern with non-target rockfish
Fishery effects on age-at-maturity and fecundity	Black rockfish show older fish have more viable larvae	Inshore rockfish results may not apply to longer-lived slope rockfish	Definite concern, studies being initiated in 2005

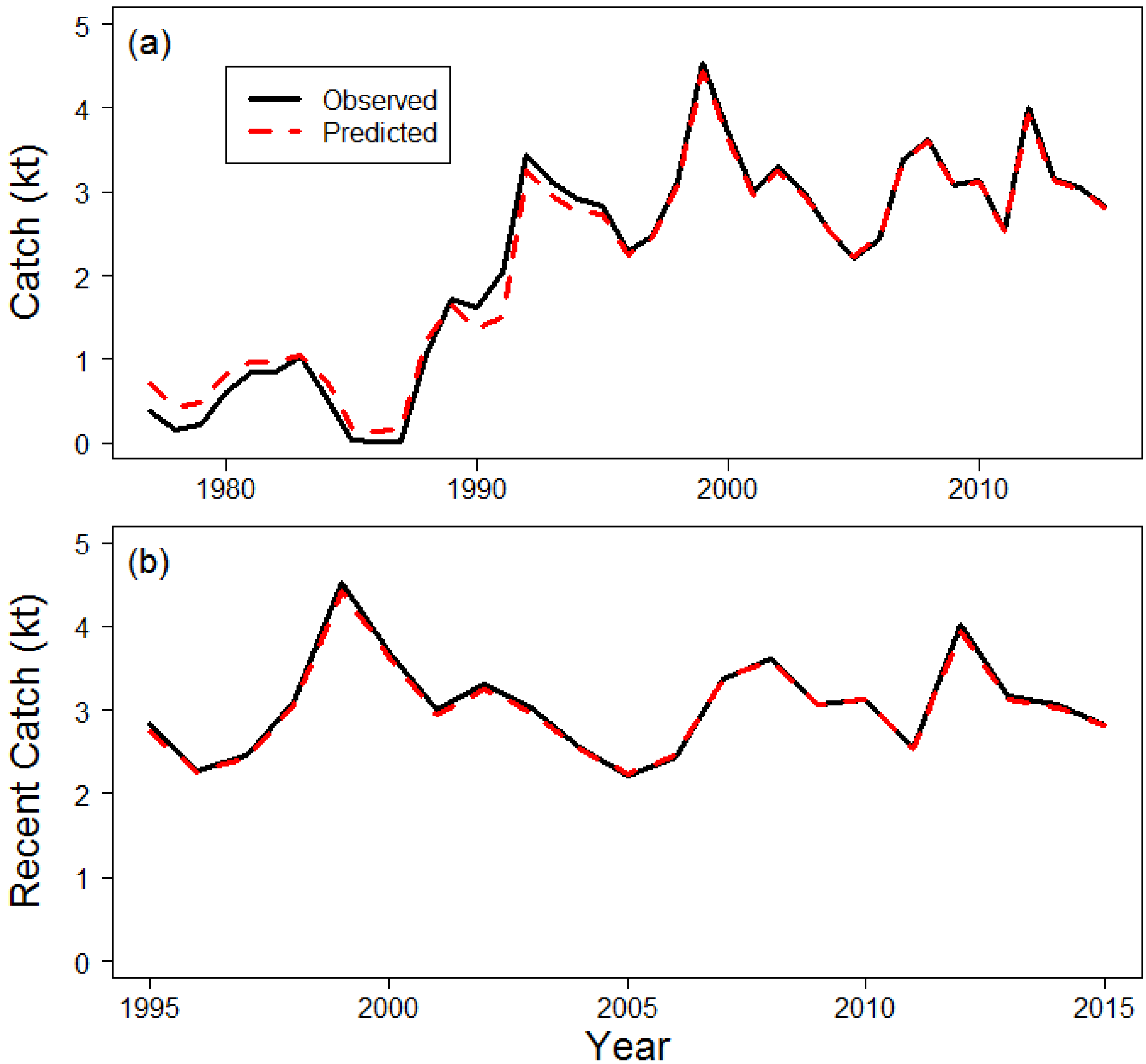

Figure 12-1. Estimated long-term (a) and short-term (b) commercial catches for GOA dusky rockfish. Observed is solid black line, predicted is dashed red line.

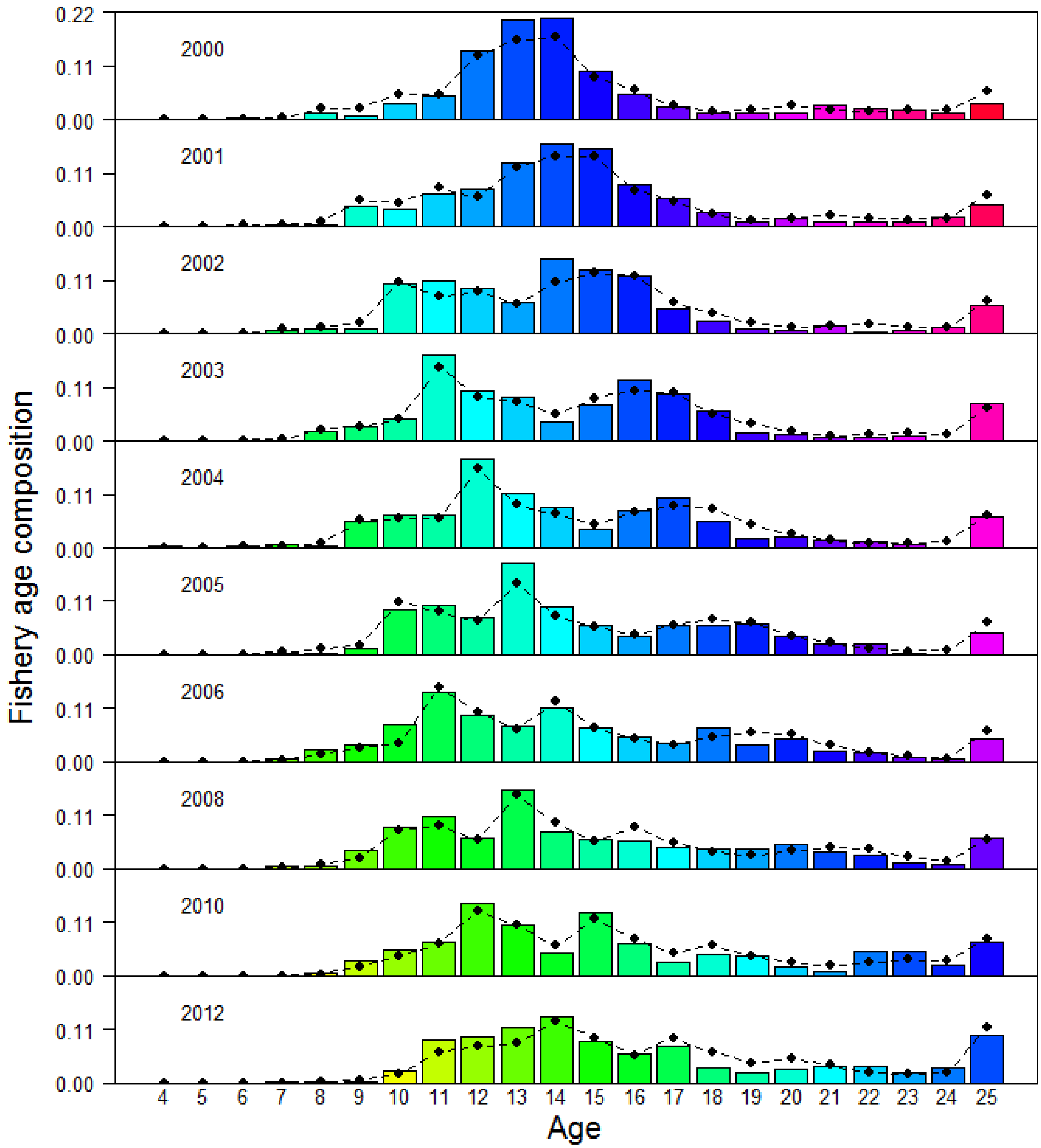

Figure 12-2. Fishery age compositions for GOA dusky rockfish. Observed is bars, author recommended model predicted is line with circles. Colors correspond to individual year classes.

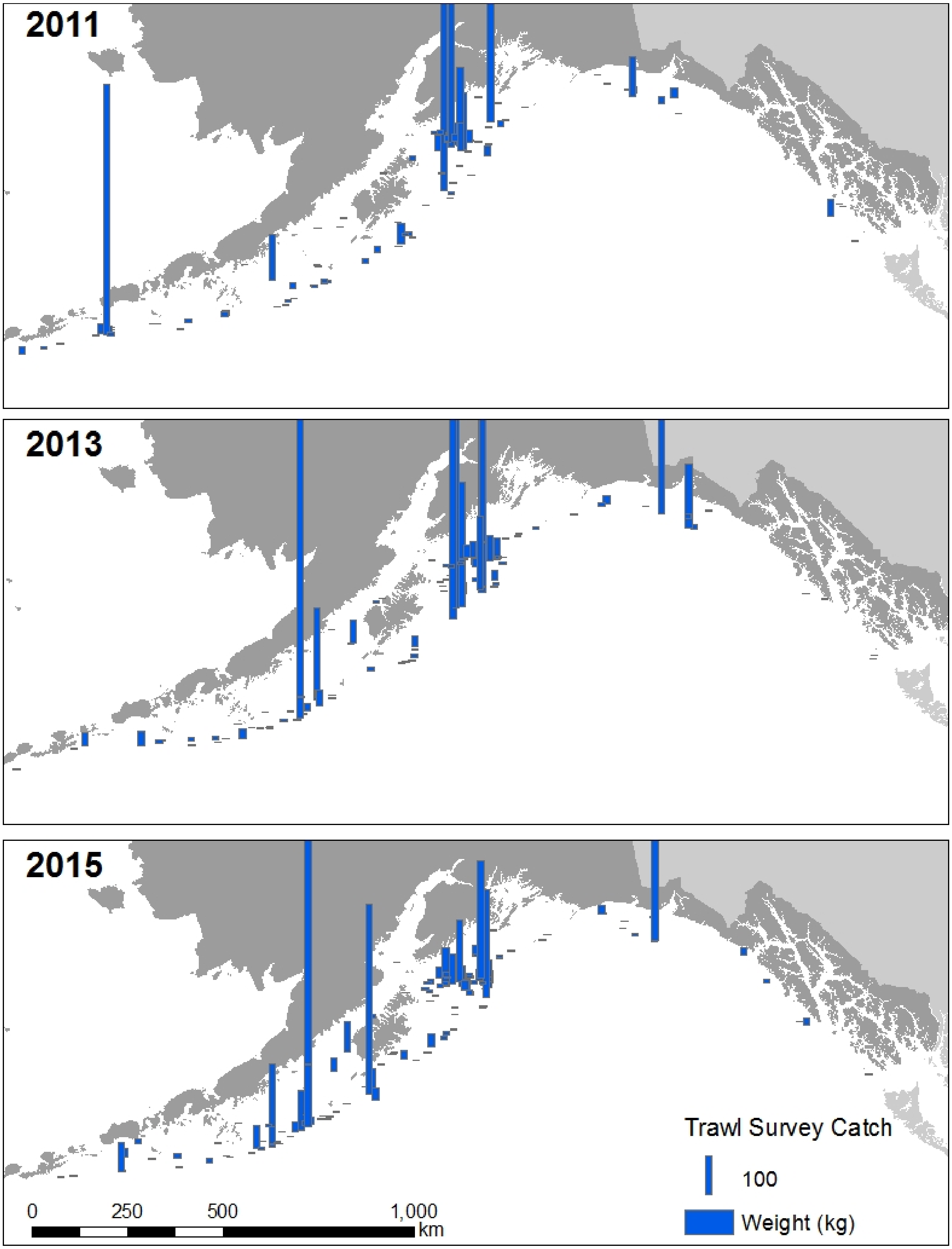

Figure 12-3. Spatial distribution of dusky rockfish in the Gulf of Alaska during the 2011, 2013, and 2015 NMFS trawls surveys.

