



# What about recreational catch?

## Potential impact on stock assessment for Hawaii's bottomfish fisheries

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### Abstract

The bottom-fish stocks of the Main Hawaiian Islands (MHI) are intensively fished, both commercially and recreationally. Recent assessments of the Bottomfish Management Unit Species (BMUS) complex suggested overfishing, and expressed concerns about missing non-commercial data. We used reported commercial time-series data and estimation ratios to indirectly estimate non-commercial catches for non-pelagic species (i.e., excluding tuna and billfishes) for 1950–2005. Using adjustment ratios, we also accounted for commercial under-reporting, which suggested that total commercial non-pelagic catches were 28–128% higher than reported commercial catches for any given year. Estimated non-commercial catches for 1950–2005 were 2.1 times higher than reported commercial catches. Reported catches underestimated likely total catches (reported and un-reported commercial plus non-commercial) of non-pelagic species and BMUS components for 1950–2005 by a factor of 3.9 and 2.9, respectively. We incorporated the reconstructed BMUS non-commercial catches into stock assessments of the officially reported commercial BMUS catches via a Schaefer production model. Total catch increased by 2.5–3.5 times with the addition of non-commercial BMUS catch estimates, which in turn increased model estimates of MSY and carrying capacity ( $k$ ) by approximately four times compared to analyses with reported commercial data alone. As the CPUE data lacked information to resolve the confounding between large, unproductive and small, productive stocks, an informative prior was used for fishing mortality rate to attain MSY ( $F_{MSY}$ ). To address uncertainty in key management parameters, independent estimates of exploitation rate, or fisheries independent estimates of abundance, and informative trends in recreational effort or catches are required. © 2007 Elsevier B.V. All rights reserved.

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### 1. Introduction

Despite focus on the June 2006 declaration by the US Government assigning the Northwest Hawaiian Islands (NWHI) as the first national marine monument in the USA, and the concomitant slow phase-out of fishing (Anonymous, 2006a), a more pressing fisheries issue in the Hawaiian archipelago relates to the pressures being exerted on marine resources in the Main Hawaiian Islands (MHI). The MHI have a high human population density (U.S. Census Bureau, <http://www.census.gov>), major tourism industry, and easy access to fishing grounds. While the majority of commercial fisheries revenue (80–90%) comes from large pelagic species, Hawaii's non-pelagic resources have substantial cultural, subsistence and recreational value (Pooley, 1993; Lowe, 2004). A major component of the non-pelagic fisheries

is the deeper-water 'bottomfish' fishery, which concentrates on a dozen species, primarily eteline snappers (Lutjanidae), jacks (Carangidae) and the Hawaiian grouper (*Epinephelus quernus*, Serranidae) at depths of about 50–300 m (Polovina, 1987). Some of these species have been fished on a subsistence basis for hundreds of years, and commercially since the early 20th century (Anonymous, 2004). Presently, they support a large number of non-commercial and commercial fishers in the MHI, and a very small number of commercial fishers in the NWHI (Anonymous, 2004).

Past disagreements between US State and Federal jurisdictions over management of the MHI bottomfish resources have contributed to relatively unsuccessful management, with assessments suggesting overfishing, and high uncertainty about stock status (Martell et al., 2006). Assessments have traditionally used relative abundance estimates based on Catch Per Unit of Effort (CPUE) indices of 'high-liners', i.e., each year's subset of most productive fishers. Such CPUE indices are known to be hyperstable, and readily mask declines in stock status (Walters and

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Table 1

List of Hawaiian Bottomfish Management Unit Species (BMUS), their taxonomic affinity and FAO common names, modified from Martell et al. (2006)

Local name	Family	Species	FAO common name
Armorhead <sup>a</sup>	Pentacerotidae	<i>Pseudopentaceros wheeleri</i>	Armorhead
Black Ulua	Carangidae	<i>Caranx lugubris</i>	Black jack
Butaguchi	Carangidae	<i>Pseudocaranx dentex</i>	White trevally
*Ehu	Lutjanidae	<i>Etelis carbunculus</i>	Ruby snapper
*Gindai	Lutjanidae	<i>Pristipomoides zonatus</i>	Oblique-banded snapper
*Hapuupuu	Serranidae	<i>Epinephelus quernus</i>	Hawaiian grouper
Kahala	Carangidae	<i>Seriola dumerii</i>	Greater amberjack
*Kalekale	Lutjanidae	<i>Pristipomoides sieboldii</i>	Lavender jobfish
Kinmedai	Berycidae	<i>Beryx spendens</i>	Alfonsin
*Lehi	Lutjanidae	<i>Aphareus rutilans</i>	Rusty jobfish
*Onaga	Lutjanidae	<i>Etelis coruscans</i>	Flame snapper
*Opakapaka	Lutjanidae	<i>Pristipomoides filamentosus</i>	Crimson jobfish
Taape <sup>b</sup>	Lutjanidae	<i>Lutjanus kasmira</i>	Bluestripe snapper
Uku	Lutjanidae	<i>Aprion virescens</i>	Green jobfish
White Ulua	Carangidae	<i>Caranx ignobilis</i>	Giant trevally
Yellowtail Kalekale	Lutjanidae	<i>Pristipomoides auricilla</i>	Goldflag jobfish

Species comprising the 'deep-seven' species of current management interest are indicated with (\*).

<sup>a</sup> This seamount taxon is not caught by recreational fishers, and the commercial seamount fisheries are closed.

<sup>b</sup> Exotic species introduced into the Hawaiian archipelago in 1958.

Martell, 2004). Also, standard assessments relied on a pooled multi-species complex (Bottomfish Management Unit Species or BMUS, Table 1) and analyses were based entirely on reported commercial catch data (Martell et al., 2006). Fundamental to the assessment problem is the realization that an unknown, but likely large percentage of data are missing, i.e., non-commercial catches. In response to the concerns about overfishing, the US federal fishery management agency (Western Pacific Regional Fishery Management Council), in collaboration with the state management agency (Hawaii Division of Aquatic Resources, HDAR) implemented a 4.5 month seasonal MHI closure for the main deep water species (called the 'deep-seven', Table 1) in 2007 and 2008 as an interim attempt to reduce fishing mortality rates, while the subsequent use of Total Allowable Catch limits (TAC) is explored.

The lack of basic catch data from some sectors (e.g., recreational sector) of a fishery is a global problem, yet until recently the scale of non-reporting and its implications have rarely been seriously considered (but see Zeller et al., 2006a; Zeller et al., 2006b; Zeller et al., 2007a). In essence, the issue of missing data, even in the form of the legal but un-accounted recreational sector in Hawaii, forms part of the global IUU (Illegal, Unregulated and Unreported) problem (Bray, 2000), which includes the issue of discarding (Zeller and Pauly, 2005).

