PACIFIC ISLANDS FISHERIES SCIENCE CENTER

Status and Trends of the Hawaiian Bottomfish Stocks: 1948-2004

A report submitted under Contract No. JJ133F-06-SE-2510
September 2006

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October 2011

Administrative Report H-11-02C

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Preface

To provide independent expertise in the analysis of Hawaii bottomfish data and development of ideas for bottomfish stock assessment, the Pacific Islands Fisheries Science Center contracted the services of scientists at the Fisheries Centre, University of British Columbia (Contract No. JJ133F-06-SE-2510). The UBC group was asked to: review and evaluate bottomfish fishery statistics and biological data; assess the stock relative to biological reference points; recommend ways to improve bottomfish data collection and stock assessment; convene a workshop to review the results; and produce a report of the findings. In September 2006, the contract report was submitted to PIFSC.

In 2010 and early 2011, PIFSC researchers completed a new stock assessment of Hawaii bottomfish in the main Hawaiian Islands, citing the UBC study in several related stock assessment documents. To make the UBC contract report more widely accessible, it is being issued here, as submitted, in the form of a PIFSC Administrative Report. The findings, conclusions and opinions expressed in the contract report are those of the authors as independent investigators and do not necessarily reflect views of PIFSC, the National Marine Fisheries Service or NOAA.

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Executive Summary

We report on the available commercial catch statistics for the Hawaiian bottomfish fishery and use this information to determine the current stock status relative to reference points concerning the level of depletion and the rate at which the stock is being depleted. There is a significant recreational fishery for bottomfish in the Main Hawaiian Islands; however, there are no long-term statistics on fishing effort or removals by the recreational sector. The impacts of the recreational fishery on the Main Hawaiian Island bottomfish stocks were not included in the assessment of stock status. We note here that if the ratio recreational fishery impacts commercial fishery impacts is constant over time then the net result in status determination is a shift in scale. If, however, the ratio of recreational catch to commercial catch has increased over time, then significant bias could be introduced into the assessment of stock status.

Commercial catch statistics were compiled from the Hawaiian Department of Aquatic Resources (HDAR), and consisted of aggregate catch over 14 different species, catch by 14 individual species, and a fishing effort index (presumably targeting all 14 species in proportion to their relative abundance). The catch statistics for the Hawaiian archipelago date back to 1948 and are complete through 2004. In the commercial sector, there have been known shifts in targeting due to improvements in fishing technologies, as well as, avoidance of species due to ciguatera poisoning.

Analytical methods focused on a semi-implicit form of the Schaefer production model. The model was condition on the historical fishing effort index and fit to observed catch data. The model assumes no errors in the reported catches and takes on a variety of structural forms to address alternative hypotheses about changes in catchability as well as variability in stock productivity. Alternative model structures were compared using Akaike Information Criterion (AIC) and model selection was based in AIC weights. Evaluation of stock status for the Hawaiian archipelago was determined by plotting the ratio of current biomass to estimates of $\mathrm{B}_{\mathrm{MSY}}$ versus the ratio of current fishing mortality rate to estimates of $\mathrm{F}_{\mathrm{MSY}}$ (Fig. 1), where the biomass in each of 3 zones was weighted by the length of the 100 fathom depth contour. Regardless of which hypothesis was assumed, over-fishing is very-likely occurring and the stock complex as a whole is below that level that would produce MSY.

Over-fishing is most severe in the Main Hawaiian Island and less severe in the North-western Hawaiian Islands. The contribution of the recreational fishery to the over-fishing problem is unknown but likely to be responsible for 200%-400% of the commercial fishery landings.

There is a great deal of uncertainty in model parameter estimates owing to limited data and contrast in the abundance estimates that were derived from fishery dependent information. As such, there is also a great deal of uncertainty in the estimates of reference points (e.g., $\mathrm{B}_{\mathrm{MSY}}$ and $\mathrm{F}_{\mathrm{MSY}}$). The residual pattern in model fits are suggestive of systematic changes in catchability or non-stationarity in the underlying production functions assumed in the assessment model. To our surprise, the data suggest that catchability has declined

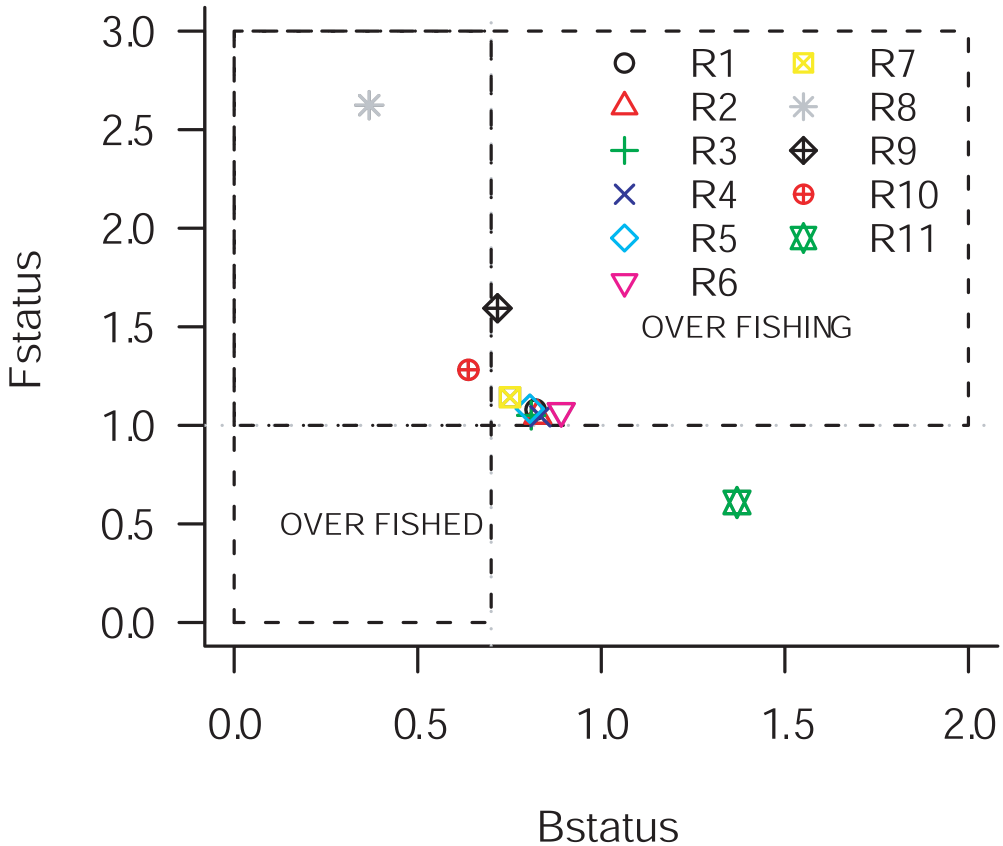

Figure 1: Stock status for all alternative hypotheses explored in this assessment document.

significantly between 1948 and the mid 1980s. In recent years, trends in catchability have increased to levels greater that those estimated in the 1950s. We were unable to conclude wheather the observed residual pattern reflects a data problem or structural problem, or wheather changes in catch composition have led to systematic changes in catchability, or weather the problem is due to changes in the fishing community.

Short-term forecasts suggest that a reduction in fishing mortality rates by 15% would reduce F to the levels that would acheive B_{MSY} in the main Hawaiian Islands, but recovery times would be very protracted. More severe harvest restrictions are warrented in the main Hawaiian Islands, and the recreational fishery is very likely contributing to the over-fishing problem.

There is very limited fisheries independent data available, and virtually no information on age or size composition in this fishery. There are additional data gaps (e.g., age at recruitment to the fishery) that force the use of informative priors and assumptions in order to proceed with stock status determination. The results presented here and in previous assessments are extremely sensesitve to informativee priors and assumptions. In this report we also provide some detailed research recommendations to improve the data for the Hawaiian Bottomfish fishery.

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1 Introduction

A workshop was conducted between May 1, 2006 and May 12, 2006, in Honolulu Hawaii. The following terms of reference were uses as a guideline for the workshop.

1.1 Terms of Reference

1. Characterize commercial and recreational catch, including landing and discards. Describe stock structure and develop a unit stock definition.
2. Review adequacy and uncertainty of fishery-independent and -dependent indices of relative abundance. If necessary, provide appropriate measures of relative abundance and document all programs used to develop indices. Provide analyses evaluating the degree to which indices adequately represent fishery and population conditions.
3. Review basic biological information (growth, fecundity, natural mortality) and develop preliminary target fishing reference points (BMSY, FMSY, MSST, MFMT) based on this information.
4. Develop appropriate analytical methods and review the estimates of fishing mortality (F), spawning stock biomass, and total stock biomass for 1981-2004, and characterize the uncertainty of these estimates.
5. Review the estimated biological reference points, as appropriate.
6. Review stock projections.
   (a) Review the projection of impacts on the stock.
   (b) Review the projection of stock response to alternative policies (if appropriate).
7. Provide declarations of stock status relative to reference points.
8. Make research recommendations for improving data collection and assessment.
9. Provide a final Assessment Workshop Report within 4 weeks of workshop conclusion.

2 Background

2.1 Fishery characteristics and management

The Hawaiian bottomfish fishery has a long history going back to at least the start of the 20th century (Haight et al. 1993), and focuses on deeper slopes and banks, targeting fish mainly in the 50-150 fathom depth range (100-300 m). With regards to the Hawaiian archipelago, the Bottomfish Management Unit Species (BMUS) consist of a 14 species complex of lutjanids, carangids, one species of serranid, and a seamount associated pentacerodit (Table 1). The bottomfish assemblage may be considered as a meta-population of fish associated with specific (but as yet poorly identified) habitat structures, interconnected by larval dispersal and most likely relatively little or no adult movements between banks/islands (Ralston et al., 2004). Participation in this fishery consists of a mix of subsistence, recreational and commercial fishers, with few full-time commercial fishers.

Table 1: List of Hawaiian Bottomfish Management Unit Species (BMUS), their taxonomic affinity and FAO common names

Local name	Family	Scientific name	FAO common name [1]
Black Ulua	Carangidae	*Caranx lugubris*	Black jack
Butaguchi	Carangidae	*Pseudocaranx dentex*	White trevally
Ehu	Lutjanidae	*Etelis carbunculus*	Ruby snapper
Gindai	Lutjanidae	*Pristipomoides zonatus*	Oblique-banded sanpper
Hapuupuu	Serranidae	*Epinephelus quernus*	Hawaiian grouper
Kahala	Carangidae	*Seriola dumerii*	Greater amberjack
Kalekale	Lutjanidae	*Pristipomoides sieboldii*	Lavender jobfish
Lehi	Lutjanidae	*Aphareus rutilans*	Rusty jobfish
Onaga	Lutjanidae	*Etelis coruscans*	Flame snapper (long tail red snapper)
Opakapaka	Lutjanidae	*Pristipomoides filamentosus*	Crimson jobfish
Taape	Lutjanidae	*Lutjanus kasmira*	Bluestripe snapper
Uku	Lutjanidae	*Aprion virescens*	Green jobfish
White Ulua	Carangidae	*Caranx ignobilis*	Giant trevally
Yellowtail Kalekale	Lutjanidae	*Pristipomoides auricilla*	Goldflag jobfish

The Western Pacific Regional Fishery Management Council (the Council) manages these resources in Hawaii, American Samoa, Guam and the Commonwealth of the Northern Mariana Islands via its Bottomfish and Seamount Groundfish Fishery Management Plan (FMP). In Hawaiian waters, the Council coordinates management with the state of Hawaii. As part of the management approach, the Hawaiian archipelago is separated into three management zones: the Main Hawaiian Islands (MHI), and two zones (Mau and Ho'omalu) in the North-West Hawaiian Islands (NWHI). As catches in the MHI zone are largely taken within state waters (3 nm limit), management in this zone is predominantly under state jurisdiction. Roughly 80% of the fishing grounds are within the 3nm state zone, the remainder is in federal waters. In contrast, the fisheries in the NWHI zones are under federal jurisdiction. For a detailed description of the fishery, see the annual Hawaiian Bottomfish and Seamount Groundfish Fishery Management reports (e.g., Anonymous 2004, available at www.wpcouncil.org).

Fishing is primarily undertaken using hook and line methods with electric, hydraulic or manual hand-lines. The fishery in the MHI zone is essentially an open access fishery with some spatial closures (currently 19 restricted fishing areas mainly in state waters), limited restrictions (recreational bag limits for onaga and ehu), and a requirement to own a Commercial Marine License if one intends on selling any part of the catch. Vessels (commercial and recreational) that fish for bottomfish must also be registered, with currently over 3,500 vessels registered (Moffitt et al. 2006). The bottomfish fishery in the two NWHI zones are limited entry fisheries (since 1988 for the Ho'omalu zone, and since 1998 for the Mau zone), with a small number of licenses (currently 4 in each zone), and virtually no recreational fisheries.

Commercial catches are estimated via two reporting mechanisms collected by the state of Hawaii: monthly catch reports provided by each fisher holding a commercial license; and monthly dealer reports of purchases of fish from fishers (primary purchases). As the original intent of the data collection system was for economic development purpose rather than for stock assessment, data quality and details differ over time, especially with regards to measures of effort. More recently, additional data have been collected for both NWHI, e.g., since 1984 improved trip data and since 1994 daily line effort data, and MHI fisheries, e.g., since 2002 improved daily line effort data (Moffitt et al. 2006).

Estimates of non-commercial (i.e., mainly recreational) catches are rare, as no reporting mechanism exists. However, a preliminary survey was conducted in the early 1990s (Hamm and Lum 1992), and a recently initiated Hawaii Marine Recreational Fisheries Survey (HMRFS) is beginning to provide information, although to date bottomfish activities appear to be under-sampled in these surveys (Allen and Bartlett 2006).

2.2 Bottomfish Management Unit Species (BMUS)

The overall broad characteristics of the bottomfish species complex can be summarized as follows (Ralston et al., 2004):

- Long-lived species (20+ years)
- Slow growing (Brody growth coefficient $K = 0.15$-0.25)
- Low natural mortality rates (Instantaneous natural mortality rate $M = 0.25$-0.5)
- Low reproductive capabilities
- Carnivorous

The demersal species assemblage comprising the BMUS often display clear separation by depth, but have overlap in preferred habitat type. Thus, fisheries targeting by depth may influence catch composition. For example, snappers of the genus *Lutjanus* (i.e., Taape, *L. kasmira*) predominantly occur in more shallow waters, species of the genus *Pristipomoides* (e.g., Opakapaka, *P. filamentosus*) prefer intermediate depths, while the genius *Etelis* comprise deep water species (e.g., Onaga, *E. coruscans*). While most serranids are generally relatively shallow water species, some also occur in deep slope waters (e.g., the Hawaiian endemic Hapuupuu, *Epinephelus quernus*). Some snappers and groupers, and most jacks (Carangidae) display schooling behavior at least at certain times, and aggregation behavior may exist also for spawning activities, as has been demonstrated for many grouper species (e.g., Zeller 1998).

2.2.1 Biology and growth

The commercially important bottomfish species in Hawaii inhabit waters ranging in depth from 100m - 400m; however, *Lutjanus kasmira* is often found in shallower nearshore waters (Moffitt et al. 1989a; Haight et al. 1993). Throughout the depth range most bottomfish species are found in small aggregations and associated with underwater headlands similar to the snapper species such as, *P. filamentosus* and *E. coruscans* (Ralston 1987).

Studies done worldwide indicate that fish species in the families Serranidae and Lutjanidae are long lived, slow growing fish with rather low rates of natural mortality (Manooch III 1987, Table 2). Table 2 summarizes the von Bertalanffy growth parameters for most of the bottomfish species listed. The maximum length (L_∞) for those species in the family Lutjanidae ranged between 29 - 117 cm and the intrinsic rate of growth ranged between 0.1-0.6 with the majority ranging between 0.1 and 0.3 (Table 2). L_∞ for *E. quernus* was equal to 116.6 and K was equal to 0.156 (Table 2). L_∞ and K ranged between 164.8cm - 212.9 cm and 0.08 - 0.25, respectively for those species in the family Carangidae (Table 2). Although the carangids attain larger sizes than the lutjanids and serranids, they also seem to be relatively slow growing (see K values in Table 2).

2.2.2 Reproductive biology and early life history

Lutjanidae. Very little is known about the general biology of the bottomfish species that are commercially fished in the Hawaiian Islands, there is especially a paucity of information concerning early life history and reproductive biology. Table 2 summarizes length at maturity for some of the bottomfish species that are targeted by the commercial fishery. The snapper species that are caught belong to the family Lutjanidae and length at 50% maturity occurs between 27cm-61cm FL (Table 2). Snappers are gonochoristic, broadcast spawners where spawning is associated with either the full or new moon (Grimes 1987). It is unclear whether snappers found in Hawaii spawn continuously throughout the year or have restricted spawning (i.e., multiple spawns over a short period during the year; Grimes 1987); however, it has been suggested that spawning peaks in the summer (Haight et al. 1993).

Snapper larvae are found throughout the year mainly over the continental shelf in mainland areas; however, in very small densities. Snapper larvae made up less than 1% of total larvae caught during surveys of the continental shelf (Leis 1987). Although these larvae make up a miniscule proportion of larval densities, peak densities occur between July and September (Leis, 1987). It is also important to note that larval position in the water column was dependent on the time of day; for example, they were not found in surface waters during the day (Leis 1987). Relatively little is known about larval settlement and the juvenile stages of these snapper species; however, planktonic larval duration is approximately 3 months (Leis and Lee 1994) and recruitment to the fishery is assumed to happen 2-3 years after settlement (Haight et al. 1993).

Serranidae *Epinephelus quernus* is the main serranid species caught by the commercial bottomfish fishery. *E. quernus* are protogynous hermaphrodites, which renders ad skewed sex ratio in favor of females (Shapiro 1987). More specifically, Everson (1992) found the female to male sex ratio to be equal to 12:1 in the Hawaiian Islands. Serranid females mature between 160mm-500mm and is species dependent; *E. quernus* measuring 560mm-750mm are considered sexually mature (Shapiro 1987; Everson 1992). Spawning aggregations usually occur over a restricted time period and produce pelagic eggs and larvae (Shapiro 1987) similar to Lutjanids. *E. quernus* has a protracted spawning season between January and August (Everson 1992).

Very little is known about the larval duration or dispersal of *Ephinepheline spp.* larvae. *E. quernus* larvae have never been caught during larval surveys over the Hawaiian continental shelf (Shapiro 1987). *Epinepheline spp.* larvae found on the Great Barrier Reef; however, exhibit diel vertical migration, avoiding surface waters during the day and uniformly distribute throughout the water column at night (Leis 1987). Similar to the snapper species, *E. quernus* juvenile habitat has not been identified in Hawaii (Moffitt et al. 1989b; Haight and Kobayashi 1993).There is some local information on juvenile settlement and habitats of opakapaka (Moffitt and Parrish 1996).

Carangidae. The main carangids caught by the commercial bottomfish fishery are *Caranx ignobilis*, white ulua; *Caranx lugubris*, black ulua; *Pseudocaranx dentex*, butaguchi; and *Seriola dumerili*, kahala (Table 2). Species belonging to the family Carangidae are gonochoristic and there are no apparent differences between males and females (Honebrink 2000). Sexual color differences; however, have been observed in *C. ignobilis* (Talbot and Williams 1956). Mature male *C. ignobilis* were observed having dusky colored heads; whereas, mature females had silvery heads and dusky colored caudal region (Talbot and Williams, 1956). Maturity of female *C. ignobilis* and *S. dumerili* is achieved at 600mm and 720mm SL, respectively (Honebrink 2000, and references therein). Spawning occurs in single pairs, small groups, and large aggregations between February and June with a peak in March and April (Honebrink 2000).

Larval carangids metamorphose into juveniles in the pelagic environment, where the juveniles remain associated with clumps of floating algae, flotsam, and drifting objects (Honebrink 2000, and references therein). Juvenile movement to nearshore waters occurs between 21mm to 50mm SL, which occurs approximately 12 months after hatching (Honebrink 2000, and references therein).

2.2.3 Historical stock assessments

Stock status assessments are undertaken annually, and summarize general recent trends in commercial catch rate data and mean size of the landed catch (e.g., Anonymous 2004). The assessment methods currently used rely almost exclusively on fishery dependent data aggregated over 14 different species, resulting in considerable uncertainties in assessments and is potentially biased. Uncertainties are enhanced by the relatively small scale of some of the fisheries, with the accompanying complexities of small number of fishers, high turnover rates, and gaps in biological and fisheries-related data. The potential meta-population structure and the patchy nature of fish distribution adds to this uncertainty.

The Western Pacific Fisheries Management Council conducted a workshop in 2004 which was tasked with reviewing the bottomfish stock assessment process for Hawaii and the other U.S. Pacific island areas, and develop a plan to improve data collection and assessment methods (Ralston et al. 2004). As part of this process, the workshop expert panel evaluated existing data sets and stock assessment approaches; identified data and assessment weakness; reviewed alternative assessment options; and proposed directions for improved assessment and data collection. The workshop panel concluded that much of the information that exists appears to be fragmentary and often not used effectively to assess and manage the bottomfish resource. It recommended that dedicated expertise should be applied to 1) comprehensively synthesize and assimilate existing data and information; 2) develop a variety of stock assessment methods ranging from simple, aggregate to more complex, detailed models, eventually incorporating species- and area-specific parameters; and 3) develop operating models to represent the complexities of the biology and fisheries of the bottomfish species complex (Ralston et al. 2004). It was suggested that the overarching aim of the recommended approach should be to expose the strength and weakness of the current survey and assessments methods, and indicate areas of research to improve on the identified weaknesses.