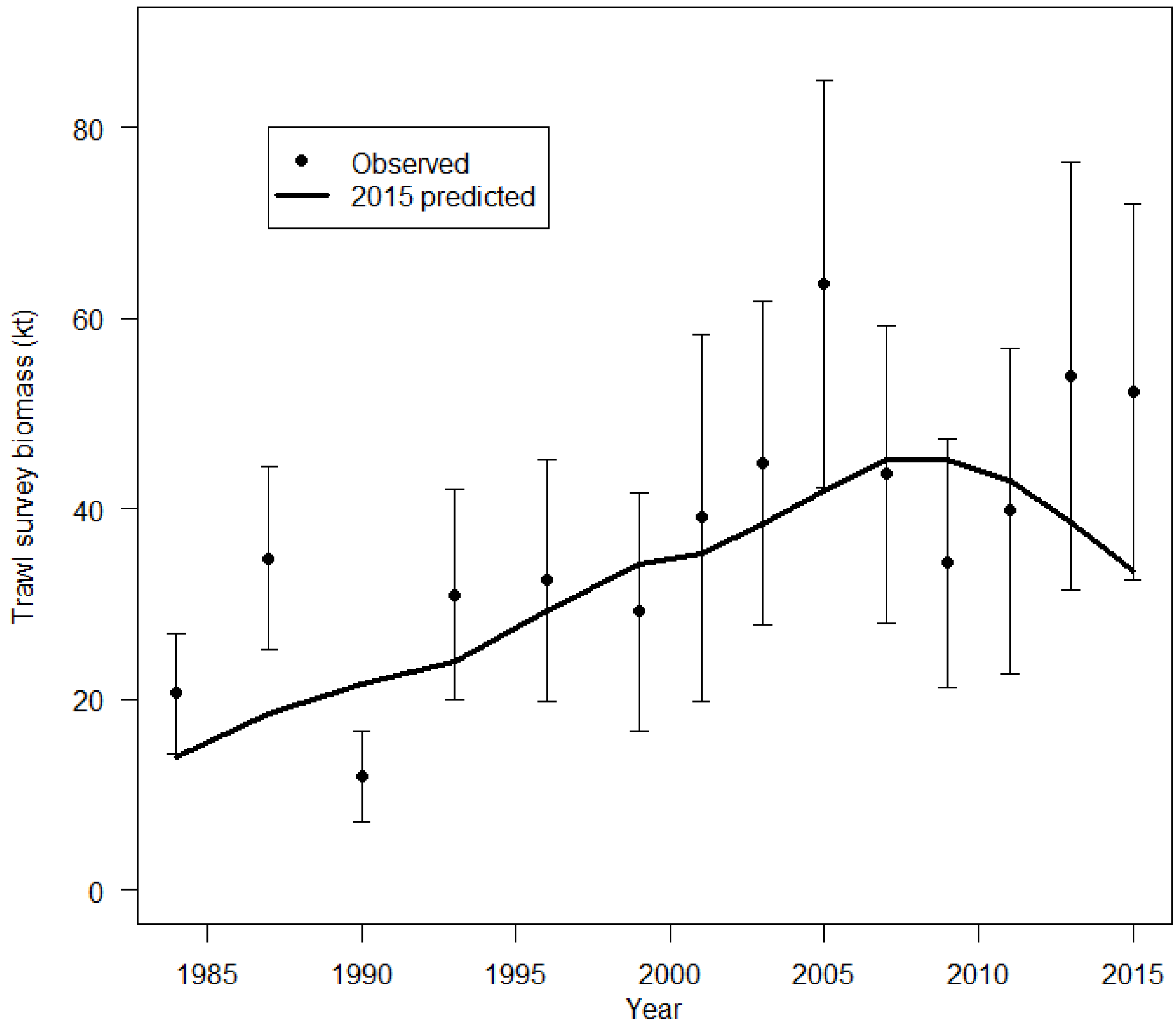

Figure 12-4. Observed and predicted GOA dusky rockfish trawl survey biomass based on the 2015 recommended model. Observed biomass is circles with approximate asymptotic 95% confidence intervals of model error.

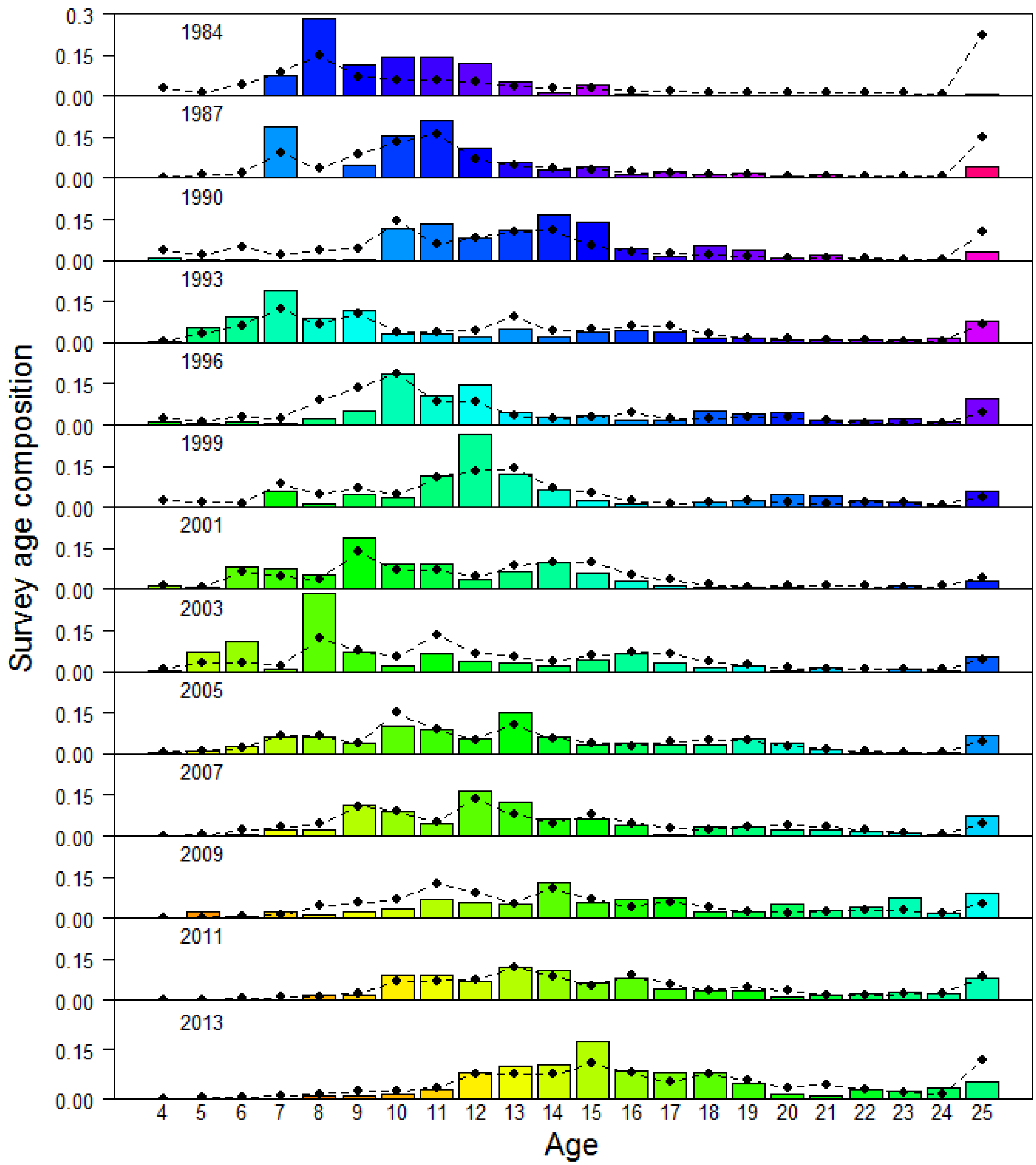

Figure 12-5. Trawl survey age composition by year for GOA dusky rockfish. Observed is bars, author recommended model predicted is line with circles. Colors correspond to individual year classes.

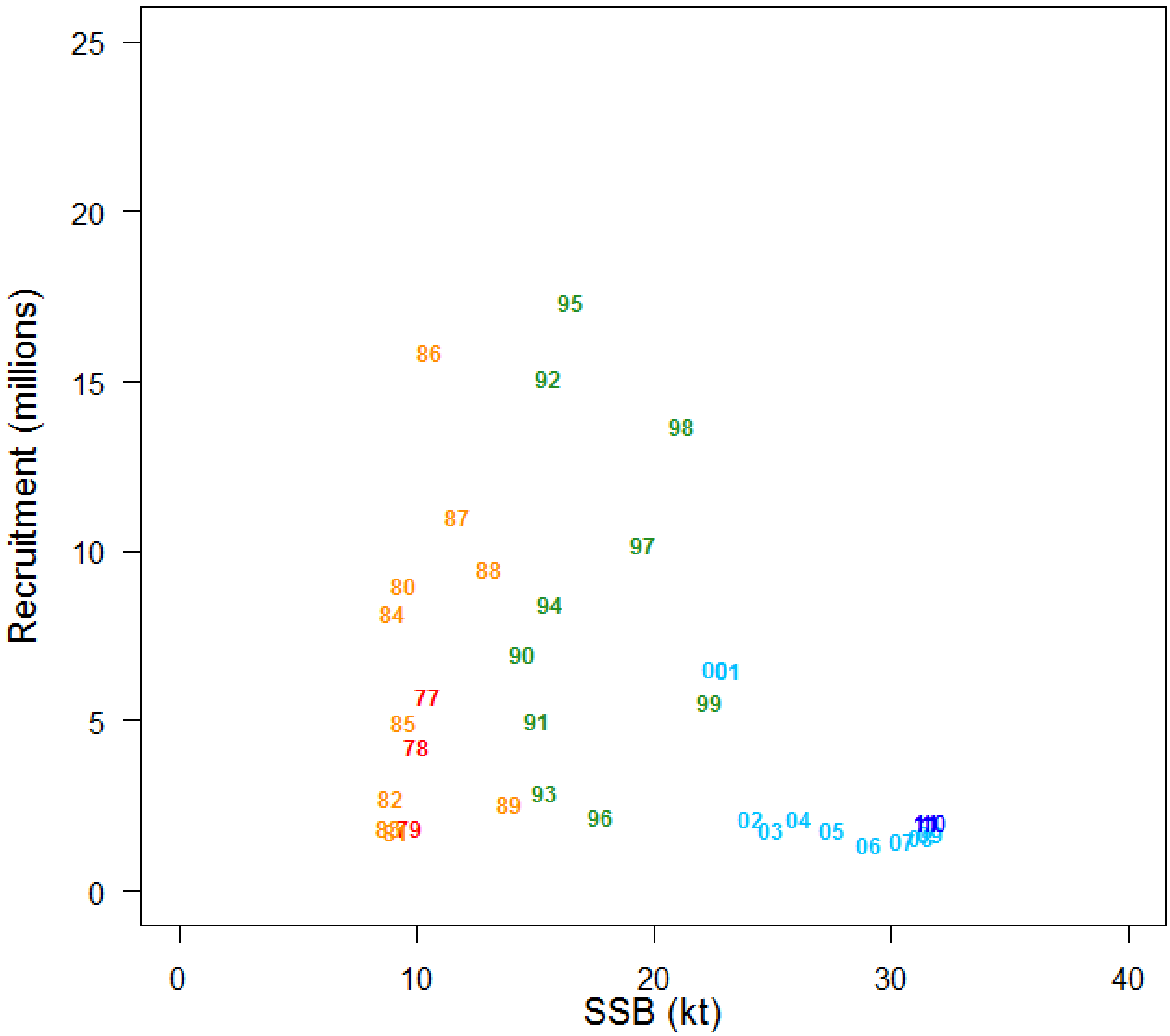

Figure 12-6. Scatterplot of spawner-recruit data for GOA dusky rockfish author recommended model. Label is year class of age 4 recruits. SSB = Spawning stock biomass in kilotons (kt).