### 1.1. Fisheries data

Holders of Hawaiian commercial fishing licenses are required to file monthly catch reports, including the reporting of unsold catch. However, it is known that not all 'commercial' catch is reported (see Zeller et al., 2007b). Illegal sales and under-reporting contribute to under-recording of commercial catches by the state catch reporting system maintained by the HDAR. Incomplete reporting may be influenced by the large fraction of 'part-time' commercial fishers being active in Hawaii, which are

known to sell only a fraction of their catch through the formal framework.

No licensing or reporting requirements currently exist for non-commercial marine fishing (Zeller et al., 2007b), despite the high proportion of residents and visitors who fish. Existing recreational bag limits for several key bottomfish target species can easily be circumvented through the purchase of the low-cost commercial fishing license (<US\$50) and the annual sale of at least one fish. Attempts have been made to estimate non-commercial catches, at least on a spatially and temporally limited scale (e.g., Hamm and Lum, 1992; Friedlander and Parrish, 1997; Everson and Friedlander, 2004). In the early 2000s, creel surveys through the Marine Recreational Fishery Statistics Survey (<http://www.hawaii.gov/dlnr/dar/surveys/>) were initiated to provide estimates of fishing effort and catches, but their design has not been optimized for assessing the bottomfish sector.

The objectives of the present study were to derive estimates of non-commercial catches for non-pelagic species (i.e., excluding tuna and billfishes) for Hawaii for 1950–2005, and to assess their potential impact on stock assessments. Given the absence of time-series data on non-commercial catches, we present an approach of 'qualitative data' application to derive approximate levels of likely catches. Specifically, we use existing reported commercial catches, available qualitative information, and local expert knowledge, to derive *adjustment ratios* for un-reported commercial catches, and *estimation ratios* for indirectly estimating non-commercial catches. While uncertainties around our estimates may be high, we remain conservative in our estimation approach. We then incorporate the reconstructed non-commercial catches of Bottomfish Management Unit Species (BMUS) into a BMUS stock assessment approach via a Schaefer production model of the reported commercial BMUS catch data to evaluate what likely impact non-commercial catches may have on formal stock assessment outcomes, and the

resultant management advice for the Hawaiian bottomfish fishery.

## 2. Methods

The State of Hawaii Division of Aquatic Resources (HDAR) provided reported, commercial landings data for non-pelagic fisheries from 1950 to 2005 for the MHI. We excluded the NWHI from the estimation process, as there is no recreational bottom-fishing in this remote area (Zeller et al., 2005; Zeller et al., 2007b). To account for under-reporting of commercial catches, we applied adjustment ratios to the reported commercial catches. Given the lack of reporting requirements for non-commercial fisheries, we estimated non-commercial catches indirectly, via estimation ratios for total catch based on reported commercial catch. Both the non-commercial estimation ratios and the commercial under-reporting adjustment ratios were derived from 'qualitative data' and literature (Zeller et al., 2007b).

### 2.1. Commercial catches

Commercial landings of algae, corals, freshwater-, and large pelagic-species (e.g., tuna and billfishes) were excluded. The adjustments for under-reporting of commercial landings were based on 12 adjustment ratios for 'total commercial to reported commercial catch' ( $R_c$ , Table 2). These adjustment ratios were considered 'anchor points' of best available data. The ratios were linearly interpolated for years between adjustment 'anchor points', and applied to annual reported commercial catches ( $C_r$ ) to derive estimates of annual total commercial catches ( $C_c$ ):

$$C_c = C_r \times R_c \quad (1)$$

Table 2

Estimated ratios used to derive total commercial catches ( $C_t$ ) and total catches (CT) for Hawaiian bottomfish fisheries, based on data for reported commercial catches ( $C_r$ ) provided by the Hawaii Division of Aquatic Resources

Year	$R_c$ Total commercial catch:reported commercial catch	$R_t$ Total catch:reported commercial catch
1950	1.70:1	3.27:1
1980	2.30:1	4.00:1
1985	1.64:1	4.00:1
1988	1.73:1	4.00:1
1990	2.00:1	3.50:1
1991	2.00:1	–
1992	1.28:1	–
1993	1.32:1	–
1996	1.37:1	–
2000	1.53:1	–
2001	1.53:1	–
2002	1.53:1	3.50:1 <sup>a</sup>

$R_c$ : Ratio of total commercial catches to reported commercial catches, accounting for the under-reporting of commercial catches;  $R_t$ : Ratio of total catches to reported commercial catches, permitting estimation of non-commercial catches as differences between total catches and total commercial catches. The present ratios were linearly interpolated for intermediate years. Ratios presented here were derived from a range of local data and information sources (Zeller et al., 2007b).

<sup>a</sup> We assumed same ratio for 2002 as for 1990.

### 2.2. Non-commercial catches

Our estimation of non-commercial catches utilized five estimation ratios of 'total catch to reported commercial catch' ( $R_t$ , Table 2) derived from 'qualitative data' sources as 'anchor points' between 1950 and 1990 (Zeller et al., 2007b). These ratios were linearly interpolated for years between anchor points, while the 1990 ratio was carried forward to 2002 unaltered. For 2003–2005 we utilized estimates derived by the recreational fisheries survey (<http://www.st.nmfs.gov/st1/recreational>), which are likely minimal estimates. The ratios were then applied to the reported commercial catches ( $C_r$ ) for each year to estimate total catches (CT) for that year:

$$CT = C_r \times R_t \quad (2)$$

Estimates of total non-commercial catches ( $C_n$ ) could then be derived by subtraction:

$$C_n = CT - C_c \quad (3)$$

To assign the estimated non-commercial catch of non-pelagic taxa to those species comprising the BMUS complex used in stock assessments (Table 1), we relied on two sources of information:

1. For the most recent years (2003–2005) we used the Hawaii National Recreational Fisheries Survey data (<http://www.st.nmfs.gov/st1/recreational>). Some BMUS taxa were individually listed (e.g., *Caranx ignobilis*, *Pristipomoides filamentosus*, Table 1). For pooled groups, we used a proportional allocation approach to assign the respective groups to their associated BMUS species. This proportional allocation mirrored that used in the commercial catch data to allocate 'other' groups to their BMUS species (Martell et al., 2006). The 'other snapper' category was allocated to the reported snapper taxa based on their reported proportion in each year. Thus, we assumed that non-specific snapper catches were taxonomically proportional to reported taxa.

