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Citation

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Use of this Report

Blue-Eye - Eastern Seamounts

Summary

An age-structured stock reduction analysis was conducted on the east coast seamount Blue-Eye data. However, uncertainty remains regarding many aspects of their biology and the fishery (e.g. selectivity and growth). The uncertainty regarding their natural mortality and steepness was covered by conducting a series of analyses using a matrix of values of ranging from 0.08 - 0.12 for natural mortality and 0.6 - 0.8 for steepness. For the sea-mounts all analyses were assumed to have started with an unfished stock. There was additional uncertainty associated with the value for maximum harvest rate. An array of values between 0.25 - 0.5 were all trialed with the full array of natural mortality and steepness combinations.

As there is no agreed harvest strategy or harvest control rule for Tier 5 assessments, the trajectories generated by the age-structured stock reduction analysis were each projected forward for 10 years under different constant catch regimes while searching for those catches that led to the trajectories being stable into the future. For those projections starting at less than the Commonwealth target reference depletion point it can be expected that any RBC from such analyses would be less than the constant catch that led to stability. How to select from teh range of possible constant catches that reflect the uncertainty over the maximum harvest rate remains a problem.

Constant catches leading to relative stability in depletion were estimated at about 25 t for lower productivity combinations of natural mortality and steepness (0.08, 0.6) and 48 t for higher productivity combinations (0.12, 0.8). This is comparable to the estimate of approximately 40 t from the catch-MSY analysis that was predicted to lead to the mean depletion remaining stable in the projections.

Fisheries that only have such catch data but that also require management advice are only marginally served by such ‘assessment’ methods. Such data-poor assessments are not usefully updated by including future catch levels if those catch levels came from the predictions of such an assessment. Rather, the application of such methods is effectively an admission that such a fishery should be classed exploratory. This implies that evidence needs to be gathered concerning any impact the exploratory fishing has upon the stock being fished.

Introduction

The array of fishing methods that have been used to catch Blue-Eye (*Hyperoglyphe antarcticus*) off the Australian east coast seamounts is diverse and exhibits no stable pattern of exploitation on any particular seamount (Haddon, 2014). Over the last five years the average catch was about 51 t with a minimum of 25 t and a maximum of 84 t (Table 1).

Table 1: Fishery data for Blue-eye. That from 1984 - 2016 is from the standard AFMA database, that from 1984 - 1996 derives from Tilzey (1997).

year	catch	year	catch	year	catch
1984	7	1996	16.000	2008	8.100
1985	9	1997	10.975	2009	43.003
1986	38	1998	1.590	2010	69.948
1987	105	1999	21.640	2011	147.192
1988	210	2000	7.258	2012	102.941
1989	174	2001	42.856	2013	43.887
1990	243	2002	48.983	2014	25.297
1991	181	2003	74.978	2015	50.385
1992	60	2004	47.021	2016	84.548
1993	38	2005	14.758	2017	55.603
1994	27	2006	15.431	.	.
1995	19	2007	16.174	.	.

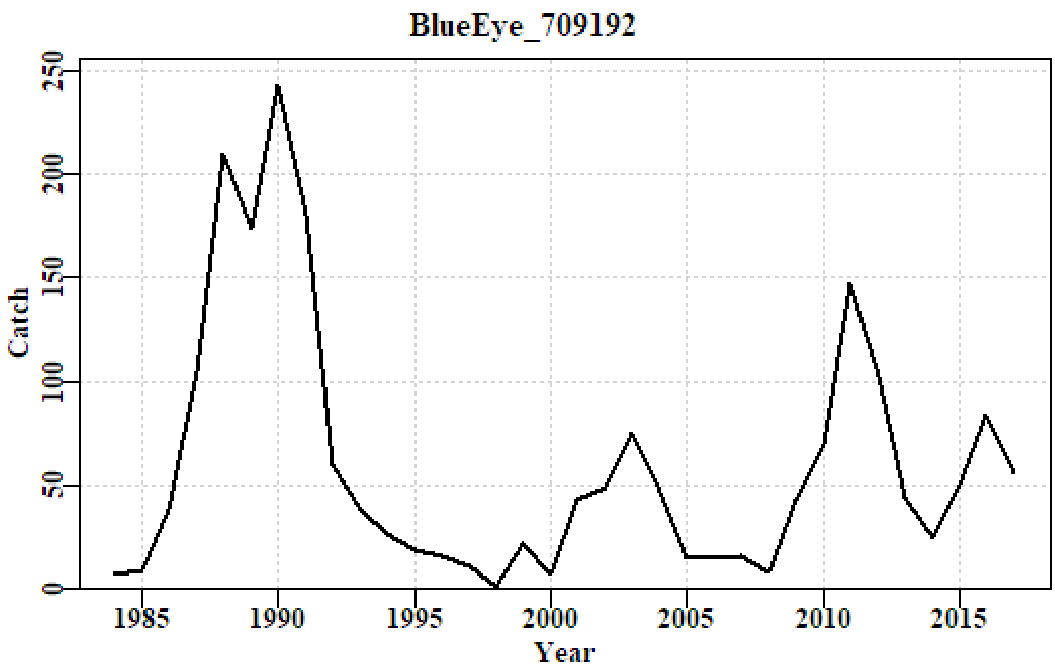

Figure 1: The catch history of the Blue-Eye fishery from the eastern seamount fishery.

It is possible to generate a sketch map of the distribution of the catches from the east coast seamounts, at least from 1997 to present where detailed data on location of catches is available.