In the present document, we present initial steps in line with the workshop panel recommendation to utilize a variety of assessment approaches, and undertook assessments of bottomfish stocks for the Hawaiian archipelago up to 2004 using several approaches (e.g., a Surplus Production model and a variety of hypotheses about the dynamics of production and fishing mortality) unrelated to the previous stock status assessment methods (e.g., Spawning Potential Ratio [SPR] method and changes in CPUE). We explored the likely status of the bottomfish BMUS, as well as selected individual species, in relation to established management metrics and reference limits. We also identified data limitations and provide recommendations for data needs and future assessment directions.

Table 2: Life history parameters and sources of information for the BMUS complex. Lm_{50} is the length at maturity, L_∞ is the asymptotic length, K is the Brody growth coefficient, t_o is the time at length =0, a and b are the length-weight coefficients in $W_a = aL_a^b$ where W_a and L_a are the mean weight- and length-at-age, respectively.

				Growth parameters				L-W		
Hawaiian Name	**Scientific Name**	**Family**	Lm_{50} **(FL cm)**	L_∞ **(cm)**	K	t_o	M	a **(kg)**	b	**Reference**
Kinmedai	*Beryx splendens*	Berycidae		51.3	0.119	-2.51				Lehodey and Grandperrin (1996)
				50.8 (?)	0.134	-2.00				Lehodey and Grandperrin (1996)
				45.2(?)	0.146	-2.34				Lehodey and Grandperrin (1996)
				54.2	0.133	-2.00				Taniuchi et al. (2004)
			33.2 (?)							Lehodey et al. (1997)
			34.5 (?)							Lehodey et al. (1997)
White ulua	*Caranx ignobilis*	Carangidae		212.9	0.082	-0.17		1.64	3.09	Smith and Parrish (2002)
			60.0							
Black ulua	*Caranx lugubris*	Carangidae	(-)	(-)	(-)	(-)	(-)	(-)	(-)	
Butaguchi	*Pseudocaranx dentex*	Carangidae		108.5	0.258	-0.12				Williams and Lowe (1997)
Kahala	*Seriola dumerili*	Carangidae		164.8	0.119	-1.23		7.20	2.70	Manooch III and Potts (1997)
Medai	*Hyperglypha japonica*	Centrolophidae	(-)	(-)	(-)	(-)	(-)	(-)	(-)	
Lehi	*Aphareus rutilans*	Lutjanidae	(-)	(-)	(-)	(-)	(-)	(-)	(-)	
Uku	*Aprion virescens*	Lutjanidae	47.0 (46% L_∞)	102.2						Haight and Kobayashi (1993)
				79.0	0.130					Piling et al. (2000)
				65.6	0.310					(Loubens 1980 in Manooch III 1987)
Ehu	*Etelis carbunculus*	Lutjanidae	30.0 (46% L_∞)	65.2						Haight and Kobayashi (1993)
			27.8							DeMartini and Lau (1999)
				71.8	0.163	3.32	0.30			Smith and Kostlan (1991)
Onaga	*Etelis coruscans*	Lutjanidae	61.0 (62% L_∞)	98.4						Haight and Kobayashi (1993)
				117.5	0.106	-0.36				Williams and Lowe (1997)
ta'ape	*Lutjanus kasmira*	Lutjanidae		34.0	0.290	-1.37				Morales-Nin and Ralston (1990)
				42.9	0.330	-0.37				Morales-Nin and Ralston (1990)[a]
				33.0	0.670					Morales-Nin and Ralston (1990)[b]
				29.9	0.410					Morales-Nin and Ralston (1990)[c]
Yellowtail kale	*Pristipomoides auricilla*	Lutjanidae			0.270		0.66			Ralston (1987)
Opakapaka	*Pristipomoides filamentous*	Lutjanidae		70.4	0.250	-0.22				DeMartini et al. (1994)
			43.0 (48% L_∞)	89.6						Grimes (1987)
				62.3	0.110					Piling et al. (2000)
			51.0	81.7	0.288			0.00005	2.70	Mees and Rousseau (1997)
				78.0	0.145					Manooch III (1987)
				78.0	0.146	-1.67				Ralston and Miyamoto (1983)
					0.220		0.55			Ralston (1987)
					0.290		0.53			Brouard and Grandperrin (1985)
Yelloweye Opaka	*Pristipomoides flavipinnis*	Lutjanidae			0.360		0.83			Brouard and Grandperrin (1985)
Kalekale	*Pristipomoides seiboldi*	Lutjanidae	29.0							DeMartini and Lau (1999)
				44.9	0.115	-0.91				Williams and Lowe (1997)
Gindai	*Pristipomoides zonatus*	Lutjanidae			0.200		0.53			Ralston (1987)
Hapu 'upu 'u	*Epinephelus quernus*	Serranidae	57.0 TL							Everson (1992)
				116.6	0.156	-0.08				Williams and Lowe (1997)

[a]based on increment width
[b]ELEFAN I
[c]ELEFAN V

3 Data sources

3.1 Commercial fisheries data

Commercial catch and effort data were compiled from sales records collected by the Hawaii Department of Aquatic Resources (HDAR). The state has been collecting this data since 1948 and the data consists of sales date (for most records), pounds sold by species, commercial license number, area fished and sale price. The database has evolved considerably over time to include additional information such as numbers sold and dates fished. Commercial catch statistics were extracted from this database and the R-code for extraction from the "raw" text files is given in Appendix A. The data files were first collated into a single data frame, then zone specific information on catch, number of trips, number of licenses and maximum number of trips per license holder each year was extracted.

Main species of interest and concern consist of the 'Deep 7' species (onaga, ehu, opakapaka, gindai, kalekale, lehi, and hapuupuu, Table 1). The aggregate catch trends for the entire BMUS complex for Hawaiian waters displays a distinct pattern of early decline (late 1950s early 1960s), a period of relatively low catches (1960s-1970s), a peak in catches in 1988 driven by high catches of Uku and Opakapaka, followed by a general decline in landings (Fig. 2a).

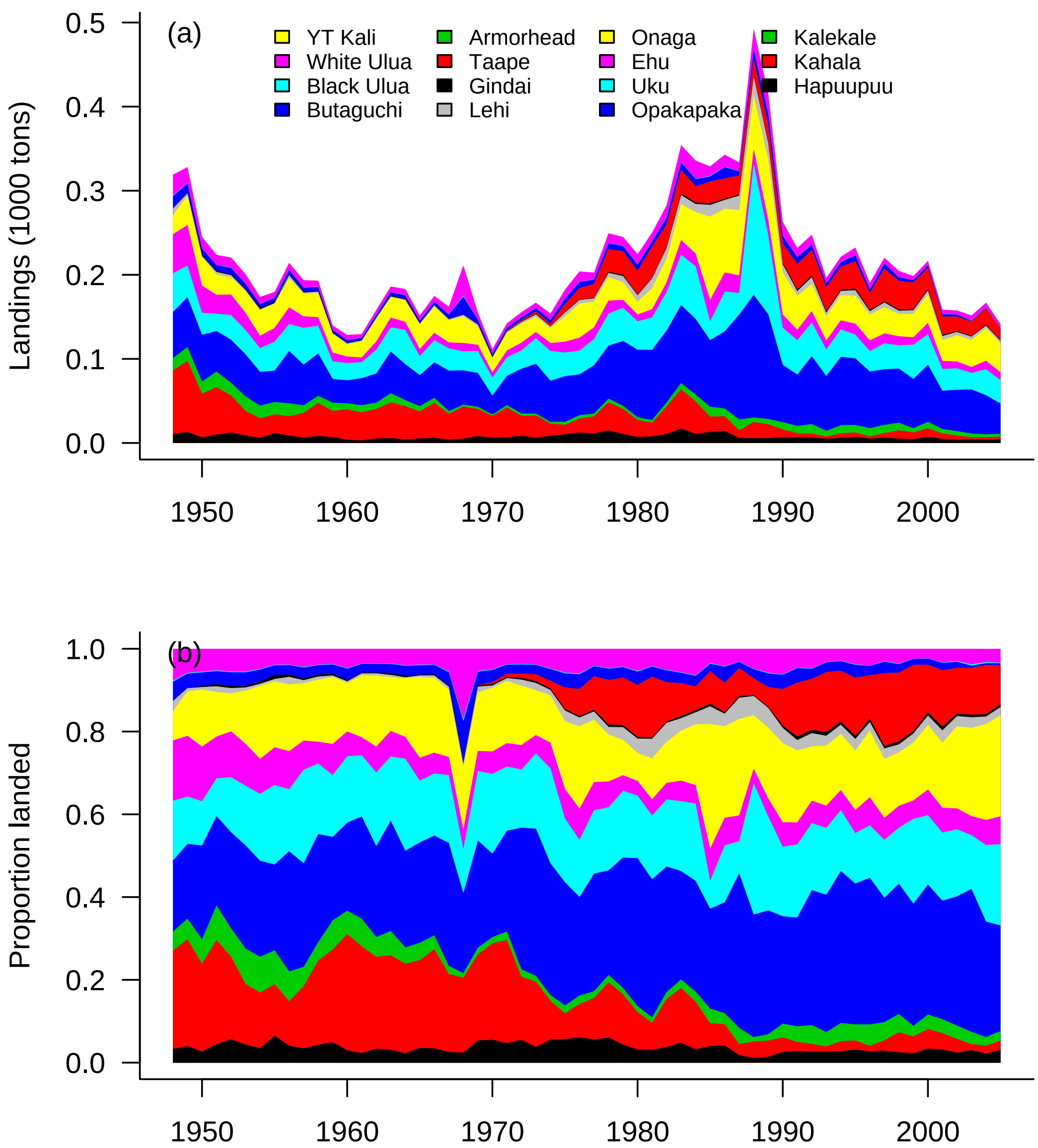

Figure 2: Species specific catches for MHI in (a) 1000 metric tons, and (b) as proportions.

In terms of relative catch composition, commercial bottomfish catches are, on average, dominated by three snapper species: Opakapaka, Onaga and Uku (Fig. 2). Ehu, which has shown an early decline in contributions, and (since the late 1970s) also Ta'ape are also contributing significantly to overall catches (Fig. 2). Ta'ape is an introduced species and became abundance in the 1960s. Kahala catches, while in the early years of the time series contributing around 20% of total catches, has shown a steady decline in relative contribution due to reduced market demand because of concerns of ciguatera contamination (Fig. 2).

Information on effort is based on the monthly catch reports, and consists of two indices: number of trips (1948-2004) and more recently hook-line-hours (1994-2004). In addition to these indices, the state of Hawaii data system also provides information on number of commercial fishing licenses over time. Considerable uncertainty is associated with the accuracy of the earlier effort index of number of trips, due to inconsistent and poor reporting of this information by fishers. In the MHI zone, we assumed that a single trip is equivalent to a single day of fishing. In the MAU and HOO zone this assumption was not appropriate due to the long travel times back to Oahu. For these two zones we used the same effort indices as in Moffitt et al. (2006).

Overall, the pattern in number of fishing licenses follows the general trend (also observed in catches, see above) of the decline in the commercial fisheries in the 1960s and 1970s, followed by a steady increase in licenses during the 1970s and 1980s (Fig 3a). An interesting, but potentially questionable pattern of effort is displayed by the number of trips, which shows a dramatic and rapid increase over a two year period in the early 1980s. We also examined changes in the average number of trips per year per licensed fisherman to determine if there has been a major shift in the number of full time fishermen (Fig 3b). The average number of trips per year, per licensed fisherman declined between 1948 and 1978, overwhich time the number of licensed fishermen grew, and has remained roughly 8 trips per year between 1980 and 2004. Effectively there are more people catching fewer fish. The data contains an anomaly in 1978-79 which may be associated with changes in reporting systems.

3.2 Recreational fishery data

Fishing, both commercial and recreational, plays a significant role in Hawaii, and the two sectors blend into each other (Helvey et al. 1987). However, no requirements exist for recreational marine fishing licensing or reporting in Hawaii (Moffitt et al. 2006), and recreational catches are thus not captured by the existing fisheries catch reporting scheme. However, several attempts have been made to develop and investigate estimates of this sector, at least on a spatially and temporally limited scale (e.g., Anonymous 1987; Hamm and Lum 1992). More recently, however, annual creel surveys have been initiated in Hawaii as part of the Hawaii Marine Recreational Fisheries Survey (Allen and Bartlett 2006). However, these surveys currently may not adequately sample bottomfish catches (P. Dalzell, Western Pacific Regional Fishery Management Council, pers. comm.), and discussions are underway to adjust the survey design to accommodate better estimation of this fisheries sector in the future. Overall, total catches of marine resources are considered under-reported in the offi-

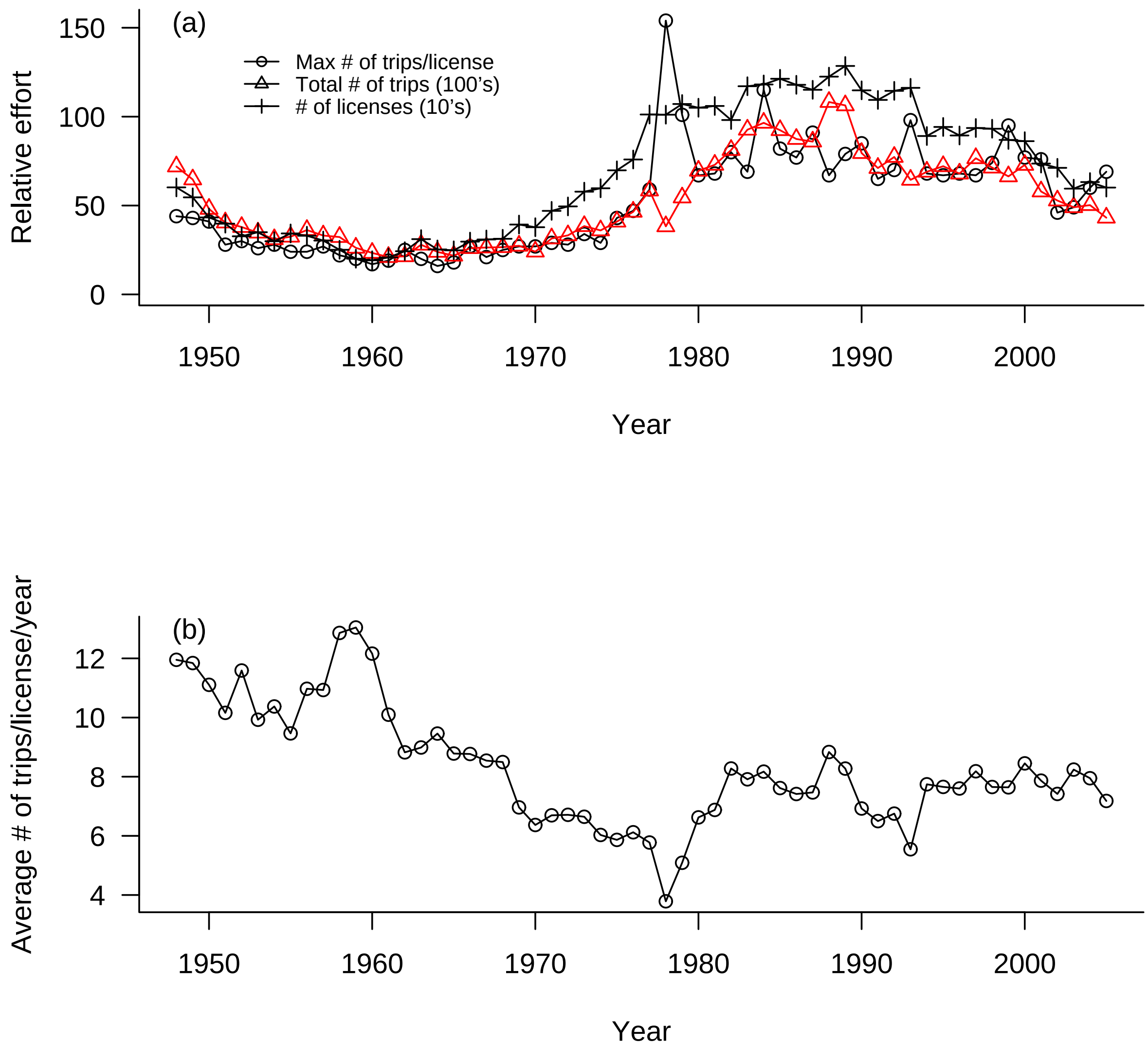

Figure 3: Indicators of effort in terms of number of commercial fishing licenses, number of trips per year, and the maximum number of trips exhibited by a single license holder (a). Panel (b) shows the average number of trips per year by license holder, and index of the number of full time fishermen.

cial statistics (Gulko et al. 2002). For recent years, recreational catches are thought to be equal to or greater than the reported commercial landings (e.g., Friedlander 1996; Gulko et al. 2002).

Here, we estimated potential recreational catches indirectly, via ratio indicators relating likely recreational catches to reported commercial catches, based on Zeller et al. (2005). For details, see Appendix I. Recreational catches were not included in the stock assessment models, as this information has not been sufficiently validated. However, these data should be considered in future assessments because it is very likely that recreation catches in the main Hawaiian Islands exceed commercial landings.

4 Analytical Methods

In the workshop (May 2006, NMFS, Honolulu HI), two separate assessment models were applied to the historical catch and effort data: 1) a Schaefer production model (SPM) and 2) and lagged recruitment survival–growth model (LRSG). Each model was fit to the same catch effort data for the BMUS complex as well as 3 separate taxa that are considered to be the target species in the Hawaiian bottomfish fishery. For each of the assessment models, reference points were derived that correspond to the maximum sustainable yield (MSY), target biomass required to achieve MSY (B_{msy}) and the target fishing mortality rate (F_{msy}). Both models were conditioned on observed fishing effort (days fished) and compared to observed catches. Model parameters were estimated using AD Model Builder (Otter Research 1994).

The LRSG model was extensively explored at the workshop conducted in Honolulu; however, results from the LRSG model are not presented here. Estimates of stock status and reference points from the LRSG model were nearly consistent with the results obtained using the Schaefer production model. The only substantial difference between the two approaches was the incorporation of delayed recruitment in the LRSG model, which tended to lower the estimate of F_{msy}.

4.1 Schaefer production model

Estimated parameters included a single value for the intrinsic rate of growth, zone specific initial biomasses and carrying capacities, catchability coefficients for each zone and the variances for observation and process errors. For numerical stability we used a semi-implicit form of the Schaefer model, this avoided the use of a difference equation that has the potential to produce negative biomasses during parameter estimation. The semi-implicit form of the model (ignoring zone subscripts i for clarity) was given by:

$$b_{t+\delta} = b_t + rb_t\delta - \frac{rb_{t+\delta}b_t\delta}{k} - f_t b_{t+\delta}\delta \tag{1}$$

solving this equation for $b_{t+\delta}$ yields:

$$b_{t+\delta} = \frac{b_t\,(1 + r\delta)\,k}{k + rb_t\delta + f_t\delta\,k}. \tag{2}$$

where r is the intrinsic rate of increase, k is the carrying capacity in each zone, δ is the implicit time step (usually 1/2 a year, i.e., $\delta = 1/2$) and f_t is the fishing mortality rate over the period $(t, t+\delta)$. Biomass in each zone i was initialized as a unknown proportion of the carry capacity (i.e., $b_{i,1} = p_i k_i$), where p_i was estimated. Annual fishing mortality was given by:

$$f_t = q_t E_t \tag{3}$$

where q is the capture probability each year per unit effort (catchability), E_t is the annual effort index. We also examined the possibility of changes in q over time, and model such changes as a random walk process (i.e., $q_{t+1} = q_t e^{\psi_t}$, where $\psi \approx (\mathrm{N}[0, \sigma^2])$ or as an annual deviation from a mean q (i.e., $q_t = \bar{q}e^{\psi_t}$) . Predicted catches over the period $(t, t+\delta)$ were given by

$$\hat{c}_{t+\delta} = b_{t+\delta} f_t \delta \tag{4}$$

Reference points were given by:

$$\mathrm{MSY} = rk/4 \tag{5}$$
$$\mathrm{B_{msy}} = k/2 \tag{6}$$
$$\mathrm{F_{msy}} = r/2 \tag{7}$$

4.2 Likelihoods & Priors

We assumed that errors in the reported catches were log-normally distributed and computed the corresponding residuals between observed and predicted non-zero catches:

$$\nu_t = \ln(c_t) - \ln(\hat{c}_t) \tag{8}$$

where c_t and $\hat{c}_t$ are the observed and predicted catches, respectively. The likelihood of the catch data was given by

$$L(c_t, E_t|\Theta) = \frac{n}{2}\ln(\sigma^2) + \frac{\sum_{t=1}^{n} \nu_t^2}{2\sigma^2} \tag{9}$$

where n is the number of observations and σ^2 is the estimated observation error variance.

In the SPM model, a noninformative prior was chosen for q and informative priors were chosen for r, P_i, K_i, ψ_t and σ^2 (Table 3).

In cases where catchability was modeled as a random walk process, the prior distribution

$$\psi \sim \ln(\tau^2) + \frac{\sum(\psi_t - \psi_{t+1})^2}{2\tau^2} \tag{10}$$

Table 3: Lower (lb) and upper (ub) bounds for estimated parameter, initial values (ival) and the phase (phz) in which parameters were estimated in the Schaefer model. Expected values and variances for prior distributions are denoted as E(Θ) and var(Θ), respectively.