Table 3

Proportion of expanded catch by taxa for bottomfish surveyed by Hamm and Lum (1992)

Taxa	Proportion
Ehu	0.020
Gindai	0.000
Hapuupuu	0.008
Kahala	0.057
Kalekale	0.000
Lehi	0.000
Onaga	0.043
Opakapaka	0.229
Taape	0.425
Uku	0.117
White ulua	0.076
Black ulua	0.001
Butaguchi	0.022

Table 4  
Proportion of reported commercial catch by species of snapper (Lutjanidae) for 1990

Taxa	Ehu	Gindai	Kahala	Kalekale	Lehi	Onaga	Opakapaka	Taape	Uku
Proportion	0.023	0.000	0.063	0.000	0.000	0.048	0.257	0.476	0.132

2. For 1990, we based our taxonomic assignments on the small-boat survey conducted by Hamm and Lum (1992). We used their data of expanded catches by taxa, converted to proportions of their expanded bottomfish catch (Table 3) to allocate the estimated recreational catch to BMUS taxa. These proportions were interpolated forward to 2002 to match the 2003 taxa specific data as described above. For the period 1950–1989, we allocated the estimated non-commercial catch data to the BMUS complex in proportion to the reported commercial data for BMUS taxa. The catch reported by Hamm and Lum (1992) as ‘other jacks’ (but excluding scads) was assigned to the three BMUS species of jacks based on the same proportions as used for the commercial catch allocation of ‘other jacks’ (Martell et al., 2006). The catch reported by Hamm and Lum as ‘other snappers’ was allocated to BMUS taxa based on the commercial proportions of all snapper taxa (Table 4).

### 2.3. Stock assessment

For our assessment to be comparable with the formal bottomfish stock assessments (e.g., Martell et al., 2006), we limited assessment to the BMUS complex (Table 1), both for the reported commercial data, and the combined total catch data.

For numerical stability, we used a semi-implicit Schaefer production model,<sup>1</sup> where initial biomass ( $b_1$ ) was set equal to the carrying capacity ( $k$ ):

$$b_{t+\delta} = b_t + rb_t\delta - rb_{t+\delta} \left(\frac{b_t}{k}\right) \delta - f_t b_{t+\delta} \delta, \quad (4)$$

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

$$b_{t+\delta} = \frac{b_t(1 + r\delta)}{1 + (r(b_t/k) + f_t)\delta}, \quad (5)$$

where  $r$  is the intrinsic rate of growth,  $\delta$  is the implicit time step ( $\delta = 1/2$ ), and  $f_t$  is the annual fishing mortality rate over the period ( $t, t + \delta$ ). Annual fishing mortality is represented by:

$$f_t = \frac{c_t}{b_t}, \quad (6)$$

where  $c_t$  is total catch in year  $t$ . Our modeling approach differed from traditional Schaefer production models, where carrying capacity  $k$  and intrinsic rate of growth  $r$  are used as leading parameters, often resulting in their estimates being negatively correlated (i.e., the population is large and not productive, or small and highly productive). To reduce correlation between  $r$

and  $k$  we used the US legislated policy parameters *Maximum Sustainable Yield* (MSY) and *fishing mortality rate to achieve MSY* ( $F_{MSY}$ ) as leading parameters, and derived  $r$  and  $k$ :

$$r = 2F_{MSY}, \quad (7)$$

and

$$k = \frac{4MSY}{r}. \quad (8)$$

This parameterization is useful in Bayesian analyses, as informative prior distributions for MSY can be developed from the observed catch data, here:

$$MSY \sim \log \text{ normal}(\ln(\bar{c}_t), 0.5), \quad (9)$$

and for  $F_{MSY}$ :

$$F_{MSY} \sim \log \text{ normal}(\ln(0.2), 0.015). \quad (10)$$

The model was conditioned on reported commercial catch data, and fit to observed commercial CPUE data. Commercial effort data since 1950, as number of trips based on monthly catch reports, were compiled from records provided by HDAR. We assumed a single trip was equivalent to a single day of fishing, a valid assumption for the MHI bottomfish sector (Moffitt et al., 2006). We also assumed that commercial CPUE was proportional to abundance of the BMUS complex:

$$CPUE = qb_t e^{\varepsilon_t}. \quad (11)$$

Further, we assumed log-normal observation errors  $\varepsilon_t$ . We used the maximum likelihood estimate (MLE) for the catchability coefficient  $q$  (see Walters and Ludwig, 1994):

$$q = \exp \left[ \frac{1}{n} \sum \ln(CPUE) - \ln(b_t) \right], \quad (12)$$

to reduce the total number of parameters being estimated to three (MSY,  $F_{MSY}$  and  $\sigma^2$ ). We conducted the assessment under two separate applications:

- Model 1. Reported commercial catch only; and
- Model 2. The sum of reported commercial and reconstructed recreational catch.

In model 2 we assumed effects of recreational catches on abundance were accounted for in the relative abundance index that was based on commercial information only.

### 2.4. Parameter estimation

We assumed that errors in the observed and predicted CPUE were log-normally distributed, and calculated the residuals  $v_t$

<sup>1</sup> Using the semi-implicit form avoids negative biomass estimates being generated by the difference equations. D. Fournier, Otter Research Ltd., P.O. Box 2040, Sidney, B.C., V8L 3S3, Canada, E-mail: otter@otter-rsch.com, http://otter-rsch.com/admodel.htm.

between  $z_t$  and  $\bar{z}$  as:

$$v_t = \ln(z_t) - \ln(\bar{z}), \tag{13}$$

where

$$z_t = \ln(\text{CPUE}) - \ln(b_t). \tag{14}$$

The negative log-likelihood of the data was given by the normal probability density function:

$$L(c_t, \varepsilon_t|\Theta) = \frac{n}{2} \ln(\sigma^2) + \frac{\sum_{t=1}^n v_t^2}{2\sigma^2}, \tag{15}$$

where  $n$  is the number of observations and  $\sigma^2$  is the estimated observation error variance. The objective function that was minimized included the likelihood of the data, plus informative prior distributions ( $P$ ) for  $\text{MSY}$ ,  $F_{\text{MSY}}$  and  $\sigma^2$ :

$$P(\Theta|c_t, \varepsilon_t) = L(c_t, \varepsilon_t|\Theta) + P(\text{MSY}) + P(r) + P(\sigma^2). \tag{16}$$

Marginal posterior distributions for parameters  $\text{MSY}$ ,  $F_{\text{MSY}}$ , and  $\sigma^2$  were constructed by sampling the joint posterior distribution using the Metropolis-Hastings Algorithm described in the *MCMCpack* package in *R* (Anonymous, 2006b). A total of 55,000 iterations were conducted, where the first 5000 iterations were discarded for burn in. A sample of 5000, systematically taken from every 10th iteration was used to construct the marginal posterior distributions for each estimated parameter. Running medians for each parameter trace were used to assess convergence of the MCMC algorithm. Marginal posterior distributions for  $r$  and  $k$  were also calculated using posterior samples of  $\text{MSY}$  and  $F_{\text{MSY}}$ .

