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Indian Ocean Kawakawa Assessment : Examining alternative data poor approaches

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Abstract

CPUE data derived from the Kawakawa CPUE standardization was used in Surplus Production model assessment. Non-informative priors were used on r, and K, assuming the population was at K when the catch time-series begins in 1950. Catch data was used from 1950 and key reference points, namely S_{MSY} & MSY were estimated using the SIR algorithm. Since there is limited information on the CPUE dataset, the range of estimates on reference points is large. The stock status appears to be healthy and not overfished based on the time-series used, though the model has convergence issues, and has a high degree of confounding in r and K estimates. Informative priors help the model converge, though the model is influenced to large extent by these priors. Due to the lack of contrast in the index of abundance data over the period examined, the model has difficulty estimating S_{MSY}, though can still be useful for evaluating stock status and optimal yield targets. The results from the standard approaches are compared to 2 other methods, namely a stock reduction approach with assumed depletion values at different times in the stock trajectory, and a newly developed posterior-focused catch-based assessment method. Both methods are based on a classical biomass dynamics model, requires only catch history but not fishing effort or CPUE. Known population growth rate will improve the assessment result. We use recently updated catch data in the analysis. The preliminary results show that for Kawakawa the median virgin biomass is about 358-408 thousand tonnes depending on the upper depletion level assumed in 2011. The combination of such carrying capacity and growth rate can support a maximum sustainable yield (MSY) of 113-136 thousand tonnes using a new posterior focussed stock reduction analysis technique. This means that catch levels in recent year may have exceeded MSY, and management should be proactive in controlling catches, and protecting the long-term yield of the stock and the overall resource.

Introduction

Most fisheries in the world have limited information for management (Pauly et. al. 2009, Hilborn and Ovando 2014). In the case of the Indian ocean, artisanal fisheries operating on the vast coastlines of Asia and Africa bordering the Indian Ocean is of primary concern as catches keep increasing in these fisheries, and limited information is available for estimating abundance and productivity trends (Parma et. al. 2003) through traditional assessment approaches. The trend in Asia and other lesser developed economies with limited data (Parma et. al. 2003) was to use equilibrium assumptions and simplified approaches like those proposed in the 1980's (Pauly 1983). This was then made accessible to multiple users through user friendly software (Sparre and Venema 1992), and lead to misleading results that could be overly optimistic/pessimistic on stock status without much information on abundance or dynamic catch trends (Parma et. al. 2003).

In recent years numerous approaches have been developed to address these data limited approaches that primarily deal with either life history based approaches (Zhou et. al. 2011), or catch based approaches (Martell and Froese 2012). In Australia, the Commonwealth harvest strategy has devoted a lot of effort to address these issues. Methods developed by CSIRO (draft report "Quantitatively defining biological and economic reference points in data poor fisheries" by Zhou et. al. 2013) highlights some methods developed for data poor fisheries using data rich fisheries as a testing platform.

The species examined in this paper is Indian Ocean kawakawa, which has shown an alarming trend of increasing catches since 2006 (IOTC 2013). Kawakawa (*Euthynnus affinis*) is found in multiple areas of the Indian Ocean along with other neritics (Figure 1). Kawakawa occurs in open waters but always remains close to the shoreline. They tend to form multi-species schools by size with other scombrid species comprising from 100 to over 5,000 individuals (Collette and Nauen 1983). They are a highly opportunistic predator feeding indiscriminately on small fishes, especially on clupeoids and atherinids; also on squids, crustaceans and zooplankton (Collette 2001, Fish Base). Although primarily distributed in the central Pacific, it is an important fishery for numerous countries in the Indian Ocean region, namely Iran, Indonesia, India, Malaysia, and Thailand. Numerous other countries also catch the species (Figure 2a). The species is primarily caught by Purse Seine and gillnets, but other gears are also used to catch the species (Figure 2b). The countries that are the primary users of the resource are India, Indonesia and Iran. An attempt to re-estimate the catches across the region is being undertaken in the Indian Ocean region, and it is likely that some of the numbers reported will be revised (Table 1).

Numerous methods are developed in this paper to examine the status of this stock. We examine traditional assessment approaches using the surplus production model, and compare it to the data poor approaches developed (Kimura and Tagart 1982, Walters et. al. 2006). One of the new methods developed is a posterior-focused catch-based assessment. The basic idea is similar to the Stock reduction Analysis (Kimura and Tagart 1982; Walters et. al. 2006; Martell and Froese 2012). The technique builds on simple surplus production models (like Shaefer, 1954), that uses removal data and some estimate of carrying capacity and population growth rate. Ideally, these models should have some measure of abundance in one or more recent years. However, with a reasonably assumed upper limit on depletion level and population growth rate, it is possible to derive biological parameters using catch data alone, particularly MSY. In addition to this approaches, a standard stock assessment was also conducted for Indian Ocean kawakawa, (*Euthynnus affinis*) using a surplus production model and an index of abundance developed using the Maldives Pole and Line fisheries in the Indian Ocean region. However, as will be evident the assessment conducted using this series (Sharma and Zhou 2013) was non-informative and the paper compares standard Biomass dynamic models with informative and non-informative priors to a standard stock reduction based approach, and a posterior focussed catch reduction based approach.

Material and Methods

<u>Catch Data</u>

As is evident from the figures, catch trends have increased in recent years primarily due to increases in effort by Iran and Indonesia (Table 1). In recent years due the effect of piracy off the coast of Somalia, effort has been concentrated and redirected from Tropical Tunas to local neritic's by the countries of Iran, Pakistan and other Arabian gulf countries. These catches in recent years (2006-2011) have increased by 50%, and thus an attempt to understand the effect of these increased catches on the species is attempted in this paper.

CPUE Indicators

GLM-based standardization of the Maldivian kawakawa (*Euthynnus affinis*, KAW) pole and line fishery catch rate data were examined for the period 2004-2011 (Figure 3). The raw data consists of around 124000 records of catch (numbers) and effort (fishing days) by month, atoll and vessel; vessel characteristics were added to the CPUE dataset based on information from the registry of vessels. A subset of 25,762 records were extracted from the dataset, identified as records of fishing activity targeting KAW. Fisheries Aggregating Devices (FAD) data was also incorporated into the analysis using the number of active FADS associated with the nearest atoll that the landing data is collected from. Techniques similar to those used in the standardization of skipjack tuna were used (Sharma et. al. 2013). The distribution of FADs was split into three regions incorporating the North Atolls, Middle

Atoll and South Atolls. Vessel specific data including hull-type effects, length of the boat (as a vessel size class) and horse power was also used in the analysis. GLM based models using a log response on CPUE were examined. The final model presented estimated log(CPUE) from independent variables Year, Month, Area (N, S, or M), number of FADs used in the area, and Length of vessel, and interaction effects between the last 3 categories. The data was analysed at a monthly resolution before being was collapsed into quarterly signals for 2004-2011, and finally an annual signal 2004-2011 for analysis in KAW surplus production assessment fit to the CPUE series derived here (Figure 3).

Methods

SIR and Surplus Production Model with Non-informative & Non Informative Priors

The model developed is a simple Graham-Schaeffer Surplus Production model (Logistic Model, Schaeffer 1954), and estimates two parameters r and K (eq. 1, Haddon 2011, Hilborn and Walters 1992) fit to estimated Biomass.

$$B_{1950} = K \qquad (1)$$

$$B_{t+1} = B_t + \left(rB_t\left(1 - \frac{B_t}{K}\right) - C_t\right) \qquad (2)$$

$$B_t = \frac{I_{t,f}}{q_{t,f}} \qquad (3)$$

Closed form solution of q was used (eq. 4)

$$\hat{q}_{t,f} = \exp\left(\frac{\sum_1^n ln\left(\frac{\hat{B}_t}{I_t}\right)}{n}\right) \qquad (4)$$

Where q is the catchability in the fleet, r is the intrinsic growth rate, and K is the carrying capacity assumed when the time series begins in 1950. The state variables are Biomass (B) and this is a function of r and K. The parameter, r, k and q are estimated by fitting the estimated Biomass using equation 2 to the observed index of abundance, based on the catch and series.