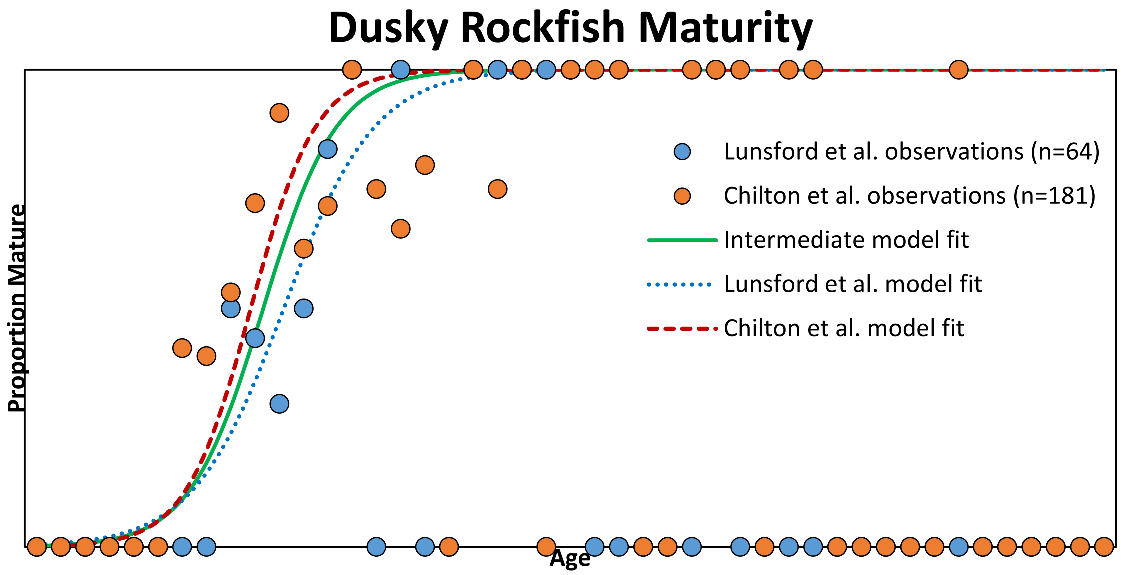

Figure 12-7. Comparison of maturity curves including intermediate curve used in determining Gulf of Alaska dusky rockfish 50% age at maturity.

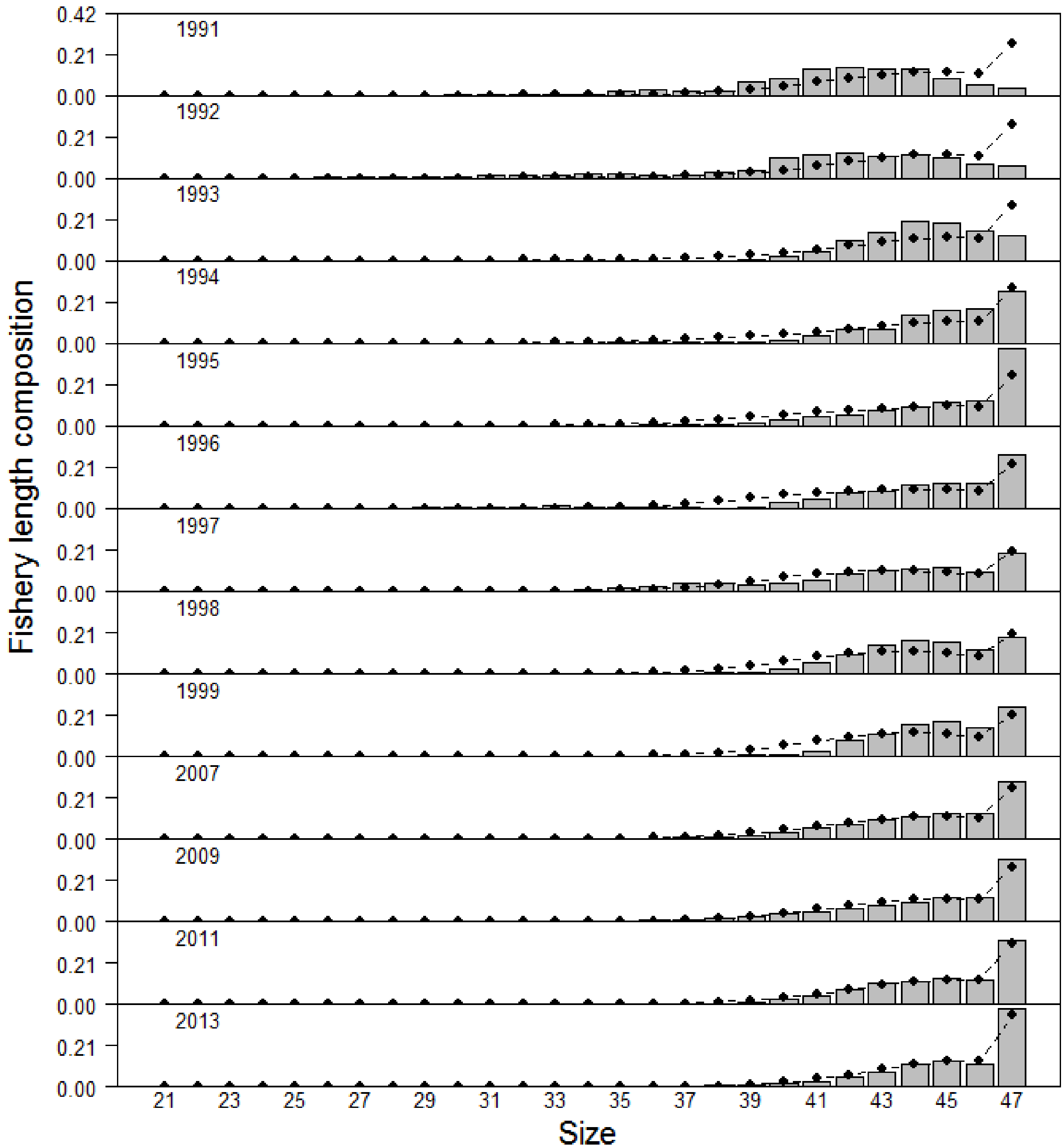

Figure 12-8. Fishery length compositions for GOA dusky rockfish. Observed is bars, 2015 model predicted is line with circles.

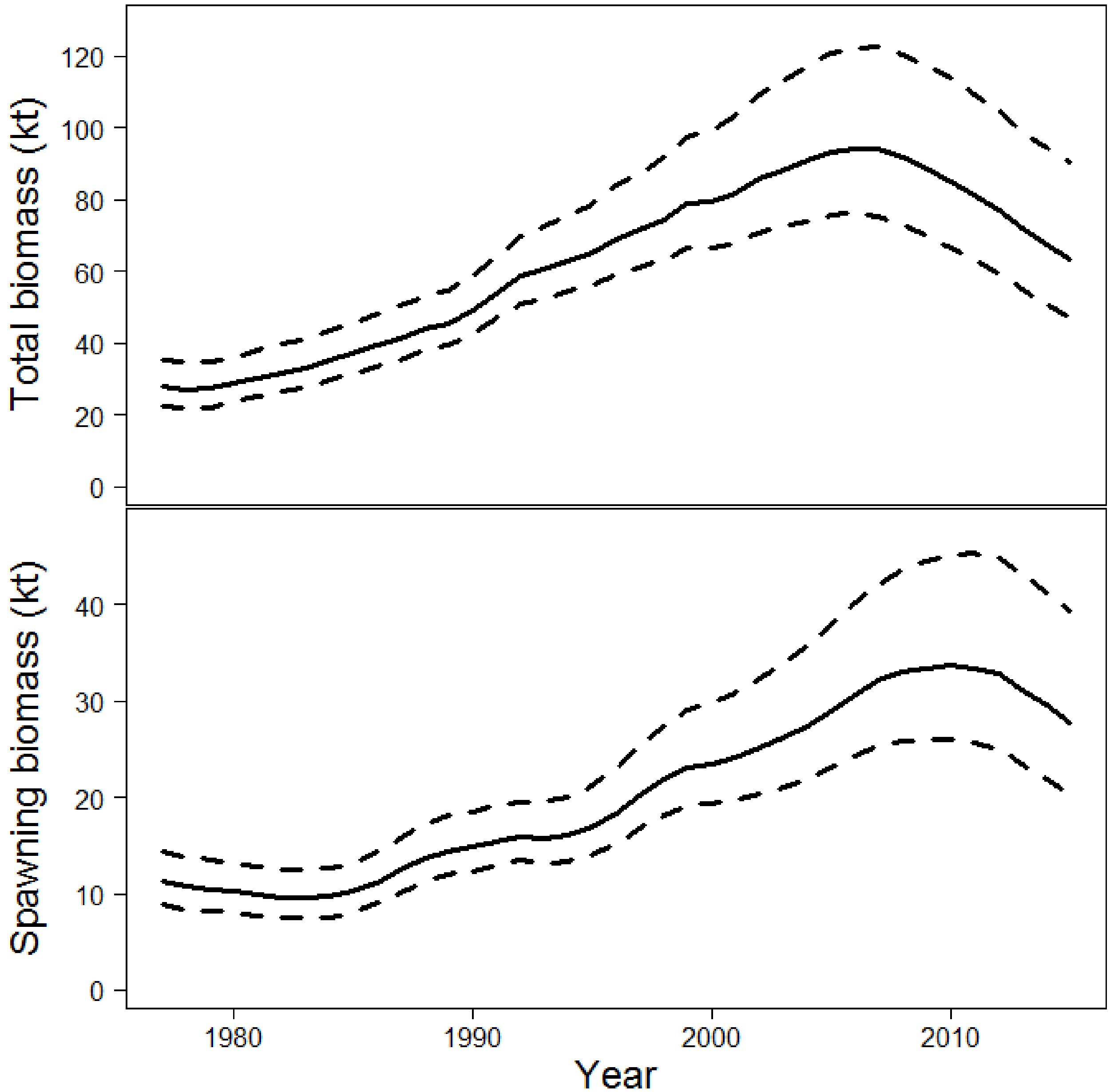

Figure 12-9. Time series of predicted total biomass and spawning biomass of GOA dusky rockfish for 2015 model. Dashed lines represent 95% credible intervals from 10 million MCMC runs.