Θ	lb	ub	ival	phz	E(Θ)	var(Θ)	Distribution
r	0.01	1	0.4	2	0.4	0.3	lognormal
p_{MHI}	0.01	1	0.95	1	0.95	5	beta
p_{MAU}	0.01	1	0.55	1	0.55	3	beta
p_{HOO}	0.01	1	0.65	1	0.5	3	beta
k_{MHI}	4	12	9.15	1	8.736	0.136	lognormal
k_{MAU}	4	10	7.23	1	6.805	0.136	lognormal
k_{HOO}	4	12	8.8	1	8.466	0.136	lognormal
q_{MHI}	0.0001	0.5	0.15	3	$1/q$	-	uniform
q_{MAU}	0.0001	0.5	0.15	3	$1/q$	-	uniform
q_{HOO}	0.0001	0.5	0.13	3	$1/q$	-	uniform
σ^2_{MHI}	0.00001	0.1	0.015	2	5	0.05	inverse gamma
σ^2_{MAU}	0.00001	0.1	0.015	2	5	0.05	inverse gamma
σ^2_{HOO}	0.00001	0.1	0.015	2	5	0.05	inverse gamma
τ^2_{MHI}	0.00001	0.5	0.01	-2	4	0.1	inverse gamma
τ^2_{MAU}	0.00001	0.5	0.01	-2	4	0.1	inverse gamma
τ^2_{HOO}	0.00001	0.5	0.01	-2	4	0.1	inverse gamma

was used to constrain how quickly q can change over time. Note that τ^2 represents the variance in the rate of change in q and was an estimated parameter.

In the case of the carrying capacities (k), an informative prior was used for each of the MHI, MAU and Ho'omalu zones. There were no fisheries independent estimates of absolute abundance in any of the zones, therefore, priors are constructed on an ad hoc basis. For the MHI zone, we assumed that the initial exploitation rate in 1948 fell somewhere between 0.01 and 0.2 and used this assumption to construct a lognormal prior for k with the 10% quantile equal to $c_{1948}/0.2$ and the 90th quantile equal to $c_{1948}/0.01$. The prior distributions for the MAU and Ho'omalu zones were scaled based on the length of the 100 fathom depth contour in each of the areas relative to that of the MHI zone. This assumed that the 100 fathom depth contour were roughly proportional to the amount of available habitat for the BMUS complex in all 3 zones.

4.3 Alternative hypotheses

Various parameterizations of the SPM and LRSG models were explored to examine alternative hypotheses about changes in catchability over time, affects of environmental correlates, and age at recruitment in the LRSG model. These alternative hypotheses were denoted by run numbers (e.g., R1, R2, etc.). In this report we only explored alternative hypotheses using the SPM model, and note here that similar results were obtained using the LRSG model.

To choose among the alternative hypotheses (i.e., which is the most likely model) there are several statistical approaches to evaluate how well the hypothesis explains the data. We used the Akaike Information Criterion (AIC) to choose the most parsimonious model. The AIC is given by:

$$\mathrm{AIC} = -2\log(\mathrm{L}) + 2\mathrm{p} \tag{11}$$

where L is the likelihood and p is the number of estimated parameters (Hilborn and Mangel 1997). In cases where the sample size was small relative to the number of estimated parameters (i.e., n/p <40, where n is the number of observed data the model is being fit to) the corrected AIC was used (see Burnham and Anderson 2002):

$$\mathrm{AIC_c} = -2\log(\mathrm{L}) + 2\mathrm{p} + \frac{2\mathrm{p}(\mathrm{p}+1)}{\mathrm{n}-\mathrm{p}-1}, \quad \text{where n} > \mathrm{p} \tag{12}$$

In cases where the number of parameters exceeded the number of observations ($p > n$), the corrected AICc favored models with a larger number of parameter values. For this reason, we only compared AIC values for models in which $p < n$. Using the $\mathrm{AIC_c}$ values, we calculated 2 measures of evidence for model selection. First was the $\Delta\mathrm{AIC_i} = \mathrm{AIC_{c,i}} - \min(\mathrm{AIC_{c,i}})$, where $\mathrm{AIC_{c,i}}$ is the AIC value for model i. As a rule of thumb, a $\Delta\mathrm{AIC_i} < 2$ suggested substantial evidence for the model, values between 3 and 7 indicated that the model has considerably less support, whereas a $\Delta\mathrm{AIC_i} > 10$ indicated that the model is very unlikely relative to the model with the lowest $\mathrm{AIC_c}$ value (Burnham and Anderson 2002). The second measure was the AIC weight ($\mathrm{AIC_w}$):

$$\mathrm{AIC_w} = \frac{\mathrm{e}^{-0.5\Delta\mathrm{AIC_i}}}{\sum_\mathrm{i} \mathrm{e}^{-0.5\Delta\mathrm{AIC_i}}} \tag{13}$$

$\mathrm{AIC_w}$ weights provided another measure of evidence for each model, and represented a ratio of $\mathrm{AIC_w}$ values for each model relative to all other models. This amounts to changing the scale of the $\Delta\mathrm{AIC_i}$ values so that the likelihood of all models sum to 1. In this case, we could place odds on which model is "correct". For instance a $\mathrm{AIC_{wi}} = 0.35$ for a given model indicated that, given the data, there was a 35% chance that model i will be correct among all the models considered. The $\mathrm{AIC_w}$ values can also be used for model averaging (see Burnham and Anderson 2002, for more details).

Following are descriptions of alternative model configurations to explore alternative hypotheses.

Run 1 (R1). In R1 we used the SPM model and assumed observation errors only. The total number of estimated parameters equaled 13.

Run 2-6 (R2-R6). In R2-R6 we included normalized sea-level height anomalies from Midway Island (Fig. 4) as an environmental correlate on stock production in the form of process errors, or the intrinsic rate of growth, or the density dependent effects. Sea level anomalies (a_t) were standardized to a mean = 0 and a standard deviation = 1. We also examined the effects of sea level height anomalies (Jan-Mar, 1947-2004) on changes in catchabilities. Sea level height was correlated with the depth of the mixed layer and can affect local productivity and or distribution of fish (Jeff Polovina, pers. comm.) The total number of estimated parameters in R2-R6 equaled 16.

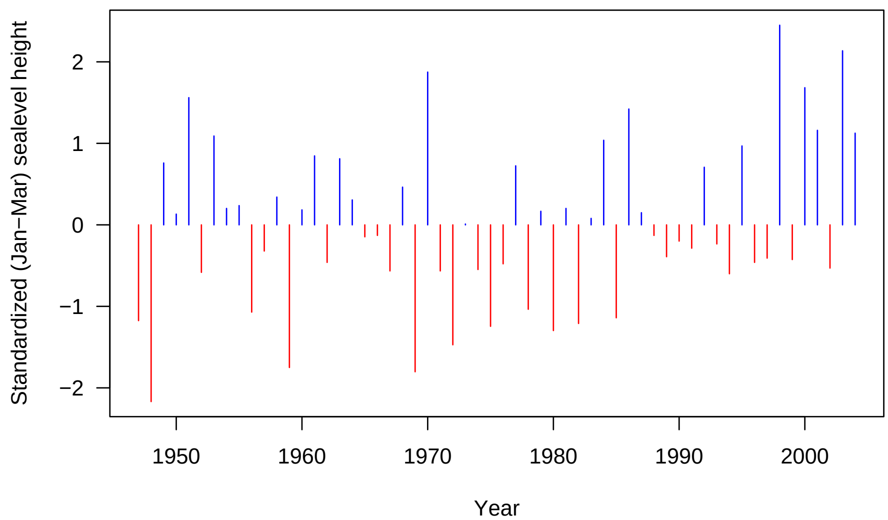

Figure 4: January to March sealevel height anomalies at Midway. Units have been standardized to have a mean 0 and a standard deviation of 1. Positive anomalies indicate above average sea level heights.

In R2, sea-level anomalies were incorporated as a total process error term:

$$b_{t+\delta} = \frac{b_t\,(1 + r\delta)\,k}{k + rb_t\delta + f_t\delta\,k} e^{ca_t} \tag{14}$$

where c is an estimated correlation coefficient for each area.

In R3, we allowed the intrinsic rate of growth to vary with sea-level height anomalies. At each time step, r was modified as $r = r\exp(ca_t)$. In this case, we assumed that the intrinsic rate of growth was a shared parameter, and variation in sea-level height (or the depth of the mixed layer) affected r over a widespread area (i.e., the whole Hawaiian archipelago).

In R4, we followed the same treatment as in R2, but applied the anomaly series to the carrying capacities (i.e., $k_i = k_i\exp(c_i a_t)$). This amounted to changing density dependent effects associated with varying sea-level heights.

In R5, we assumed a constant production function (i.e., r, k_i are constant over time) and assumed that catchability was related to sea-level height anomalies via $q_{i,t} = q_i\exp(c_i, a_t)$. In effect, if the depth of the mixed layer changes such that fish are concentrated into a smaller area, then it is expected that capture probabilities per unit of effort will increase, and vise versa.

In R6, we assumed constant production and variation in catchability was partially explained by the cumulative effects of changes in sea-level height (i.e., $q_{i,t+1} = q_{i,t}\exp(c_i, a_t)$). The notion here was that changes in catchability change slowly over time and are autocorrelated. In this sense, the estimated c_i parameter was equivalent to an autocorrelation coefficient.

Run 7-9 (R7-R9). In R7-R9, we adopted a mixed error approach (observation and process error) to parameter estimation, where the variances in observation error terms and process error terms were estimated. Priors for variance terms are listed in Table 3 and were fixed at the same values for R7-R9.

In R7, we assumed the following dynamic model

$$b_{t+\delta} = \frac{b_t\,(1 + r\delta)\,k}{k + rb_t\delta + f_t\delta\,k}e^{w_t} \tag{15}$$

and treated the process error terms (w_t) as estimated quantities. We assumed that w_t were normally distributed with a mean=0 and a variance $= \tau^2$, and τ^2 being an estimated quantity with a inverse-gamma distribution. The number of estimated parameters equaled 107.

In R8, we treated changes in catchability as a random walk process, and estimated a sequence of anomalies (ψ_t). Again, we assumed that values of ψ_t were normally distributed with a mean $= 0$ and a variance $= \tau^2$, where τ^2 was estimated and the objective function value was penalized assuming τ^2 has an inverse-gamma distribution with parameters listed in Table 3. The number of estimated parameters equaled 107.

In R9, we estimated both changes in catchability over time and model process error terms (i.e., combined R7 and R8), and assumed that the variance in q_t and w_t were equal. In this case the total number of estimated parameters equaled 198.

Run 10-11 (R10-R11). Preliminary results from R6 and R8 showed some interesting patterns that were counter-intuitive with respect to changes in catchability over time. Kobayashi (1996) had assumed catchability increased over time, and this assumption was also assumed by Moffitt et al. (2006); whereas R6 and R8 suggested that catchability may have decreased over time. Thus, in R10, we repeated the four stage increase in catchability (documented in Moffitt et al. 2006), within the four time periods being: (1) 1948-1967, (2) 1968-1984,(3) 1985-1991, and (4) 1992-2004. In R10, we estimated a single $q_{(3)}$ for each area corresponding to the (3) time period, then q in time period (1) was equal to $q_{(1)} = 0.7q_{(3)}$, in the (2) time period $q_{(2)} = 0.8q_{(3)}$ and in the (4) time period $q_{(4)} = 1.2q_{(3)}$. The result was a "forced" stepped increase in q over time.

In R11 we adopted the same 4 time periods, but then estimated 3 additional parameters that corresponded to the relative change in $\bar{q}$, where $\bar{q}$ is the catchability in the (3) time period.

$$q_{(1)} = c_1\bar{q}, \quad q_{(1)} = c_2\bar{q}, \quad q_{(1)} = \bar{q}, \quad q_{(1)} = c_3\bar{q}$$

where $c_{1,2,3}$ were estimated parameters.

In both R10 and R11, we assumed changes in q were associated with changes in fishing power, and fishing power changes were equal among and occurred at the same time period in all 3 zones. The total number of estimated parameters in R10 and R11 was 16.

4.4 Stock status & reference points

National Standard 1 of the Sustainable Fisheries Act (SFA) requires that federally managed fish stocks be maintained at levels of abundance that would allow for long-term Maximum Sustainable Yields. The SFA requires reference points (thresholds) be defined to determine if the stock is over-fished and whether or not over-fishing is occurring. Over-fishing is defined as a fishing mortality rate that is larger than $\mathrm{F_{msy}}$, and over-fished is when the biomass is reduced to 70% of $\mathrm{B_{msy}}$. The ratio of $F_t : \mathrm{F_{msy}}$ is defined as the fishing mortality status and the ratio of $B_t : \mathrm{B_{msy}}$ is defined as the biomass status. The determination of archipelagic stock status is developed by combining status indices from the 3 different zones using weighting factors (MHI=0.447, MAU=0.124, HOO=0.429) that are based on the relative habitat (length of the 100-fathom depth contour) in each zone. Results from each of the alternative models were plotted on control plots (e.g., Fig. 5) to determine the current status, and historical status on an archipelagic and zone-specific case.

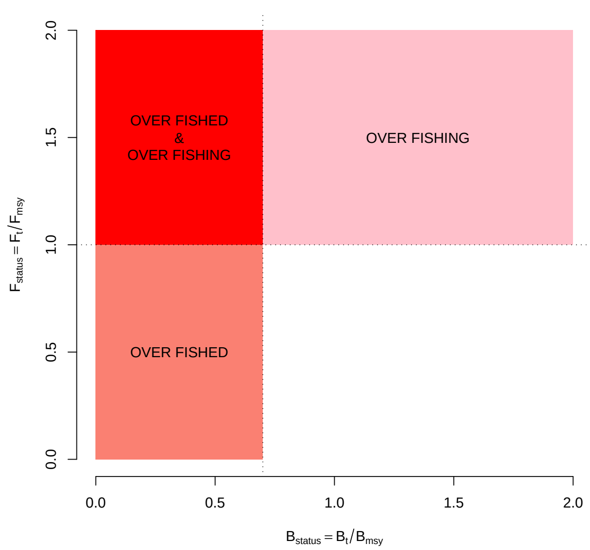

Figure 5: Example of a control plot for determining stock status and fishing status.

5 Results

5.1 Schaefer production model

Trends in estimated biomass and fishing mortality rates were qualitatively similar over all 11 alternative model structures (Fig. 6). In the Main Hawaiian Islands (MHI zone), estimates of unfished biomass (or k) ranged from 1.63 kilotons in R6 to 1.87 kilotons in R3 (Table 4). In R1 the estimated B_o was 1.84, 0.33 and 0.71 kilotons in the MHI, MAU, and HOO zones, respectively, and the estimated intrinsic rate of growth for all three areas was 0.52. In (R1), residuals between the predicted and observed catches appeared to be normally distributed (Fig. 7g); however, there was a pattern in the catch residuals that was suggestive of non-stationarity in the production function, or systematic changes in catchability over time (Fig. 7d,e,f). Models R6, R8 and R9 tended to have lower B_o estimates in the MHI zone, and overall biomass from R8 and R9 were lower in the MAU and HOO zones.

Trends in MHI biomass for runs R10 and R11 were similar between 1948 and the mid 1980s, but post 1985 the two models diverged substantially. In R10, biomass declined to a severely low level, whereas in R11, biomass increases substantially. The difference in biomass between these 2 runs owed to the assumed direction of change in catchability over time. In R10, catchabilty was assumed to increase, whereas in R11, a more parsimonious explanation of the data was that catchability declined over this period. Assuming that catchability increased over time led to a much sharper decline in biomass and an increase in fishing mortality in recent years.

Estimates of leading parameters (k and r) were fairly sensitive to the assumed variance of the prior distribution on r. Increasing the variance for the prior distribution on r tended to result in increased estimates of r and decreases in estimates of k (i.e., r and k were negatively correlated). However, estimates of MSY for all zones (Table 4) are somewhat insensitive to the r-k tradeoff because of the negative correlation.

A key feature to focus on in the model comparison was the results obtained from R6. Recall that in R6, the environmental anomalies (Midway Island sea-level heights used as a proxy for the depth of the mixed layer) were incorporated as a moving average process in the catchability coefficients over time. Incorporating the environmental anomaly sequence in this way led to an estimated decline in catchability in the MHI between 1970 and 1985, and a period of low catchability between 1950 and 1997, then a sharp increase in catchability in the remaining years. Overall there was an improvement in the negative loglikelihood for the catch data in the MHI area, but no real improvement in the MAU or HOO zones (Table 5). In the MHI zone, the qualitative trends (Fig. 8) in R6 appeared to be consistent with trends in q_t in R8 (where deviations in catchability were estimated freely) but were inconsistent in the latter years with R9 (where process errors and catchability deviations were estimated).

The estimates of q_t obtained from R11 were more consistent with the hypotheses in R6 and R8, suggesting that catchability declined between 1948 and the mid 1980's. However, estimates of catchability post 1985 in R11 were inconsistent with the estimated increases in R6 and R8. For comparison, (Kobayashi 1996) assumed the scalers for periods (1),(2) and

(4) to be 0.7, 0.8, and 1.2, respectively. In R11, estimated scalers for these same periods were 2.02, 1.37 0.75. This implies that catchability in period (1) was two times the catchability in period (3) or 1985-1991, and the trend is decreasing, not increasing as assumed in Kobayashi (1996); Moffitt et al. (2006).

Among the alternative hypotheses that utilize the sea-level height data (R2-R6), R6 appeared to be the most likely relative to R1, and was also consistent with the over-parameterized model that suggested catchability has systematically declined between 1948 and 1985, then increased between 1997 and 2004 (R7). Incorporating environmental effects on the production function or as independent process error terms explained very little of the variation in catch residuals.

Table 4: Key parameter estimates and reference points for the Schaefer production model under alternative hypotheses (see R1-R9 descriptions in previous section).

		Bo (1000 tons)			B_{msy} (1000 tons)			MSY (tons)		
Run #	r	MHI	MAU	HOO	MHI	MAU	HOO	MHI	MAU	HOO
R1	0.52	1.84	0.33	0.71	0.92	0.17	0.36	240.1	43.4	93.1
R2	0.52	1.84	0.32	0.74	0.92	0.16	0.37	240.2	42.3	96.1
R3	0.55	1.78	0.33	0.70	0.89	0.16	0.35	242.1	44.3	95.7
R4	0.52	1.85	0.33	0.74	0.92	0.16	0.37	241.0	42.8	96.3
R5	0.53	1.82	0.34	0.71	0.91	0.17	0.35	240.5	44.4	93.5
R6	0.51	1.71	0.33	0.75	0.86	0.16	0.38	219.3	41.6	96.2
R7	0.49	1.91	0.31	0.68	0.96	0.16	0.34	234.9	38.5	83.6
R8	0.59	1.64	0.28	0.64	0.82	0.14	0.32	240.9	40.7	93.5
R9	0.57	1.63	0.26	0.61	0.82	0.13	0.31	231.7	37.0	86.8
R10	0.60	1.87	0.29	0.64	0.93	0.14	0.32	278.6	42.7	94.8
R11	0.65	1.64	0.29	0.60	0.82	0.15	0.30	267.5	47.8	98.6
Average	0.55	1.78	0.31	0.68	0.89	0.15	0.34	243.34	42.31	93.46
Moffitt et al.	0.46	1.45	0.40	1.39						

5.1.1 Model selection

Among the models that did not estimate nuisance parameters (i.e., w_t or ψ_t) the most parsimonious model was R1 (the simplest deterministic model with constant catchability and 13 estimated parameters) based on the AIC_c criterion (Table 6). The next most likely model was R6 where catchability was modeled as an autocorrelated series related to the environmental anomaly sequence. The least likely model is R10, where the catchability was assume to increase in a 4 level step function over time (Table 6). This increase in q_t was assumed in the previous assessments. The other model that could not be rejected was R3, where the intrinsic rate of growth was allowed to vary with sea-level height anomalies.

Table 5: Break down of the objective function values into its components [f=$L(C|\Theta) + P(\Theta)P(w_t) + P(\varphi_t) + P(\tau^2)$] and estimates of MSY for alternative hypotheses R1-R9.

		$L(C\|\Theta)$			$P(\Theta)$			$P(w_t)P(\varphi_t)P(\tau^2)$		
Run #	f	MHI	MAU	HOO	MHI	MAU	HOO	MHI	MAU	HOO
R1	14.7	-50.8	-13.4	-26.3	43.1	35.3	26.8	0	0	0
R2	13.4	-50.8	-13.4	-27.9	43.1	34.9	27.5	0	0	0
R3	14.3	-50.3	-13.4	-27.3	42.9	35.3	27.1	0	0	0
R4	13.9	-50.9	-13.2	-27.7	43.1	35.1	27.5	0	0	0
R5	13.7	-50.7	-14.0	-26.7	43.0	35.4	26.9	0	0	0
R6	10.5	-52.3	-13.4	-28.0	41.6	34.8	27.7	0	0	0
R7	-279.7	-66.8	-15.8	-31.2	42.5	33.3	26.6	-152.7	-57.6	-57.9
R8	-302.1	-87.7	-16.0	-31.3	42.7	33.2	27.6	-153.1	-58.1	-59.3
R9	-589.7	-91.3	-18.6	-32.7	42.6	31.6	27.0	-313.5	-116.0	-118.7
R10	20.0	-48.0	-11.8	-26.8	45.2	34.6	26.7	0	0	0
R11	12.0	-56.4	-14.9	-21.2	42.6	35.5	26.5	0	0	0

Table 6: Objective function values, likelihoods, number of estimated parameters (p), AIC and AIC_c, ΔAIC_c, and AIC weights (AIC_w) for each of the 11 model runs. Runs with the lower AIC values and higher AIC weights are more probable models. Runs R7-R9 are not comparable due to the large number of estimated parameters and additional priors added to the objective function value (f).