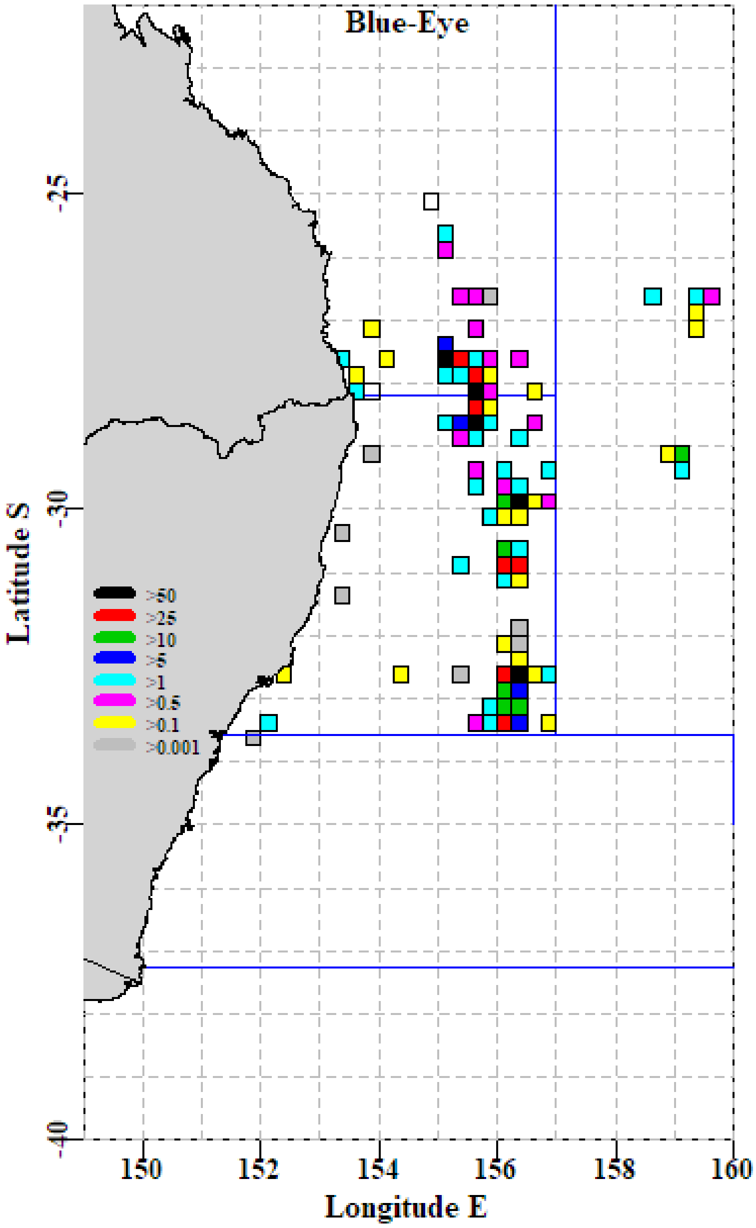

Figure 2: Schematic map of all Blue-Eye catches since 1997 off the east coast (zones 70, 90, and 91. The grid-scale is 1.0 and 0.25 degree and the catch-scale is tonnes.

Catch by Gear

Ten different gear types are recorded in AFMA's catch and effort database, although some appear to be erroneous or potential mis-attribution (e.g. LLP and PL; see **Table 2**). The methods that dominate in terms of total catch from 1997 - 2017 include auto-line, drop-line, hand-line, rod-and-reel and finally otter trawl. Only drop-line has a consistent catch history over the period 1997 - 2017 although in some years the amount of catch and number of records was insufficient to be representative. Some of the methods used in relatively recent years such as LDR and RR may be equivalent to hand-line (although often with hydraulic winching). Importantly for this current attempt at assessment no studies of the relative selectivity of these different gears have been conducted or are available for the east coast seamounts.

Implications for Stock Assessment

The only regularly available fisheries data available for the east coast seamounts are the commercial catches. Any recreational catches are unknown. There are no fully representative samples of age- or size- composition from the fishery although more restricted sampling of lengths and ages were made for the study by Williams *et al*. (2017). The multiple methods and episodic nature of the fishing on the eastern seamounts means there is no index of relative abundance available. This means the application of even simple surplus-production models or age-structured production models is not a viable option.

The catch-MSY method (Martell and Froese, 2013) has been implemented in a relatively simple to use R package (Haddon *et al*., 2018). This method implements a stock reduction analysis and uses a Schaefer surplus production model to simulate the underlying population dynamics and productivity. This approach has been implemented for the eastern seamounts Blue-Eye Fishery (Haddon and Sporcic, 2018). However, because Blue-Eye are relatively long-lived (~55 years or more) it can be argued that using a simple surplus production model to simulate the productivity of the stock ignores the age-structured dynamics expected for this species. To counter such an argument, this current document details an option for conducting a similar stock reduction approach but using an age-structured model for the underlying population dynamics.

Table 2: The catch by gear across the zones 90, 91, and 70 (the east coast above Barrenjoey and the eastern seamounts). AL - auto-line, BL - bottom-line, DL - drop-line, HL - hand-line, LDR - unknown, LLP - pelagic long-line, PL - pole-line, RR - rod-reel, TL - trot-line, and TW - otter trawl.

	AL	BL	DL	HL	LDR	LLP	PL	RR	TL	TW
1997	.	.	5.503	.	.	.	.	.	5.47	0.002
1998	.	.	1.590	.	.	.	.	.	.	.
1999	10.120	.	11.520	.	.	.	.	.	.	.
2000	1.330	.	0.520	.	.	.	.	.	.	5.408
2001	.	.	7.986	.	.	.	.	.	.	34.870
2002	2.100	.	44.114	.	.	.	.	.	.	2.769
2003	7.230	.	54.380	.	.	.	.	.	.	13.368
2004	6.080	.	5.165	.	.	.	.	.	.	35.776
2005	0.011	1.55	11.120	.	.	.	.	.	.	2.077
2006	5.555	.	9.860	.	.	0.016	.	.	.	.
2007	.	.	2.700	0.400	.	.	.	.	.	13.074
2008	.	.	8.100	.	.	.	.	.	.	.
2009	4.585	.	25.560	.	.	.	3.138	7.550	.	2.171
2010	.	.	13.160	.	.	.	.	56.788	.	.
2011	40.196	.	27.013	17.091	.	.	.	59.934	.	2.957
2012	36.777	.	16.179	21.171	.	.	.	14.782	.	14.031
2013	3.853	.	0.529	24.083	.	.	.	14.125	.	1.296
2014	4.505	.	0.510	19.932	.	.	.	0.350	.	.
2015	4.322	.	45.384	.	0.679	.	.	.	.	.
2016	5.308	.	69.647	4.000	5.593	.	.	.	.	.
2017	1.294	1.20	40.585	8.502	4.022	.	.	.	.	.
Total	133.266	2.75	401.125	95.179	10.294	0.016	3.138	153.529	5.47	127.799

Age-Structured Stock Reduction Modelling

Introduction

A stock reduction analysis uses a mathematical model to describe the dynamics of a fishery by simulating the stock dynamics and each year removes the known catches. The model used to simulate the dynamics needs to allow for changes in the stock biomass each year (natural mortality, fishing mortality, individual growth, and recruitment). It can do this with a simple or a more complex model. The stock may be assumed to start off in an unfished state or at some level of depletion. Essentially the model is used to simulate the stock productivity and its response to fishing pressure.