The Likelihood Equations used a log-normal error structure for the catch and normal error structure for the Index of abundance (eq. 5):

$$-\ln L(\underline{\theta} \mid I_{t,f}) = \sum_{f=1}^{n} \ln(\sigma_f) + \frac{\ln((B_{t,f}) - \ln(\hat{B}_{t,f}))^2}{2\sigma_f^2} \qquad (5)$$

where $\underline{\theta}$ is the set of parameters, namely (r, K, and q, which may be fishery and block specific) that are estimated to get the best fit by minimizing the negative log-likelihood function (eq. 6 above) fitting to the Biomass using the index of abundance, and q.

Since r and K are highly correlated, we used non-informative Uniform priors on each parameter and the SIR algorithm (Rubin 1988) to estimate the uncertainty in r, K and derived parameters of interest B_{2011}, B_{MSY} and MSY. In addition we computed two ratios, B_{2011}/ B_{MSY} and C_{2011}/ C_{MSY} to evaluate the current status of the stock relative to these target reference points.

<u>Priors on r and K</u>

We initially fit the model using the MLE solution, but due to parameter confounding observed a surface that had a number of solutions that could best fit the data (Figure 4). Based on this r could be anywhere from 0.4-1.8 and K anywhere from 1.4 M tons to >2.6 M tons. As a result, we ran the SIR algorithm with uniform priors on r and K; r ~ U [0.2, 2.2] and K ~ U [120k, 4.12 M]. Informative priors were also run as a comparison with normal priors on r and K; r~N(1.2, 0.1) and K~N(800,200).

Surplus production Model using Catch data Only (Stock Reduction Model).

This simple model (eq. 2) was used in this analysis. It has two unknown parameters, r and K. We set reasonably wide prior range, for example, K between C_{max} and 500 * C_{max}. We used the approach proposed in Martell and Froese (2012) for "resiliency" estimates that tied to the productivity parameter r (low resiliency levels indicated r between 0.05-0.5, medium resiliency indicated a r between 0.2-1, and high between 0.5-1.5). These were compared to values obtained in the literature and alternative methods.

We run model (eq. 2) to find all mathematically feasible *r* values by searching through wide range of Ks for all depletion levels. The model begins at K in 1950 (eq.1). If the feasible choice of r and k chosen meets the intermediate (0.1 and 1 level of depletion in 1980), and last point depletion levels (the range specified was 0.3-0.7 level of depletion for Kawakawa) it is kept. The summary of all runs which meet these criteria are then used, and geometric mean values are reported to be the better representation of yield targets (Martell and Froese 2012). Biological parameters, including K, r, MSY, are derived from the retained pool of [r, K] values. The geometric mean values of these are then used to assess the stock dynamics over time and reported using a phase plot.

Posterior Focussed Stock Reduction Approach (Adapted SRA as developed by Zhou and Sharma 2013).

We again used the Graham-Shaefer surplus production model shown in equation 2 above (Shaefer 1954). This simple model has two unknown parameters, r and K. We set reasonably wide prior range, for example, K between C_{max} and 500 * C_{max}. We use six methods to derive possible range for the intrinsic population growth rate r. Note, that the model assumes a carrying capacity when the first data point is estimated in 1950 (eq. 1), i.e. the model begins at K in 1950 (eq.1).

r from literature (fishbase.org).

$r = 2\,\omega M$, where M is obtained from literature and $\omega = 0.87$ is a scale linking Fmsy to M for teleosts (Zhou et al. 2012).

$r = 2\,\omega M$, where $\ln(M) = 1.44 - 0.982 \ln(t_m)$ (eq. 6, Hoenig 1983).

$r = 2\,\omega M$, where $\log(M) = 0.566 - 0.718 Log(L_\infty) + 0.02T$ (eq. 7 from www.Fishbase.org)

$r = 2\,\omega M$, where $M = 1.65/t_{mat}$ (eq. 8, Jensen 1996).

$r = 2\,\omega$ M, where $\ln(M) = 0.55 - 1.61 \ln(L) + 1.44 \ln(L_\infty) + \ln(\kappa)$ (eq. 9, Gislason et al. 2010).

$r = 2\,\omega$ M, where $M = (L/L_\infty)^{-1.5}\,\kappa$ (eq. 10,Charnov et al. 2012).

In these equations, r is the intrinsic population growth rate, κ and L_∞ are von Bertalanffy growth parameters, T = average annual water temperature, t_m = maximum reproductive age, and t_{mat} = average age at maturity. The range (min to max) from these methods is used as prior for Model 1. Further, we set up a series of assumed depletion level $D = B_T/K$, e.g., $D = 0.02$ to 0.80. Here B_T is the assumed true biomass at the end of the time series. It is unlikely that the any tuna stock has biomass greater than 80% of unfished virgin population size.

We run model (eq. 2) to find all mathematically feasible r values by searching through wide range of Ks for all depletion levels. Optimization routine is used by minimizing objective function $|B_{end} - DK|$, where B_{end} is the simulated final year biomass (i.e., at the end of time series t).

Biological parameters, including K, r, MSY, are derived from the retained pool of [r, K] values. Using these K, r, and known catch, stochastic simulations are carried out by re-running Model (1) without any further restrain. From a large number of simulations (e.g., 1000), biomass trajectories, as well as ending biomass and depletion level are stored. Not all iterations may be viable. Some simulations may result in $B_t \leq 0$ (extinction) before the end of the time series. These iterations are removed while the remaining viable quantities are used for parameter references.

Results

Sample Importance Resample (SIR) using non-informative and informative priors on r and K

The data from the CPUE standardization process (Figure 3b) is flat between 2004-2011, and is such is not informative as the catch trends increase significantly during the same period (Figure 2b).Using non-informative priors on r and K and the standard surplus production models, we observe that we have very little information on r and K (Figure 5, Table 2). However, nonetheless based on these non-informative priors still give us some information on the target reference points like maximum yield (Figure 5), and currents stock status (Table 2). Since information on r, and K is non-informative, SB_{2011} is also uninformative. Note, that the values for yield seem unrealistically high (between 178-1386 Kt).

As a result, we used informative priors on r and K (Figure 6, Table 3), which gave us a fairly optimistic picture on the stock. This is primarily based on the flat CPUE series generated through the standardization (Figure 3b). However, Maldives CPUE series may not be fully representative of the Indian Ocean stock as it accounts for less than 5% of the overall landings and the overall Indian ocean catches have almost doubled in magnitude from 2005 to 2011. In addition, if we change the priors on r, we can get very different outcomes in the results (not shown here). Values of maximum yield are still too high (between 164 Kt- 354 Kt), and thus alternative catch based approaches are used.

Stock Reduction Approach (SRA)

Using deterministic projections on catches (i.e. without uncertainty), and assumptions on Carrying capacity and r, we can build multiple stock trajectories that fit the criteria defined in the methods section (namely that depletion is between 0.1-1 in 1980 and between 0.3 and 0.7 in 2011). Stock trajectories are not shown, but the resulting overall biomass trajectory indicates that the population size could be anywhere from 0.8 to 1.5 of optimal Biomass for maximum yield. Based on this model the optimal yield targets maybe exceeded in recent years as it shows a median estimate of 132 Kt (range 0f 101 Kt-161 Kt, Figure 7). As shown before there is a high amount of parameter confounding with r and K (Figure 7a), though marginal distributions for r and K (Figure 7b, and Figure 7c) can then be estimated over all possible runs (9054 possible combinations fit these criteria shown above). Since the criteria of what we fit is quite broad and we use the data on catch without error, there is a broad range of results seen over all runs analysed, and thus there is quite a large amount of uncertainty in current biomass levels and fishing mortality (Table 2). Regardless, the approach however provides reasonable rates for target yields and at that level maybe a useful management tool when other information on abundance is missing.

Posterior Focussed Stock reduction Approach (PFSRA)

Six methods were used to estimate r, that ranged from 1.056 to 2.04 for kawakawa (based on eq. 6-10). We first explored how assumed depletion may affect the result. We used eight assumed depletion level in 2011: 0.1, 0.2,…0.8 (Figure 8). The results indicate that with the r range used, the population must have been greater than 30% of unfished level in 2011. Typically, the key parameters (i.e., K, r, MSY) have to be larger to maintain a higher population (i.e., larger depletion, D relative to initial Biomass in 1950).