Run #	f	$\sum L(C\|\Theta)$	p	AIC	AIC_c	ΔAIC_c	AIC_w
R1	14.72	-90.41	13	55.43	60.16	0.00	0.380
R2	13.44	-92.03	16	58.88	66.23	6.07	0.018
R3	14.27	-90.96	14	56.54	62.06	1.90	0.147
R4	13.86	-91.81	16	59.72	67.07	6.91	0.012
R5	13.72	-91.51	16	59.44	66.79	6.63	0.014
R6	10.48	-93.64	16	52.96	60.31	0.15	0.353
R10	19.98	-86.52	13	65.96	70.68	10.52	0.002
R11	12.05	-92.53	16	56.10	63.45	3.29	0.074
R7	-279.72	-113.87	107	-345.43	-1704.96	44.80	0.000
R8	-302.12	-134.98	107	-390.23	-1749.76	0.00	1.000
R9	-589.70	-142.66	198	-783.40	-1513.07	236.69	0.000

5.2 Stock Status & Reference Points

For R1, the status of the BMUS complex in the MHI zone was overfished, and overfishing continues. For all other hypotheses about stock dynamics, except R8, R9, and R11, similar trends in the stock status were observed (Fig. 9a and Table 7) In the R8 and R9 cases, two divergent predictions were made on the stock status: in R8, the stock is severely over-fished and severe overfishing continues. This could be attributed to depensatory fishing associated with recent increases in catchability. In R9, the stock is not over-fished nor is overfishing going on since 2001. This could be attributed to a sharp decline in estimated catchabilities since the early 1990's (Fig. 8a). Regardless of which model is assumed to be correct (with the exception of R9 and R11), the biomass ratio in the MHI zone is below the minimum stock size threshold (MSST) ratio of 0.7.

In the MAU zone, trends in the control plot for all 11 alternative hypotheses were similar (Fig. 9b), and with exception of R9 and R8, the stock status is not overfished, and overfishing is not occurring. In the R8 and R9 cases, overfishing is occurring and this could be attributed to increases in catchability in recent years (Fig. 8b), and lower estimates of population abundance (Fig 6b). For all models, the biomass ratio in the MAU zone is above the MSST, and the fishing mortality ratio is below the maximum fishing mortality threshold (MFMT) ratio of 1.0.

In the HOO zone, trends in the stock status indicated that overfishing is occurring, but the stock is overfished only in the R6, R8, R9 and R10 cases (Fig. 9c). Overfished in these cases could be attributed to increases in catchability since the mid 1990s, whereas all other hypotheses assume catchability was either constant or varies around a mean q (i.e., R5). For models R1-R7, the biomass ratio is above the MSST ratio; however, the fishing mortality ratio is above the MFMT ratio of 1.0, (i.e., overfishing but not overfished).

Table 7: Zone specific estimates of stock status and uncertainty for each alternative hypotheses.

	Bstatus			Std in Bstatus			Fstatus			Std in Fstatus		
Run #	MHI	MAU	HOO	MHI	MAU	HOO	MHI	MAU	HOO	MHI	MAU	HOO
R1	0.69	1.23	0.84	0.06	0.14	0.13	1.2	0.66	1.07	0.05	0.1	0.12
R2	0.69	1.36	0.82	0.07	0.21	0.12	1.2	0.65	1	0.05	0.1	0.13
R3	0.67	1.21	0.84	0.06	0.14	0.13	1.18	0.65	1.03	0.05	0.1	0.12
R4	0.69	1.28	0.86	0.06	0.17	0.13	1.21	0.66	0.99	0.05	0.1	0.14
R5	0.68	1.27	0.8	0.07	0.13	0.13	1.2	0.65	1.09	0.05	0.1	0.11
R6	0.7	1.17	1.01	0.07	0.17	0.17	1.41	0.8	0.8	0.11	0.21	0.19
R7	0.59	1.28	0.77	0.07	0.21	0.14	1.25	0.73	1.15	0.07	0.12	0.17
R8	0.25	0.99	0.31	0.09	0.53	0.13	2.95	1.01	2.75	1.32	0.68	1.5
R9	1.03	0.91	0.34	0.43	0.51	0.16	0.61	1.25	2.72	0.28	0.87	1.64
R10	0.38	1.19	0.75	0.04	0.14	0.11	1.55	0.71	1.17	0.04	0.1	0.1
R11	1.57	1.41	1.15	0.11	0.13	0.24	0.45	0.53	0.8	0.11	0.1	0.21

In the Hawaiian Bottomfish Fisheries Management Plan (FMP), stock status determination for overfishing and overfished are applied to the archipelagic stock as a whole. In addition, if the archipelagic stock is determined to be overfished or overfishing is occurring, area-specific metrics are to be evaluated by managers to identify where the problems may arise, so that measures may be taken to correct the overfishing–overfished problem. In present assessments, at the archipelagic scale, almost all of the alternative hypotheses (R1-R10) indicated that over-fishing is occurring and the stocks are overfished (i.e., $B_t : \mathrm{B}_{\mathrm{MSY}} < 1.0$), however, only models R8 and R10 indicated that the stock as a whole below the MSST (Fig. 9d). Overfishing is largely occurring in the MHI zone and the HOO zone, and the stocks are below the MSST in the MHI zone.

As the number of estimated parameters increases, the uncertainty in stock status increases (Table 7), and uncertainty in the MAU and HOO zones was greater than the MHI zone because there is less time-series information in these zones.

5.3 Stock projections

Stock projections were carried out using the R1 model and 5 alternative fishing policies were explored. The same fishing policy was prescribed to each of the three management zones. The first policy was based on the status quo, i.e., continue fishing at a rate the is equal to the current fishing mortality rate. Under this policy there would be negligible increases in biomass in all three zones and the stocks would remain in an over-fished state (Table 8). The second policy we explored was to reduce the current fishing mortality rates by 15%. Under this policy, there are marginal increases in stock biomass and initially landings in the MHI zone would decline by 25 tons over the status quo policy (Table 8). The third policy was a 25% reduction in fishing mortality rates relative to the status quo, which results in a >50 ton decrease in landings in the MHI zone and a slightly more significant increase in the biomass status. Fishing at $\mathrm{F}_{\mathrm{MSY}}$ was nearly equivalent to the 15% reduction in F policy in the MHI zone; however, there would be an increase in yields from the MAU and HOO zones (Table 8). Adopting a more conservative policy of 75% of $\mathrm{F}_{\mathrm{MSY}}$ was the only policy in which the MHI biomass would bring the Bstatus ratio near 1.

Table 8: Stock projections

		Projected Biomass (t)			Projected Bstatus			Projected Landings		
Policy	Year	MHI	MAU	HOO	MHI	MAU	HOO	MHI	MAU	HOO
Status Quo	2005	645.4	210.0	305.8	0.70	1.26	0.86	201.4	35.8	85.3
	2006	657.9	213.4	310.0	0.71	1.28	0.87	205.4	36.4	86.5
	2007	668.8	215.9	313.6	0.73	1.30	0.88	209.0	36.9	87.5
	2008	678.2	217.9	316.6	0.74	1.31	0.89	212.1	37.2	88.4
Reduce F 15%	2005	669.5	214.1	315.9	0.73	1.29	0.88	176.0	30.9	74.3
	2006	704.1	220.7	328.8	0.76	1.33	0.92	185.5	31.9	77.5
	2007	734.7	225.7	339.8	0.80	1.36	0.95	193.9	32.7	80.2
	2008	761.5	229.5	349.1	0.83	1.38	0.98	201.3	33.3	82.5
Reduce F 25%	2005	686.4	216.9	322.8	0.75	1.30	0.90	158.3	27.5	66.7
	2006	737.0	225.7	342.1	0.80	1.36	0.96	170.5	28.7	70.8
	2007	782.3	232.4	358.5	0.85	1.40	1.00	181.5	29.7	74.4
	2008	822.0	237.5	372.3	0.89	1.43	1.04	191.2	30.4	77.5
F_{MSY}	2005	672.7	196.6	310.4	0.73	1.18	0.87	172.7	51.8	80.3
	2006	710.3	189.9	318.5	0.77	1.14	0.89	182.7	49.9	82.5
	2007	743.7	184.8	325.4	0.81	1.11	0.91	191.7	48.5	84.4
	2008	772.8	180.9	331.2	0.84	1.09	0.93	199.6	47.4	86.0
75% F_{MSY}	2005	708.6	206.3	326.5	0.77	1.24	0.91	134.8	40.3	62.6
	2006	781.2	206.7	349.2	0.85	1.24	0.98	149.2	40.4	67.2
	2007	847.1	207.1	368.6	0.92	1.24	1.03	162.5	40.5	71.1
	2008	904.9	207.3	384.8	0.98	1.24	1.08	174.2	40.5	74.5

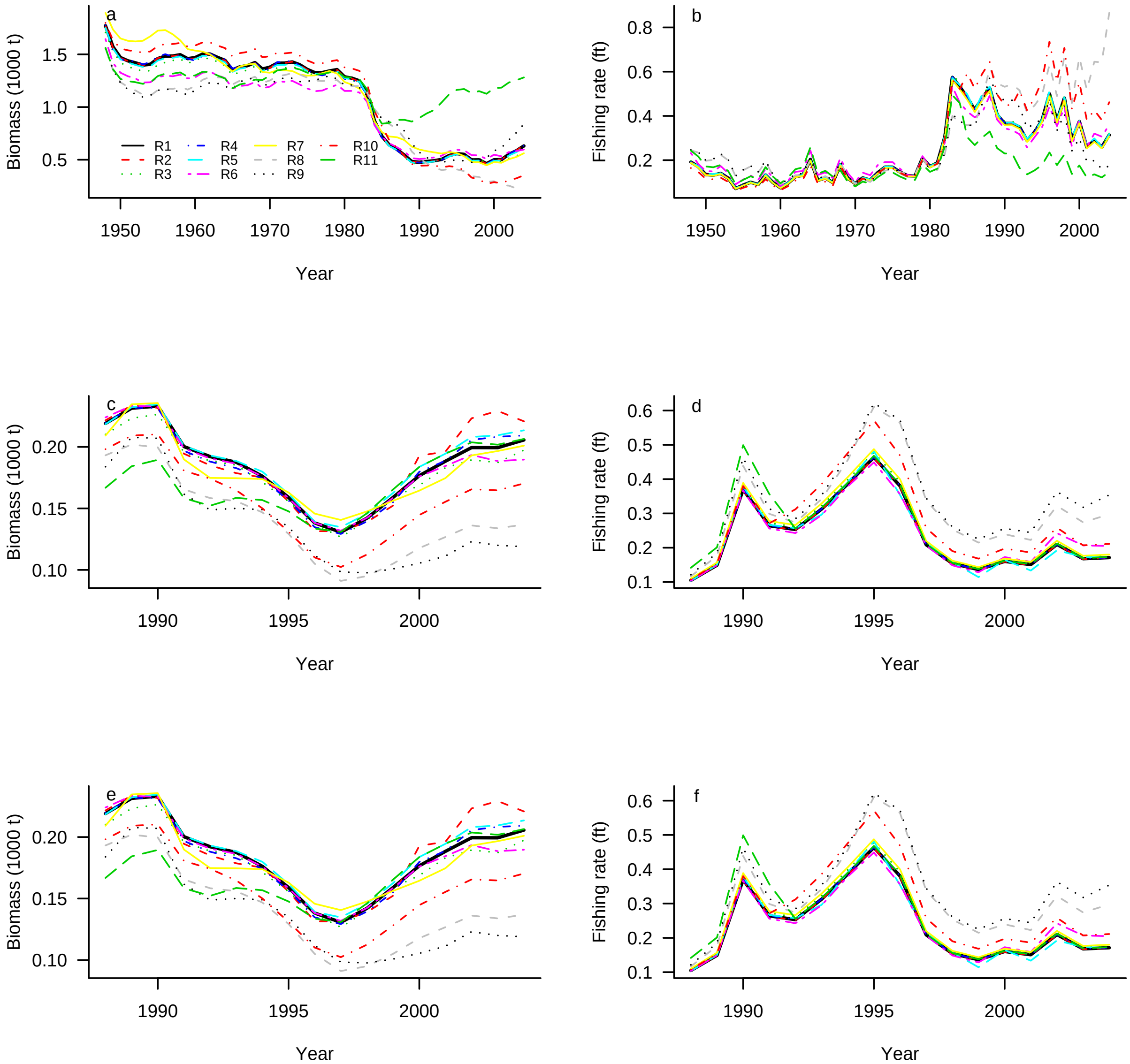

Figure 6: Comparison of historical biomass estimates and fishing mortality rates for the BMUS complex in the MHI zone (a,b), MAU zone (c,d) and HOO zone (e,f) for alternative hypotheses R1-R9.

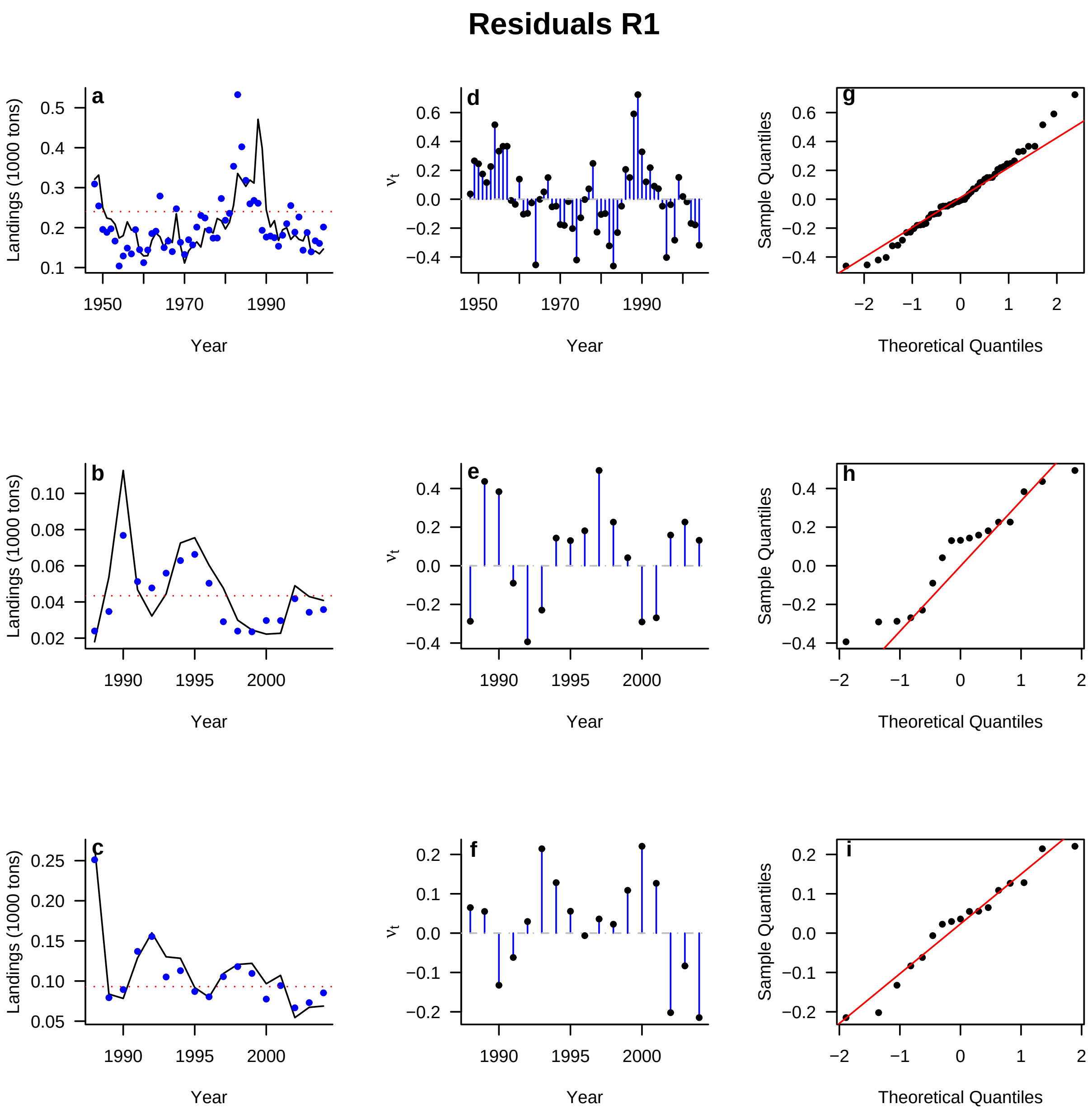

Figure 7: Predicted and observed catches for R1 in each of the 3 zones (MHI=a, MAU=b, HOO=c), corresponding residual patterns (d,e,f) and quantile-quantile plots of the residual patterns.

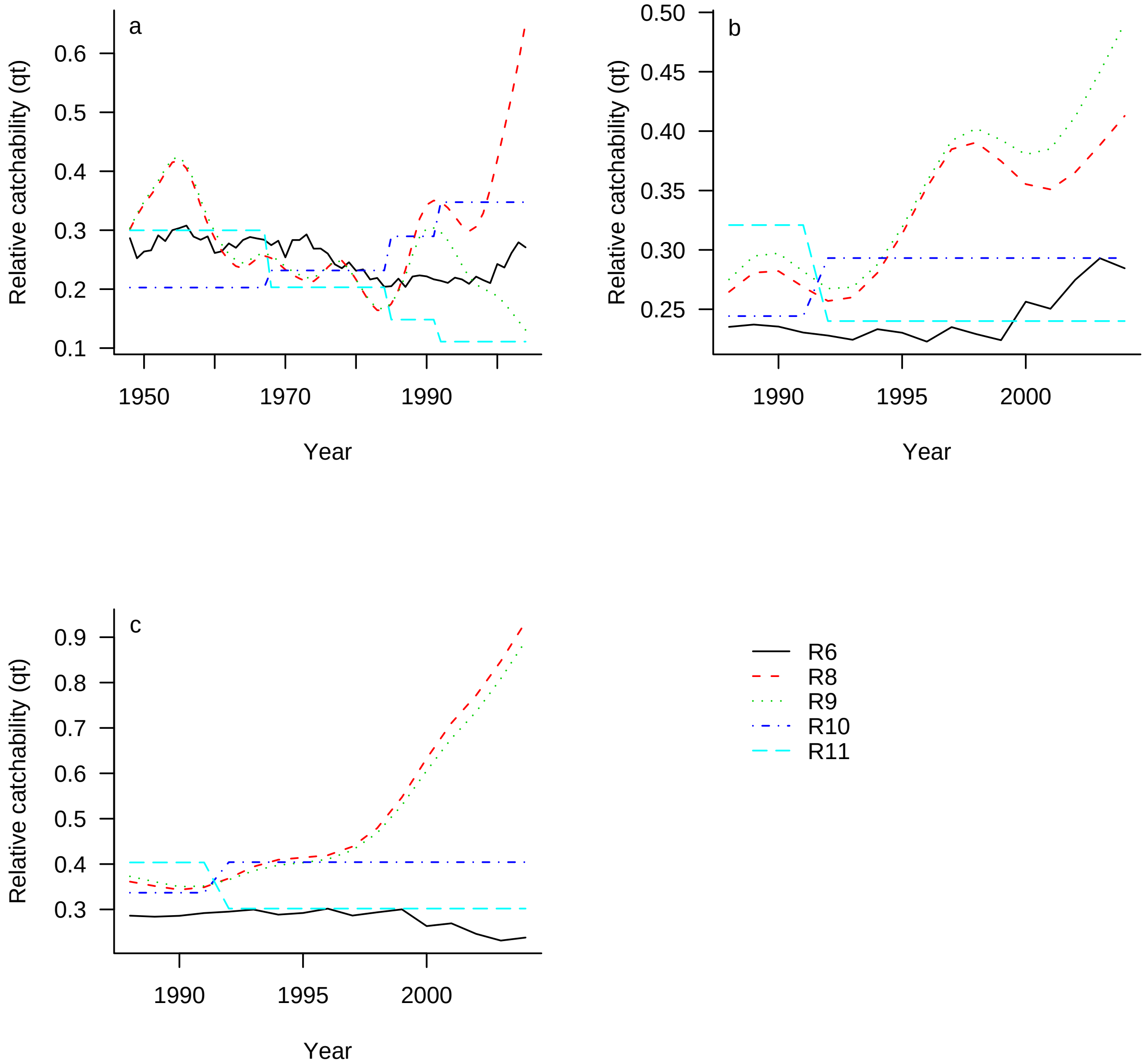

Figure 8: Comparison between changes in catchability over time in the MHI zone (a), MAU zone (b) and the HOO zone (c) for the R6, R8 and R9 model runs.