### 3. Results

#### 3.1. Commercial catches

Commercial non-pelagic catches as reported by HDAR for the MHI ( $C_r$ ), indicated high catches in the early 1950s (approximately 800–1000 t year<sup>-1</sup>), declining sharply to approximately 600 t year<sup>-1</sup> by 1960 (Table 5, Fig. 1a). Since the late 1960s, reported commercial catches increased steadily (with inter-annual fluctuations) to a peak of approximately 1200 t year<sup>-1</sup> by 1989, before declining again to below 1000 t year<sup>-1</sup> by the early 2000s (Fig. 1a). The adjustments for under-reporting of commercial catches, using the adjustment ratios  $R_c$  (Table 2), suggested that total commercial catches ( $C_c$ ) were 28–128% higher than reported catches for any given year (Table 5, Fig. 1a). Thus, the peak in total commercial catches in 1989 may have been closer to 2300 t year<sup>-1</sup> (Fig. 1a).

This time series incorporated not only the deeper water bottomfish, but also commercial catches taken in shallow waters (e.g., coral reefs). The subset of reported catches that comprise the BMUS complex suggested a similar but more steady pattern, ranging from 200 t year<sup>-1</sup> in the early period to a peak of just under 500 t year<sup>-1</sup> in the late 1980s, before declining to around 150 t year<sup>-1</sup> by the early 2000s (Fig. 1a). It is uncertain, but possible that the proportion of unreported commercial catch from shallow water fishing is higher than from the deeper-water BMUS complex. For the subsequent stock assessment we utilized the reported commercial BMUS data only.

#### 3.2. Non-commercial catches

The estimation of non-commercial non-pelagic catches ( $C_n$ ) in the MHI suggested that catches increased from approximately 1800 t year<sup>-1</sup> in 1950 to a peak in 1986 of approximately 3000 t year<sup>-1</sup>, before declining in more recent years to just under 1700 t year<sup>-1</sup> (Table 5, Fig. 1b). Notable, however, is that total

Table 5  
Reported commercial catches ( $C_r$ ), by decade and 1989 peak year, for the Main Hawaiian Islands non-pelagic fisheries, and derived estimates of total commercial catches ( $C_c$ ), non-commercial catches ( $C_n$ ), and total catch (CT)

Year	Human population	MHI catch (t)			
		Reported commercial <sup>a</sup>	Total commercial <sup>b</sup>	Non-commercial <sup>c</sup>	Total <sup>d</sup>
		$C_r$	$C_c$	$C_n$	CT
1950	498,000	990	1,684	1,809	3,493
1960	642,000	578	1,099	1,014	2,113
1970	770,000	839	1,762	1,445	3,207
1980	694,691	885	2,035	1,714	3,750
1989	–	1,221	2,278	2,961	5,239
1990	1,112,703	994	1,987	1,963	3,950
2000	1,212,343	1,002	1,534	2,227	3,761
2002	1,240,663	748	1,144	1,695	2,840
Time series total		44,874	82,508	94,817	177,325

Human population data obtain from U.S. Census Bureau <http://www.census.gov>.

<sup>a</sup> Source: HDAR.

<sup>b</sup> Adjusted for unreported commercial catches via  $R_c$  from Table 2,  $R_c$  being linearly interpolated between data anchor point years.

<sup>c</sup>  $C_n = \text{CT} - C_c$ .

<sup>d</sup> Estimated from reported commercial catch via  $R_t$  from Table 2,  $R_t$  being linearly interpolated between data anchor point years.



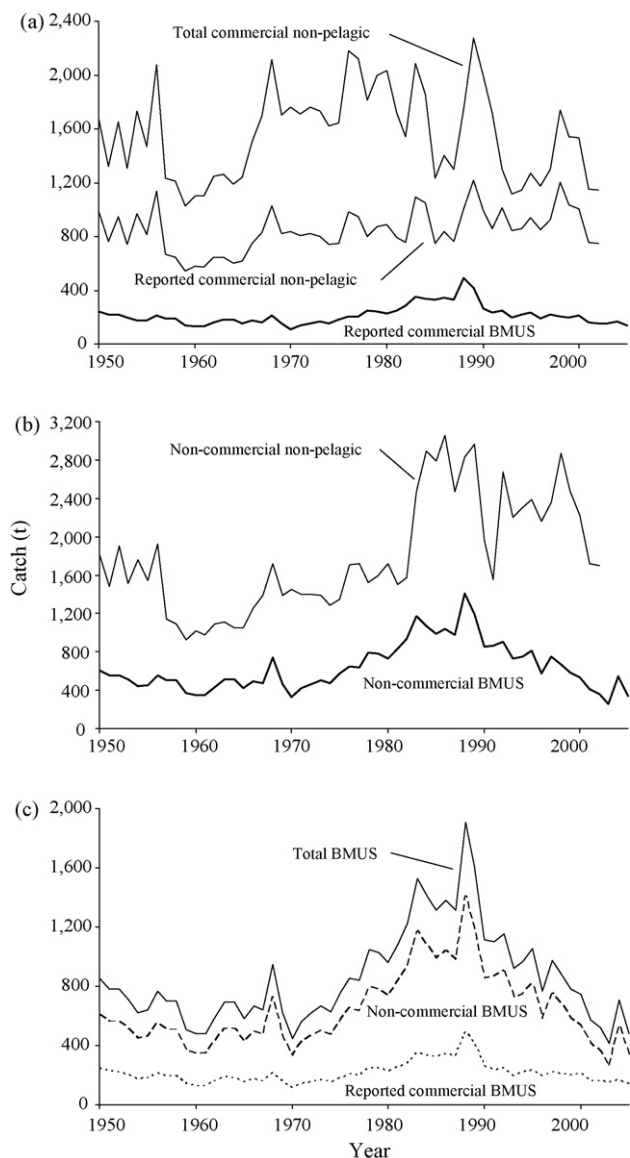


Fig. 1. Time series of non-pelagic fisheries catches for the Main Hawaiian Islands, consisting of (a) commercial catches reported by HDAR, including separate presentation of Bottomfish Management Unit Species (BMUS, a subset of reported commercial catches), and the estimated total commercial catches (i.e., including under-reporting adjustments); (b) indirect estimates of non-commercial catches for all non-pelagic taxa ( $C_n$ ) and subset of estimated non-commercial catches of the BMUS complex; and (c) summary presentation of reported commercial and reconstructed non-commercial catches for the BMUS complex used in the stock assessment analysis, as well as total BMUS catch estimates (ignoring likely under-reported commercial catches), illustrating the more rapid increase and decrease in non-commercial catches for the 1970–1980s and 1990–2000s periods, respectively.