We then used depletion level between 0.02 and 0.80 at a step of 0.02 in Model 1 and combined all feasible results (Figure 9). The possible unfished population may range from about 300 thousand ton to nearly 800 thousand ton (Figure 9). The lowest possible depletion level is 0.38. At this depletion level, 2 data points are retained: r = 1.11, K = 393617, and r = 1.06, K= 409353.

Since within the assumed depletion levels the upper limit has some effect on the result, we tested the sensitivity by three alternative upper limits: *D* = 0.80, 0.70, and 0.60. Again, assuming a higher D results in a higher r, K, MSY, B_{2011}, and D_{2011} (Table 3). However, the magnitude appears to be relatively small. For example, for the three assumed upper depletions, MSY is about 151, 135, and 128 thousand tons, respectively (Table 3).

While the catch increases over time, biomass continues to decline (Figure 10a). To evaluate management strategy, we investigated two hypothetic harvest levels for the next 10 years. This exercise is based on the conservative upper depletion level **<u>D = 0.6</u>**. First, we assumed catch remains at 2011 level from 2012 to 2021 (Figure 10a). The projected biomass trajectories show a quick depletion of the population. Hence, the catch level in 2011 appears to be unsustainable. We then assumed that annual catch is 100 thousand tonnes for the next 10 years (Figure 10b). This results in a very different picture. The population recovers to a higher level and becomes stable after about 7 or 8 years.

Discussion

As noted by Parma et. al. (2003), "*Uncertainty and information quality can be viewed as a continuum ranging from very data-rich situations to total lack of information. In theory, harvest targets could be adjusted along this gradient according to any given degree of risk-aversion. Consideration of other fisheries attributes beyond data availability, however, shows that data-poor cases are not a random set of all fisheries. Rather, data poverty tends to be associated with some structural features of the system, which compound the management problem and require qualitatively different solutions.*"

With respect to the above statement and Indian Ocean fisheries, we realize that the information content, other than overall catch is not systematically collected over time. Traditional approaches of assessment like those used in standard integrated assessments rely on a standardized index of abundance that is representative of the stock being analysed. In our case the index is based on a very small proportion of the catch being caught and is probably not a good indicator of abundance. Species, such as kawakawa, account for 10% of the overall catch in the Indian ocean, with other coastal tuna (Neritics) accounting for almost 33% of the catches in the Indian Ocean. Unlike tropical tuna (like yellowfin/bigeye account for another 30% with skipjack another 30%) normally have systematic sampling programs for the major fleets (longline, purse seine and pole and line for skipjack) that collect size-based data, as well as estimated index of abundance that is used in estimating biomass trajectories over time; neritic tuna only report catch, are caught in small subsistence fleets, and have no systematic sampling on other components of the catch information. As noted, before, the normal approach in these countries and regions with limited data (Parma et. al. 2003) was to use equilibrium assumptions and simplified approaches like those proposed in the 1980's (Pauly 1983), which often lead to misleading conclusion of the stock status. Given the importance of these fish to coastal communities, management advice needs to be generated for the coastal communities, and thus an attempt to integrate information using alternative approaches is made in this paper.

Based on the trajectories that is actually estimating fishing mortality (Table 3, PFSRA approach), we can project what may happened to the stock over time given a certain projected catch. Based on PFSRA based approach (Figure 10), it appears that the catches in recent years maybe unsustainable and the stock maybe experiencing some overfishing (Table 2, Figure 10). Catches should be in the vicinity of 110-130 Kt according to this approach. In addition (Figure 11, based on estimated F, and the SRA, Table 2), we can also assess that although the stock appears to be currently healthy (using the SRA approach, 101-160Kt, Table 2), the uncertainty indicates that overfishing is likely to occur and that the stock is on the boundary where larger catches maybe detrimental to the overall persistence of the resource. Based on this limited data, and no other information, we can already see that the stock maybe experiencing overfishing using the SRA, and is experiencing overfishing using the PFSRA. As such some management measures that may restrict overall catch to 120K t at most should be implemented in the Indian Ocean Region. We discount the CPUE based traditional Surplus production analysis as the fits are poor and the CPUE data is largely uninformative (Figure 3), and using a more precautionary based approach, based on alternative methods recommend reducing the target catch levels in the Indian Ocean region to be lesser than the current catch levels for this stock.

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List of Tables

Table 1: Catch data on IO Kawakawa from 1950-2011 (source IOTC Database)

Year	KAW East IO	KAW West IO	TOT KAW Catch	Year	KAW East IO	KAW West IO	TOT KAW Catch
1950	1,952	3,614	5,567	1981	14,279	15,919	30,198
1951	1,760	1,486	3,246	1982	15,789	19,112	34,901
1952	1,637	1,639	3,276	1983	14,487	16,789	31,276
1953	1,474	1,760	3,234	1984	14,700	20,690	35,391
1954	1,941	2,545	4,486	1985	18,072	23,734	41,806
1955	2,180	3,191	5,372	1986	18,492	24,690	43,181
1956	2,492	3,364	5,855	1987	22,574	23,195	45,769
1957	2,199	3,192	5,390	1988	21,538	28,278	49,816
1958	2,229	2,838	5,067	1989	23,011	23,890	46,901
1959	2,275	2,992	5,267	1990	24,988	27,221	52,209
1960	2,961	4,009	6,970	1991	29,911	26,192	56,103
1961	3,660	5,018	8,678	1992	34,007	32,326	66,333
1962	3,279	2,709	5,988	1993	33,908	25,680	59,588
1963	4,157	4,104	8,261	1994	34,617	32,307	66,924
1964	4,530	5,619	10,149	1995	38,728	32,008	70,735
1965	4,224	4,548	8,772	1996	39,399	35,521	74,920
1966	4,555	4,262	8,818	1997	42,369	41,278	83,648
1967	4,944	4,928	9,872	1998	42,939	44,046	86,985
1968	5,248	5,241	10,489	1999	41,318	47,247	88,565
1969	5,419	5,028	10,447	2000	45,256	48,248	93,504
1970	5,644	5,008	10,651	2001	42,608	45,095	87,703
1971	5,547	6,176	11,724	2002	44,534	49,129	93,663
1972	7,036	6,615	13,651	2003	47,299	47,256	94,554
1973	7,174	6,534	13,708	2004	51,616	50,524	102,140
1974	8,435	10,035	18,470	2005	49,550	52,418	101,968
1975	9,910	9,952	19,861	2006	57,382	57,486	114,868
1976	13,265	15,596	28,861	2007	59,578	60,141	119,719
1977	12,413	12,348	24,761	2008	64,865	71,621	136,486
1978	12,850	10,881	23,731	2009	66,855	70,033	136,888
1979	13,447	18,353	31,800	2010	68,256	63,301	131,557
1980	14,551	17,063	31,614	2011	67,282	76,370	143,652

SIR Non Informative Priors

Parameters	5%	50%	95%
B_{MSY}	296	1236	1900
MSY	178	622	1386
r	0.31	1.18	1.88
B_{2011}	632	>2000	>2000
B_{2011}/B_{MSY}	1.55	1.88	1.95
F_{2011}/F_{MSY} *	0.09	0.245	0.795

SIR Informative Priors

Parameters	5%	50%	95%
B_{MSY}	284	420	584
MSY	164	252	354
r	1.04	1.2	1.37
B_{2011}	416	712	1030
B_{2011}/B_{MSY}	1.45	1.69	1.79
F_{2011}/F_{MSY} *	0.4	0.57	0.87

SRA

Parameters	5%	50%	95%
B_{MSY}	149	233	317
MSY	101	132	164
r	0.67	1.18	1.68
B_{2011}	182	267	353
B_{2011}/B_{MSY}	0.78	1.15	1.51
F_{2011}/F_{MSY}	0.12	0.58	1.04

PFCRA**

Parameters	5%	50%	95%
B_{MSY}	161	179	198
MSY	113	128	136
r	1.29	1.43	1.58
B_{2011}	181	193	204
B_{2011}/B_{MSY}	0.96	1.08	1.2
F_{2011}/F_{MSY} *	1.05	1.12	1.27