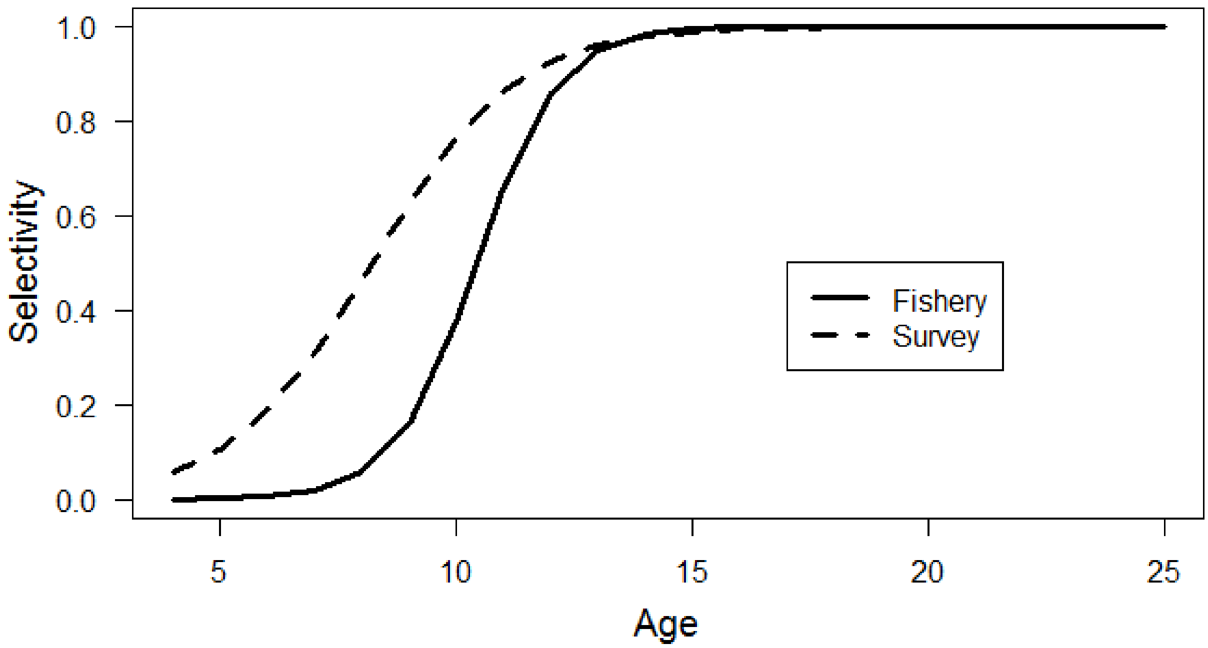

Figure 12-10. Estimated fishery and survey selectivity for GOA dusky rockfish from the 2015 model. Dashed line is survey selectivity and solid line is fishery selectivity.

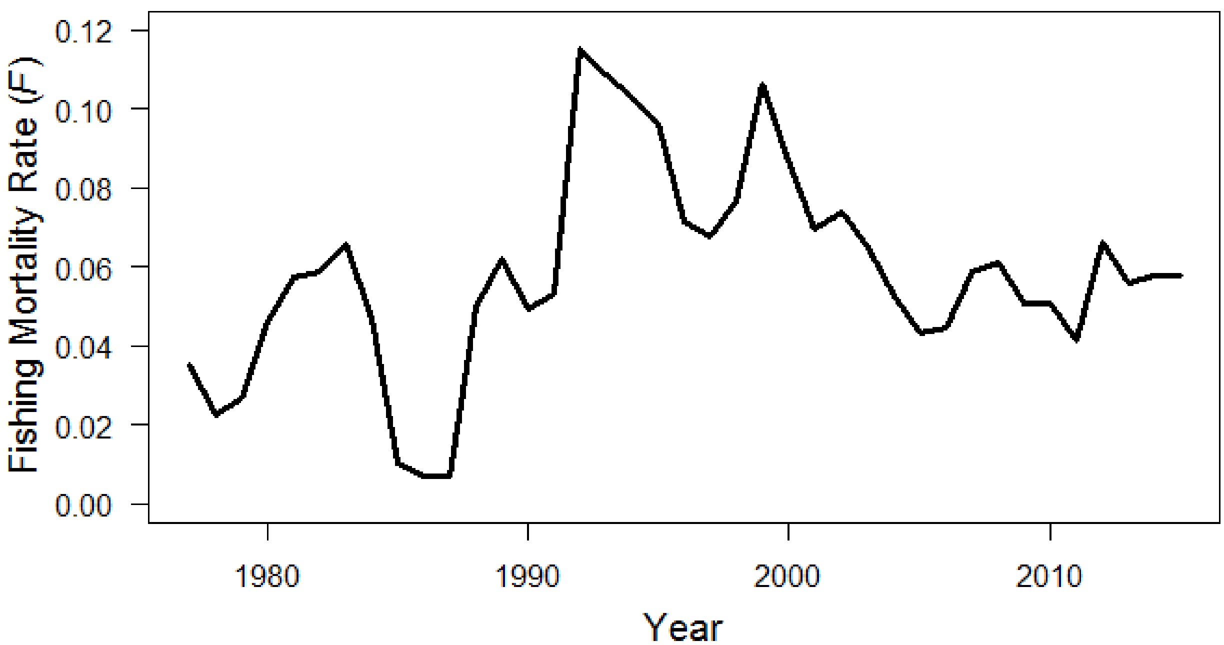

Figure 12-11. Time series of estimated fully selected fishing mortality for GOA dusky rockfish from the 2015 model.

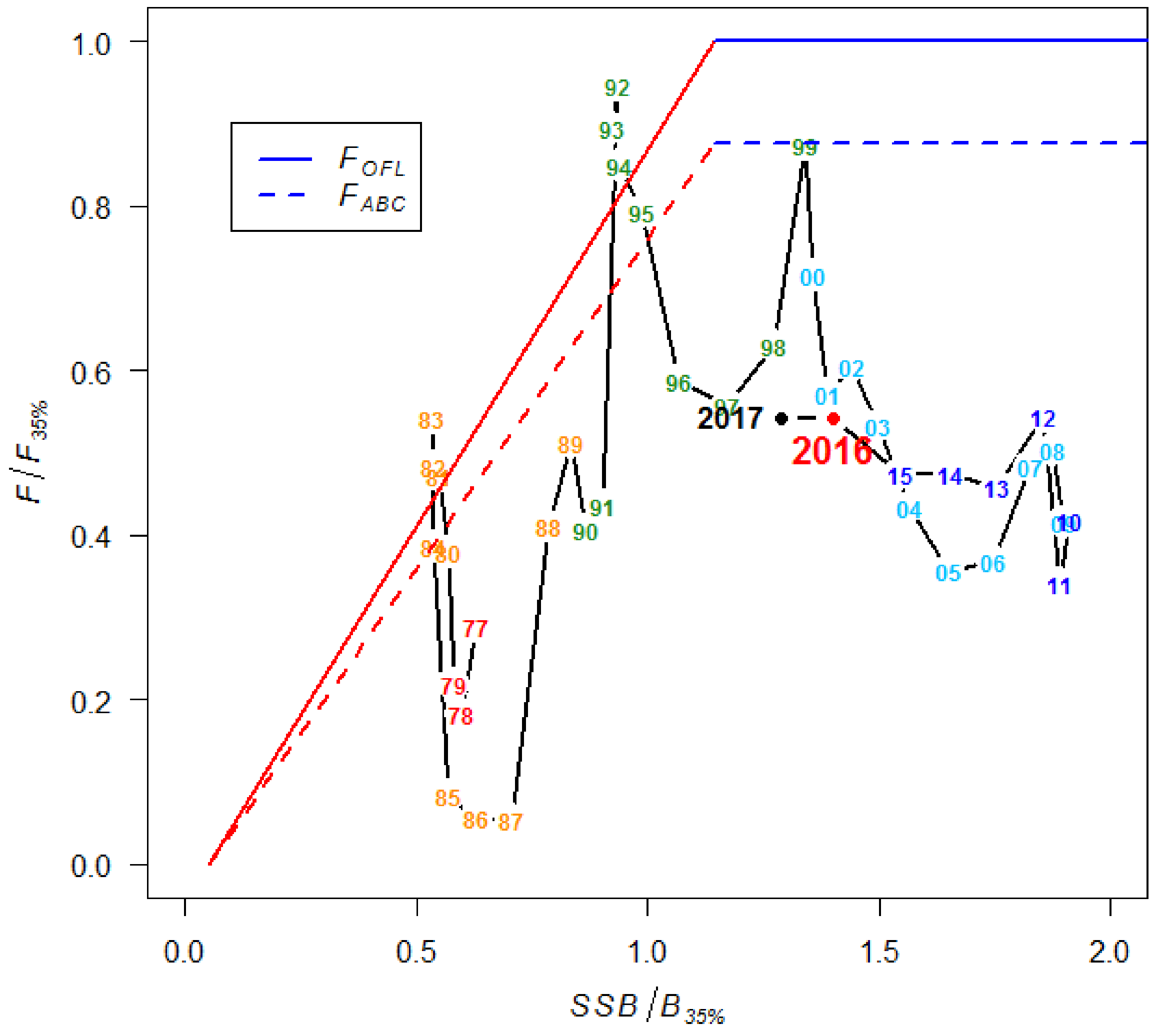

Figure 12-12. Time series of dusky rockfish estimated spawning biomass relative to the unfished level and fishing mortality relative to F_{OFL} for the 2015 model.

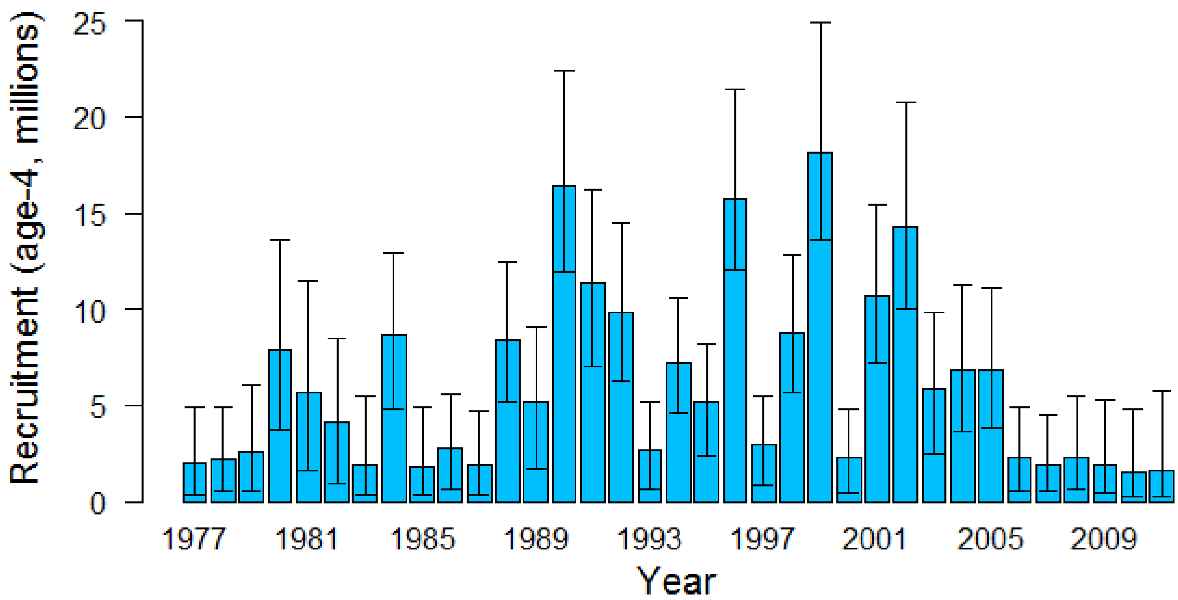

Figure 12-13. Estimated recruitments (age 4) for GOA dusky rockfish from the 2015 model.