Using a surplus production model to describe the dynamics means there are few model parameters required (perhaps *r*, *K*, and *Binit*; see Haddon, 2018) along with the time-series of catches. Such an approach compresses the details of the stock dynamics into these simplified parameters, which for a long-lived species, might intuitively appear to be too great an approximation. Alternatively, one could use an age-structured production model. However, this would require more information, including a description of the growth (length-at-age and weight-at-age), maturity (maturity-at-age), a stock recruitment relationship (steepness and unfished recruitment), selectivity-at-age, and the natural mortality rate. As a minimum this entails many more parameters, which for a relatively data-poor species may not be well known or only known for stocks in different areas or countries. However the stock reduction is structured, the expected output is one or more stock biomass trajectories with associated harvest rates and depletion levels relative to unfished levels.

When the only data from a commercial fishery are the catches then any stock reduction can only provide an estimate of the minimum unfished biomass required to account for those known catches. With age-structured dynamics one would search for the unfished recruitment, log(*R0*), which would allow the catches to be taken without the stock going extinct (which is equivalent to the harvest rate reaching 1.0, implying 100% of exploitable fish are taken in a single year). In addition, if a plausible argument can be made, perhaps using a weight of evidence approach, for some other upper limit on the maximum harvest rate expected to have occurred. This can further constrain the lower limit of productivity and improve the plausibility of any result.

Unfortunately, without information concerning how a fishery may have influenced the stock (a trend in CPUE or survey abundance through time, the age- or length-composition of catches through time, or estimates of total mortality on the stock) then there remains no information on what the upper limit of unfished biomass may be. For example, 50 times the minimum unfished biomass would enable the same catches to be taken as 10 times the minimum unfished biomass, albeit at a different harvest rate, but without further information, which scenario is closer to reality would remain unknown. Thus a different strategy is required to set an upper limit on total productivity for a stock. Ideally, one would have available other constraints on the dynamics that could restrict the possible stock reduction trajectories, even if it were something simple such as the representative catch-rates in one year are known to have been much lower than in a different known year. Such constraints can be included in the analysis to eliminate what would become implausible stock reduction trajectories. Bentley and Langley (2012) adopt the phrase "thread the needle" to describe their 'Feasible Stock Trajectories' approach, which involves searching for stock reduction trajectories (threads) that meet or pass through an array of constraints (needles) in the process of eliminating implausible trajectories. This descriptive phrase derived from Walters *et al*. (2006) who used the phrase to relate to reconciling multiple sometimes inconsistent data sets within a stock reduction framework. Something like the Feasible Stock Trajectories (FST) approach seems the only approach applicable given the truly data-poor situations being considered in the eastern seamounts with respect to Blue-Eye.

Possible Implementation

One such approach is described briefly by Cordue (2018). For stocks with only commercial catch data, and in the context of some orange roughy (*Hoplostethus atlanticus*) fisheries, Cordue suggested that:

"A given catch history implies a minimum level of virgin biomass – the amount necessary to allow the catch to have been taken. Also, the catch cannot have reached 100% of the available biomass in any year as it is not physically possible for vessels to take every last fish. In these assessments three different levels of maximum exploitation rate (50%, 20%, 10%) were used to calculate a virgin biomass consistent with the maximum exploitation rate and the given catch history. A simple model with deterministic recruitment, a Beverton Holt stock recruitment relationship (steepness = 0.75), fixed natural mortality (0.045), and a single fishery (at the end of the year) on the spawning fish was used to do the calculations." (Cordue, 2018, p2)

Such an approach can generate time-series of harvest or exploitation rates, spawning biomass, exploitable biomass, and depletion relative to unfished biomass (*B0*). In the case described in the quotation above, however, the result would be a single set of such outputs for each stock examined. One major problem with this approach is it ignores the uncertainty that surrounds the adopted values for natural mortality and steepness (and the other biological properties used to set up the simple age-structured model). In addition, the selection of the plausible values of harvest rate appears limited and somewhat subjective when this are the only constraint imposed on the dynamics of the stock reduction.

What appears to be recommended is to use an age-structured model with deterministic dynamics based on the average recruitment predicted by a Beverton-Holt stock recruitment curve from a fixed natural mortality rate and a fixed steepness. This is to be applied to the known catches from defined fishing grounds. The only source of uncertainty that appears to be included is to assume a different fixed maximum possible level of harvest rate (exploitation rate) over the known catch history. Cordue (2018) implemented this procedure using CASAL (Bull *et al.*, 2012) and, for each given maximum harvest rate, presumably searches for the unfished recruitment levels (log(*R0*)) that produce a productivity level for the stock that, when it has the known catches removed, leads to a maximum harvest rate in at least one year for each given stock.

Relying on selected single values for the variables that significantly influence productivity will likely provide an inadequate resolution of the potential variation in the population dynamics inherent to each stock being considered. Preferable to this restrictive methodology would be, as a minimum, to consider a grid of values across the natural mortality and the steepness with each combination being trialed over a range of maximum harvest rates. In most highly data-poor situations where only catches are known it would be unusual if the biological properties required to implement an age-structured production model were well known. So, in addition, alternative scenarios involving the growth and maturity characteristics could also be considered. Finally, the selectivity of fishing can be very difficult to characterize if there are multiple methods in a fishery, such as for Blue-Eye. This too may need to be considered and varied if the full uncertainty in the productivity is to be characterized. Here these extra sources of uncertainty are not considered and so the results produced must be considered in the light of the fact that not all sources of uncertainty have been explored.

Methods

A more general implementation of an age-structured stock reduction analysis can be made by using a simple age-structured model of population dynamics (see *Appendix 1:Age-Structured Model Equations*). Akin to the catch-MSY approach, future versions of this age-structured stock reduction analysis could include a range of possible initial depletion levels, but for now the simplest case is where the stock concerned begins in an unfished state. In that way one only has to search for a value of unfished recruitment, log(*R0*), that generates stock dynamics that account for the known catches and maximum harvest rate assumed for the fishery. If any other constraints are known for the fishery these too could be included. However,given the multiple fishing methods used and the episodic nature of fishing for Blue-Eye on any single seamount the only fisheries data available for the eastern seamount Blue-Eye remains the catches (Table 1, Figure 1).

Growth Characteristics

The growth characteristics of Blue-Eye are known to vary by region (Williams et al, 2016, p38 - p59). Three sources of growth estimates and weight-at-age estimates were considered (Table 3).

Table 3: Alternative values for constants used to represent plausible values for different constants used to characterize the properties of the age-structured population.