* Indicates that a proxy F is calculated relative to Yield, i.e. C_{2011}/C_{MSY}

** Results for the PFCRA are based on the depletion maximum depletion level of 0.6 (Table 3)

379 **Table 3: Posterior key biological parameters for Kawaka under three assumed upper depletion level.**

Upper D	Param	Mean	5%	25%	50%	75%	95%
0.8	K	406.02	350.84	376.13	**408.12**	434.72	458.6
0.8	r	1.5	1.32	1.39	**1.48**	1.61	1.72
0.8	MSY	155.32	117.68	132.92	**150.96**	171.8	205.16
0.8	B_{2011}	266.14	243.36	255.37	**265.15**	276.48	290.8
0.8	D_{2011}	0.66	0.56	0.61	**0.65**	0.71	0.77
0.7	K	368.01	327.36	346.52	**366.84**	387.5	407.86
0.7	r	1.48	1.33	1.4	**1.48**	1.56	1.66
0.7	MSY	136.17	115.63	126.96	**135.47**	146.83	157.28
0.7	B_{2011}	214.75	203.08	208.11	**213.46**	220.14	228.83
0.7	D_{2011}	0.59	0.51	0.55	**0.58**	0.62	0.67
0.6	K	358.05	322.45	337.65	**358.04**	377.72	394.55
0.6	r	1.43	1.29	1.35	**1.43**	1.51	1.58
0.6	MSY	126.42	113.16	120.92	**127.57**	132.48	136.37
0.6	B_{2011}	192.03	181.29	187	**191.81**	196.55	203.82
0.6	D_{2011}	0.54	0.48	0.51	**0.54**	0.57	0.6

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List of Figures

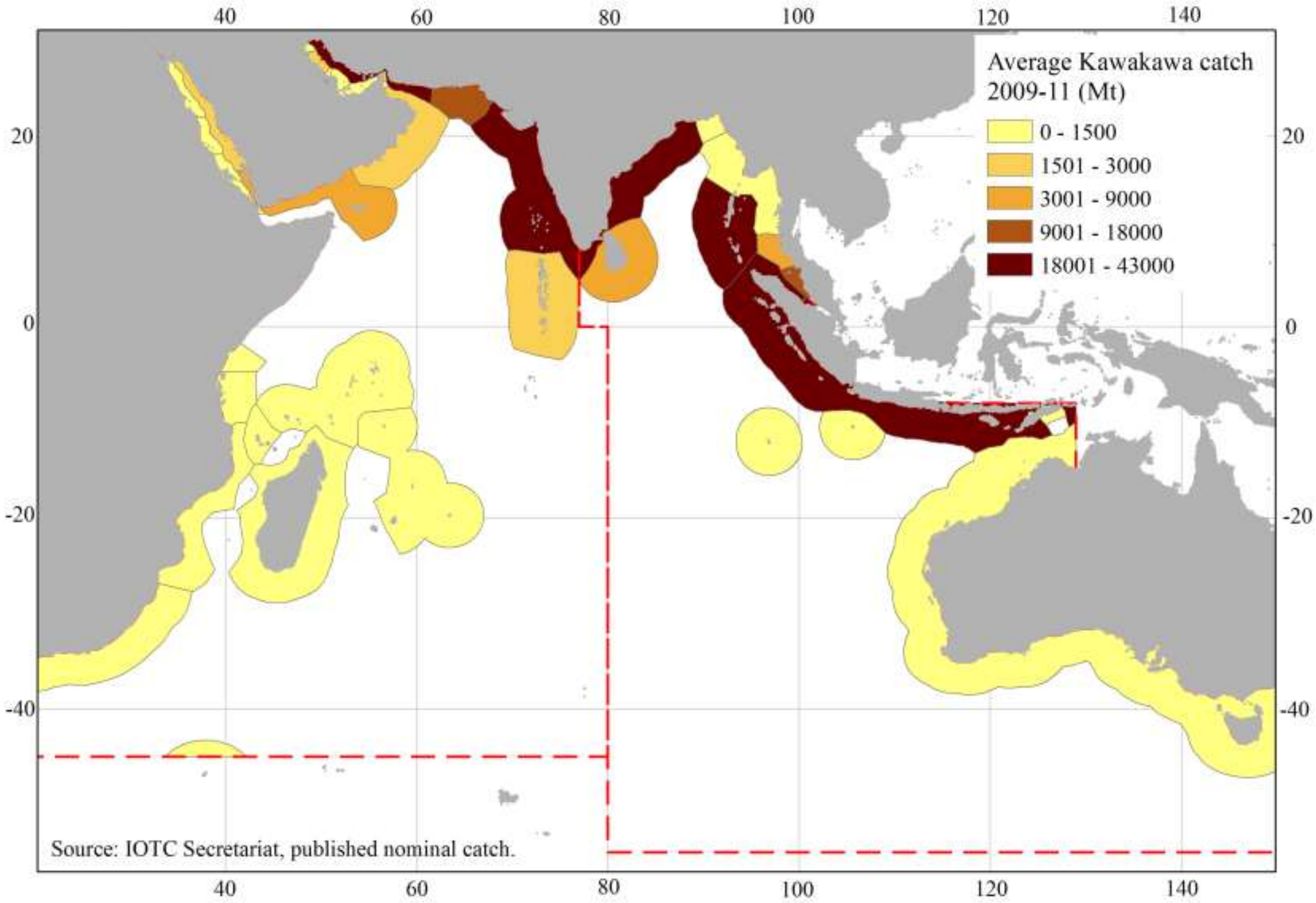
Average Kawakawa catch
2009-11 (Mt)
0 - 1500
1501 - 3000
3001 - 9000
9001 - 18000
18001 - 43000
Source: IOTC Secretariat, published nominal catch.
40
60
80
100
120
140
20
0
-20
-40

Figure 1: Average catch of Kawakawa in the Indian Ocean (2009-2011, Source IOTC Database)