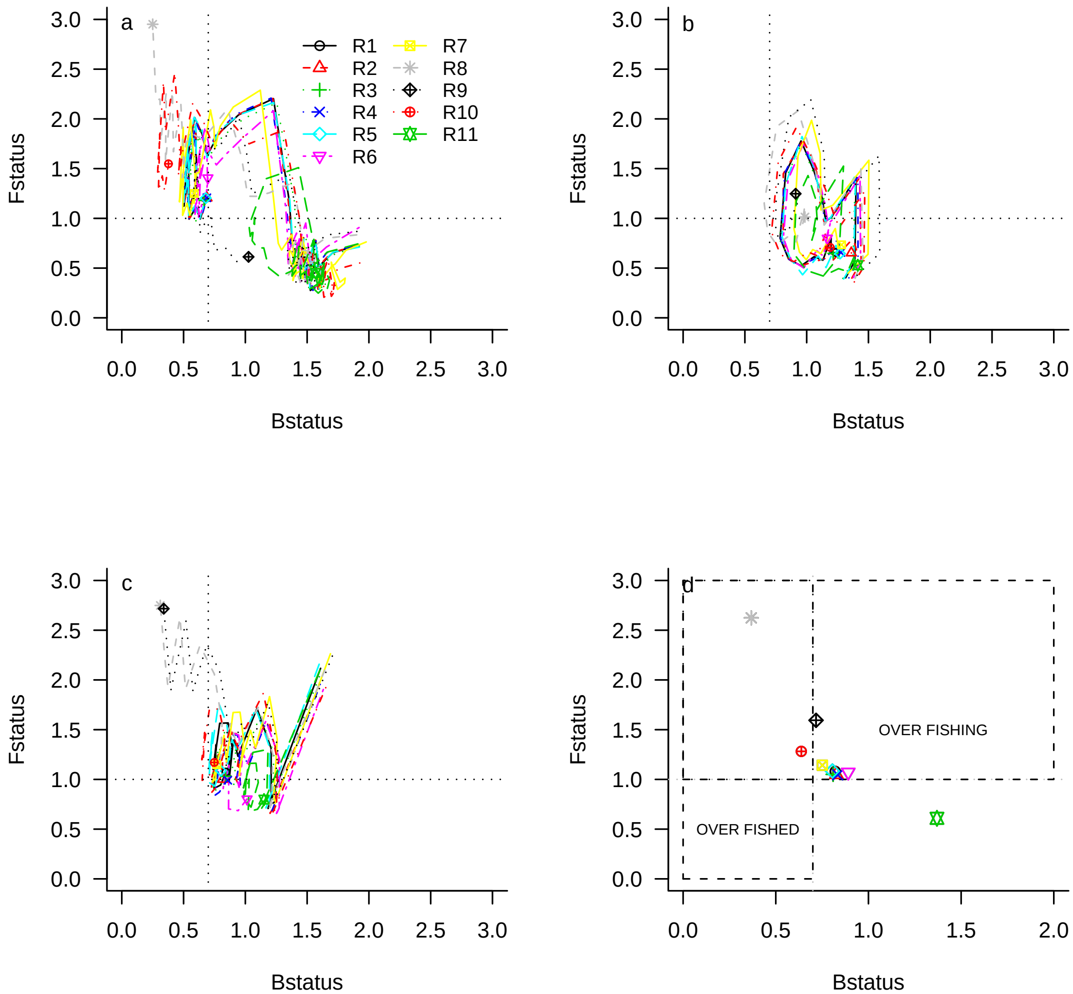

Figure 9: Control plots for stock status and fishing status in the MHI (a), MAU (b) and HOO (c) zones. Values of Fstatus > 1 indicate overfishing, and values of Bstatus < 0.7 indicate the stock is overfished. Panel (d) is the archipelago control plot where the weighting factors (MHI=0.447, MAU=0.124, and HOO=0.429) are used to scale the contributions from each zone.

6 Discussion

On an archipelagic scale, the present assessments suggested that the Bottomfish Management Unit Species complex (BMUS) is overfished in the sense that the aggregated stock is below B_{MSY}, but is likely not below the minimum stock size threshold (MSST). Overfishing of the BMUS complex is also occurring, but the level of overfishing appears to be declining in recent years. These results were consistent with hypotheses that included proxies for local physical oceanography that may or may not affect net production or changes in catchability. Among the 3 different zones, the Main Hawaiian Islands (MHI) appear to be the most severely overfished region, and overfishing is also most severe in this region. The available time series data for the MAU and HOO zones were much shorter and much less informative about parameter estimates in this region. The results obtained for these 2 regions is largely determined by prior information on: carrying capacities, intrinsic rate of growth, and the expected value of the beta prior distributions for the initial population size.

Estimates of the archipelagic-wide estimates of MSY and B_{MSY} were similar to those obtained by Moffitt et al. (2006). Moffitt et al. obtained an estimate of 368 tons for MSY and in the present assessment we obtained an estimate of 371 tons (or 817,906 lbs), averaged over all 9 alternative hypotheses. However, our zonal estimates of MSY differed slightly to that of Moffitt et al. 2006. In Moffitt et al. zonal estimates of MSY were calculated by dividing the archipelagic estimate of MSY by the relative length 100-fathom depth contour in each of the zones. In contrast, in the present assessment, zonal MSY estimates were a function of the estimated carrying capacities for each of the three zones. The principle difference here is that in Moffitt et al. only the carrying capacity for the MAU zone was estimated and the carrying capacities for the other 2 zones were based on the relative length of the 100-fathom depth contour. Zonal estimates of MSY in the present assessment are higher in the MHI zone, and lower in the HOO and MAU zones because the limited data suggested that the length of the 100-fathom contour in each zone is not proportional to the carrying capacity.

In the simplest model (R1), the residual pattern in the predicted and observed catches suggested long-term systematic changes in either production or capture probability, or both. We explored both changes in production and changes in catchability associated with changes in the depth of the mixed layer (as measured by sea-level height anomalies at Midway Island). There was no correlation between the sea level height anomalies and the catch residuals in R1. It should be of little surprise that incorporating the environmental as an annual effect may not improve the overall model fit. However, when the environmental anomaly was incorporated as an autocorrelated effect (e.g., R6), there was some improvement in the overall objective function value relative to R1-R5. As a result, changes in catchability in the MHI zone declined from the mid 1950s to the mid 1980s, then increased from about 1998 to 2004. Similar qualitative patterns in catchability changes were obtained in R8 and R9, where catchability was modeled as a random walk process.

Previous assessments of the BMUS complex (Moffitt et al. 2006) assumed a four-level stepwise increase in catchability over time in the MHI, and the notion was that improvements in fishing technology led to increased efficiency. There was also a strong residual pattern in the Moffitt et al. (2006) assessment that was inconsistent with an increase in catchability. Specifically, the results presented in the present assessment also contradict the notion that catchability increased over the entire time period. Alternative explanations of the residual patterns are warranted, and these could include: systematic changes in the reporting system or overall vessel power (i.e., highliners retiring from the fishery) that led to a biased CPUE index, or systematic changes in catchability associated with changes in the environment, or systematic changes in the catch composition associated with the depletion of highly catchable species or avoidance of contaminated species (e.g., ciguatera poisoning in kahala, see also Lorenzen et al. 2006), or a combination of all these factors.

The last potential factor that could severely bias the assessment of stock status is the omission of the recreational impacts on the resource, especially if there have been systematic changes in the ratio of recreational landings to commercial landings. First, if the proportion of recreational landings to commercial landings is constant over time, then the problem reduces to a biased estimate in the overall scale (i.e., estimates of B_{msy} and k), but is not biased in the estimates of the intrinsic rate of growth or estimates of fishing mortality rates to achieve MSY. If however, there has been a systematic increase in the ratio of recreational landings to commercial landings, then estimates of the intrinsic rate of growth and F_{msy} may be biased downward. Given increasing recreational opportunities over the last few decades, (e.g., increased availability of recreational vessels and technology, etc.), this latter scenario may apply.

7 Recommendations and future work

The recommendations listed here are motivated by concerns about the time series data used for model fitting, the structural assumptions of the models, and the aggregated nature of the data in a multispecies fishery. Many of these concerns were also listed in Ralston et al. (2004) and a few have been addressed here. Due to time constraints we were not able to address all of the points listed in Ralston et al. (2004).

7.1 Data standardization

There are concerns over the assumption that commercial CPUE indices are proportional to the BMUS complex stock size. First and foremost, current CPUE indices are based on the top-10 highliners each year (which may or may not be the same individuals each year). The use of such a standardization technique is likely to produce a hyperstable index of relative abundance (i.e., the stock size declines much quicker than the CPUE of the top-10 individuals due to their extensive experience or luck). Information for individual vessels is beginning to accumulate, and as such the use of weighted CPUE indices relative to a single standard index (e.g., see Gulland 1983) should be explored. Alternatively, more extensive multivariate analysis using generalized linear models or integrated GLM's (e.g., Gavaris 1980; Maunder 2001) should be considered.

Secondly, a simple exercise to determine the effects of stock aggregation would be to remove one or more individual species from the aggregated BMUS complex, and examine changes in key population parameter estimates and alternative assumptions about changes in catchability or production over time. For example, we were not able to conclude if the apparent decline in catchabiliy was associated with changes in the environment or depletion of highly catchable species or active avoidance (or discarding) of a particular species. Removing the kahala data from the aggregated data may shed some light on which factor is responsible for the apparent change in catchability. Ideally, all of the data should be broken down into single species components, and a time series of "effective effort" for each species be developed.

We recommend that a high research priority be placed on developing appropriate data and data standardization for the Hawaiian bottomfish fishery. There are some deficiencies in HDAR database: namely it is very difficult to work with in its present form (a series of fixed width text files for each fiscal year and it took us nearly 20 days to independently reconstruct the catch time series from the 3 areas); there have been substantial changes in the reporting systems over the years that make temporal comparisons difficult or misleading without knowing the extensive history; also, there are several nuances in the database that are easily corrected pertaining to changes in species names and or codes. We recommend that the bottomfish data be standardized and transferred into a more modern relational database, and that a formal data workshop be held to develop a consensus for proper data standardization.

Finally, extensive effort needs to be applied to deal with the recreational component of the catch. Omission of these data in the stock assessment almost certainly biases the estimates of key targets and reference points. We have provided an initial starting point to investigate this issue (Appendix C), and a search for more "anchor points" may shore up some of the uncertainties in the recreational impact on the resource.

7.2 Other structural uncertainties

Other structural assumptions should also be explored. First, disaggregation of catch data to species, or at a minimum disaggregation to groups with similar life-histories and time of year when the resource is harvested. For example, Uku is abundant during the summer months and much of the bottom fish effort shifts to pelagic fisheries during the summer months; therefore, most of the bottomfish are targeted during the winter months. Thus, the aggregated data are probably not informative about the relative abundance of Uku. Similarly, Onaga is only fished at night, Opakapaka fished day or night, and other species only during the day. Again these categorical variables could be included into a GLM for standardization.

Second, the differences in life-histories among the BMUS complex may also add to some structural problems when using the aggregated datasets. For example the age of recruitment to the fishing gear is highly variable (1-8 years) among the 14 species in the BMUS complex. Such differences may give rise to data that aren't supported by a simple quadratic expression for the analysis of yield and effort data (Lorenzen et al. 2006). Here, we recommend further disaggregation of these data (at a minimum into groups with similar life-histories) and further exploration of alternative models that incorporate lagged effects (i.e., a lagged recruitment model). At a bare minimum, life-history information from each of the species and rough approximations of size or age at which the fish recruit to the fishery should be assembled to determine optimal fishing mortality rates for each species. This relatively simple exercise would highlight species of special concern and could be used as an indicator species to manage the species complex (i.e., weak stock management).

Based on discussions with NOAA/NMFS staff, there appears to be limited information on the age at which each species recruits to the fishery. We recommend that biological samples be collected at a minimum for age-determination. This information will greatly reduce the reliance on risky assumptions in the stock assessment models, and aid in better understanding of recruitment dynamics in the future. Additional spinoffs could include otolith micro-chemistry to establish source and settlement of various species, fine tuning of physical models for larval dispersal, as well as a better understanding of essential fish habitats for juvenile fishes.

Finally, the zonal weighting system that is used to develop stock status for the Hawaiian archipelago is based on the relative length of the 100-fathom contour. Our results here suggest that this has biased the estimates of carrying capacity for the Ho'omalu zone upwards (i.e., the length of the 100-fathom contour is not correlated with carrying capacity). This weighting scheme gives the appearance at the archipelagic level that the fishery is ok; however, the stocks are very likely over-fished in the MHI zone and over-fishing is fairly severe. The weighting system down weights the local depletion in the Main Hawaiian Islands. With the newly erected sanctuaries program, and various closed areas for bottomfish, it will be even more difficult to determine stock status. Developing refined measure of habitat to improve prior information on carrying capacity is appropriate, but future monitoring and recovery of potential habitat is necessary to ensure that these improved measures are correlated carrying capacity. Future research in this area should include an investigation of Stock Reduction Analysis, where the stock assessment model is conditioned on observed catch rather than observed effort. This approach would allow for the historical catch data to be included in the assessments for the MAU and HOO zones, as well as, shed additional light on the apparent changes in catchability.

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A Documentation of data preparation

Raw data were provided in the form of fixed format width text files. Five principle sources of information were provided: 1) Hawaii Department of Aquatic Resources (HDAR hereafter) Fishermen Reporting System, 2) HDAR Dealer Reporting System, 3) Observer, 4) Insular Research, and 5) the UFA Daily fish auction sampling. In this appendix we document procedures used to summarize the raw data into the formats used in these assessments.

A.1 HDAR Fishermen Reporting System (FRS)

Data for the fishermen reporting system (FRS) consists of a single ”fixed width format” file for each year. The sequence of operations for generating the fishery dependent data is outlined in the following pseudocode:

Pseudocode

1. A vector of file names in the working directory was assembled and read into R (R Development Core Team 2005) using the `read.fwf()` function.
2. For each year, columns containing LICENSE, TRIP END, FISHED, AREA, SUB-AREA, BANK, BANK QUAD, DEPTH BEG, DEPTH END, LNAME, FNAME, VESSEL, SPECIES, CAUGHT, LBS, NUM SOLD, LBS SOLD, and VALUE were selected.
   (a) The FISHED field was partitioned into a year month day, date format
   (b) Only rows containing information on Hapuupuu, Kahala, Kalekale, Opakapaka, Uku, Ehu, Onaga, All Ulua, Lehi, Gindai, Taape, Armorhead, Butaguchi, Black Ulua, White Ulua, YT Kali were extracted.
   (c) The species codes for the previous list were `spcode=c`(19, 22, 21, 15, 20, 97, 17, 208, 114, 58, 16, 200, 205, 202, 140, 36, 23), and historical data on Ehu was previously stored as species code 36 and 21. All species codes for Ehu were changed to 21.
3. Each year of data was concatenated to a single data frame `HIdata`.
4. For each record, a corresponding zone was added to the `HIdata` data frame. Zone 1 corresponded to the Main Hawaiian Islands (MHI), zone 2 corresponded to the MAU zone, and zone 3 corresponded to the Ho’omalu zone.
5. The `HIdata` data frame was then saved as an `.rda` object which can then be read into R using the `load()` function.

The following R code was used to construct the `HIdata.rda` file.

R code

```
#HDAR.R
#Use this to reformat the txt files into and rda data set for R.
#Note there is a formatting change in the database between 2001 and 2002.

#Get file list for reading
l.fn=list.files(pattern="FRS_")
nyrs=length(l.fn); yrs=1948:2005

#Get width formats and field names
fmat=read.table("HDARformat.txt",header=T,sep="\t"); w1=fmat$Width
fmat2=read.table("HDARformat2002.txt",header=T,sep="\t");w2=fmat2$Width
#NB 36 was also Ehu and should be changed to 21
#NB spcode 23 is a general Caragidae to be assigned to other Caranx groups.
spcode=c(19,22,21,15,20,97,17,208,114,58,16,200,205,202,140,36,23)
ec1=c(1:3,5,6,14:17,38:40,46:51);
ec2=c(1:3,5,6,14:17,38:40,46:50,55);

HIdata=data.frame(row.names=1)
for(i in 1:nyrs)
{
    if(yrs[i]<2002)
    {   x=read.fwf(l.fn[i],w1,n=-1)     #This takes huge time.
        names(x)=fmat$Field.Name
        xx=x[,ec1]; rm(x)   #Extract selected cols from data frame.
    }
    if(yrs[i]>=2002)
    {   x=read.fwf(l.fn[i],w2,n=-1) #This takes huge time.
        names(x)=fmat2$Field.Name
        xx=x[,ec2]; rm(x)   #Extract selected cols from data frame.
    }

    #need to format dates correctly. (FISHED feild)
    dd=xx$FISHED
    yy=as.integer(substr(paste(dd),1,4))
    mm=as.integer(substr(paste(dd),5,6))
    dd=as.integer(substr(paste(dd),7,8))
    xx=cbind(yy,mm,dd,xx[,-6])
    #Extract relevant information for target species
    HIdata=rbind(HIdata,xx[xx$SPECIES%in%spcode,])
}
#Convert old Ehu species code to new code (36 to 21)
HIdata[HIdata$SPECIES==36,]$SPECIES=21
```

```
#This is the new data file that contains only the bottom fish information.
row.names(HIdata)=1:dim(HIdata)[1]

#Add zoning column
zone=rep(0,length=dim(HIdata)[1])
HIdata=cbind(HIdata,zone)

    #MAIN HAWAIIAN ISLANDS (zone=1)
    a=unique(HIdata$AREA)
    MHI=a[a<600]; MHI=MHI[MHI>0]
    HIdata[HIdata$AREA%in%MHI,]$zone=1

    #MAU ZONE (zone=2)  note code changes in June of 1990 (600-1140)
    MAU=a[a>600]; MAU=MAU[MAU<=1140]
    b=a[a>=2600]; b=b[b<16500]; MAU=c(MAU,b)
    HIdata[HIdata$AREA%in%MAU,]$zone=2

    #HO'OMALU ZONE (zone 3) note code changes in June of 1990 (1140-2600)
    HOO=a[a>1140]; HOO=HOO[HOO<2600]
    b=a[a>16500]; b=b[b<30000]; HOO=c(HOO,b)
    HIdata[HIdata$AREA%in%HOO,]$zone=3

save(HIdata,file="HIdata.rda",compress=T)
```

A.2 Reported catch

Total reported catch, and catch by zone was extracted from the `HIdata.rda` file using the `reshape1()` function in R (requires package reshape). The following R code is used to construct total catches and catch by zone:
Rcode

```
library(reshape)
load("HIdata.rda")  #Loads the HIdata data.frame
spcode=sort(c(19,22,21,15,20,97,17,208,114,58,16,200,205,202,140,23))
names(HIdata)=tolower(names(HIdata))  #make all names lower case

#melt the data frame (requires "reshape" package)
HI=melt(HIdata[,c(1,2,3,4,21,7,15,17)],id=1:7)

#Total Catch by species by year for all areas combined
HI.Ct=reshape1(HI,c("yy"),c("species"),sum)

#MHI catch HIarea=subset(HI,zone==1)
```

```
MHI.Ct=reshape1(HIarea,c("yy"),c("species"),sum)

#MAU zone catch HIarea=subset(HI,zone==2)
MAU.Ct=reshape1(HIarea,c("yy"),c("species"),sum)

#HO'OMALU zone catch HIarea=subset(HI,zone==3)
HOO.Ct=reshape1(HIarea,c("yy"),c("species"),sum)
```

A.3 Effort index

The effort index was based on number of trips per annum. Total number of trips and number of licenses fished were extracted from the `HIdata.rda` for each zone.
Rcode

```
#FRSeffort.R library("reshape")
if(!exists("HIdata")){
    load("HIdata.rda");names(HIdata)=tolower(names(HIdata))
    #Add a date column to HIdata
    d=as.Date(paste(HIdata$yy,HIdata$mm,HIdata$dd,sep="-"))
    HIdata=cbind(d,HIdata)
    }
#Psuedocode for extracting number of trips by area.
#1) Extract data from specific area
#2) Loop over years and extract date and license info

MHI=subset(HIdata,zone==1)
eff=vector();lic=vector();highliner=vector();

yr=sort(unique(MHI$yy)) for(i in yr) {
    tmp=MHI[MHI$yy==i,c(1,5)]#daily c(1,5), monthly c(3,5), annually c(2,5)
    x=table(tmp); x[x>0]=1;  #necessary b/c may have landed 2 or more species
                             #on the same day
    f=sum(x)                 #number of trips by individual license x=table(tmp)
    #eff = total trips by all license
    eff=c(eff,f)
    lic=c(lic,dim(x)[2])     #number of licenses issued by year
    highliner=c(highliner,max(rowSums(x))) #max number of trips
}
```

B Fisheries dependent data

Table 9: Fishing effort by zone extracted from the HDAR database. Note that 2005 data is incomplete.

	MHI zone			MAU	HOO
Year	# of trips	# of licenses	Trips/license	# of trips	# of trips
1948	7195	602	11.95		
1949	6466	546	11.84		
1950	4809	433	11.11		
1951	4043	398	10.16		
1952	3790	327	11.59		
1953	3474	350	9.926		
1954	3102	299	10.37		
1955	3246	343	9.464		
1956	3621	330	10.97		
1957	3312	303	10.93		
1958	3228	251	12.86		
1959	2622	201	13.04		
1960	2335	192	12.16		
1961	2100	208	10.1		
1962	2144	243	8.823		
1963	2795	311	8.987		
1964	2393	253	9.458		
1965	2178	248	8.782		
1966	2604	297	8.768		
1967	2640	309	8.544		
1968	2659	313	8.495		
1969	2736	393	6.962		
1970	2407	378	6.368		
1971	3146	470	6.694		
1972	3322	495	6.711		
1973	3841	578	6.645		
1974	3600	597	6.03		
1975	4093	698	5.864		
1976	4646	759	6.121		
1977	5843	1012	5.774		
1978	3829	1011	3.787		
1979	5451	1071	5.09		
1980	6955	1050	6.624		
1981	7289	1060	6.876		
1982	8120	981	8.277		
1983	9264	1171	7.911		
1984	9651	1181	8.172		
1985	9238	1213	7.616		
1986	8742	1179	7.415		
1987	8595	1151	7.467		
1988	10820	1225	8.835	123	682
1989	10630	1285	8.274	175	228
1990	7949	1148	6.924	434	256
1991	7109	1094	6.498	310	423
1992	7731	1145	6.752	297	552
1993	6444	1162	5.546	367	397
1994	6899	891	7.743	453	450
1995	7211	942	7.655	544	348
1996	6795	894	7.601	446	313
1997	7660	936	8.184	245	420
1998	7131	932	7.651	181	505
1999	6639	869	7.64	160	504
2000	7284	862	8.45	188	354
2001	5790	736	7.867	177	435
2002	5281	712	7.417	246	293
2003	4903	595	8.24	197	304
2004	5023	632	7.948	201	346
2005	4315	601	7.18		

Table 10: Total reported catch (in metric tons) in the Hawaiian archipelago (including catches take from outside the 3 zones). Data were compiled from the HDAR Fisherman Reporting System. Note that 2005 data is incomplete.