	Tilzey, 1997	Smith and Wayte, 2004	Williams et al., 2016
Linf	92.950	92.950	88.826
K	0.080	0.080	0.183
t0	-5.555	-5.555	-2.370
WatAa	0.018	0.018	.
WatAb	3.016	3.016	.

The expected length-at-age parameters (L_∞, K, and t_0) differ by gender but average values can be used. From Tilzey (1997) to Smith and Wayte (2004) the same values were presented, later analyses used other values.

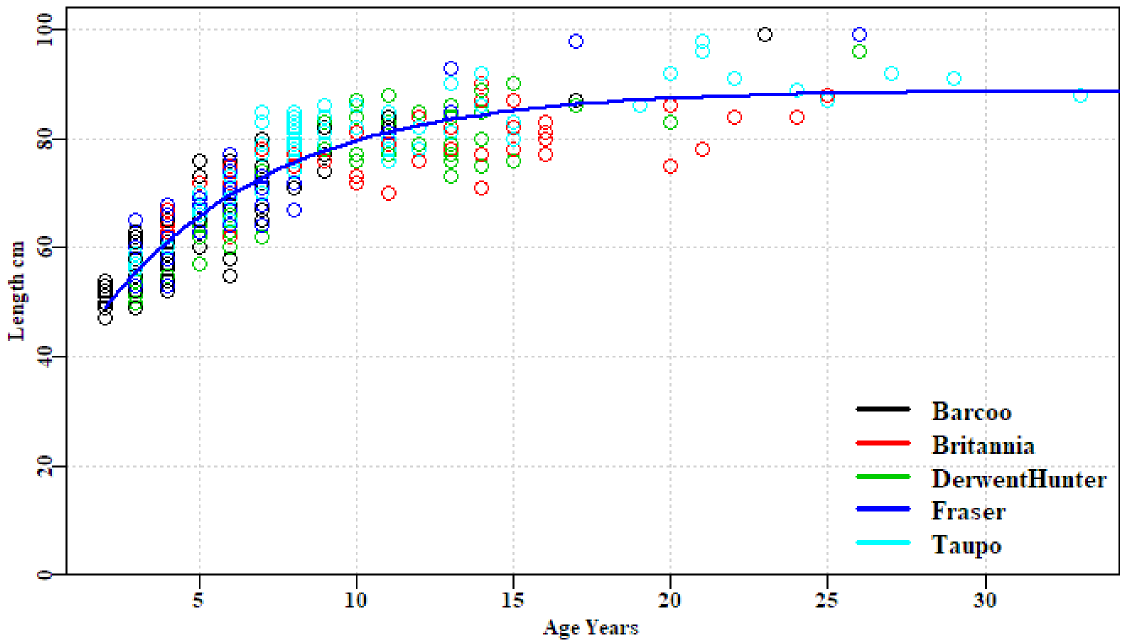

Figure 3: The length-at-age data for five seamounts with data ranging from 2 - 33 years of age and lengths 47 - 99. The optimum von Bertalanffy curve parameters were $Linf$ = 88.8266, K = 0.18285, and t_0 = -2.3773. See Figure 2 for locations.

Biological Properties

Biological properties were obtained from earlier texts (Tilzey, 1997; Smith and Wayte, 2004) and were consistent through time although their origins were not always clear.

Table 4: The biological and fishery properties assumed to represent Blue-Eye taken in the south-east seamounts. The range of *M* and *h* are indicated by the low and high values with the increment in the inc column.

	Values	Low	High	inc
Natural Mortality M	0.1000	0.08	0.12	0.01
steepness h	0.7000	0.60	0.80	0.10
Linf	88.8260	.	.	.
K	0.1829	.	.	.
t0	-2.3700	.	.	.
weight-at-age a	0.0180	.	.	.
weight-at-age b	3.0160	.	.	.
Maturity A50	11.0000	.	.	.
deltaMat	1.0000	.	.	.
Selectivity A50	10.0000	.	.	.
delataSel	1.5000	.	.	.
maxage	55.0000	.	.	.

Table 5: The biological and fishery properties assumed to represent Blue-Eye taken in the south-east seamounts. The range of *M* and *h* used in the analyses are indicated by the low and high values with the increment in the inc column.

	Low	High	inc	Comment
log(R0)	9.5	11	0.01	Range of Unfished log(R0)
MaxH	0.25	0.5	0.01	The range of maximum harvest rates
steepness	0.6	0.8	0.1	Range of steepness

The Algorithm Used

The approach used is to step through the combinations of log(*R0*) and *h* (steepness), which directly affect the potential productivity of the modelled stock, plus any other variations one adopts, run the dynamics for each combination and then determine which combinations generate maximum harvest rates matching the constraints assumed. The combinations and constraints were defined in **Table 5**.

In this way the implications for depletion levels and stock status given the range of possible maximum harvest rates and range of productivity can be characterized. Combinations of variables that match the constraints can then have their dynamics projected forward under different conditions of constant catch to determine the expected effect of different levels of total catch. The usual harvest control rules can also be approximated. Because this approach merely puts bounds on what might be deemed possible it is uncertain in a different manner to more usual methods of stock assessment. Currently there are no harvest control rules defined for such approaches but, until a particular HCR is agreed, one can at least search for projected catches that generally lead to the lowest and highest assumed maximum harvest rate trajectories projecting forwards in an approximately stable manner. It can be expected that those trajectories that finish in a state depleted below the Commonwealth target of 0.48_B_0_ would lead to RBCs lower than the catches that lead to stability.

Results

An Example Age-Structured Stock Reduction

We have assumed the maximum harvest rate could lie anywhere between 0.25 and 0.5, which implies that across the time series of catches the maximum harvest rate could not be greater than the set of values between those limits. The steepness adopted in this first example was 0.6. For values of log(*R0*) between 9.5 - 10.5, in steps of 0.01, the dynamics were run and the summary results are given in Table 5.

```
inR0 <- seq(9.5,10.5,0.01)
limitH <- c(0.25,0.5)
glb$M <- 0.08
glb$steep <- 0.6
reduct <- asmreduction(inR0,fish,glb,props,limitH=limitH)
```

Table 6: Summary table of outputs for the array of initial recruitment levels log(*R0*), with a natural mortality of 0.08 and a steepness of 0.6. This table is the ‘pickR’ rows of the ‘answer’ object within the ‘reduct’ object.