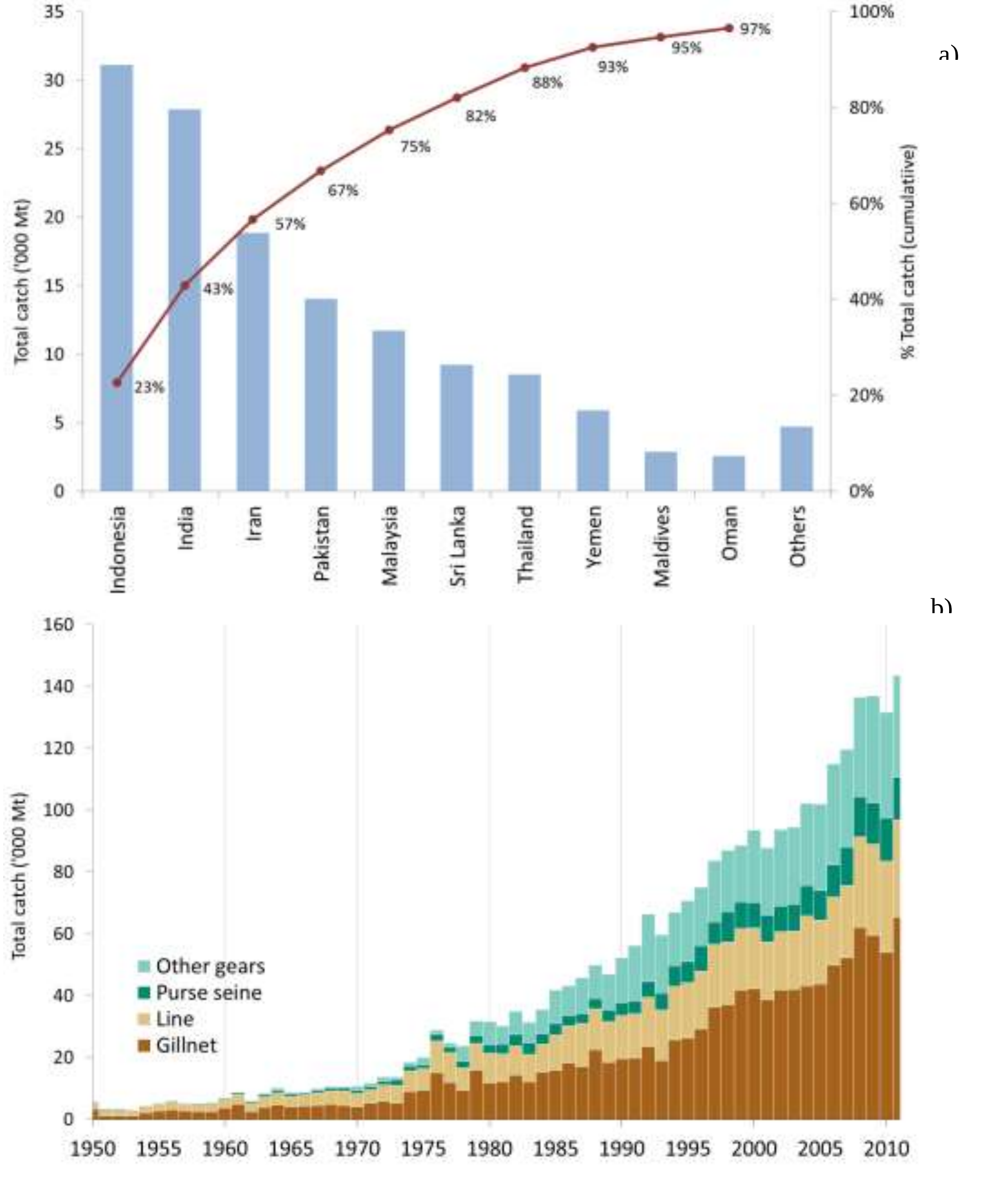

Figure 2

a) Average catch of Kawakawa (2009-2011) by country (in ranked) order. The red line indicates the cumulative proportion of total kawakawa catch for the countries concerned, over the total combined catch of kawakawa reported from all countries and fisheries. Source: IOTC database

b) Annual catches of kawakawa by main gear (1950-2011). Source: IOTC database.

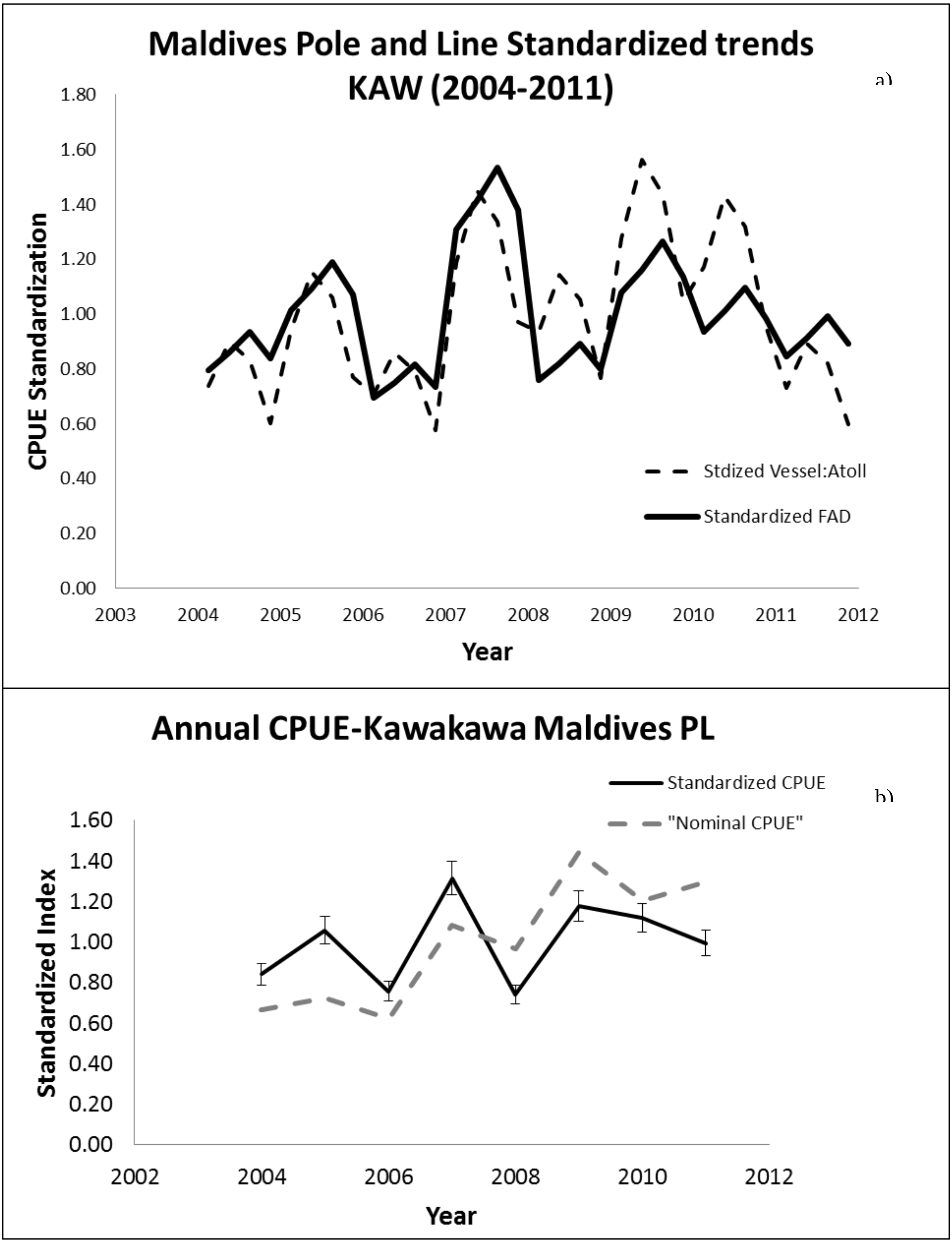

Figure 3: Standardized Index of the KAW CPUE Abundance trends using the 2 models, one with FAD effects at a Broad spatial scale, and the other with vessel and atoll effects at a finer spatial scale. Inset a shows the standardized signal by quarter, while inset b shows it by year along with the nominal CPUE.