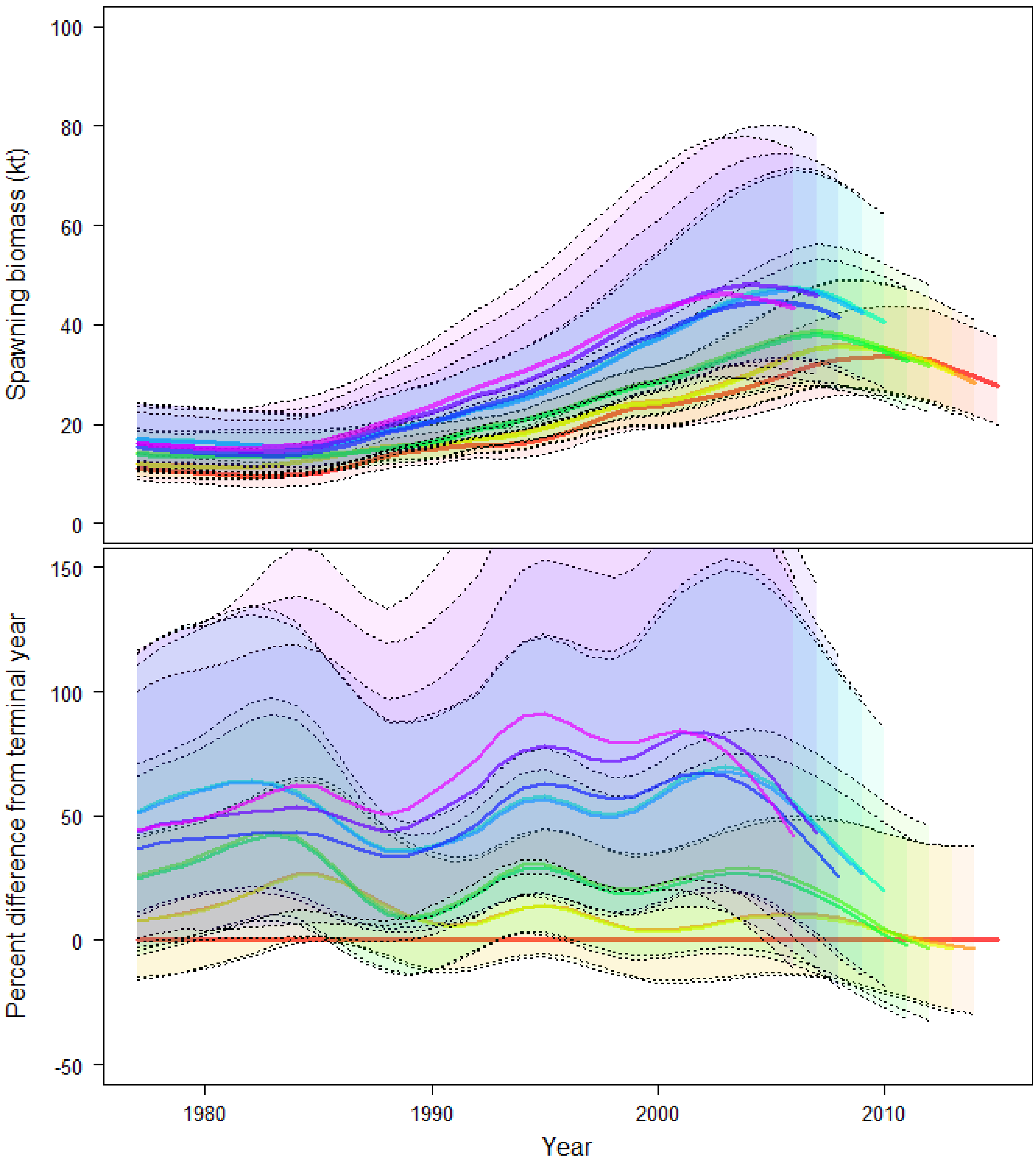

Figure 12-14. Retrospective peels of estimated female spawning biomass for the past 10 years from the recommended model with 95% credible intervals derived from MCMC (top), and the percent difference in female spawning biomass from the recommended model in the terminal year with 95% credible intervals from MCMC.

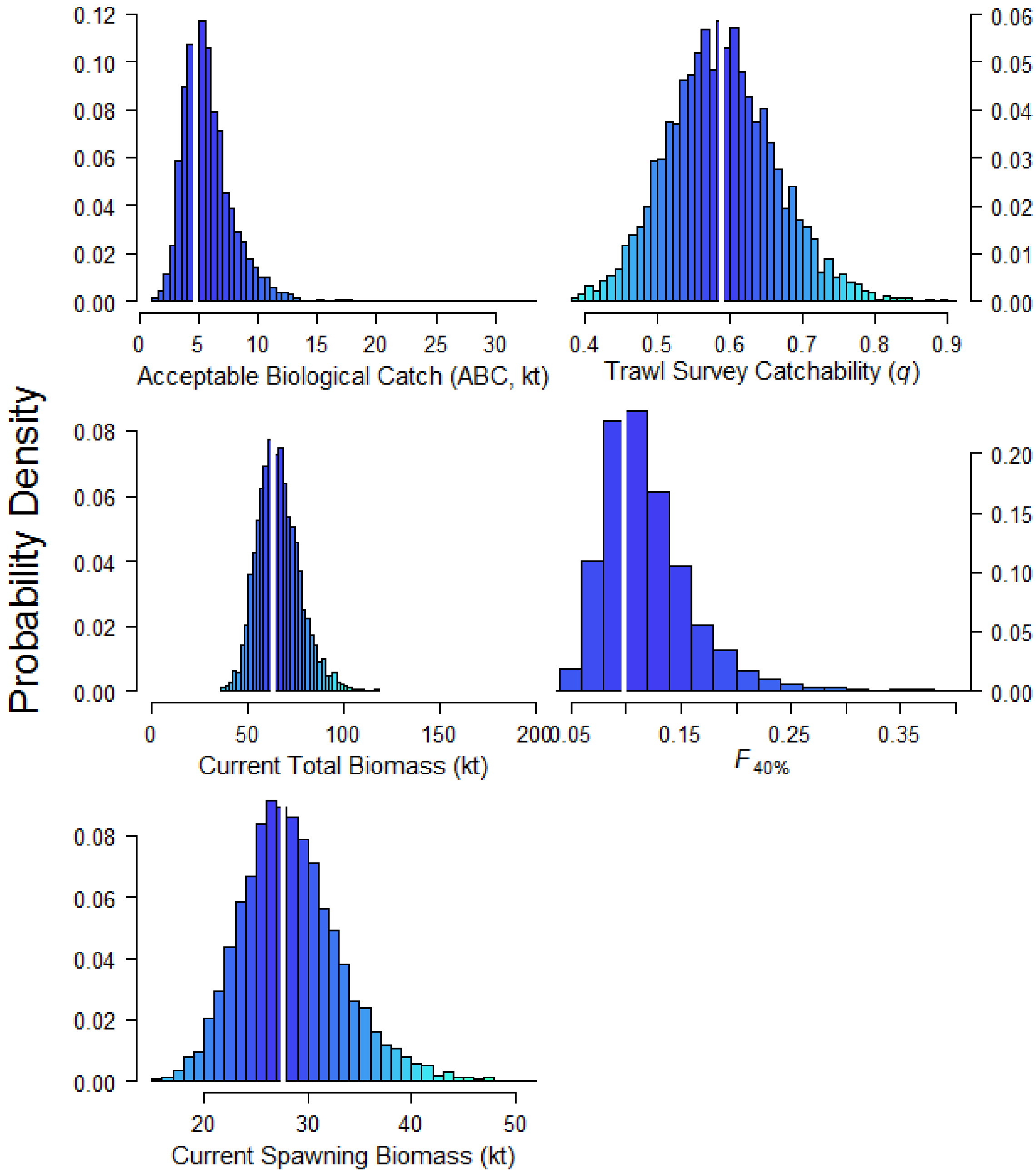

Figure 12-15. Histograms of estimated posterior distributions for key parameters derived from the MCMC for GOA dusky rockfish. Vertical white lines represent the maximum likelihood estimate for comparison with the MCMC results.

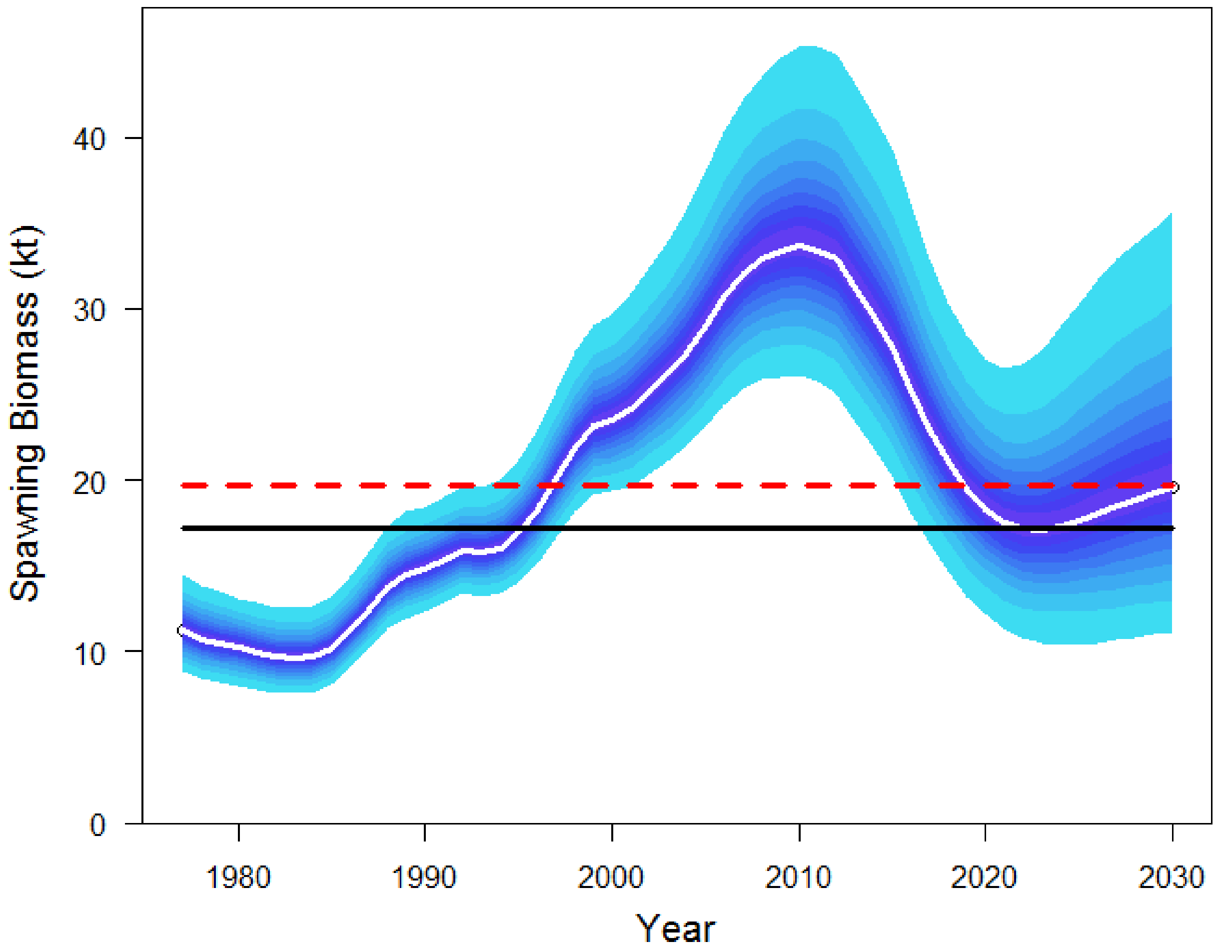

Figure 12-16. Bayesian credible intervals for entire spawning stock biomass series including projections through 2030. Red dashed line is $B_{40\%}$ and black solid line is $B_{35\%}$ based on recruitments from 1981-2011. The white line is the median of MCMC simulations. Each shade is 5% of the posterior distribution.