Year	Hapuupuu	Kahala	Kalekale	Opakapaka	Uku	Ehu	Onaga	Lehi	Gindai	Taape	Armorhead	Butaguchi	Black Ulua	White Ulua	YT Kali
1948	38.64	87.6	14.78	104.8	46.88	49.32	23.61	7.809	0.1293			90.32	1.926	31.17	
1949	31.76	96.73	16.72	116.6	38.74	54.33	36.34	2.742	0.1329			72.96	1.556	25.18	
1950	37.05	70.48	15.22	106.8	31.1	38.73	37.2	1.448	1.053			59.52	1.27	20.54	
1951	31.11	75.55	19.49	119.2	22.65	27.87	25.75	3.144	1.739			56.14	1.197	19.37	
1952	44.86	80.25	16.23	143.6	32.94	26.09	20.99	2.926	1.633			81.59	1.74	28.16	
1953	34.97	44.69	17.37	105.9	32.98	21.89	26.72	1.569	1.271			103	2.197	35.55	
1954	19.02	31.62	15.12	67.99	31.22	15.31	30.79	0.8804	1.238			72.94	1.556	25.17	
1955	30.97	37.93	15.39	82.27	37.38	17.77	29.27	0.9616	2.663			61.41	1.31	21.19	
1956	20.35	27.27	15.88	70.56	37.99	22.72	40.62	4.01	1.628			32.95	0.7028	11.37	
1957	14.63	31.81	9.361	57.62	45.82	14.69	28.12	1.4	1.03			32.08	0.6842	11.07	
1958	12.93	40.38	8.705	54.96	33.7	10.57	29.24	1.526	0.9349			29.02	0.6189	10.01	
1959	14.44	35.88	9.948	39.96	20.94	10.58	22.56	0.5348	0.6459			18.29	0.3901	6.312	
1960	10.15	39.1	7.398	40.15	20.63	8.154	18.53	0.5339	0.489			31.36	0.669	10.82	
1961	9.31	34.75	8.659	42.26	19.19	5.816	19.5	0.6473	0.3148			22.85	0.4873	7.884	
1962	10.41	39.22	8.298	47.37	28.94	10.7	28.39	0.929	0.4032			23.5	0.5012	8.11	
1963	14.84	47.94	11.03	54.94	29.51	12.73	24.46	1.041	1.05			29.56	0.6305	10.2	
1964	10.96	43.51	7.294	48.02	40.78	10.57	26.1	0.4486	0.7312			36.04	0.7688	12.44	
1965	9.619	34.01	6.355	37.76	22.88	9.007	29.89	0.6269	0.2123			25.04	0.5341	8.642	
1966	15.01	44.94	5.928	44.23	26.36	8.885	31.63	1.071	0.4622			21.5	0.4585	7.419	
1967	10.61	31.52	3.191	49.61	26.6	7.278	26.36	1.181	0.3012			25.84	0.5511	8.917	
1968	9.587	39.57	2.324	41.19	22.62	10.38	31.73	1.821	0.3434			93.14	1.987	32.14	
1969	9.619	32.83	2.562	40.59	26.12	7.531	21.98	2.142	0.6182			31.74	0.6769	10.95	
1970	18.36	31.81	2.026	23.96	22.35	7.57	17.32	0.6087	0.7634	0.5062		21.49	0.4585	7.418	
1971	22.48	37.81	3.16	37.39	22.23	9.918	21.75	0.9652	0.9358	1.003		20.34	0.4338	7.019	
1972	16.74	25.85	3.224	53.59	23.69	13.71	22.81	2.293	0.8768	1.608		14.77	0.3149	5.096	
1973	23.04	29.99	2.932	59.91	31.39	10	19.35	2.943	1.179	2.759		16.08	0.343	5.55	
1974	17.89	15.46	2.636	50.59	37.49	12.16	18.38	1.95	0.7003	2.857		20.82	0.444	7.183	
1975	27.13	13.69	4.02	73.28	28.28	14.5	30.03	4.789	0.8904	9.409		34.59	0.7378	11.94	
1976	26.48	18.61	4.167	55.27	28.75	16.2	41.1	4.327	0.6895	13.39		32.84	0.7004	11.33	
1977	22.29	26.02	3.332	68.46	32.88	14.37	30.55	4.073	0.8038	16.39		25.95	0.5534	8.954	
1978	33.79	44.95	4.445	80.12	38.92	16.02	28.29	4.636	1.68	26.8		40.61	0.8662	14.02	
1979	29.46	37.95	3.761	93.17	39.88	9.897	22.13	7.457	1.623	27.98		31.61	0.6742	10.91	
1980	25	22.56	3.211	104.7	34	8.323	15.56	7.825	1.07	28.19		53.05	1.131	18.31	
1981	14.05	17.3	3.298	86.67	38.61	10.03	24.9	11.88	0.7693	36.87		32.73	0.664	12.8	
1982	20.62	33.45	4.736	91.23	45.81	11.59	28.42	13.02	0.9389	26.89		36.07	0.6548	24.31	
1983	20.43	46.83	7.439	102.1	63.6	17.76	42.95	10.74	1.877	28.21		36.93	0.7432	19.29	
1984	26.92	38.56	8.367	158.7	66.87	16.9	52.49	9.675	2.214	19.26		43.6	0.7692	21.54	
1985	44.92	18.77	13.14	137.7	24.83	31.78	108.9	14	3.309	27.31		41.05	1.354	21.05	
1986	46.93	18.23	10.61	138.5	48.32	27.41	108.7	10.46	2.384	24.37		52.07	0.6479	15.18	
1987	34.09	9.18	13.55	186.7	26.31	24.9	89.24	17.12	2.247	22.57		57.19	1.023	15.64	
1988	15.37	19.35	5.631	160.1	157.8	23.24	72.89	23.22	1.22	20.24		49.15	1.064	27.21	
1989	30.53	16.28	6.652	168.6	96.79	21.83	74.97	19.94	1.35	19.84		67.39	1.111	31.38	
1990	33.92	9.25	11.29	101.1	77.36	25.15	59.2	9.9	2.719	23.77		63.36	0.8752	18.49	
1991	29.95	5.562	11.48	98.44	68.51	21.27	58.36	5.863	3.069	30.25	0.01406	49.93	0.6529	12.85	
1992	25.41	4.696	12.69	116.4	59.66	16.19	39.72	8.21	2.617	30.45		44.85	0.5117	14.53	
1993	30.23	2.566	8.459	134.4	45.92	15.14	46.35	4.662	3.328	28.42		40.38	0.7044	7.663	
1994	35.99	8.547	12.53	146.8	66.31	17	46.27	5.097	3.975	27.3		42.02	0.4848	10.24	
1995	31.43	7.051	11.25	125.9	62.03	18.14	56.03	6.675	3	32.63		41.68	0.9086	10.2	
1996	26.34	2.613	14.28	103.7	53.37	21.57	44.67	4.115	4.18	20.06		36.34	0.715	12.83	0.02223
1997	32.91	5.514	13.51	117	48.75	18.81	56.58	5.655	3.702	38.78		40.88	0.6957	8.448	
1998	38.19	10.11	11.49	103	52.77	18.96	49.9	3.942	3.898	33.95	0.005443	32.31	0.6589	9.529	0.01134
1999	32.61	8.575	7.175	94.76	59.3	17.16	72.37	4.488	2.89	31.79	0.00499	22.76	0.2963	5.541	0.002722
2000	18.79	11.16	9.495	94.05	55.74	19.58	76.81	5.177	2.561	24.97	0.003629	25.2	0.4645	5.441	
2001	16.57	6.591	6.975	71.41	52.54	16.08	58.74	4.741	2.347	21.59		21.62	0.3664	7.353	0.002268
2002	17.18	5.761	6.682	65.82	52.27	12.01	56.37	3.933	1.917	17.39		20.32	0.9047	5.88	0.003175
2003	20.87	2.656	5.402	62.39	62.1	10.93	56.17	3.904	1.823	17.14		11.86	0.6862	5.887	0.003629
2004	20.15	3.846	4.263	61.12	64.98	13.36	70.62	3.023	2.031	19.82	0.001814	10.73	0.6001	5.52	0.02336
2005	22.48	3.565	3.967	47.57	65.99	13.64	49.04	2.865	2.845	13.29	0.002722	6.391	0.4011	5.291	0.02

Table 11: Total reported catch (in metric tons) in the Main Hawaiian Islands (zone = 1).

Year	Hapuupuu	Kahala	Kalekale	Opakapaka	Uku	Ehu	Onaga	Lehi	Gindai	Taape	Armorhead	Butaguchi	Black Ulua	White Ulua	YT Kali	BMUS
1948.000	10.590	75.840	14.620	54.790	46.060	46.480	22.630	7.794	0.129			14.750	0.820	24.590		319.100
1949.000	13.170	84.560	16.390	59.300	37.630	48.060	35.040	2.742	0.133			11.410	0.634	19.020		328.100
1950.000	6.584	52.050	14.420	55.580	26.230	32.340	33.830	1.440	0.602			8.106	0.450	13.510		245.100
1951.000	9.979	56.280	18.670	48.270	20.440	22.540	24.050	3.141	1.189			7.011	0.390	11.680		223.700
1952.000	12.470	43.970	15.140	51.230	29.390	24.370	20.230	2.835	1.176			7.256	0.403	12.090		220.600
1953.000	8.765	29.360	17.210	50.030	28.930	20.320	25.830	1.530	0.720			6.623	0.368	11.040		200.700
1954.000	6.063	23.310	15.050	40.270	28.090	14.660	30.660	0.874	0.909			5.063	0.281	8.439		173.700
1955.000	11.750	22.350	14.660	37.260	34.500	16.360	28.680	0.956	1.784			4.162	0.231	6.936		179.600
1956.000	8.772	22.950	15.470	62.220	32.090	19.690	34.480	4.010	1.174			4.894	0.272	8.156		214.200
1957.000	6.708	29.050	9.036	48.420	43.750	13.680	26.860	1.390	0.796			5.100	0.283	8.500		193.600
1958.000	8.316	39.220	8.596	50.510	32.890	10.120	28.930	1.526	0.845			4.435	0.246	7.392		193.000
1959.000	6.937	31.210	9.838	28.190	20.880	10.480	22.560	0.535	0.610			3.086	0.171	5.143		139.600
1960.000	3.818	36.100	7.232	27.350	20.610	7.694	15.040	0.534	0.358			3.573	0.199	5.955		128.500
1961.000	3.013	33.410	8.627	32.030	19.140	5.611	19.370	0.647	0.269			2.729	0.152	4.548		129.500
1962.000	5.311	35.080	7.552	34.700	28.150	9.862	27.120	0.886	0.256			3.338	0.186	5.564		158.000
1963.000	5.836	42.510	10.850	49.630	28.830	11.470	24.140	1.041	0.925			3.983	0.221	6.638		186.100
1964.000	4.159	39.600	7.225	42.790	40.760	9.599	25.970	0.449	0.695			4.370	0.243	7.283		183.100
1965.000	5.398	32.160	6.346	36.790	22.630	8.367	29.560	0.627	0.211			3.506	0.195	5.844		151.600
1966.000	6.022	41.860	5.921	42.100	26.240	8.773	31.590	1.071	0.459			3.956	0.220	6.594		174.800
1967.000	4.152	30.530	3.172	48.160	26.560	7.079	26.360	1.181	0.279			5.346	0.297	8.909		162.000
1968.000	5.120	38.200	2.312	40.780	22.530	9.972	31.720	1.821	0.291			21.410	1.190	35.690		211.000
1969.000	8.301	32.220	2.553	40.200	26.100	7.477	21.980	2.142	0.598			4.990	0.277	8.316		155.100
1970.000	6.192	26.000	1.679	22.520	21.510	6.062	17.190	0.609	0.388	0.506		3.308	0.184	5.514		111.700
1971.000	6.689	35.460	2.976	34.650	22.090	7.995	21.430	0.965	0.422	1.003		3.177	0.177	5.295		142.300
1972.000	8.616	23.650	2.822	53.240	21.810	9.229	22.320	2.293	0.603	1.608		3.434	0.191	5.723		155.500
1973.000	6.295	26.360	2.301	59.320	30.330	7.410	18.060	2.943	0.724	2.759		3.777	0.210	6.296		166.800
1974.000	8.561	14.390	2.205	48.910	35.350	9.532	17.640	1.950	0.518	2.857		4.381	0.243	7.302		153.800
1975.000	10.370	11.310	3.479	54.310	28.100	12.910	29.830	4.785	0.630	9.409		6.287	0.349	10.480		182.200
1976.000	12.450	16.490	4.145	48.600	28.200	15.320	40.610	4.327	0.690	13.390		7.276	0.404	12.130		204.000
1977.000	11.370	20.300	3.294	57.590	31.060	13.810	30.530	4.073	0.752	16.390		4.962	0.276	8.271		202.700
1978.000	15.090	33.350	4.406	63.020	38.010	15.570	28.220	4.635	1.447	26.800		6.922	0.385	11.540		249.400
1979.000	10.680	29.780	3.757	77.190	39.520	9.226	20.990	7.457	1.270	27.980		6.294	0.350	10.490		245.000
1980.000	7.214	20.150	3.210	80.290	33.890	8.005	15.130	7.815	0.859	28.190		7.212	0.401	12.020		224.400
1981.000	7.834	16.240	3.293	83.440	38.590	9.717	24.770	11.880	0.654	36.870		6.101	0.339	10.390		250.100
1982.000	10.650	32.810	4.735	85.720	45.780	11.320	28.020	13.020	0.795	26.890		8.066	0.393	14.380		282.600
1983.000	17.140	46.730	7.380	92.750	59.810	17.580	42.710	10.730	1.786	28.190		8.884	0.462	20.060		354.200
1984.000	10.890	38.470	8.141	89.930	62.740	14.980	49.460	9.668	1.721	19.240		8.618	0.458	21.500		335.800
1985.000	13.180	18.130	11.720	79.260	22.350	25.420	99.130	13.990	1.971	25.920		5.914	0.636	11.280		328.900
1986.000	14.350	17.420	9.240	91.840	47.200	22.800	75.800	10.460	1.221	24.260		13.440	0.422	14.420		342.900
1987.000	6.002	9.033	12.960	124.700	25.740	20.870	77.750	17.110	1.331	22.460		4.985	0.262	10.410		333.600
1988.000	5.823	19.280	5.249	145.700	156.100	17.490	63.430	22.970	0.849	20.100		10.800	0.609	23.720		492.200
1989.000	5.889	16.280	6.457	124.500	94.450	17.900	71.250	19.930	0.945	19.810		13.790	0.731	24.030		415.900
1990.000	6.793	9.250	8.713	68.220	44.130	15.570	50.200	9.718	1.479	23.190		9.116	0.362	16.090		262.800
1991.000	6.457	5.108	8.785	60.930	40.990	12.260	40.380	5.770	1.921	30.250	0.014	8.080	0.261	10.580		231.800
1992.000	6.556	4.696	11.230	80.750	40.130	13.360	32.530	7.971	1.927	30.450		6.076	0.324	11.650		247.700
1993.000	5.132	2.566	6.761	65.170	31.740	10.480	28.510	4.635	1.759	28.420		4.648	0.194	6.215		196.200
1994.000	6.115	5.375	9.691	81.400	32.580	10.710	30.020	4.999	1.711	27.100		5.199	0.248	6.348		221.500
1995.000	7.322	5.146	9.027	79.040	28.340	12.960	33.330	6.528	1.767	32.590		7.199	0.326	8.720		232.300
1996.000	5.201	2.507	9.883	67.460	24.180	12.830	30.640	4.009	1.426	20.050		4.384	0.185	7.660		190.400
1997.000	6.448	5.492	9.640	66.140	30.830	11.700	31.360	5.610	1.276	38.780		6.063	0.275	6.624		220.200
1998.000	5.147	9.891	9.020	64.390	27.720	10.760	26.460	3.922	1.518	33.950		4.211	0.328	7.234		204.500
1999.000	4.584	7.983	5.076	58.580	40.750	8.813	27.660	4.472	1.084	31.780		2.859	0.119	4.758		198.500
2000.000	7.341	10.240	7.556	67.980	36.300	13.390	33.810	4.914	1.657	24.970		3.115	0.139	5.021		216.400
2001.000	5.037	6.270	5.334	45.360	26.070	9.485	24.940	4.730	1.418	21.570		2.795	0.167	5.252	0.002	158.400
2002.000	3.802	5.178	5.179	49.200	25.520	7.968	31.250	3.914	0.957	17.380		2.354	0.283	4.658	0.000	157.600
2003.000	4.593	2.216	4.450	52.410	19.660	6.974	32.360	3.877	0.916	17.140		0.827	0.489	5.698		151.600
2004.000	3.661	3.153	3.487	46.560	30.900	10.110	38.680	3.023	0.974	19.800		0.754	0.461	5.303	0.018	166.900
2005.000	4.406	3.146	3.238	36.120	27.790	9.470	34.500	2.815	0.955	13.280		0.754	0.183	4.754	0.011	141.400

Table 12: Total reported catch (in metric tons) in the MAU zone. Data were compiled from the HDAR Fisherman Reporting System. Note that 2005 data is incomplete.

Year	Hapuupuu	Kahala	Kalekale	Opakapaka	Uku	Ehu	Onaga	Lehi	Gindai	Taape	Butaguchi	Black Ulua	White Ulua	YT Kali	BMUS
1948	25.13	10.52	0.1352	47.51	0.8224	2.777	0.978	0.01497			29.23	0.7307	3.288		0.1447
1949	11.55	5.858	0.2019	33.75	0.9498	4.367	1.099				17.92	0.448	2.016		0.1488
1950	24.76	16.15	0.6709	40.61	4.668	5.364	2.292	0.008165	0.3134		16.29	0.4074	1.833		0.1112
1951	16.51	16.8	0.7702	60.06	2.167	4.723	1.666	0.003175	0.4795		24.42	0.6104	2.747		0.1014
1952	17.99	23.42	0.6037	56.12	3.367	1.364	0.337	0.01225	0.2826		33.03	0.8257	3.716		0.1
1953	4.658	3.7	0.03266	16.79	1.135	0.3996	0.0567		0.09707		21.96	0.5491	2.471		0.09104
1954	4.15	1.938	0.01315	9.967	2.952	0.1891			0.09979		13.77	0.3442	1.549		0.07878
1955	12.81	7.447	0.5656	21.66	2.584	1.099	0.4527		0.269		20.82	0.5204	2.342		0.08148
1956	5.218	2.093	0.3016	1.073	5.872	1.037	4.828		0.2277		0.7976	0.01994	0.08973		0.09716
1957	7.457	2.485	0.288	8.432	2.053	0.9457	1.247	0.001361	0.22		10.47	0.2618	1.178		0.0878
1958	1.147	0.4586	0.02177	1.718	0.8106	0.07847			0.0186		1.395	0.03486	0.1569		0.08756
1959	1.805	1.16	0.04128	1.89	0.03039	0.02223			0.01633		0.4543	0.01136	0.05111		0.06334
1960	1.887	1.02	0.1279	6.118	0.005443	0.2136	3.382		0.03901		6.305	0.1576	0.7094		0.05827
1961	5.015	0.9997	0.02177	7.737	0.044	0.1882	0.1275		0.0313		7.91	0.1978	0.8899		0.05876
1962	4.705	2.199	0.1551	8.627	0.05035	0.3152	0.1043		0.1016		10.34	0.2585	1.163		0.07167
1963	9.005	5.433	0.1855	5.309	0.6836	1.263	0.3148		0.1243		14.61	0.3653	1.644		0.0844
1964	6.561	3.757	0.06033	5.23	0.01724	0.958	0.1338		0.03674		16.94	0.4234	1.905		0.08307
1965	2.318	0.2123	0.001814	0.6899	0.0195	0.3878	0.04672				11.71	0.2928	1.318		0.06878
1966	8.991	3.083	0.007711	2.126	0.1216	0.1111	0.04581		0.003175		5.918	0.148	0.6658		0.07929
1967	6.461	0.9916	0.01814	1.449	0.04037	0.1996	0.001361		0.02177		4.487	0.1122	0.5048		0.0735
1968	4.467	1.375	0.01179	0.4123	0.08392	0.4091	0.01089		0.05262		6.654	0.1663	0.7485		0.09572
1969	1.319	0.6128	0.009072	0.3937	0.01814	0.05398			0.01996		12.52	0.313	1.408		0.07038
1970	12.17	5.809	0.3465	1.441	0.8428	1.508	0.1347		0.3751		8.794	0.2199	0.9894		0.05065
1971	15.8	2.351	0.1846	2.739	0.1338	1.923	0.3193		0.5139		8.115	0.2029	0.9129		0.06456
1972	8.129	2.195	0.4019	0.3484	1.882	4.485	0.4908		0.2735		0.88	0.022	0.099		0.07055
1973	16.74	3.635	0.631	0.5838	1.057	2.59	1.297		0.4554		0.7933	0.01983	0.08924		0.07565
1974	9.328	1.07	0.4309	1.684	2.134	2.625	0.7453		0.1823		3.235	0.08088	0.3639		0.06978
1975	16.76	2.379	0.5407	18.97	0.1787	1.596	0.2023	0.004082	0.2608	0.000454	9.871	0.2468	1.11		0.08267
1976	14.04	2.116	0.02223	6.672	0.5525	0.8786	0.4917				3.562	0.08904	0.4007		0.09254
1977	10.92	5.66	0.03765	8.917	1.817	0.5629	0.01633		0.05171	0.000907	6.308	0.1577	0.7096		0.09194
1978	18.34	11.6	0.03946	15.61	0.9117	0.445	0.07666	0.000907	0.2322	0.000907	12.54	0.3135	1.411		0.1131
1979	15.23	8.173	0.003629	10.12	0.3597	0.6632	0.5089		0.3125		5.679	0.142	0.6389		0.1111
1980	3.71	0.5647	0.000907	2.458	0.01633	0.1755	0.2957	0.000907	0.09526		2.406	0.06014	0.2706		0.1018
1981	0.8564	0.2808		0.6827	0.007258	0.007711	0.02132	0.004536	0.02449		1.259	0.02994	1.749		0.1135
1982	0.02359	0.006804			0.02858	0.001361				0.003175	0.1633	0.004082	0.01837		0.1282
1983	1.713	0.08437	0.04717	1.083	3.531	0.07983	0.04808	0.000907	0.03992	0.009979	0.4046	0.007258	0.6441		0.1607
1984	2.856	0.03266	0.04082	12.65	2.756	1.118	2.566		0.06804	0.01225	4.1	0.01701	0.07382		0.1523
1985	19.19	0.03992	0.699	29.93	2.316	3.659	3.536	0.003629	0.6768	1.086	6.935	0.1293	0.02907		0.1492
1986	8.285	0.04037	0.6613	4.82	0.518	1.733	5.906		0.2903		4.681	0.07415	0.1062		0.1555
1987	2.833		0.2186	7.16	0.3638	0.323	1.477		0.05806	0.02676	4.187	0.04968	0.2988		0.1513
1988	2.626		0.2345	2.549	0.9267	3.776	4.595	0.2549	0.1492	0.009979	2.11	0.152	0.02662		0.2232
1989	8.363		0.04717	19.99	1.976	0.6799	0.9213	0.009979	0.1597	0.003629	8.536	0.02007	1.319		0.1887
1990	14.48		2.336	13.83	24.95	8.78	3.912	0.1338	1.149	0.5679	21.73	0.2782	0.1547		0.1192
1991	7.326	0.4536	2.346	5.494	10.56	7.108	4.16	0.08528	0.6709	0.000907	6.841	0.165	0.09468		0.1051
1992	3.768		1.029	8.738	1.814	1.025	2.617	0.1515	0.1628						0.1123
1993	5.21		1.111	10.12	2.994	1.781	1.671	0.01134	0.3883	0.00635	11.64	0.2028	0.004368		0.08901
1994	6.516	2.391	1.425	8.548	23.51	3.467	4.278	0.06396	1.145	0.1728	16.45	0.1172	0.4492		0.1005
1995	6.246	1.905	1.393	6.393	27.87	2.859	10.25	0.1039	0.6269	0.02676	11.37	0.3826	0.2814		0.1054
1996	9.147	0.09299	3.506	7.091	21.6	5.551	4.928	0.09117	1.582	0.01814	11.48	0.3957	0.3717	0.02223	0.08637
1997	6.277		1.808	12.06	11.17	1.846	7.848	0.02132	0.4699	0.004082					0.0999
1998	3.41	0.2177	0.7394	4.32	14.58	1.402	0.8324	0.0195	0.2781	0.000907	4.138	0.2042	0.108	0.01134	0.09278
1999	2.62	0.547	0.5702	3.592	12.31	1.919	1.8	0.01633	0.503	0.002268				0.002722	0.09005
2000	2.112	0.9181	1.197	3.169	5.912	2.34	1.57	0.2608	0.3815	0.007711	6.53	0.08337	0.1368		0.09817
2001	1.935	0.1755	0.9145	1.897	8.657	2.759	1.735	0.01134	0.2758	0.02132					0.07186
2002	7.456	0.5829	1.126	6.626	20.19	2.811	4.275	0.01134	0.4373	0.01089				0.002722	0.07151
2003	8.063	0.4404	0.5743	2.925	25.12	1.263	2.722	0.02722	0.3352	0.000454				0.003629	0.06877
2004	5.35	0.6886	0.3243	4.606	20.77	0.9979	4.115		0.3461	0.002268				0.00499	0.07569
2005	3.819	0.4001	0.4822	5.985	25.22	2.201	1.475	0.01361	0.2594	0.00635				0.008618	0.06414