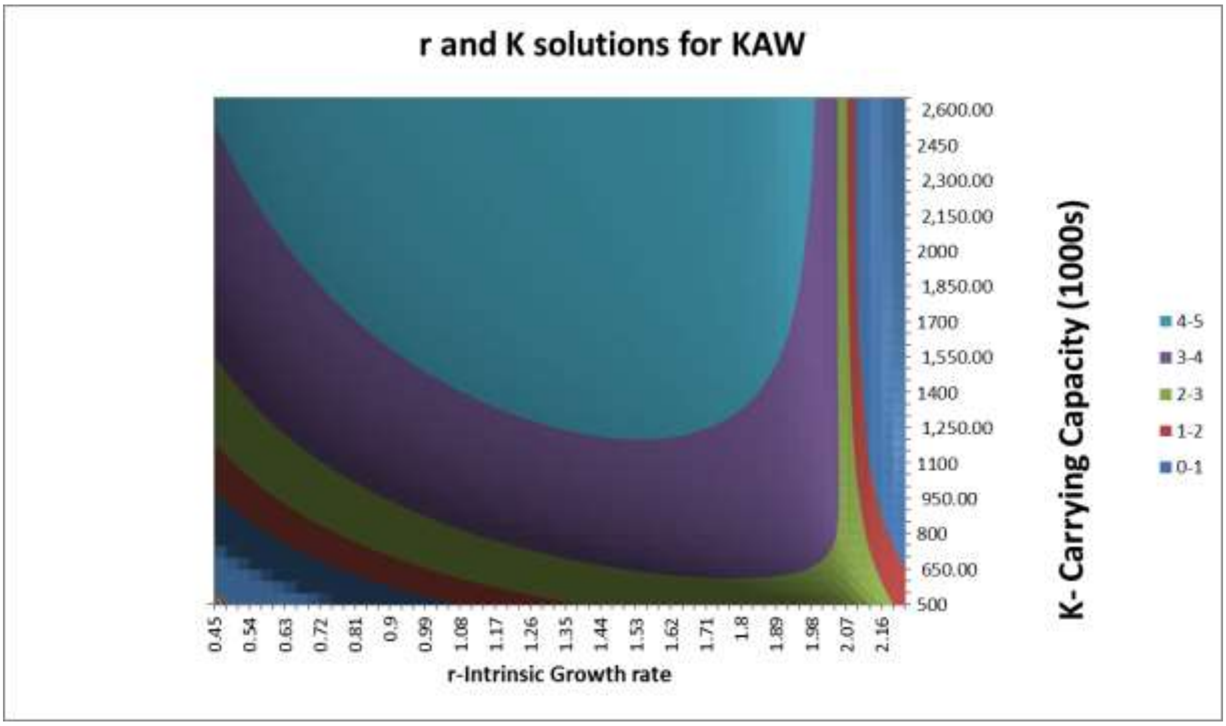

Figure 4: MLE surface for KAW based on r and K values

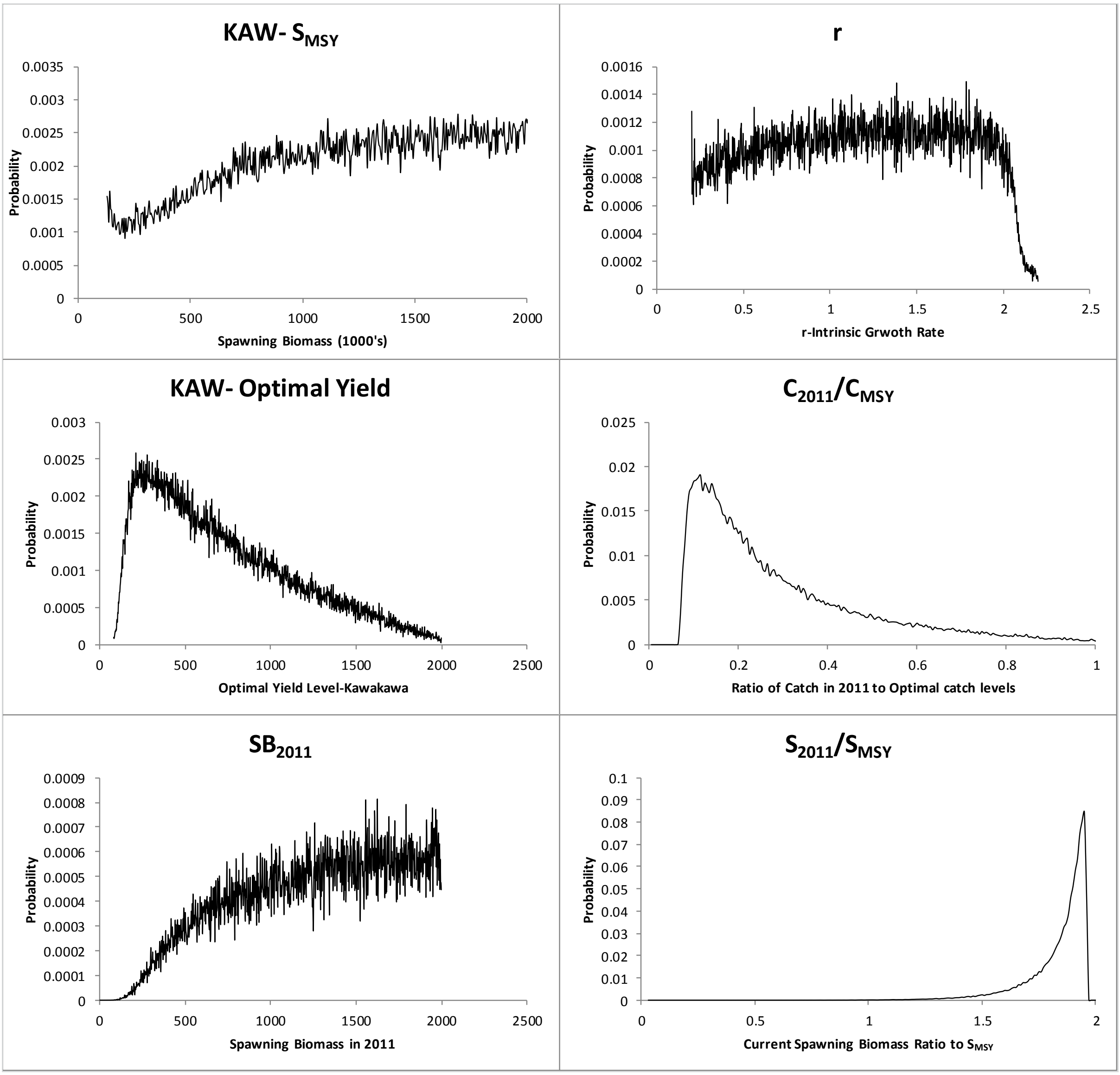

Figure 5: Derived reference points and parameters estimated using the SIR algorithm with non-informative priors on r and K.

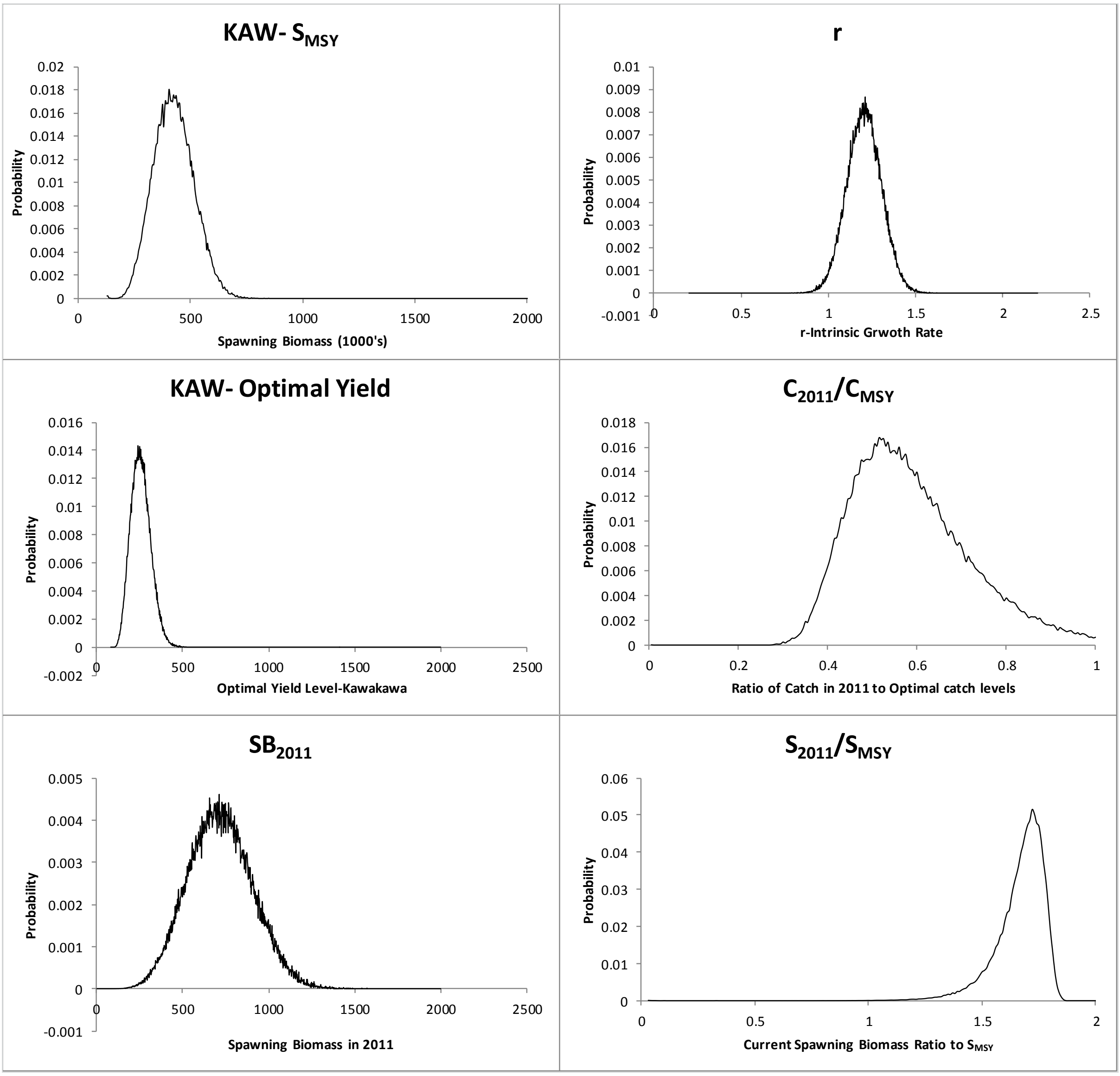

Figure 6: Derived reference points and parameters estimated using the SIR algorithm and informative priors on r and K