non-commercial catches may have increased at a faster rate than reported commercial catches since 1960, suggesting an increasing impact of non-commercial fisheries on stocks. This is also true when comparing the non-commercial and commercially reported data for only the BMUS complex (Fig. 1c). Our estimates suggested that, averaged over the entire time period, the non-commercial catches were approximately 2.1-times higher than the officially reported catches, and when considering only the BMUS complex, non-commercial catches were 2.9 times

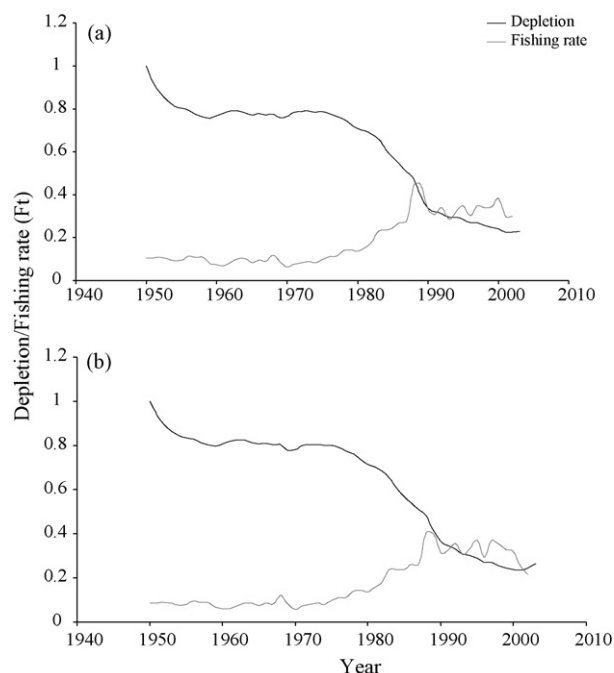


Fig. 2. Depletion and fishing rate trends for BMUS complex in the MHI for (a) model 1 (total catch = reported commercial catch); and (b) model 2 (total catch = reported commercial catch + non-commercial catch).

higher than the officially reported catches (Table 5). Allocation of estimated non-commercial catches to taxa constituting the BMUS complex suggested that non-commercial BMUS catches may have increased from approximately 350–600 t year<sup>-1</sup> during the early decades to a peak of approximately 1400 t in the late 1980s, before declining to around 300–500 t year<sup>-1</sup> by the early 2000s (Fig. 1b). Total BMUS catches (ignoring the likely under-reporting of commercial BMUS catches) may have peaked in the late 1980s at around 1900 t year<sup>-1</sup>, before declining to 400–700 t year<sup>-1</sup> by the early 2000s (Fig. 1c). For the stock assessment undertaken here, we utilized the combination of reported commercial and non-commercial BMUS data.

### 3.3. Total catches

The combined data (i.e., including commercial reporting adjustments) suggested that total non-pelagic catches (CT) peaked in 1989 with approximately 5200 t year<sup>-1</sup>, before declining to around 2800 t year<sup>-1</sup> by the early 2000s (Table 5). Overall, the official reported statistics may have underestimated total non-pelagic catches for the MHI by a factor of 3.9 over the full time period (Table 5).

### 3.4. Assessment results

Trends in depletion and fishing rates were similar for both model runs (Fig. 2), indicating that stocks had been depleted by approximately 20% over the course of the first 6 and 9 years of data for models 1 and 2, respectively (Fig. 2). Thereafter, the trend leveled off. A dramatic increase in the reduction of stocks occurred again in the 1980s, corresponding to increasing fish-

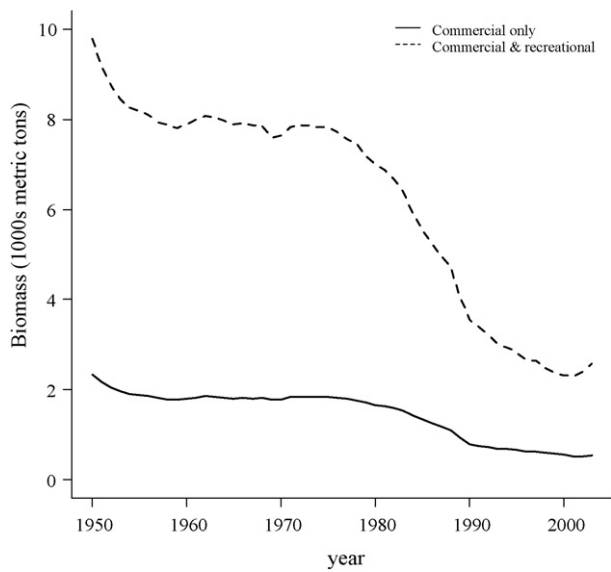


Fig. 3. Estimated biomass from model 1 (total catch = reported commercial catch) and model 2 (total catch = reported commercial catch + non-commercial catch) for BMUS species in the MHI.

ing rates (Fig. 2). In the 1990s and 2000s, depletion as well as fishing rates leveled off (Fig. 2). The depletion trends were similar to the biomass trajectory (Fig. 3). A pronounced decline in biomass was estimated to have occurred in the 1980s (Fig. 3) and corresponded with an increase in catch during this time period (Fig. 1c). The biomass estimates based on the reported commercial data increased by a factor of 4 when non-commercial catch estimates were incorporated into the model (Fig. 3).

The commercial BMUS CPUE data used to condition this model exemplified a ‘one-way trip’, where CPUE consistently declined over time (Fig. 4). When assessments rely on such data, leading parameters that represent population scale and productivity are completely confounded (i.e.,  $r$  and  $k$  have a strong negative correlation; for an example see Fig. 5b). However, estimates of MSY can be fairly well determined despite this strong confounding, if the absolute removals are known (Hilborn and Walters, 1992). Using MSY and  $F_{MSY}$  as leading parameters reduced this confounding.