Table 13: Total reported catch (in metric tons) in the Ho'omalu zone. Data were compiled from the HDAR Fisherman Reporting System. Note that 2005 data is incomplete.

Year	Hapuupuu	Kahala	Kalekale	Opakapaka	Uku	Ehu	Onaga	Lehi	Gindai	Taape	Armorhead	Butaguchi	Black Ulua	White Ulua	BMUS
1948	2.921	1.231	0.024	2.496		0.069					3.829	0.015	0.834		11.420
1949	6.813	5.893	0.080	22.540	0.114	1.878	0.027				10.410	0.040	2.270		50.070
1950	5.710	2.250	0.126	10.540	0.171	1.031	0.709		0.137		12.380	0.048	2.697		35.790
1951	4.617	2.467	0.046	10.870	0.046	0.603	0.035		0.070		5.648	0.022	1.231		25.650
1952	14.380	12.730	0.482	36.210	0.159	0.366	0.421	0.079	0.175		23.180	0.089	5.052		93.320
1953	21.310	11.430	0.098	38.210	2.864	1.092	0.653	0.000	0.447		59.560	0.229	12.980		148.900
1954	8.806	6.371	0.054	17.760	0.176	0.455	0.133	0.007	0.230		42.370	0.163	9.235		85.760
1955	6.413	8.142	0.168	23.350	0.296	0.310	0.140	0.006	0.610		27.120	0.104	5.911		72.570
1956	6.362	2.227	0.100	7.267	0.021	1.997	1.306		0.227		13.130	0.051	2.862		35.550
1957	0.464	0.271	0.037	0.768	0.022	0.065	0.009	0.009	0.014		1.882	0.007	0.410		3.959
1958	3.470	0.693	0.087	2.727		0.367	0.310		0.071		10.350	0.040	2.255		20.370
1959	5.702	3.507	0.069	9.882	0.030	0.073			0.020		5.679	0.022	1.238		26.220
1960	4.440	1.987	0.038	6.684	0.017	0.247	0.108		0.092		11.800	0.045	2.571		28.030
1961	1.283	0.338	0.010	2.496	0.005	0.017			0.015		4.813	0.019	1.049		10.040
1964											2.968	0.011	0.647		3.627
1965	1.903	1.640	0.007	0.275	0.230	0.252	0.276		0.002		0.077	0.000	0.017		4.680
1977		0.054		1.950											2.005
1978	0.363			1.497							1.061	0.004	0.231		3.157
1979	3.558			5.860		0.008	0.630		0.041		0.883	0.003	0.192		11.180
1980	14.080	1.845		21.940	0.093	0.143	0.138	0.009	0.116		22.950	0.088	5.001		66.400
1981	5.362	0.782	0.005	2.550	0.011	0.302	0.113		0.091		5.576	1.560	1.215	0.225	17.790
1982	9.946	0.635	0.001	5.503		0.270	0.405		0.144		1.888	4.388	0.412	11.130	34.720
1983	1.150		0.010	8.244	0.016	0.080	0.164		0.043		0.755	1.407	0.165	0.436	12.470
1984	12.220		0.081	55.710	1.105	0.637	0.299	0.001	0.403		1.638	6.906	0.389	1.258	80.650
1985	12.490	0.235	0.571	28.450	0.144	2.251	5.953		0.610	0.027	1.113	14.570	0.680	10.420	77.520
1986	24.300		0.663	41.570	0.600	2.786	26.950		0.869	0.002	0.268	19.440	0.060	1.736	119.200
1987	25.250		0.346	54.840	0.198	3.583	9.812		0.856		3.178	32.090	1.209	4.962	136.300
1988	6.841		0.103	11.770	0.589	1.590	4.645		0.202		0.379	10.880	0.122	5.224	42.340
1989	16.230		0.113	23.860	0.288	2.719	2.074		0.241	0.014	3.882	13.690	0.846	7.148	71.100
1990	12.540		0.240	18.720	5.739	0.651	5.049	0.008	0.089		0.110	13.530	0.064	3.696	60.430
1991	16.160		0.354	31.810	16.910	1.891	13.820	0.008	0.472		1.519	19.810	0.389	2.781	105.900
1992	14.430		0.390	24.770	17.560	1.726	4.530	0.018	0.465		0.151	17.230	0.050	4.164	85.480
1993	19.880		0.562	59.020	11.190	2.830	16.030	0.016	1.176					2.204	112.900
1994	23.340	0.780	0.867	56.510	10.220	2.464	11.860		0.951		0.032	10.860	0.007	4.098	122.000
1995	17.830		0.780	40.340	5.816	2.170	12.380	0.010	0.561		0.035	9.367	0.053	1.868	91.210
1996	11.030	0.014	0.775	28.480	7.429	2.840	9.031	0.015	1.118					5.283	66.010
1997	20.180	0.022	1.775	38.770	6.737	5.094	17.370	0.008	1.945					2.379	94.280
1998	29.630		1.683	34.260	10.450	6.799	22.610		2.042					2.959	110.400
1999	25.410	0.045	1.452	32.590	6.241	6.423	42.910		1.297					1.197	117.600
2000	9.342		0.709	22.900	13.530	3.850	41.440	0.002	0.523					0.737	93.030
2001	9.594	0.145	0.684	24.160	17.520	3.818	32.060		0.618					2.381	90.980
2002	5.925	0.000	0.320	9.947	6.490	1.231	20.840	0.005	0.509					1.258	46.530
2003	8.128	0.000	0.363	7.041	17.260	2.674	21.060		0.566		0.002	6.402	0.000	0.176	63.680
2004	11.140	0.004	0.412	9.903	13.220	2.253	27.770		0.710					0.190	65.600
2005	14.240	0.000	0.247	5.357	12.970	1.952	12.870		1.631					0.544	49.810

C Recreational catch estimation

To estimate the approximate recreational catch for the 1948-2005 period, we relied on three sources of information: For the most recent years we used the Hawaii National Recreational Fisheries Survey data provided with the help of Nicole Bartlett (NMFS Recreational Fisheries Coordinator) via `www.st.nmfs.gov/st1/recreational`. For 1990 we based our estimation on the preliminary small-boat survey conducted by Hamm and Lum (1992), while for the 1980 and 1950 time period we relied on the information assembled by K. Lowe (HDAR) for the catch reconstruction report by Zeller et al. (2005) undertaken for the Council. Several adjustments to the source information were undertaken, as described below.

For the 1950 and 1980 anchor points we relied on work done by K. Lowe (Hawaii Division of Aquatic Resources) as part of the historic catch re-estimation report for the WPRFMC (Zeller et al. 2005). These anchor points consisted of ratios of total catch to reported commercial catch based on review of available data, literature and information. The ratios were used to estimate likely total catch for these years, and non-commercial catch (i.e., recreational catches) using simple subtraction. Subsequently the ratio of recreational to commercial catch was calculated (Table 14).

Table 14: Anchor points used for estimating likely recreational catches for 1950 and 1980.

Year	Ratio total:commercial catch	Reported commercial catch (t)b	Estimated total catch (t)	Estimated recreational catch (t)	Ratio recreational:commercial catch
1950	3.27	268.11	876.72	608.61	2.27
1980	4	244.82	979.3	734.47	3

To estimate the approximate recreational catch for 1990, we used information derived from Hamm and Lum (1992), whose survey was based predominantly on 1990. They reported that on average, 34% of bottomfish catch was to be sold. We utilized this information (despite being aware that more catch may have been sold illegally than was being indicated in the survey) to derive the ratio of likely recreational catch to sold commercial catch of 1.94 (i.e., proportion of 0.66 not sold versus 0.34 sold). Hence, total recreational catch for 1990 was estimated as 1.94 times the sold commercial catch.

We allocated the two 'other' categories (jacks, snappers) from Hamm and Lum (1992) to species specific level as follows:

- The catch reported by Hamm and Lum (1992) as 'other jacks' (but excluding scads) was assigned to the three major bottomfish species of jacks based on the same proportions as used for the commercial catch allocation of 'other jacks', i.e., 0.3, 0.01 and 0.18 for white ulua, black ulua and butaguchi, respectively.

- The catch reported by Hamm and Lum (1992) as 'other snappers' was assigned to the reported snapper taxa based on the commercial proportions of all snapper taxa (Table 15).

Table 15: Proportion of commercial reported catch by species of snapper (Lutjanidae) for 1990.

Taxa	Ehu	Gindai	Kahala	Kalekale	Lehi	Onaga	Opakapaka	Taape	Uku
Proportion	0.023	0	0.063	0	0	0.048	0.257	0.476	0.132

Table 16: Proportion of expanded catch by taxa for bottomfish surveyed by Hamm & Lum (1992)

Taxa	Proportion	Taxa	Proportion
Ehu	0.02	Opakapaka	0.229
Gindai	0	Taape	0.425
Hapuupuu	0.008	Uku	0.117
Kahala	0.057	White ulua	0.076
Kalekale	0	Black ulua	0.001
Lehi	0	Butaguchi	0.022
Onaga	0.043		

- To better account for species specific differences in recreational catch, we used Hamm and Lum (1992) data of expanded catches by taxa, converted to proportions of their expanded catch, and used these proportions (Table 16) to allocate the overall total estimated recreational catch as derived via the 1.94 multiplier of sold commercial catch to individual taxa.

- Furthermore, given that the survey by Hamm and Lum (1992) covered Oahu only, we applied a scaling factor to the estimated total recreational catch, based on the National Recreational Fisheries Survey (Allen and Bartlett 2006). Based on almost equal sampling sizes of interviewed households, Oahu was shown to have approximately 7% of fishing households, compared to an archipelago-wide average of 11%. Thus, the recreational catches derived from the Hamm and Lum (1992) survey was scaled to the overall average percentage of fishing households (11%), under the assumption that catches are similar between islands (although there seem to be some indications that this might not hold for the big island).

These adjustments and approximations suggested a total recreational catch for 1990 of approximately 854 t (Table 17).

For 2004 and 2005 we used the National Recreational Fisheries Survey data as provided via `www.st.nmfs.gov/st1/recreational`. As the 2005 data were not yet publicly available, Nicole Bartlett from NMFS arranged access to these data. The 2003 survey data were not used, as they represented the first year of survey data availability, and coverage appeared incomplete.

Taxa that were individually listed and matched with the BMUS list for species were used as presented (e.g., giant trevally = white ulua). There were several other trevally taxa listed, as well as an 'other jacks' group. In order to remain consistent in the taxa that

Table 17: Estimated recreational catch for 1990 by major bottomfish taxa, based on Hamm & Lum (1992) with adjustments as described in text.

Taxa	Estimated recreational catch (t)	Taxa	Estimated recreational catch (t)
Ehu	17.27	Opakapaka	195.86
Gindai	0.23	Taape	362.41
Hapuupuu	6.92	Uku	100.26
Kahala	48.31	White Ulua	65.19
Kalekale	0.28	Black Ulua	1.05
Lehi	0.35	Butaguchi	18.98
Onaga	36.54	**Total**	**853.66**

were considered in the present assessment (i.e., bottomfish BMUS), we used a proportional allocation approach to assign the 'other jack' catch to the three BMUS jack species (white and black ulua, and butaguchi). The allocation consisted of the same proportional allocation of jacks that were used in the commercial catch data to allocate 'other jacks' to the three BMUS species in the commercial data, e.g., 0.18 butaguchi, 0.3 white ulua and 0.01 black ulua.

The 'other snapper' category was allocated to the reported taxa of snapper based on their reported proportion in each year. Thus, we assumed that non-specific snapper catches (i.e., 'other snappers') were taxonomically proportional to reported taxa. Hence, our adjusted taxa specific snapper catches are higher than the taxa specific recreational data reported. While taape (*Lutjanus kasmira*) is also taken in shallow waters and by shore-based fishing, the species is listed as BMUS, thus we considered total species extraction, not only boat-based.

Overall, the estimated ratios of recreational (non-sold) catch to commercial (sold and reported) catch suggested that recreational catches of bottomfish species might be between 2 and 3 times the reported commercial catches for bottomfish (Fig. 10). The available information also suggested an increasing trend between 1950 and 2005, with an average rate of increase of ≈1% per year (Fig. 10). Given the ratio dependence on commercial catches used here as estimation procedure, recreational catch trajectories follow those of the commercial data, and may have ranged from less than 300 t to as high as 1,400 t (Fig. 11). Based on the estimation of potential recreational catches used here, total catches of bottomfish may have peaked at just under 2,000 t in 1988, and currently may be in the range of 400-700 t per year (Fig. 11).

C.1 Taxa specific interpolation and extrapolation:

For 1948-1950, we carried back the reported 1950 ratio of 'not sold' (i.e., recreational) to 'sold' (reported commercial) of 2.27 (Table A5) for each taxon.

For 1951-1980 we linearly interpolated between the 1950 ratio of 2.27 and the 1980 ratio

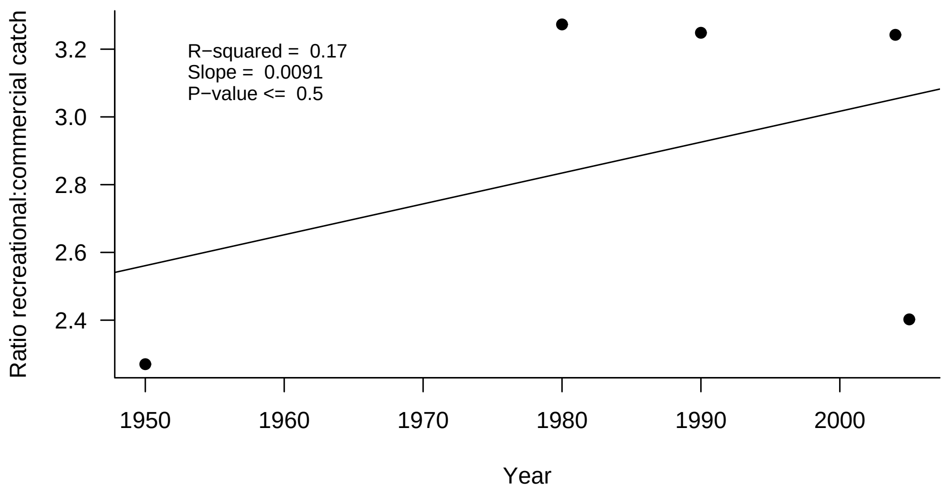

Figure 10: Estimated ratios of recreational to commercial catches for 1950-2005 used for approximating likely recreational catches for the MHI.

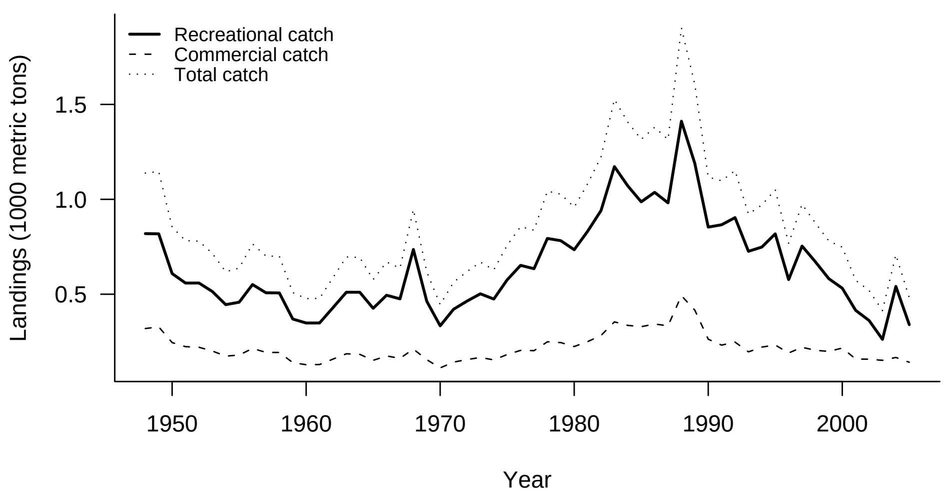

Figure 11: Estimated recreational catch for bottomfish species in the MHI zone, based on the estimated ratios of recreational to commercial catches derived in this report and associated documents. Shown also are the commercially reported (sold) catches and the derived total catch estimates.

Table 18: Ratios of recreational (non-sold) catches to commercial (sold) catches derived from literature, and used to estimate likely recreational catches of bottomfish between 1948-2005.

Taxa	Ratio recreational:commercial catch				
	1950	1980	1990	2004	2005
Black Ulua	2.27	3	1.24	0.15	0.35
Butaguchi	2.27	3	1.29	1.43	1.4
Ehu	2.27	3	1.11	0	0
Gindai	2.27	3	0.15	0	0
Hapuupuu	2.27	3	1.02	0.42	0.99
Kahala	2.27	3	5.22	4.69	0
Kalekale	2.27	3	0.03	0	0
Lehi	2.27	3	0.04	0	0
Onaga	2.27	3	0.73	0	0
Opakapaka	2.27	3	2.87	5.95	1.64
Taape	2.27	3	15.63	0.55	3.33
Uku	2.27	3	2.27	2.49	4.51
White Ulua	2.27	3	2.41	28.51	21.24

of 3.0 (Table A5).

For 1981-1990 we applied interpolation between the 1980 value of 3.0 and each taxon specific ratio as estimated for 1990 (Table A5).

For 1991-2004 we applied interpolation between the 1990 and 2004 taxon specific ratios (Table A5).

Taxa specific estimation of likely recreational catches suggested that snappers may dominate the catch of bottomfish, with opakapaka, taape and uku dominating the catch over the last couple of decades (Fig. 12a). Other snappers, such as onaga and kahala contributed less, while white ulua made up a minor, but significant component of the catch, as did butaguchi (Fig. 12b).