logR0	B0	Bcurr	depl	MaxH	logR0	B0	Bcurr	depl	MaxH
9.64	998.671	89.0957	0.0892	0.51	9.82	1195.626	331.0968	0.28	0.324
9.65	1008.708	102.4478	0.1016	0.49	9.83	1207.642	344.8977	0.29	0.317
9.66	1018.846	115.7975	0.1137	0.48	9.84	1219.780	358.7652	0.29	0.312
9.67	1029.085	129.1409	0.1255	0.47	9.85	1232.039	372.7029	0.30	0.307
9.68	1039.428	142.4786	0.1371	0.45	9.86	1244.421	386.7143	0.31	0.302
9.69	1049.874	155.8132	0.1484	0.44	9.87	1256.927	400.8028	0.32	0.297
9.70	1060.425	169.1488	0.1595	0.43	9.88	1269.560	414.9717	0.33	0.293
9.71	1071.083	182.4902	0.1704	0.42	9.89	1282.319	429.2242	0.33	0.288
9.72	1081.847	195.8426	0.1810	0.41	9.90	1295.207	443.5632	0.34	0.284
9.73	1092.720	209.2113	0.1915	0.40	9.91	1308.224	457.9919	0.35	0.279
9.74	1103.702	222.6016	0.2017	0.39	9.92	1321.371	472.5132	0.36	0.275
9.75	1114.795	236.0188	0.2117	0.38	9.93	1334.651	487.1298	0.36	0.271
9.76	1125.998	249.4679	0.2216	0.37	9.94	1348.065	501.8446	0.37	0.267
9.77	1137.315	262.9538	0.2312	0.36	9.95	1361.613	516.6602	0.38	0.263
9.78	1148.745	276.4814	0.2407	0.35	9.96	1375.298	531.5793	0.39	0.259
9.79	1160.290	290.0551	0.2500	0.35	9.97	1389.120	546.6045	0.39	0.255
9.80	1171.951	303.6795	0.2591	0.34	9.98	1403.081	561.7384	0.40	0.251
9.81	1183.730	317.3587	0.2681	0.33	.	.	.	.	.

The fully selected harvest rate, the spawning biomass, and the stock depletion level are plotted for those trajectories whose maximum harvest rate lies between 0.25 and 0.5 (Figure 4).

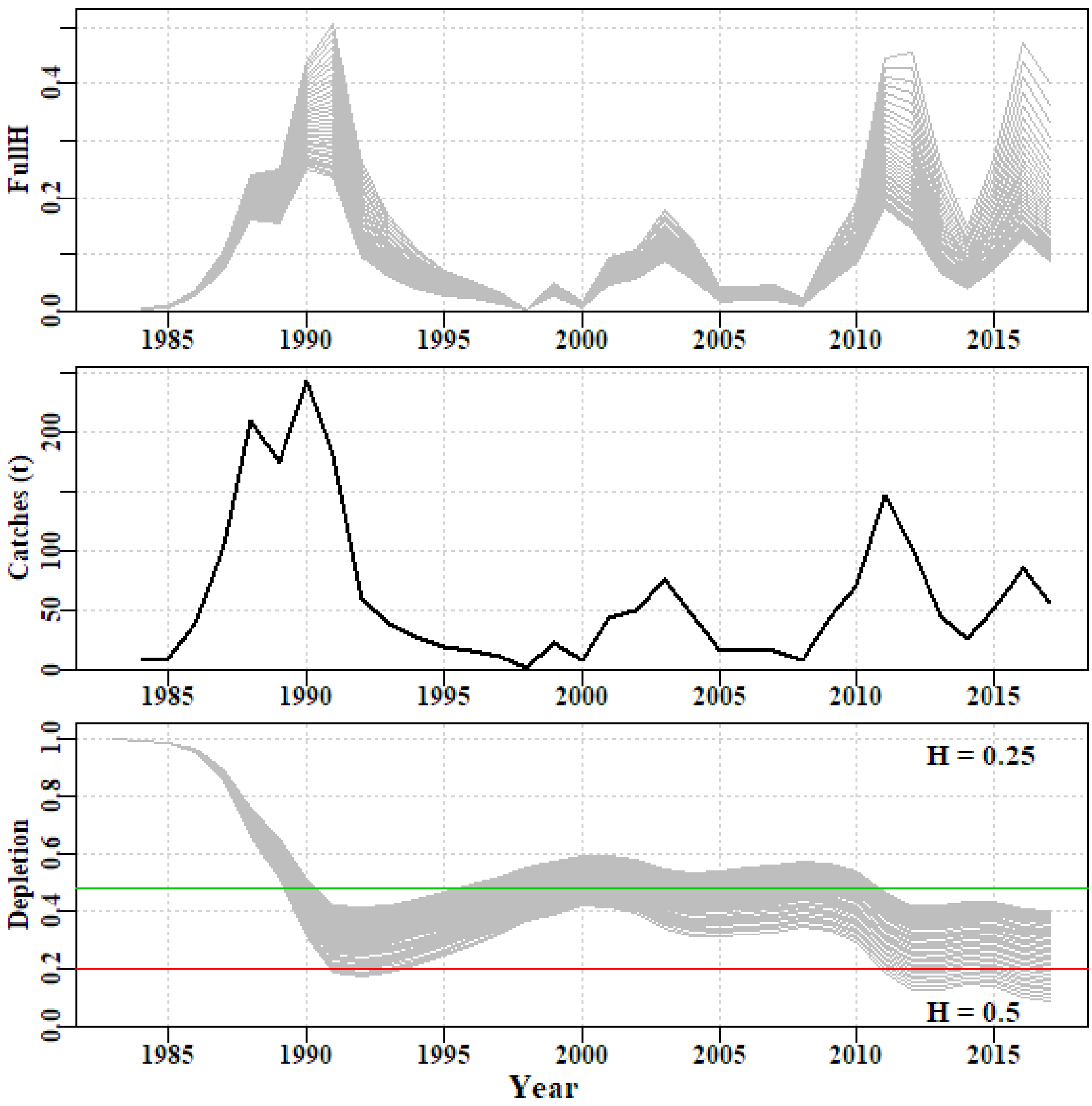

Figure 4: The stock reduction for east-coast seamounts using a natural mortality of 0.08 and steepness of 0.6. Each grey trajectory equates to a value of maximum harvest rate between 0.25 and 0.5 and represents a different unfished recruitment level *R0*.

Under the conditions of *M* = 0.08 and *h* = 0.6 (and all the other biological properties of growth, maturity, and selectivity, **Table 4**) the known catches lead to the stock being depleted to about 9%*B0* at an *MaxH* = 0.5. According to **Table 5** the maximum harvest rate would need to be less than about 0.39 (39% of exploitable biomass per annum) for the stock not to be depleted below the limit reference point of 0.2 in the final year.