Appendix 12A

Total Catch Accounting Data

In order to comply with the Annual Catch Limit (ACL) requirements, a dataset has been generated to help estimate total catch and removals from NMFS stocks in Alaska. This dataset estimates total removals that do not occur during directed groundfish fishing activities. This includes removals incurred during research, subsistence, personal use, recreational, and exempted fishing permit activities, but does not include removals taken in fisheries other than those managed under the groundfish FMP. These estimates represent additional sources of removals to the existing Catch Accounting System estimates. For Gulf of Alaska (GOA) dusky rockfish, these estimates can be compared to the research removals reported in previous assessments (Lunsford et al. 2009) (Table 12A-1). Dusky rockfish research removals are minimal relative to the fishery catch and when compared to the research removals of other species. The majority of research removals are taken by the Alaska Fisheries Science Center's (AFSC) biennial bottom trawl survey which is the primary research survey used for assessing the population status of dusky rockfish in the GOA. Other research activities that harvest dusky rockfish include longline surveys by the International Pacific Halibut Commission and the AFSC and the State of Alaska's small mesh trawl surveys. Recreational harvest of dusky rockfish does occur and has been between 5 t and 11 t. Total removals from activities other than a directed fishery have been near 10 t since 2010 with a high of 18 t in 2013. This is <1% of the 2013 recommended ABC of 6,436 t and represents a very low risk to the dusky rockfish stock. Research harvests in recent years are higher in odd years due to the biennial cycle of the AFSC bottom trawl survey in the GOA and have been less than 10 t except in 2005 when 13 t were removed. Even when accounting for recreational harvest, the estimated removals would generally be less than 20 t, which do not pose a significant risk to the dusky rockfish stock in the GOA.

References:

Lunsford, C., S.K. Shotwell, and D. Hanselman. Gulf of Alaska pelagic shelf rockfish. 2009. In Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 2010. North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 9950. pp. 925-992.

Table 12A-1. Total removals of Gulf of Alaska dusky rockfish (t) from activities not related to directed fishing, since 1977. Trawl survey sources are a combination of the NMFS echo-integration, State of Alaska small-mesh, GOA bottom trawl surveys, and occasional short-term research projects. Other is longline, personal use, scallop dredge, and subsistence harvest.

Year	Source	Trawl	Recreational	Other	Total
1977-1995 (avg)*	**Assessment of Pelagic shelf rockfish in the Gulf of Alaska (Lunsford et al. 2009)**	3.9			3.9
1996		7			7
1997		1			1
1998		8			8
1999		6			6
2000		0			0
2001		3			3
2002		0			0
2003		6			6
2004		0			0
2005		13			13
2006		0			0
2007		7			7
2008		0			0
2009		5			5
2010	AKRO	<1	9	<1	9
2011	AKRO	5	5	<1	10
2012	AKRO	<1	8	<1	8
2013	AKRO	7	11	<1	18
2014	AKRO	<1	16	<1	17

*May include catch of dark rockfish.

Appendix 12B

Application of a geostatistical generalized linear mixed model to Gulf of Alaska rockfish survey estimates

Introduction

Estimates of rockfish biomass from the Gulf of Alaska (GOA) bottom trawl survey have been shown high annual and interannual variability which has been problematic for their use in stock assessment. This problem has been examined for some time using different designed based approaches (e.g., Hanselman et al. 2003, Hanselman et al. 2012).The primary issue is that the current design-based index is highly sensitive to occasional large catches, as is often the case for patchily distributed species (Hanselman et al. 2003). The Center for Independent Experts review of Alaska rockfish in 2013 stated that poorly sampled species may be better off using a model-based estimator such as a hurdle model or delta-GLM3 and recommended exploration of these alternative estimators for GOA rockfish. These models have gained popularity recently (Zuur et al. 2009, Thorson and Ward. 2013) to handle spatially aggregated or patchy populations.

These estimators are able to take advantage of temporal geostationarity in habitat, spatial heterogeneity in population distribution, and missing strata. Use of these alternative estimators has been employed at the Northwest Fisheries Science Center (NWFSC) and endorsed by the Pacific Council for the last several years (Thorson et al. 2015) for trawl survey biomass estimation of species such as canary (Thorson and Wetzel 2015) and darkblotched rockfish.

In regards to GOA rockfish, many of the alternative sampling strategies researched have been focused on improving the precision of estimates of Gulf of Alaska Pacific ocean perch because of an improbable increase in population abundance in the 1990s, with an accompanying imprecision in biomass estimates. However, the 2nd and 3rd largest rockfish biomass species in the GOA (northern and dusky rockfish) have produced the most imprecise estimates. In this appendix we examine the utility of a geostatistical estimator of trawl survey abundance for five species of rockfish in the GOA.

Methods and results

Here we briefly review the methods of Thorson et al. (2015) and an application to five rockfish species in the Gulf of Alaska that have varying degrees of survey precision. The foundation of the Thorson et al. (2015) model uses a delta model framework (Lo et al. 1993) which involves combining a binomial model to estimate the annual presence/absence of occurrence of a species with a probability density function that describes when presence occurs. Traditionally, this latter distribution has been the lognormal distribution; however the gamma, normal, and other distributions are potentially useful. Thorson and Ward (2013) describe a variant of this approach which was initially used for West coast groundfish stocks, but has been supplanted by a more precise geostatistical approach (Pettigas 2001, Thorson et al. 2015). The difference between the standard design-based approach used for bottom trawl surveys in Alaska and Thorson’s latest geostatistical approach is that spatial grids are used instead of strata, which base the fish density in each cell on the average density predicted by standard Gaussian imputation. The random effects are estimated for the grids that are not sampled, and grids that are not sampled recently or nearby employ the “shrinkage” benefit of random effects to estimate the density in those cells to be similar to the expected value of that cell. In practice, the reason to use such a model is that is uses spatial information as a proxy for sampling in the preferred or avoided habitat of patchily distributed species.

We analyze data from the Gulf of Alaska bottom trawl survey using version 3.2.0 of the geostatistical model of Thorson et al. (2015), implemented as an R package `SpatialDeltaGLMM` and publicly available at: https://github.com/nwfsc-assess/geostatistical_delta-GLMM. This software uses Template

3 http://www.afsc.noaa.gov/REFM/stocks/Plan_Team/2013/Sept/2013_Rockfish_CIE_Response.pdf

Model Builder (Kristensen et al. 2015) to integrate across the latent probability of random effects, when maximizing the marginal likelihood function (Thorson and Minto In 2015). We conduct model evaluation for dusky rockfish, but also apply the model to other GOA rockfish species for comparison. We select among three potential model treatments, i.e., treating positive catch rates as following a lognormal, gamma, or lognormal-ECE (Extreme Catch Event). The model using the lognormal-ECE distribution did not converge, and AIC indicated greatest support for the lognormal distribution among the converged models (Table 1). We therefore used the geostatistical model with the lognormal distribution to generate an index of abundance for Gulf of Alaska dusky rockfish for years 1984-2015 (Table 2, Figure 1). Following advice from the West Coast assessment guidelines, we display the Quantile-Quantile (Q-Q) plot, generated by comparing each observed datum with its predicted distribution under the fitted model, calculating the quantile of that datum, and comparing the distribution of quantiles with its expectation under a null model (i.e., a uniform distribution). The Q-Q plots for the three options are shown in Figure 3, and while the lognormal model fails to completely capture the shape of dispersion shown in the positive catch rate data, it appears to be slightly better than the gamma model and much better than the lognormal-ECE model. The estimated spatial distribution of dusky densities is shown in Figure 3, and shows that the highest densities are predicted to occur near Kodiak and Yakutat. A comparison of stratified (design-based) and geostatistical (model-based) indices of abundance (Figure 1) illustrates that the design-based index is highly sensitive to occasional large catches, as is often the case for patchily distributed species (Hanselman et al. 2003). The design based and geostatistical indices generally capture the same trends, although the geostatistical model has much higher precision and less interannual variability. We consider this characteristic of geostatistical estimators to be a desirable feature because high interannual variability is unlikely for a long-lived, lightly exploited stock.

Other species

We evaluated a range of other GOA rockfish species to see how the same model (lognormal) performed. Figures 4-7 show the results of the model compared with the traditional designed based estimators. Pacific ocean perch and shortraker rockfish are much more widely distributed in the Gulf of Alaska and generally have higher design-based precision than the other three rockfish. These models result in relatively higher estimated values of biomass than the design-based models yet the levels of precision are similar. These two species are frequently caught in the Eastern Gulf of Alaska which was not sampled in the 2001 survey, but the model clearly accounts for the lack of sampling in 2001 in that area.
The application of the model to harlequin and northern rockfish behaves much differently and more like dusky rockfish. Both species have had years where several large survey catches have resulted in large increases in the design-based biomass estimates and associated variance estimates. These anomalous estimates are smoothed by the model-based estimates. There also is a notable increase in precision when compared with the design-based estimators.

Conclusions

The geostatistical GLMM appears to work well in smoothing out the dramatic and unlikely swings in abundance that occur in some of the more patchily distributed GOA rockfish. The model also increases precision relative to the design-based estimators by incorporating spatial and temporal covariation. The absolute scale of the resulting biomass estimates from the geostatistical model may be uncertain, but this should not be an issue for age-structured models that are scaling biomass by estimating catchability. The absolute scale of the estimates would become important for biomass-only (Tier 5) species and for use in apportionment, and warrants further investigation. While the design-based estimators may work adequately for the more ubiquitous species (POP and shortraker), we recommend that the geostatistical model be considered for dusky rockfish and northern rockfish and other patchily distributed stocks in the future.

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Zuur, A., E. N. Ieno, N. Walker, A.A. Saveiliev, G.M. and Smith. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer, New York. 317 pp.

Table 12B-1. Comparison of dusky GLMM results to design-based estimates. 2.5% and 97.5% are the approximate asymptotic confidence intervals.