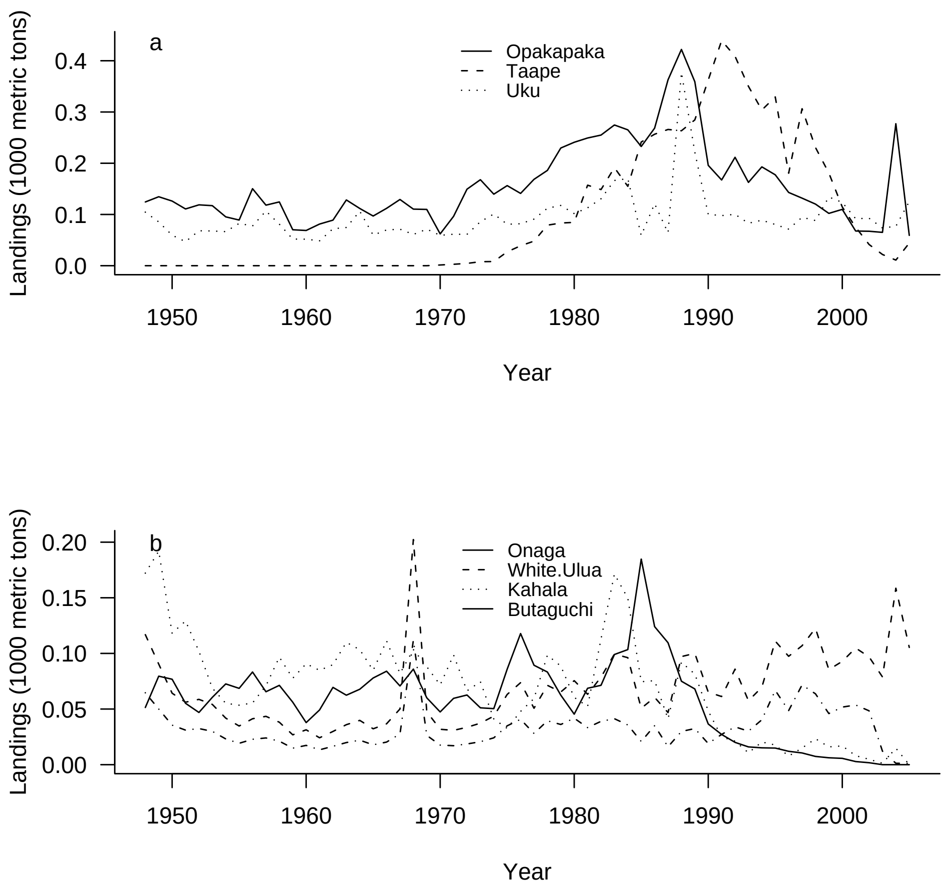

Figure 12: Taxa specific estimates of recreational catches for selected bottomfish species.

D ADModel Builder Code

The following code was used to implement the semi-implicit Schaefer production model.

```
//*****************************************************
//  Programmer: A team
//*****************************************************/
DATA_SECTION
    init_adstring datafilename;
    init_int na;
    init_matrix control_matrix(1,16,1,6);
    number LO;
    number HI;
    number IVAL;
    int PHZ;
    LOC_CALCS
        LO=control_matrix(1,1);
        HI=control_matrix(1,2);
        IVAL=control_matrix(1,3);
        PHZ=control_matrix(1,4);
    END_CALCS

    //controls for p1 vector
    vector pLO(1,na);
    vector pHI(1,na);
    vector pIVAL(1,na);
    ivector pPHZ(1,na);
    LOC_CALCS
        for(int i=1; i<=na; i++)
        {
            pLO(i)=control_matrix(1+i,1);
            pHI(i)=control_matrix(1+i,2);
            pIVAL(i)=control_matrix(1+i,3);
            pPHZ(i)=control_matrix(1+i,4);
        }
    END_CALCS

    //controls for k vector
    vector kLO(1,na);
    vector kHI(1,na);
    vector kIVAL(1,na);
    ivector kPHZ(1,na);
    LOC_CALCS
        for(i=1; i<=na; i++)
        {
            kLO(i)=control_matrix(4+i,1);
            kHI(i)=control_matrix(4+i,2);
            kIVAL(i)=control_matrix(4+i,3);
            kPHZ(i)=control_matrix(4+i,4);
        }
    END_CALCS

    //controls for q vector
    vector qLO(1,na);
    vector qHI(1,na);
    vector qIVAL(1,na);
    ivector qPHZ(1,na);
    LOC_CALCS
        for(i=1; i<=na; i++)
        {
            qLO(i)=control_matrix(7+i,1);
            qHI(i)=control_matrix(7+i,2);
            qIVAL(i)=control_matrix(7+i,3);
            qPHZ(i)=control_matrix(7+i,4);
        }
    END_CALCS

    //controls for obserror vector
    vector vLO(1,na);
    vector vHI(1,na);
    vector vIVAL(1,na);
    ivector vPHZ(1,na);
    LOC_CALCS
        for(i=1; i<=na; i++)
        {
            vLO(i)=control_matrix(10+i,1);
            vHI(i)=control_matrix(10+i,2);
            vIVAL(i)=control_matrix(10+i,3);
            vPHZ(i)=control_matrix(10+i,4);
        }
    END_CALCS

    //controls for process error vector
    vector tLO(1,na);
```

```
    vector tHI(1,na);
    vector tIVAL(1,na);
    ivector tPHZ(1,na);

    LOC_CALCS
        for(i=1; i<=na; i++)
        {
            tLO(i)=control_matrix(13+i,1);
            tHI(i)=control_matrix(13+i,2);
            tIVAL(i)=control_matrix(13+i,3);
            tPHZ(i)=control_matrix(13+i,4);
        }
    END_CALCS

    //Sea level anomalies
    init_int at_PHZ;
    init_int at_flag;              //Flag for implementing environmental anomalies.
    int ncs;

    //Process errors
    init_int wt_PHZ;

    //Random walk in catchability
    init_int qdev_PHZ;
    //______________________________________________//
    //                      END OF CONTROL FILE                              //
    //______________________________________________//

    //Switching to the parameter control file here
    !! ad_comm::change_datafile_name(datafilename);
    init_int syr;
    init_int nyr;
    init_int nareas;

    init_vector wt(1,nareas);
    init_ivector sctyr(1,nareas);
    init_ivector nctyr(1,nareas);

    init_matrix ct(1,nareas,sctyr,nctyr);
    init_matrix eff(1,nareas,sctyr,nctyr);

    matrix cpe(1,nareas,sctyr,nctyr);
    LOC_CALCS
        //use in data or parameter sections only.
        ct/=2204.6; //convert catch from lbs to tons
        //ct(1)*=2.5;  //increase total catch
        //for(int j=syr;j<=nyr;j++)ct(1,j)*=pow(0.03,j);
        for(i=1; i<=nareas; i++)
        {
            cpe(i)=elem_div(ct(i),eff(i));
            eff(i)/=mean(eff(i));
        }
    END_CALCS

    //read in sea level height anomalies
    init_int asyr;
    init_int nsyr;
    init_vector at(asyr,nsyr);
    //!!cout<<at<<endl;
    //!!cout<<ct<<endl;
    //______________________________________________//
    //                          END OF DATA FILE                              //
    //______________________________________________//



PARAMETER_SECTION
    init_bounded_number r(LO,HI,PHZ);
    !!ncs=nareas;
    !!if(at_flag==2) ncs=1;     //change the number of estimated c's if applying at to r.
    init_vector c(1,nareas,at_PHZ);                                           //correlation coefficient for at anomalies
    init_bounded_number_vector p1(1,nareas,pLO,pHI,pPHZ);
    init_bounded_number_vector log_k(1,nareas,kLO,kHI,kPHZ);
    init_bounded_number_vector q(1,nareas,qLO,qHI,qPHZ);
    init_bounded_number_vector sig(1,nareas,vLO,vHI,vPHZ);             //observation error variance
    init_bounded_number_vector tau(1,nareas,tLO,tHI,tPHZ);             //process error variance
    init_bounded_matrix wt(1,nareas,sctyr,nctyr,-5,5,wt_PHZ);              //process error terms
    init_bounded_matrix q_dev(1,nareas,sctyr,nctyr,-5,5,qdev_PHZ);      //catchability deviations

    LOC_CALCS
        r=IVAL;
        for(int i=1;i<=nareas; i++)
        {
            p1[i]=pIVAL[i];
            log_k[i]=kIVAL[i];
            q[i]=qIVAL[i];
```

```
            sig[i]=vIVAL[i];
            tau[i]=tIVAL[i];
        }
    END_CALCS

    objective_function_value f;

    sdreport_number bratio;
    vector k(1,nareas);                     //carrying capacity for one of the zones.
    vector MSY(1,nareas);
    vector Bmsy(1,nareas);
    vector Fmsy(1,nareas);
    vector Emsy(1,nareas);
    vector CPEmsy(1,nareas);
    vector fvec(1,nareas);
    vector pvec(1,nareas);
    vector pvec2(1,nareas);

    matrix Bstatus(1,nareas,sctyr,nctyr);
    matrix Fstatus(1,nareas,sctyr,nctyr);

    matrix bt(1,nareas,sctyr,nctyr);
    matrix ut(1,nareas,sctyr,nctyr);
    matrix ft(1,nareas,sctyr,nctyr);
    matrix yt(1,nareas,sctyr,nctyr);
    matrix qt(1,nareas,sctyr,nctyr);
    matrix nu(1,nareas,sctyr,nctyr);        //residuals for the cpue observations
    matrix chat(1,nareas,sctyr,nctyr);  //predicted catch

PROCEDURE_SECTION
    //******************************
    init_model();
    calc_fishingrate();
    calc_biomass_catch();
    calc_objective_function();

    if(mceval_phase()) mcmc_output();
    bratio=bt(1,nctyr[1])/(k[1]/2.);
    //******************************

FUNCTION init_model
    int i;
    bt.initialize();
    for(i=1;i<=nareas;i++)
    {
        k[i]=mfexp(log_k[i]);
        //if(!active(p1[i])) p1[i]=ct(i,sctyr[i])/(ft(i,sctyr[i])*k[i]);
        bt(i,sctyr(i))=p1[i]*k[i]*exp(wt(i,sctyr(i)));//mean(cpe(i)(sctyr(i)+1,sctyr(i)+3))/q(i);
    }
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>

FUNCTION calc_fishingrate
    int i,j;
    for(i=1;i<=nareas;i++)
    {
        qt(i,sctyr[i])=q[i];
        for(j=sctyr[i];j<nctyr[i];j++)
        {
            qt(i,j+1)=qt(i,j)*exp(q_dev(i,j));
            if(at_flag==4) qt(i,j)=q[i]*exp(c[i]*at[j]);
            if(at_flag==5) qt(i,j+1)*=exp(c[i]*at[j]);
        }
        ft(i)=elem_prod(qt(i),eff(i));
        //ft(i)=elem_prod(q[i]*exp(q_dev(i)),eff(i));
    }
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>

FUNCTION calc_biomass_catch
    int i,j,kk;
    dvariable bio_tmp;
    dvariable c_tmp;
    dvariable r_tmp; r_tmp=r;
    dvariable k_tmp;
    nu.initialize();
    int nsteps=2.;
    double delta=1./nsteps;
    //Integrate logistic dynamics over nsteps per year
    for(i=1;i<=nareas;i++)
    {
        k_tmp=k[i];
        for(j=sctyr[i];j<=nctyr[i];j++)
        {
            bio_tmp=1.e-30+bt(i,j);
            c_tmp=0.;
            if(at_flag==2) r_tmp=r*exp(c(1)*at(j));
            if(at_flag==3) k_tmp=k[i]*exp(c[i]*at[j]);
            for(kk=1; kk<=nsteps; kk++)
```

```
            {
                bio_tmp=bio_tmp*(1.+r_tmp*delta)
                                /(1.+(r_tmp*bio_tmp/k_tmp+ft(i,j))*delta);
                c_tmp+=ft(i,j)*bio_tmp*delta;
            }
            chat(i,j)=c_tmp;
            if(j<nctyr[i])
            {
                bt(i,j+1)=bio_tmp*exp(wt(i,j+1));
                if(at_flag==1)bt(i,j+1)*=exp(c[i]*at[j]);
            }
        }
        nu(i)=log(ct(i))-log(chat(i));
    }
    //cout<<nu<<endl;
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>

FUNCTION mcmc_output
    reference_points();
    ofstream ofs1("PARS.MCMC",ios::app);
    ofstream ofs2("Bstatus1.MCMC",ios::app);
    ofstream ofs3("Bstatus2.MCMC",ios::app);
    ofstream ofs4("Bstatus3.MCMC",ios::app);
    ofstream ofs5("Fstatus1.MCMC",ios::app);
    ofstream ofs6("Fstatus2.MCMC",ios::app);
    ofstream ofs7("Fstatus3.MCMC",ios::app);

    ofs1<<r<<"\t"<<p1<<log_k<<q<<sig<<tau<<MSY<<Bmsy<<Fmsy<<endl;
    ofs2<<Bstatus(1)<<endl;
    ofs3<<Bstatus(2)<<endl;
    ofs4<<Bstatus(3)<<endl;

    ofs5<<Fstatus(1)<<endl;
    ofs6<<Fstatus(2)<<endl;
    ofs7<<Fstatus(3)<<endl;

//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
FUNCTION reference_points
    int i;
    for(i=1; i<=nareas;i++)
    {
        MSY[i]=r*k[i]/4.;
        Bmsy[i]=k[i]/2.;
        Fmsy[i]=r/2.;
        Emsy[i]=r/(2.*q[i]);
        CPEmsy[i]=(2.*q[i]*k[i])/4;
        Bstatus(i)= bt(i) / Bmsy[i];
        Fstatus(i)= ft(i)/Fmsy[i];   //elem_div(ct(i),bt(i)) / Fmsy[i];
    }
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>

FUNCTION calc_objective_function
    //k(1)=3.61*k(2); k(3)=3.47*k(2);       //K in MHI and Ho'omalu is based on ratio's of 100fm contour lengths
    int i;
    long n;
    double o=1.e-30;
    dvector a(1,nareas);
    dvector b(1,nareas);
    dvector aa(1,nareas);
    dvector bb(1,nareas);

    pvec.initialize(); pvec2.initialize();
    fvec.initialize();

    for(i=1;i<=nareas;i++)
    {
        n=size_count(cpe(i));
        //fvec(i)=0.5*n*log(sig[i])+norm2(log(cpe(i)+o)-log(yt(i)+o))/(2.*sig[i]);
        fvec(i)=0.5*n*log(sig[i])+norm2(nu(i))/(2.*sig[i]);
        //a[i]=control_matrix(10+i,5); b[i]=control_matrix(10+i,6);//*(a[i]-1.);
        //aa[i]=control_matrix(13+i,5); bb[i]=control_matrix(13+i,6);//*(aa[i]-1.);

        pvec[i]=log(q[i])
                +d_inverse_gamma(sig[i],control_matrix(10+i,6),b[i]=control_matrix(10+i,5))                 //prior obs error variance
                +d_beta(p1[i],control_matrix(1+i,6),control_matrix(1+i,5))                                              //BETA for p1
                +log(r)+0.5*square(log(r)-log(control_matrix(1,5)))/square(control_matrix(1,6))         //prior on r
                +log(log_k[i])+0.5*square(log_k[i]-log(control_matrix(4+i,5)))/square(control_matrix(4+i,6));//prior on k

        if(active(q_dev))
        {
            pvec2[i]+=0.5*(n-1.)*log(tau[i])+norm2(first_difference(q_dev(i)))/(2.*tau[i])
            +d_inverse_gamma(tau[i],control_matrix(13+i,6),b[i]=control_matrix(13+i,5));                //prior process error variance
        }

        if(active(wt))
        {
            pvec2[i]+=0.5*(n-1.)*log(tau[i])+norm2(wt[i])/(2.*tau[i])   //process errors
```

```
            +d_inverse_gamma(tau[i],control_matrix(13+i,6),b[i]=control_matrix(13+i,5));
        }
    }

    f=sum(fvec)+sum(pvec)+sum(pvec2);
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>

FUNCTION dvariable d_inverse_gamma(dvariable theta, double alpha, double mode)
    {   //retunrs the inverse-gamma (log space) of theta given mode and alpha
        RETURN_ARRAYS_INCREMENT();
        double beta=mode*(alpha-1.);
        dvariable p_invgamma=(alpha+1.)*log(theta)+beta/theta;
        RETURN_ARRAYS_DECREMENT();
        return (p_invgamma);
    }

FUNCTION dvariable d_beta(dvariable theta, double alpha, double mode)
    {   //returns the beta probability (log space) of theta given mu and var of the beta distribution.
        //note that the following must be satisfied: 0<theta<1 and alpha > 1.
        RETURN_ARRAYS_INCREMENT();
        double beta=(alpha-1.)/mode+2.-alpha;
        dvariable p_beta=-(alpha-1.)*log(theta)-(beta-1.)*log(1.-theta);
        RETURN_ARRAYS_DECREMENT();
        return (p_beta);
    }
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
TOP_OF_MAIN_SECTION
    time(&start);
    arrmblsize = 50000000;
    gradient_structure::set_GRADSTACK_BUFFER_SIZE(1.e7);
    gradient_structure::set_CMPDIF_BUFFER_SIZE(1.e7);
    gradient_structure::set_MAX_NVAR_OFFSET(5000);
    gradient_structure::set_NUM_DEPENDENT_VARIABLES(5000);

GLOBALS_SECTION
    #include <admodel.h>
    #include <time.h>
    time_t start,finish;
    long hour,minute,second;
    double elapsed_time;
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>

FINAL_SECTION
    time(&finish);
    elapsed_time=difftime(finish,start);

    hour=long(elapsed_time)/3600;
    minute=long(elapsed_time)%3600/60;
    second=(long(elapsed_time)%3600)%60;
    cout<<endl<<endl<<"*******************************************"<<endl;
    cout<<"--Start time: "<<ctime(&start)<<endl;
    cout<<"--Finish time: "<<ctime(&finish)<<endl;
    cout<<"--Runtime: ";
    cout<<hour<<" hours, "<<minute<<" minutes, "<<second<<" seconds"<<endl;
    cout<<"*******************************************"<<endl;
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
//  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>  >-<>
REPORT_SECTION
    reference_points();

    report<<"yrs\n"<<syr<<"\t"<<nyr<<endl;
    report<<"nctyrs\n"<<sctyr<<endl<<nctyr<<endl;
    report<<"nareas\n"<<nareas<<endl;
    report<<"biomass \n"<<bt<<endl;
    report<<"observed catch \n"<<ct<<endl;
    report<<"obsct \n"<<ct<<endl;
    report<<"predct \n"<<chat<<endl;
    report<<"residuals\n"<<nu<<endl;
    report<<"epsilon\n"<<wt<<endl;
    report<<"ft\n"<<ft<<endl;
    report<<"qt\n"<<qt<<endl;
    report<<"Bo\n"<<k<<endl;


    report<<"MSY\n"<<MSY<<endl;
    report<<"r \n"<<r<<endl;
    report<<"Bmsy\n"<<Bmsy<<endl;
    report<<"Fmsy\n"<<Fmsy<<endl;
    report<<"Emsy\n"<<Emsy<<endl;
    report<<"CPEmsy\n"<<CPEmsy<<endl;
    report<<"Bstatus\n"<<Bstatus<<endl;
    report<<"Fstatus\n"<<Fstatus<<endl;
```

```
    //Objective Function Values
    report<<"f \n"<<f<<endl;
    report<<"Fvec\n"<<fvec<<endl;
    report<<"Pvec \n"<<pvec<<endl;
    report<<"Pvec2 \n"<<pvec2<<endl;
    report<<"c\n"<<c<<endl;     //correlation coefficient for the environmental correlates
```

The following is the data file used for the Hawaiian archipelago assessment.

```
#Data file for Surplus.dat
#syr nyr
1948 2004
#nareas (1=MHI, 2=MAU, 3=Ho'omalu)
3
#weighting factors
0.1 6. 0.8
#Catch by years (ivectors for indexing)
1948    1988 1988
2004    2004    2004
#Catch data by area (lbs)
707129 731106 550086 493758 487637 459895 383625 396408 472869 427229 425976 308150 284500 285879 370274
410654 390289 330120 385782 358438 517028 342630 245423 311885 339705 361973 333552 434763 426348 411154
491373 478993 433205 470694 564403 739676 703928 668623 703413 686502 1038660 878735 539510 444716
479318 370225 428836 440676 375868 400369 376008 367788 421722 301918 311302 296163 322830
#
39627 118391 248410 103267 71000 98000 160000 166451 133000 105000 66000 54000 49000 50000 108000
94739 90023
#
590732 184609 172590 283733 353000 287000 283000 202549 176000 241000 266000 269000 213000 236000
120000 148236 151660
#
#Number of trips by area (days fished)
1152 1025 813 795 845 713 432 525 603 541 799 594 452 576 754 793 1223 656 720 595 1082 714 567 720 661 860 1014
1011 879 780 774 1261 1029 1131 1838 3456 3200 2907 2567 2897 3157 2434 2202 2202 2102 1738 1967 2283 3007
2275 2892 1760 2255 1556 1741 1558 1888
#
123 175 434 310 297 367 453 544 446 245 181 160 188 177 246 197 201
#
682 228 256 423 552 397 450 348 313 420 505 504 354 435 293 304 346
#Sea level height anomalies at Midway
1947 2004
-1.174991639 -2.168221197 0.759193076 0.131889877 1.560746965 -0.582538757 1.090269655 0.201590153
0.23644047 -1.070441046 -0.321162275 0.340990883 -1.750019541 0.184165173 0.84631851 -0.460563005
0.811468193 0.306140745 -0.146911513 -0.129486426 -0.565113598 0.462966456 -1.802295196 1.874398385 -
0.565113598 -1.47121808 0.009914269 -0.54768844 -1.244692094 -0.477988164 0.724342759 -1.035590908
0.166740051 -1.296967211 0.201590153 -1.209841777 0.079614616 1.037994358 -1.140141501 1.421346234
0.149314964 -0.129486426 -0.390862729 -0.199186702 -0.286312137 0.706917779 -0.234037019 -0.599963736
0.968294083 -0.460563005 -0.408287888 2.449427004 -0.425712867 1.682722537 1.159969931 -0.53026346
2.135774867 1.125119793
```