If the steepness, *h* is increased to 0.7 this increases the productivity but the *MaxH* = 0.5 still leads to a depletion level of about 14.5%*B0* in 2017. The *MaxH* would need to be less than about 0.41 (41%) for the stock to be above 20% in 2017. Finally, with a steepness of 0.8 as long as the *MaxH* is less than 0.5 then the catches imply that at worst, the stock is depleted to the 20%*B0* limit reference point, in 2017.

```
inR0 <- seq(9.5,10.5,0.01)
limitH <- c(0.25,0.5)
glb$M <- 0.08
glb$steep <- 0.8
reduct <- asmreduction(inR0,fish,glb,props,limitH=limitH)
```

Table 7: Summary table of outputs for the array of initial recruitment levels *R0*, with a natural mortality of 0.08 and a steepness of 0.8. This table is the 'pickR' rows of the 'answer' object within the 'reduct' object.

logR0	B0	Bcurr	depl	MaxH	logR0	B0	Bcurr	depl	MaxH
9.64	998.671	194.9038	0.1952	0.51	9.82	1195.626	420.1378	0.35	0.324
9.65	1008.708	207.1995	0.2054	0.49	9.83	1207.642	433.2096	0.36	0.317
9.66	1018.846	219.4804	0.2154	0.48	9.84	1219.780	446.3672	0.37	0.312
9.67	1029.085	231.7565	0.2252	0.47	9.85	1232.039	459.6134	0.37	0.307
9.68	1039.428	244.0371	0.2348	0.45	9.86	1244.421	472.9513	0.38	0.302
9.69	1049.874	256.3306	0.2442	0.44	9.87	1256.927	486.3836	0.39	0.297
9.70	1060.425	268.6447	0.2533	0.43	9.88	1269.560	499.9130	0.39	0.293
9.71	1071.083	280.9865	0.2623	0.42	9.89	1282.319	513.5420	0.40	0.288
9.72	1081.847	293.3624	0.2712	0.41	9.90	1295.207	527.2734	0.41	0.284
9.73	1092.720	305.7785	0.2798	0.40	9.91	1308.224	541.1094	0.41	0.279
9.74	1103.702	318.2402	0.2883	0.39	9.92	1321.371	555.0526	0.42	0.275
9.75	1114.795	330.7529	0.2967	0.38	9.93	1334.651	569.1053	0.43	0.271
9.76	1125.998	343.3213	0.3049	0.37	9.94	1348.065	583.2697	0.43	0.267
9.77	1137.315	355.9500	0.3130	0.36	9.95	1361.613	597.5482	0.44	0.263
9.78	1148.745	368.6431	0.3209	0.35	9.96	1375.298	611.9430	0.44	0.259
9.79	1160.290	381.4048	0.3287	0.35	9.97	1389.120	626.4561	0.45	0.255
9.80	1171.951	394.2387	0.3364	0.34	9.98	1403.081	641.0899	0.46	0.251
9.81	1183.730	407.1486	0.3440	0.33	.	.	.	.	.

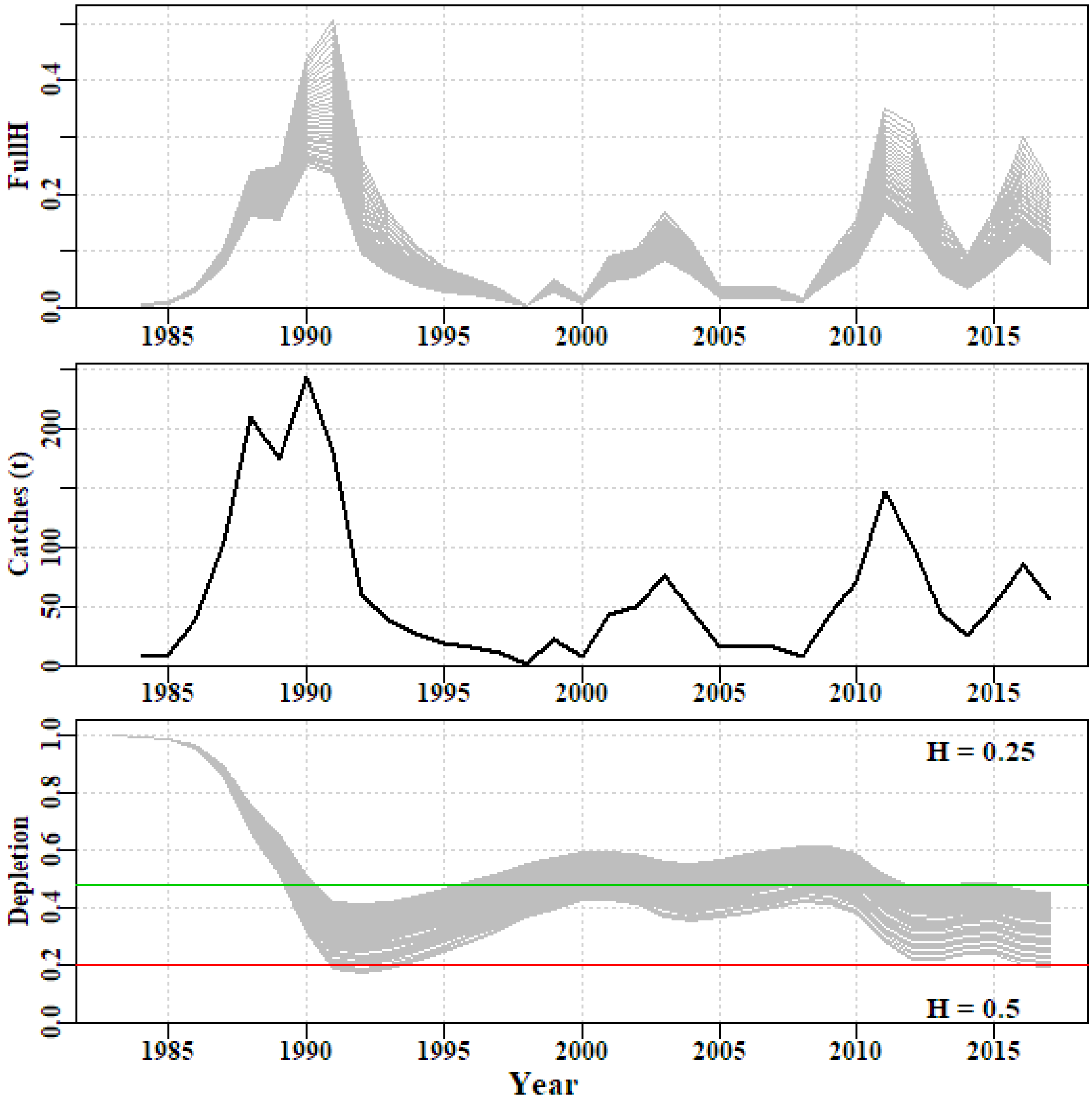

Figure 5: The stock reduction for east-coast seamounts using a natural mortality of 0.08 and steepness of 0.8. Each grey trajectory equates to a value of maximum harvest rate between 0.25 and 0.5 and represents a different unfished recruitment level *R0*. Note that the harvest rates at the end of the time series are lower than those seen in the lower productivity case represented by **Figure 4**.