Tables 6 and 7 summarize the posterior mean and 95% confidence interval estimates for MSY,  $F_{MSY}$ ,  $k$ , and  $r$ . Table 6 shows the results from model runs using different prior variances with a consistent prior mean for MSY and  $F_{MSY}$ . The posterior mean for MSY ranged from approximately 220–230 t and 950–970 t for models 1 and 2, respectively (Table 6). Regardless of the prior variance for MSY, the posterior mean was approximately four times greater when commercial and non-commercial data were combined to represent total catch than when using commercial data alone. The posterior mean for  $F_{MSY}$  ranged between 0.16 and 0.19 for models 1 and 2, respectively. The posterior mean for  $F_{MSY}$  increased by approximately nine percent when commercial and non-commercial data were combined. Carrying capacity  $k$  and intrinsic rate of growth  $r$  were calculated from the posterior estimates of MSY and  $F_{MSY}$  and showed similar trends to MSY and  $F_{MSY}$  when using the commercial only, and the combined commercial and recreational datasets (Table 7).

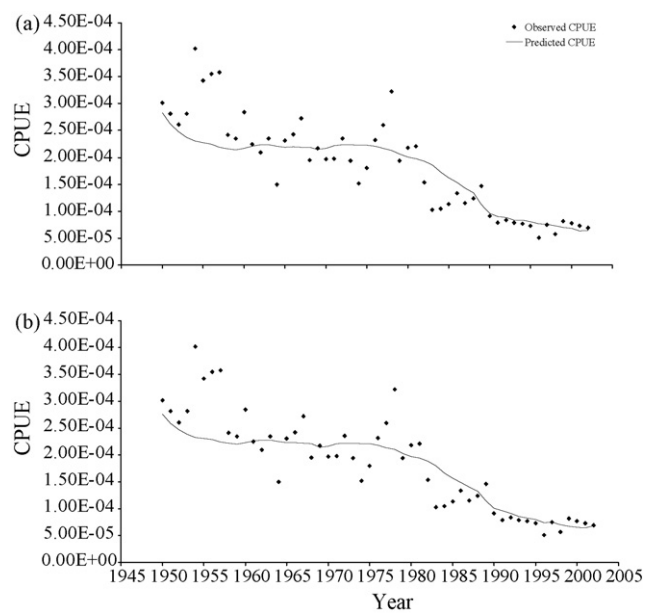


Fig. 4. Observed (●) and predicted (line) CPUE from (a) model 1 (total catch = reported commercial catch); and (b) model 2 (total catch = reported commercial catch + non-commercial catch) for BMUS species in the Main Hawaiian Islands.

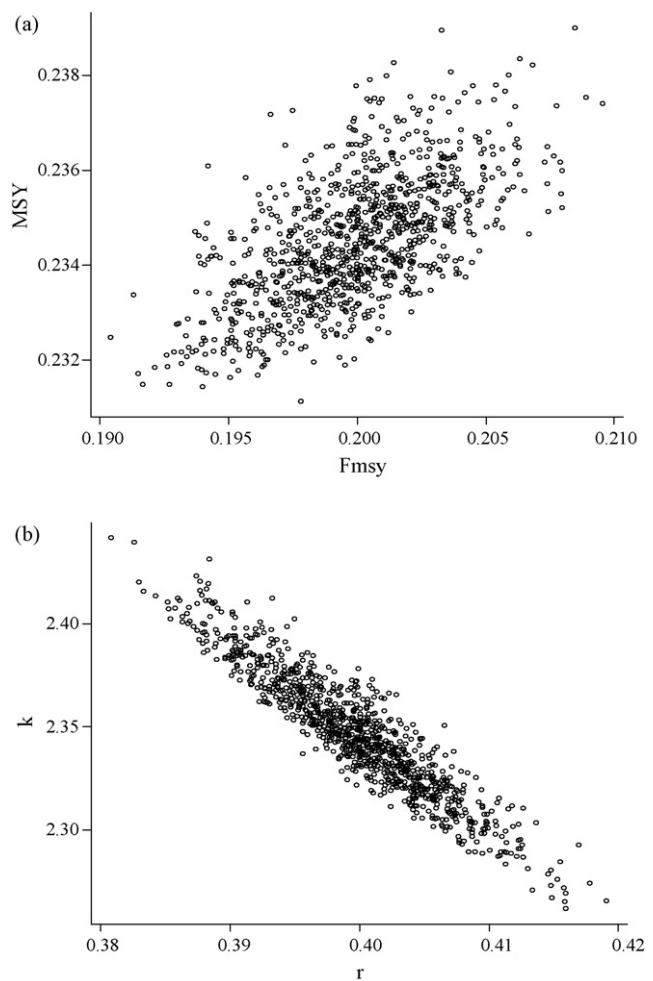


Fig. 5. Correlation plots of estimated (a) MSY and  $F_{MSY}$ ; and (b)  $r$  and  $k$  based on reported commercial data.

Table 6  
Summary of posterior mean and 95% confidence interval for MSY (kilotonne) and  $F_{MSY}$

Prior variance	Parameter	Data	Posterior mean	Lower 95% CI	Upper 95% CI
0.5 (MSY), 0.015 ( $F_{MSY}$ )	MSY	Commercial	0.2345	0.2321	0.2374
	MSY	Commercial and recreational	0.9790	0.9687	0.9917
	$F_{MSY}$	Commercial	0.1999	0.1939	0.2059
	$F_{MSY}$	Commercial and recreational	0.1999	0.1932	0.2058
0.5 (MSY), 0.2 ( $F_{MSY}$ )	MSY	Commercial	0.2234	0.2031	0.2435
	MSY	Commercial and recreational	0.9534	0.8612	1.0400
	$F_{MSY}$	Commercial	0.1656	0.1124	0.2412
	$F_{MSY}$	Commercial and recreational	0.1828	0.1202	0.2736
1.0 (MSY), 0.015( $F_{MSY}$ )	MSY	Commercial	0.2238	0.2018	0.2449
	MSY	Commercial and recreational	0.9791	0.9685	0.9908
	$F_{MSY}$	Commercial	0.1671	0.1098	0.2452
	$F_{MSY}$	Commercial and recreational	0.1999	0.1937	0.2061
1.0 (MSY), 0.2 ( $F_{MSY}$ )	MSY	Commercial	0.2238	0.2018	0.2449
	MSY	Commercial and recreational	0.9519	0.8645	1.0386
	$F_{MSY}$	Commercial	0.1671	0.1098	0.2452
	$F_{MSY}$	Commercial and recreational	0.1812	0.1209	0.2644

The prior means for MSY and  $F_{MSY}$  were the log of mean MSY and  $\log(0.2)$ , respectively, for all trials.