Year	GLMM-log	2.5%	97.5%	GLMM-gamma	2.5%	97.5%	Design	2.5%	97.5%
1984	20.6	14.1	27.1	12.1	8.7	15.5	25.6	13.8	37.4
1987	34.8	25.1	44.5	30.4	21.5	39.3	94.2	35.4	153.0
1990	11.9	7.1	16.7	7.4	4.1	10.7	26.9	9.6	44.2
1993	31.0	19.8	42.2	21.2	13.7	28.7	57.2	24.0	90.4
1996	32.5	19.5	45.5	28.0	17.7	38.3	74.5	8.8	140.2
1999	29.2	16.4	42.0	15.6	8.7	22.6	49.6	11.2	88.0
2001	39.1	19.5	58.8	22.4	11.1	33.8	31.0	12.4	49.6
2003	44.8	27.5	62.1	32.8	20.5	45.1	70.9	2.2	139.6
2005	63.6	41.7	85.5	56.6	35.1	78.0	170.5	67.2	273.8
2007	43.6	27.7	59.6	28.3	16.6	40.0	73.1	4.1	142.1
2009	34.3	21.0	47.6	19.7	12.6	26.8	72.1	22.7	121.5
2011	39.8	22.5	57.1	22.7	13.0	32.4	83.4	9.8	157.0
2013	53.9	31.1	76.8	34.0	20.4	47.6	99.2	27.6	170.7
2015	**52.3**	**32.2**	**72.4**	**26.2**	**16.9**	**35.6**	**32.8**	**17.0**	**48.5**

Table 12B-2. Model fits of gamma and lognormal versions of the spatial GLMM for Gulf of Alaska dusky rockfish. AIC = Akiake Information Criterion, n is number of fixed effect parameters.

Distribution	n	-lnL	AIC	ΔAIC
gamma	36	10729.8	21531.6	376.3
lognormal	36	10541.6	21155.3	

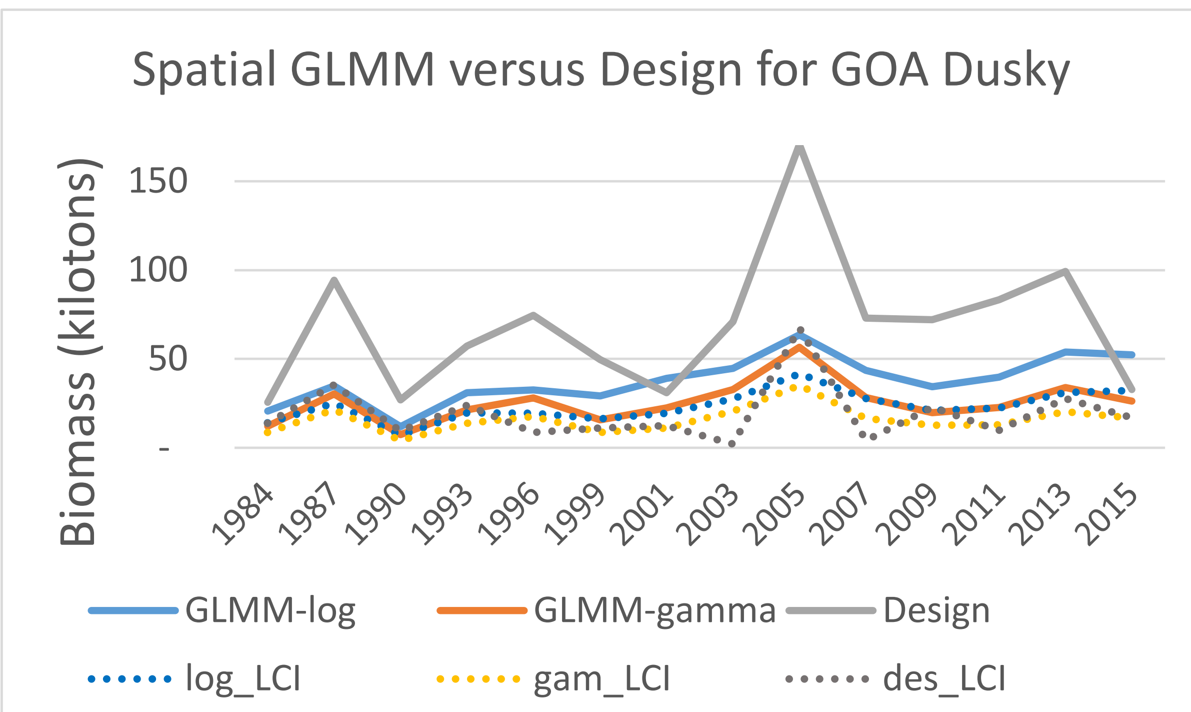

Figure 12B-1. The lognormal geostatistical GLMM model estimates versus the traditional designed based estimates for the Gulf of Alaska dusky rockfish. Only lower 95% confidence intervals are shown to make point estimates more visible.

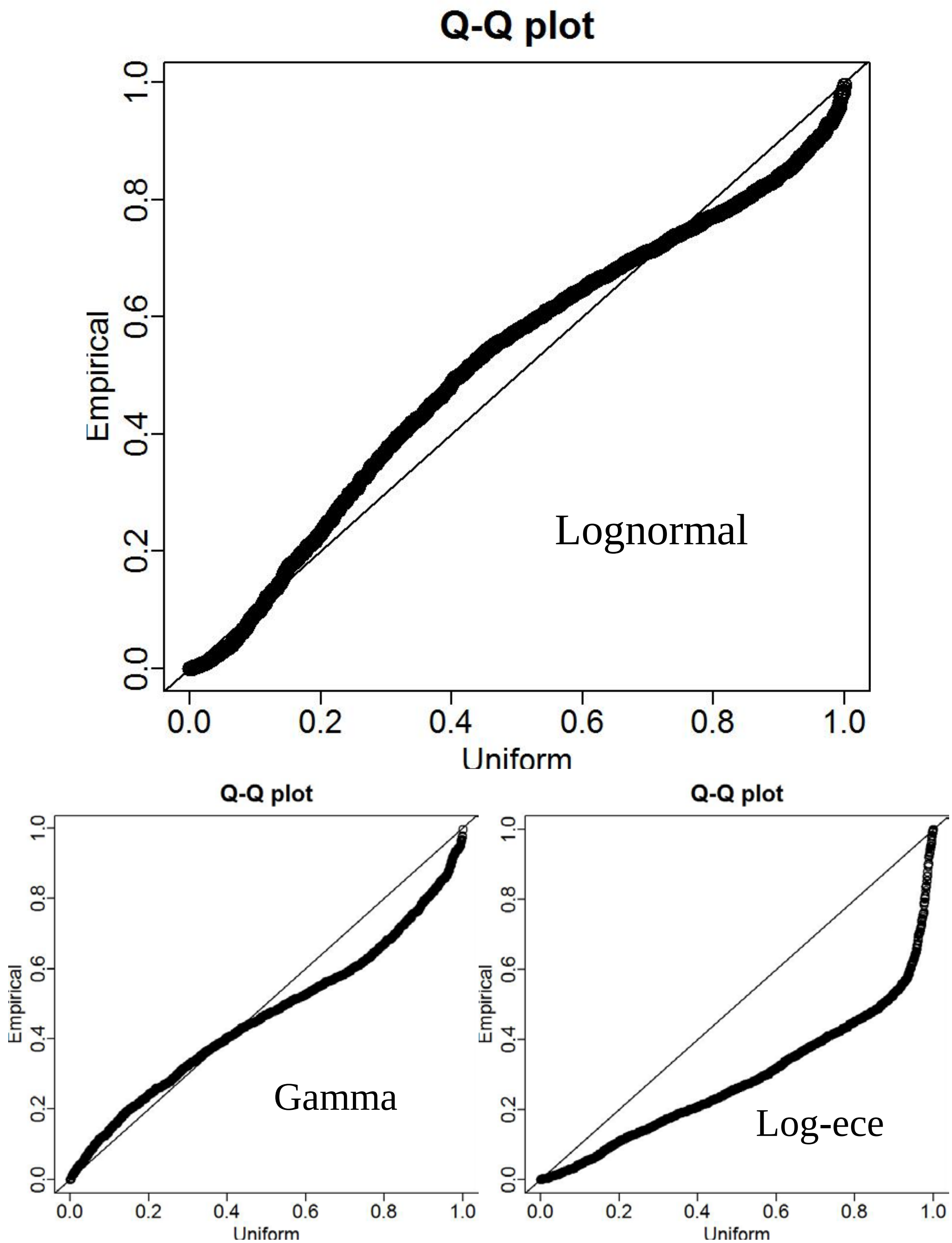

Figure 12B-2. Quantile-quantile plots of three different distributions used in the spatial GLMM model.

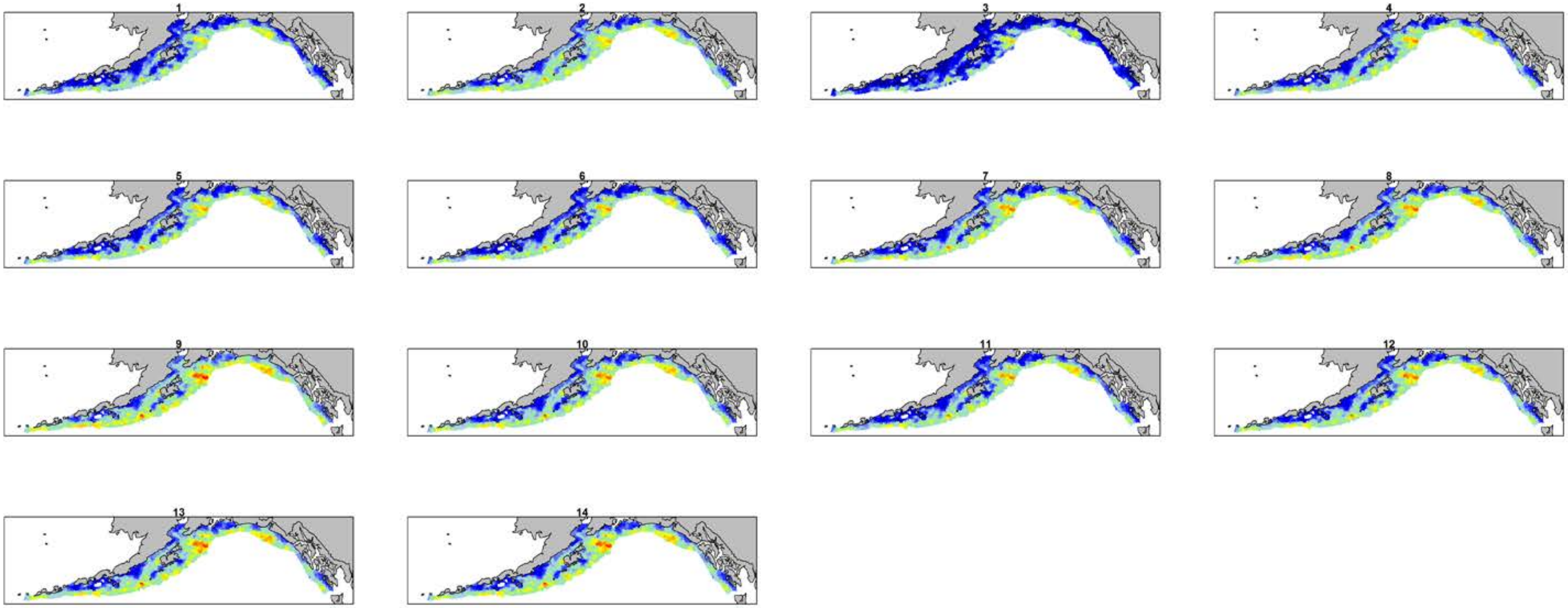

Figure 12B-3. Estimated spatial densities of dusky rockfish as estimated by the lognormal geostatistical GLMM model.