The two spikes in harvest rate in the final years (2011 and 2016) relate to catches of 147 t and 84 t (**Table 1**). The decreases in spawning biomass and increases in depletion suggest that sustainable catches are likely to be less than such levels.

A comparison can be made of a search for the constant catch required for the two examples considered that would maintain each trajectory essentially in equilibrium (i.e. the depletion level and spawning biomass projected forward is flat). If projections of 10 years are made for the range of steepness considered at the natural mortality of 0.08 we can see that besides the lesser depletion level of the steepness at 0.8 the stock is naturally more productive and can withstand greater catches than the steepness of 0.6 (**Figure 6**).

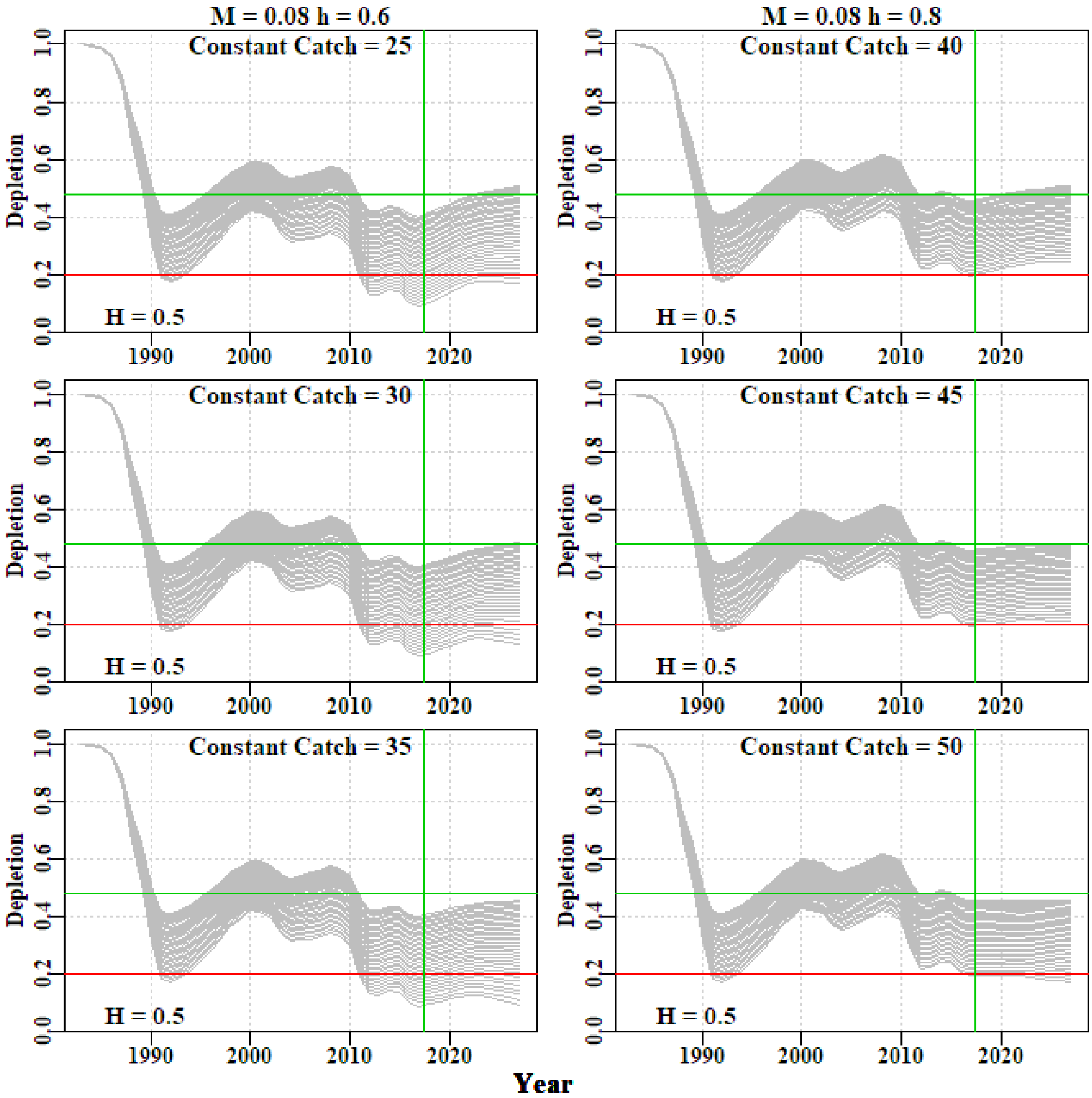

Figure 6: The stock reduction for east-coast seamounts using a natural mortality of 0.08 and steepness of 0.6 and 0.8 with different constant catch projections.

To obtain increases in biomass and reductions in the depletion level for all trajectories there is a distinct difference between the steepness of 0.6 and 0.8. With *h* = 0.6 even a constant projected catch of 30t leads to some of the trajectories for the higher *MaxH* values to decline after about 5 years of increase (middle panel **Figure 6**). So catches need to be as low as 25 t for all trajectories to increase, although this still leaves some trajectories below 20%*B0* after 10 years. With the *h* = 0.8 a constant projection catch of 40 t permits all trajectories to decrease the depletion level. This is partly the increased productivity implied by the higher steepness, and partly the lower level of depletion in 2017, which even for a *MaxH* of 0.5 is close to 20%*B0*. A steepness of 0.7 is in between these constant projected catches.