Table 7  
Summary of posterior mean and 95% confidence intervals for carrying capacity ( $k$ ) and intrinsic rate of growth ( $r$ )

Parameter	Data	Posterior mean	Lower 95% CI	Upper 95% CI
$k$	Commercial	2.346	2.289	2.407
$k$	Commercial and recreational	9.795	9.441	10.233
$r$	Commercial	0.390	0.388	0.412
$r$	Commercial and recreational	0.390	0.382	0.419

The mean carrying capacity was estimated at 2346 t and 9795 t for models 1 and 2, respectively. However, the mean intrinsic rate of growth ( $r$ ) was 0.39 for both models.

## 4. Discussion

### 4.1. Catches

The estimation approach we used for historic non-commercial catches in the MHI area suggested that these catches, being 2.1 times higher than reported commercial catches over the entire time period, may be of greater importance in determining total catch levels than previously considered. The apparent faster changes in catches over time of the non-commercial sector indicated that this sector is important with regards to catch monitoring and assessment requirements, and thus requires more management attention and consideration.

The catch estimates documented here provide the first attempt to quantify total catches of non-pelagic species on a large-scale basis for Hawaii. Although we presented these catches only for the MHI, state-wide estimates are presented by Zeller et al. (2005, 2007b). However, as non-commercial fishing for bottomfish is absent from the NWHI, we excluded these data here. While several studies have estimated non-commercial catches on a spatially and temporally limited scale (e.g., Hamm and Lum, 1992), none have attempted to expand their estimates MHI-wide. Our study suggested that total non-pelagic catches

(including commercial reporting adjustment) in the MHI may have been 3.9 times higher than reported data suggested. Future estimates of non-commercial fisheries catches, possibly provided by an improved Marine Recreational Fishery Statistics Survey (<http://www.hawaii.gov/dlnr/dar/surveys/>) should shed better light on the magnitude of present day non-commercial non-pelagic catches. Such data are crucial in view of growing demands for better public accounting of resource use, increasing evidence of the indirect economic contribution of un-accounted sectors (Zeller et al., 2006b), and the shift towards ecosystem-based management (Pikitch et al., 2004). Better validated estimates have to be taken into consideration in future stock assessments (as also suggested by Martell et al., 2006), likely in conjunction with the more uncertain historic estimates for non-commercial catches as presented here.

The problem of missing data in catch reporting is not restricted to Hawaii, but is rather a global issue (Bray, 2000; Zeller and Pauly, 2005), driven by historic misperceptions of key fisheries impacts, and the associated economic drivers on which sectors were historically mandated to report catches (i.e., focusing on large-scale, commercial operations). Therefore, so-called 'small-scale' fisheries sectors, either in the form of subsistence fisheries (Zeller et al., 2006a; Zeller et al., 2007a), or recreational fishing (as presented here) do not usually form part of comprehensive data collection or estimation frameworks (let alone formal stock assessments). Hence, they generally do not contribute directly to the management framework. This



likely contributes to erroneous assessments of resource status, and is increasingly recognized as a stock assessment challenge (Walters and Martell, 2004).

#### 4.2. Stock assessment

If our estimates of non-commercial catches of the BMUS complex (despite high uncertainty) would have been considered in the formal stock assessment of Martell et al. (2006), the consequences of ignoring the recreational component of the fishery were likely to produce an underestimate of MSY that could be achieved in the (combined) fishery. When using the combination of commercial and non-commercial catch data, the MSY estimates were four times greater (950–970 t) than either the current assessment using only commercial catch data or results in Martell et al. (2006). Total catch was increased by 2.5–3.5 times with the addition of non-commercial BMUS catch estimates, which in turn increased model estimates of MSY and  $k$  by approximately four times compared to analyses with reported commercial data alone. Conversely, we detected no appreciable difference in  $F_{MSY}$  or  $r$  between the models, as the CPUE data lacked information to resolve the confounding between large, unproductive and small, productive stocks.

Given the one-way declining CPUE data, the parameters representing population size (here MSY) and productivity (here  $F_{MSY}$ ) were positively correlated (Fig. 5a). Due to lack of contrast in CPUE, it is difficult to resolve where along this correlation contour the most likely parameter values lie. Furthermore, as these data were not informative, it was necessary to use a relatively informative prior on at least one of the leading parameters ( $F_{MSY}$ ), resulting in the estimated  $F_{MSY}$  being highly influenced by the assumed prior distribution.

Importantly, the MSY estimates from the present analysis (commercial data only; 218.2–243.6 t) were comparable to those from Martell et al. (2006), i.e., 220–230 t. In the current analysis, we used MSY as a leading parameter, whereas in Martell et al. (2006) MSY was derived from the posterior estimates of  $r$  and  $k$ . When using  $r$  and  $k$  as leading parameters in surplus production models, they are usually negatively correlated and lead to rather precise estimates of MSY (Walters and Martell, 2004). Hence, this may explain why the estimated range of MSY from Martell et al. (2006) is smaller than the estimated range from the present study. The estimate of  $k$  from the current analysis (2346 t) was larger than the estimates of 1600–1910 t from Martell et al. (2006), likely due to the negative correlation between  $r$  and  $k$ . Their estimate of  $r$  was approximately 0.52, which would lead to smaller values for  $k$ .

Of importance also is the fact that the estimated non-commercial catch data are not independent of the commercial data, due to the reconstruction approach using ratio estimates based on reported data. Future non-commercial catch data, relying on independent sampling (e.g., improved Marine Recreational Fisheries Survey) could correct this situation for recent years. In this context it cannot be understated how important such independent estimates are. Also crucial are independent estimates of biomass, relative abundance, or exploitation rates (see Martell et al., 2006). Such information would drastically

improve assessments and resolve parameter confounding. Failure to account for all catches and to obtain independent estimates of either biomass or exploitation rates (Walters and Martell, 2004) will increasingly exacerbate fisheries management failure, and hence continue to erode public trust in management practices. Increasingly, commercial fisheries are entering rebuilding phases because stocks are progressively overfished (Rosenberg et al., 2006). Similar to most stock assessments, fishery rebuilding plans usually ignore the impact of non-commercial fisheries, which may lead to unintended results. The main aim of most rebuilding plans is to decrease commercial effort and in turn increase a stock's biomass. Unmanaged recreational effort, however, could usurp the reduction in commercial effort, and biomass would continue to decline. This has been demonstrated, for example, for the Florida pompano (*Trachinotus carolinus*) fishery (Walters and Martell, 2004).