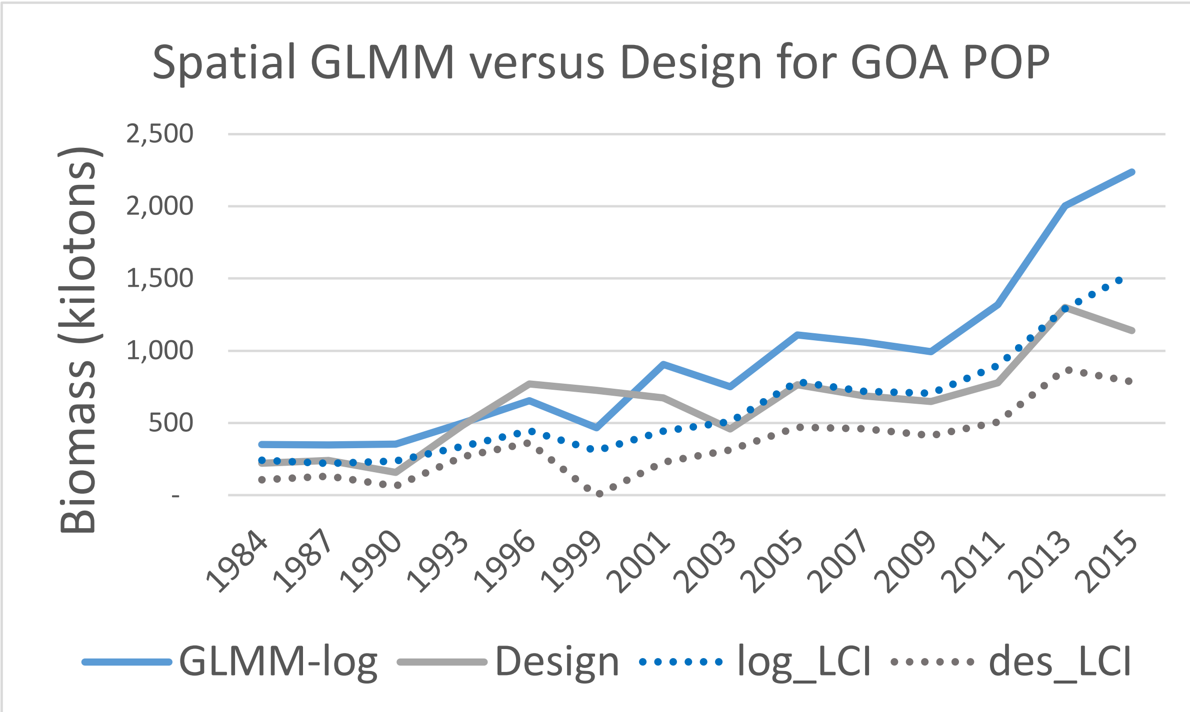

Figure 12B-4. The lognormal geostatistical GLMM model estimates versus the traditional designed based estimates for the Gulf of Alaska Pacific ocean perch. Only lower 95% confidence intervals are shown.

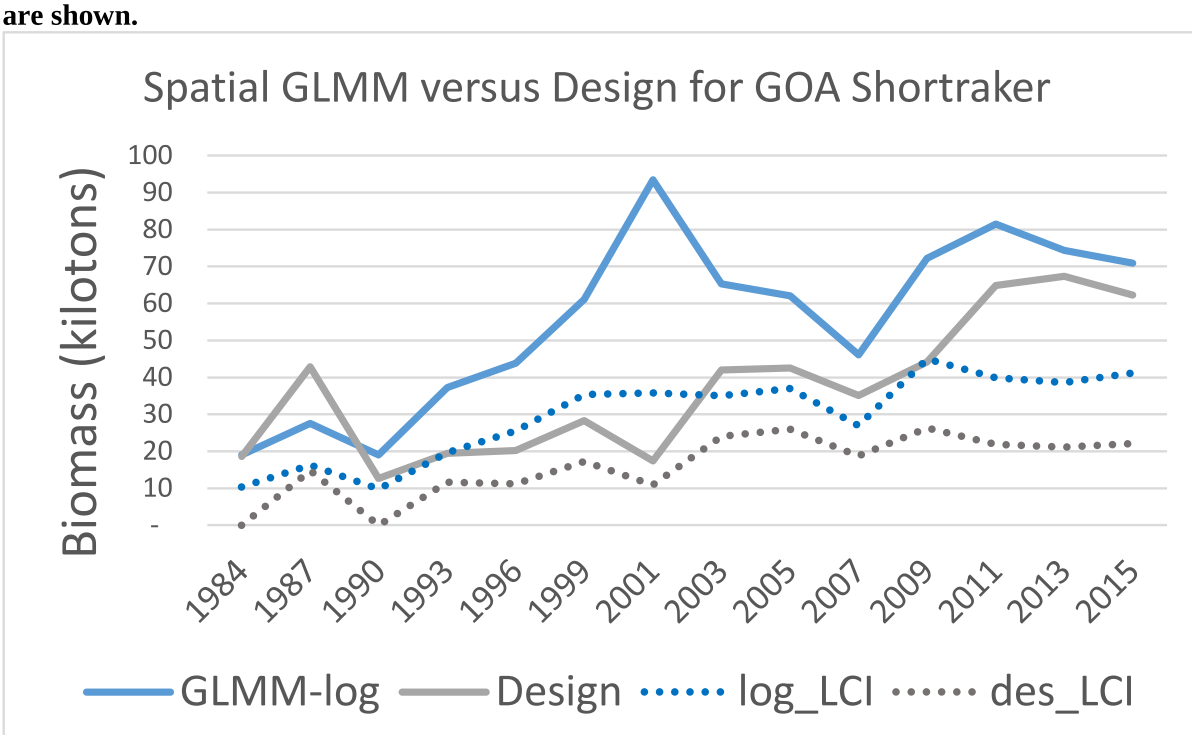

Figure 12B-5. The lognormal geostatistical GLMM model estimates versus the traditional designed based estimates for the Gulf of Alaska shortraker rockfish. Only lower 95% confidence intervals are shown.

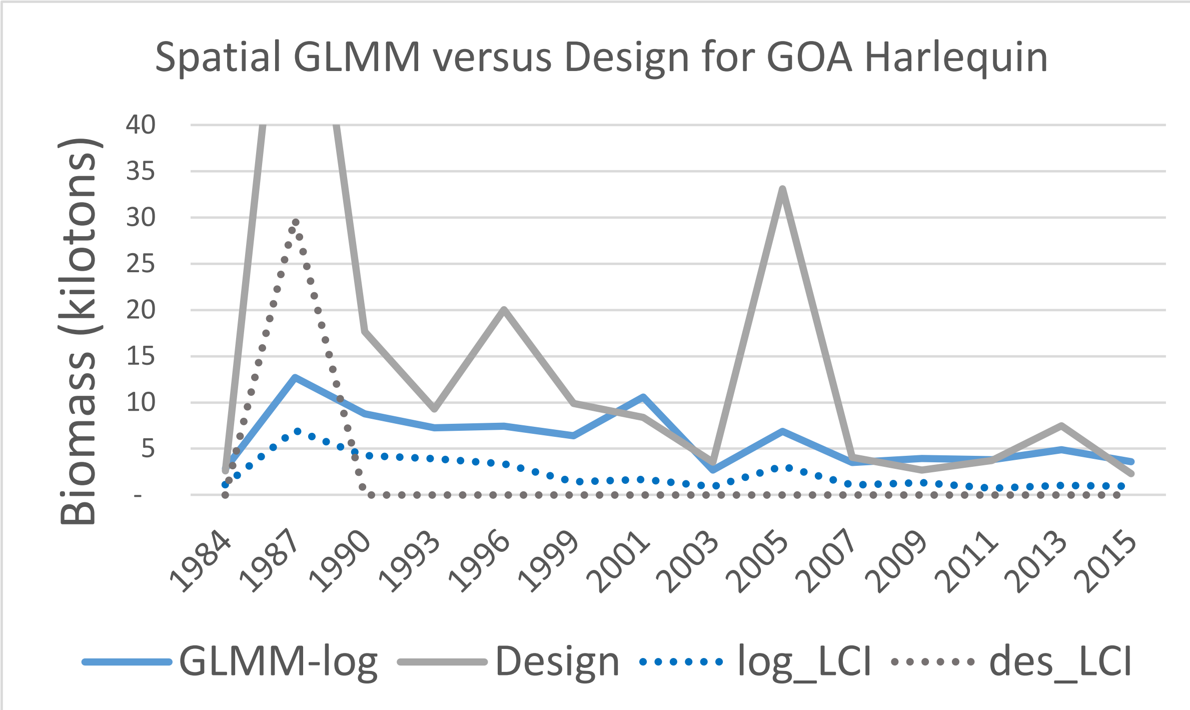

Figure 12B-6. The lognormal geostatistical GLMM model estimates versus the traditional designed based estimates for the Gulf of Alaska harlequin rockfish. Only lower 95% confidence intervals are shown.

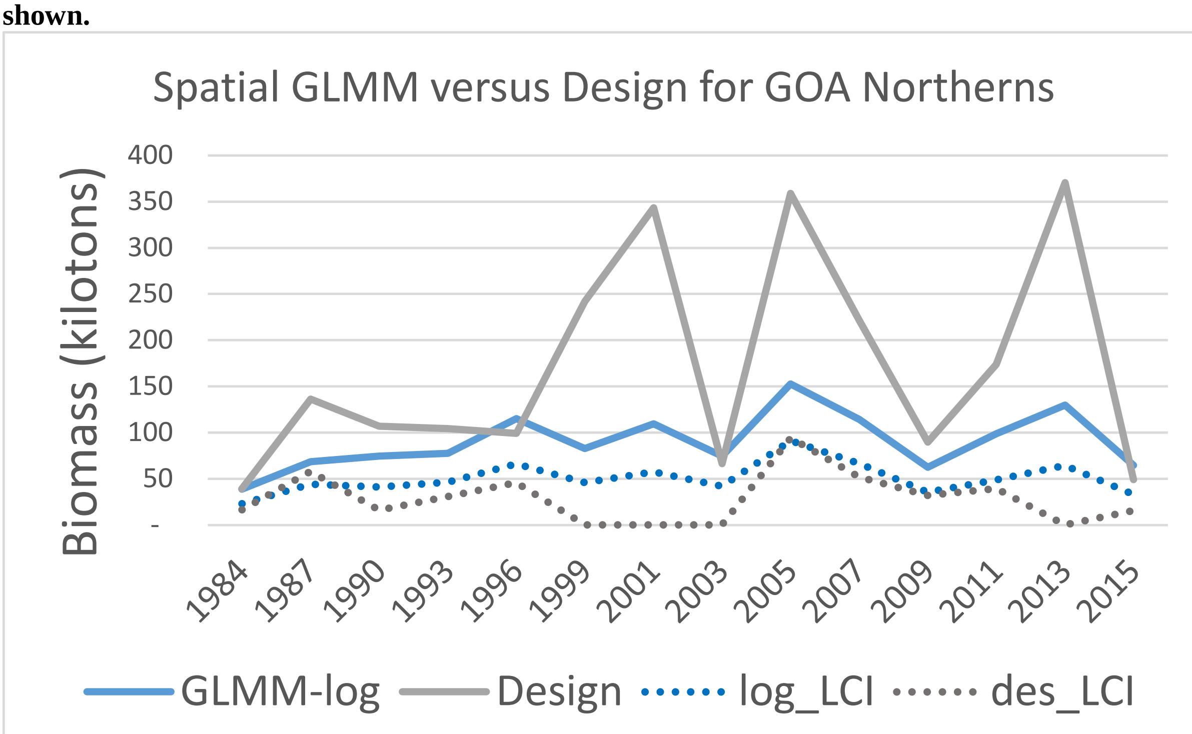

Figure 12B-7. The lognormal geostatistical GLMM model estimates versus the traditional designed based estimates for the Gulf of Alaska northern rockfish. Only lower 95% confidence intervals are shown.

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