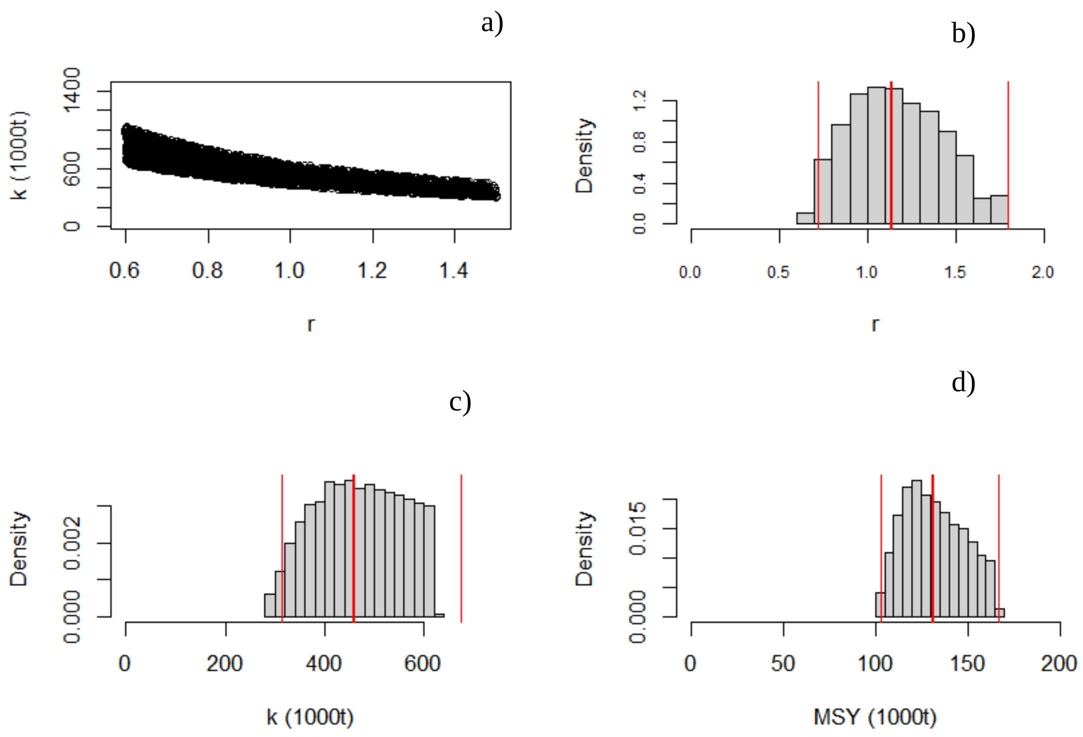

Figure 7 (needs to be changed): a) Parameter confounding between r and K (inset a); b) conditional distribution of r, c) conditional distribution of K, and d) estimated MSY distribution based on r and K values chosen in a, and b.

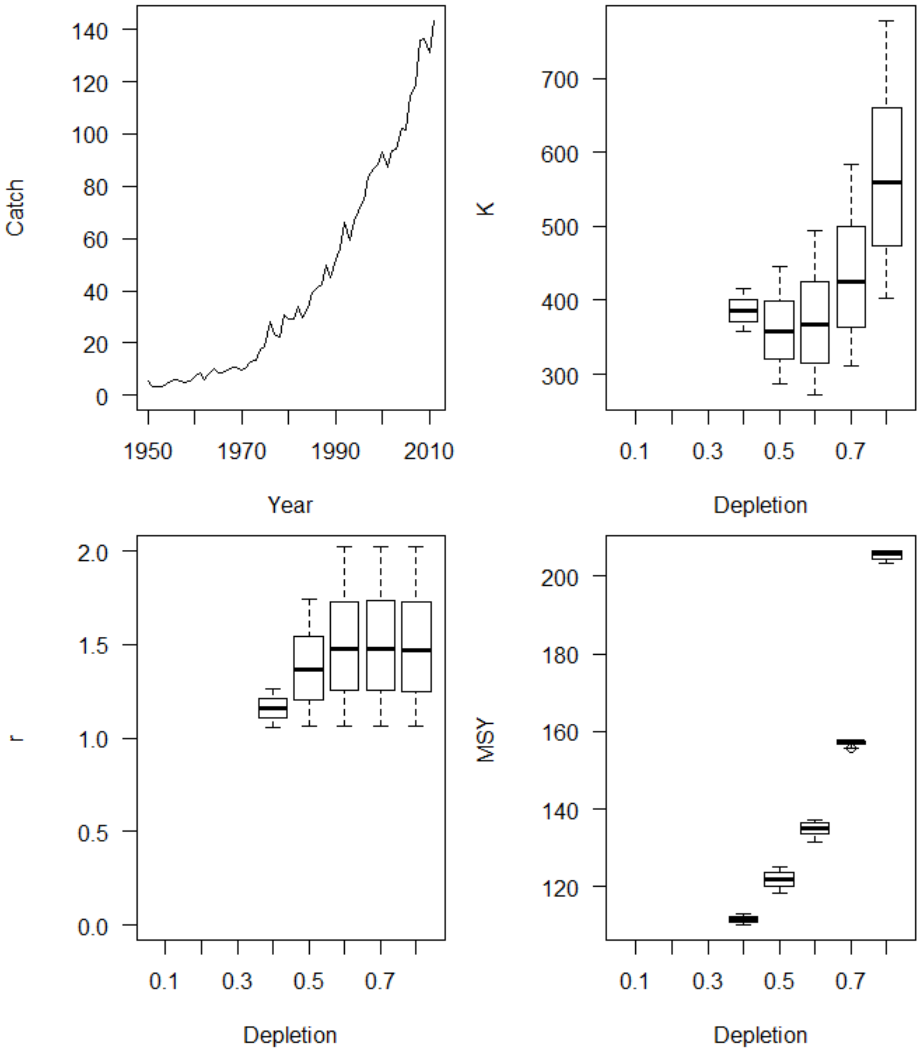

Figure 8: Posterior focussed catch reduction method showing estimates of r, k and MSY with respect to assumed depletion levels.