The present study, by relying on estimation approaches, suggested that non-commercial non-pelagic catches contributed substantially to total catches, and illustrated clearly the urgent need to address the long-standing neglect by most countries to account or estimate all catches being taken by all fisheries sectors (e.g., Zeller et al., 2006a, 2007a). Reliable stock assessments informing potentially sustainable policy options cannot be undertaken in the absence of 50% or more of relevant data (see Martell et al., 2006), and is further hampered by absence of fisheries independent data (Walters and Martell, 2004).

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#### References

- Anonymous, 2004. Bottom fish and seamount groundfish fisheries of the Western Pacific region, 2002 Annual Report. A report of the Western Pacific Regional Fishery Management Council, NOAA award Number NA07FC0025, Honolulu, p. 174.
- Anonymous, 2006a. President's rules for NWHI: unfair to fishermen? In: Pacific Islands Fishery News, Fall 2006. Western Pacific Regional Fishery Management Council, Honolulu, pp. 1–2.
- Anonymous, 2006b. R: A language and environment for statistical computing, V2.4.0. R Development Core Team, R Foundation for Statistical Computing, Vienna, Austria.
- Bray, K., 2000. A global review of Illegal. In: Unreported and Unregulated (IUU) fishing. Food and Agriculture Organization (FAO), AUS:IUU/2000/6, Rome, p. 53.
- Everson, A., Friedlander, A., 2004. Catch, effort, and yields for coral reef fisheries in Kane'ohe Bay, O'ahu and Hanalei Bay, Kaua'i: a large urban and a small rural embayment. In: Friedlander, A.S. (Ed.), Status of Hawaii's Coastal Fisheries in the New Millennium, revised 2004 edition. Proceedings of the 2001 fisheries symposium sponsored by the American Fisheries

- Society, Hawaii Chapter. Hawaii Audubon Society, Honolulu, Hawaii, pp. 108–128.
- Friedlander, A., Parrish, J.D., 1997. Fisheries harvest and standing stock in a Hawaiian bay. *Fish. Res.* 32, 33–50.
- Hamm, D., Lum, H.K., 1992. Preliminary results of the Hawaii small-boat fisheries survey. Southwest Fisheries Center, National Marine Fisheries Service, Administrative Report H-92-08, Honolulu, p. 35.
- Hilborn, R., Walters, C.J., 1992. Quantitative fisheries stock assessment. In: Choice, Dynamics and Uncertainty. Chapman & Hall, New York.
- Lowe, M.K., 2004. The status of inshore fisheries ecosystems in the main Hawaiian Islands at the dawn of the millennium: cultural impacts, fisheries trends and management challenges. In: Friedlander, A.s. (Ed.), Status of Hawaii's Coastal Fisheries in the New Millennium, revised 2004 edition. Proceedings of the 2001 fisheries symposium sponsored by the American Fisheries Society, Hawaii Chapter. Hawaii Audubon Society, Honolulu, Hawaii, pp. 12–107.
- Martell, S.J., Korman, J., Darcy, M., Christensen, L.B., Zeller, D., 2006. Status and Trends of the Hawaiian Bottomfish Stocks: 1948–2006. Report to NOAA NMFS Pacific Islands Fisheries Science Center. University of British Columbia Fisheries Centre, Vancouver, p. 55.
- Moffitt, R.B., Kobayashi, D.R., DiNardo, G.T., 2006. Status of the Hawaiian Bottomfish Stocks, 2004. Administrative Report H-06-01. Pacific Islands Fisheries Science Center, National Marine Fisheries Service, NOAA, Honolulu, p. 45.
- Pikitch, E.K., Santora, C., Babcock, E.A., Bakun, A., Bonfil, R., Conover, D.O., Dayton, P., Doukakis, P., Fluharty, D.L., Heneman, B., Houde, E.D., Link, J., Livingston, P.A., Mangel, M., McAllister, M.K., Pope, J., Sainsbury, K.J., 2004. Ecosystem-based fishery management. *Science* 305, 346–347.
- Polovina, J.J., 1987. Assessment and management of deepwater bottom fishes in Hawaii and the Marianas. In: Polovina, J.J., Ralston, S.s., s (Eds.), Tropical Snappers and Groupers. Biology and Fisheries Management. Ocean Resource and Marine Policy Series. Westview Press, Boulder, pp. 505–532.
- Pooley, S.G., 1993. Hawaii's marine fisheries: some history, long-term trends, and recent developments. *Mar. Fish. Rev.* 55, 7–19.
- Rosenberg, A.A., Swasey, J.H., Bowman, M., 2006. Rebuilding US fisheries: progress and problems. *Front. Ecol. Environ.* 4, 303–308.
- Walters, C., Ludwig, D., 1994. Calculation of Bayes posterior probability distributions for key population parameters. *Can. J. Fish Aquat. Sci.* 51, 713–722.
- Walters, C.J., Martell, S.J., 2004. Fisheries Ecology and Management. Princeton University Press, Princeton.
- Zeller, D., Booth, S., Craig, P., Pauly, D., 2006a. Reconstruction of coral reef fisheries catches in American Samoa, 1950–2002. *Coral Reefs* 25, 144–152.
- Zeller, D., Booth, S., Davis, G., Pauly, D., 2007a. Re-estimation of small-scale fisheries catches for U.S. flag island areas in the Western Pacific: the last 50 years. *Fish. Bull.* 105, 266–277.
- Zeller, D., Booth, S., Pauly, D., 2005. Reconstruction of coral reef- and bottom-fisheries catches for U.S. flag island areas in the Western Pacific, 1950 to 2002. Report to the Western Pacific Regional Fishery Management Council, Honolulu, p. 110.
- Zeller, D., Booth, S., Pauly, D., 2006b. Fisheries contributions to GDP: underestimating small-scale fisheries in the Pacific. *Mar. Resour. Econ.* 21, 355–374.
- Zeller, D., Booth, S., Pauly, D., 2007b. Historic catch reconstruction for coral reef- and bottom-fisheries in the State of Hawaii, 1950–2002. Working Paper #2007–06, The University of British Columbia, Vancouver, B.C., Canada [Available at: <http://www.fisheries.ubc.ca/publications/working/index.php>], Vancouver, p. 24.
- Zeller, D., Pauly, D., 2005. Good news, bad news: global fisheries discards are declining, but so are total catches. *Fish Fisheries* 6, 156–159.