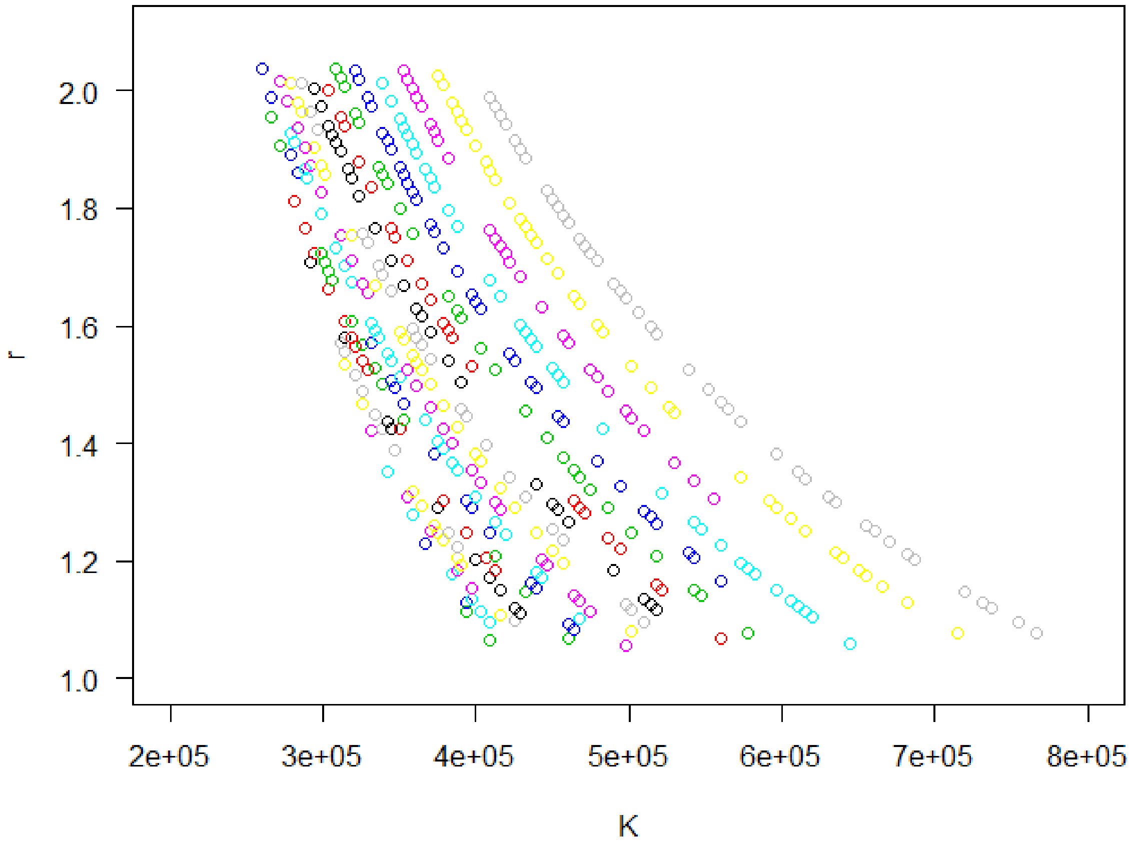

Figure 9: Possible combination of [r, K] from assumed depletion level [0.02, 0.80] for kawakawa. Prior r range is [1.056, 2.04]. Each line is an assumed depletion level. There is no feasible [r, K] pairs when depletion is lower than 0.38.

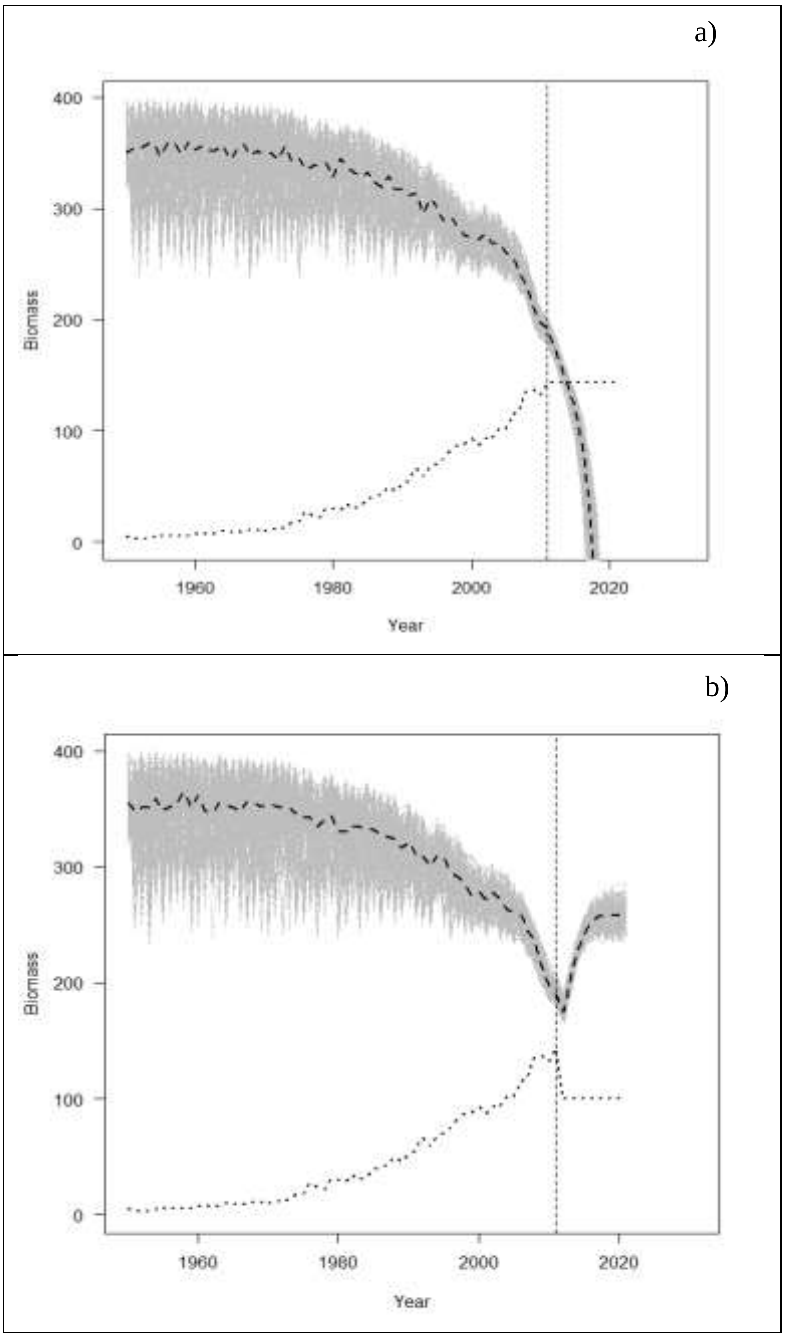

Figure 10: Kawakawa Biomass trajectory projected to 2020 using current catch levels of 143K T (inset a) versus catch levels of 100K T (inset b)

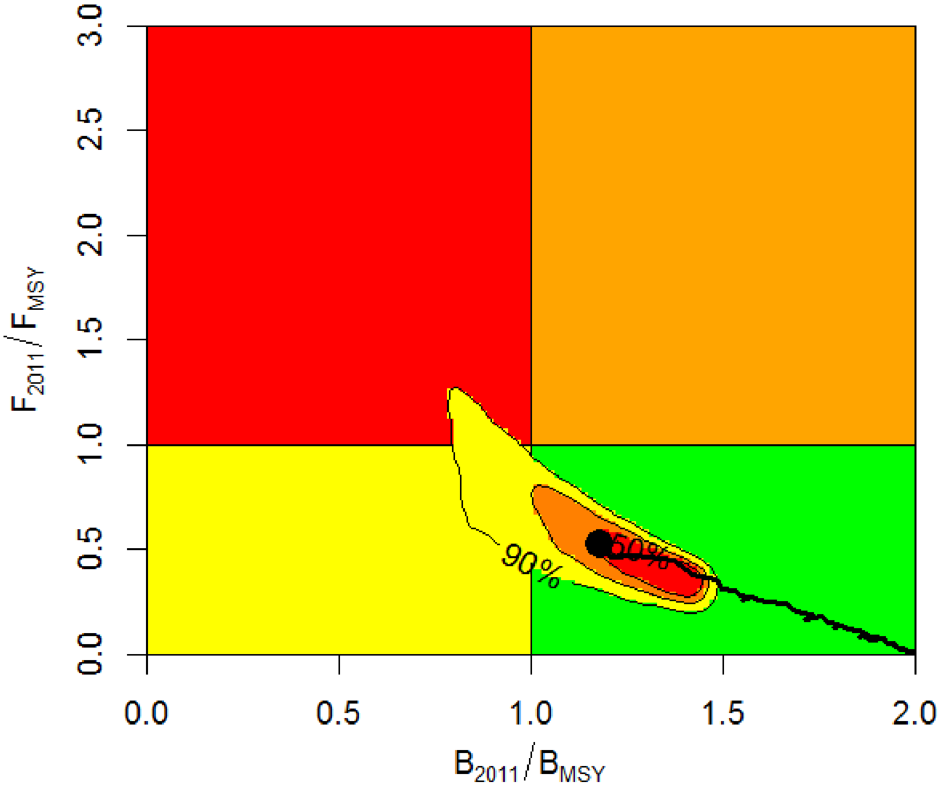

Figure 11: Kawakawa stock trajectory with respect to reference points, B_{MSY} and F_{MSY}. The black dot represents 2011, with all the uncertainty around it in the contour intervals across all runs. The dark line shows the trajectory of the geometric mean (r,K) of all runs over time from 1950 to 2011.