h vs *M* Scenarios

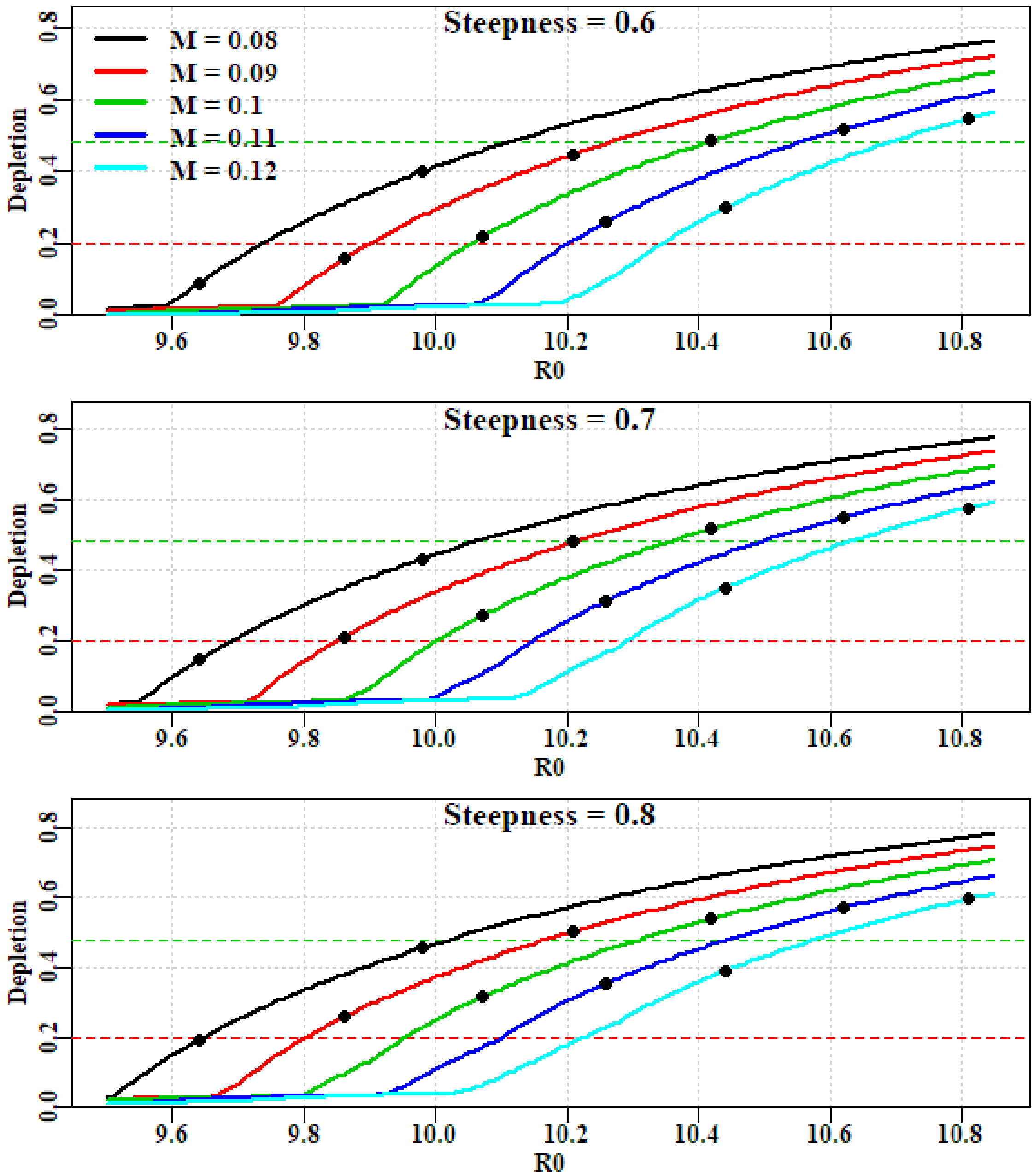

Figure 7: The stock depletion predicted for Age-Structured stock reductions of east-coast seamount Blue-Eye catches across the ranges of *M* and *h* depicted in **Table 4**.

The bottom set of points in **Figure 7** along each of the different summary lines relate to the *MaxH* of 0.5 while the upper set of points in each plot relate to the implication of a maximum harvest rate of 0.25. If these points are extracted the implications for stock depletion of the range of maximum harvest rates can be made clearer.

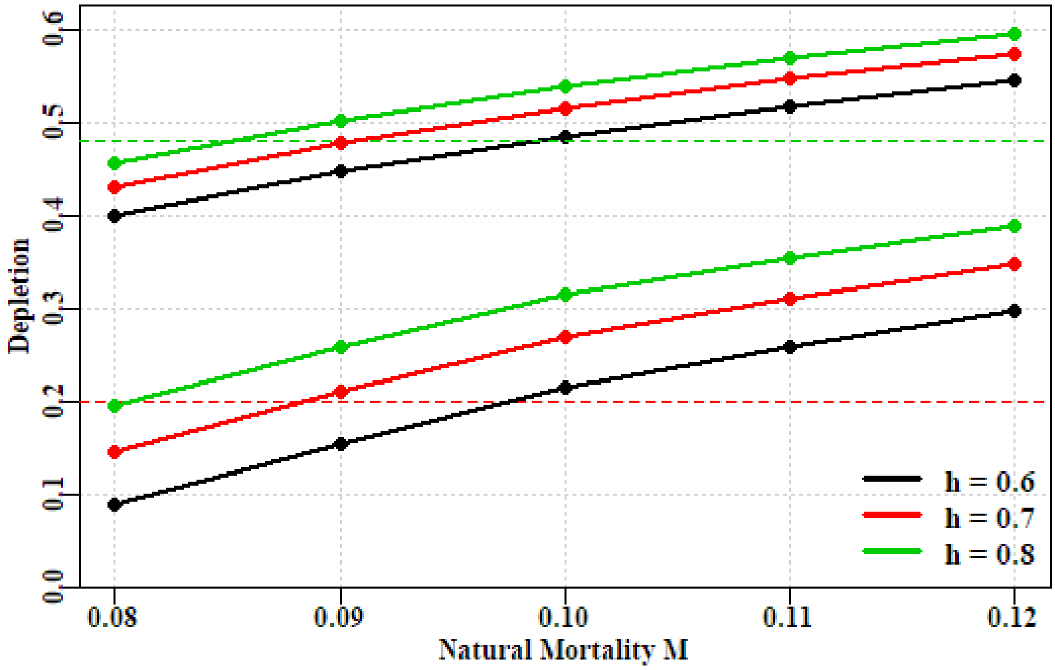

Figure 8: The stock depletion levels predicted for age-structured stock reductions of east-coast seamount Blue-Eye catches at the lower and upper maximum harvest rates (H=0.25 - upper set, and H=0.5 - lower set).

To ensure clarity a table of these figures is also presented **Table 8**.

Table 8: Summary table of predicted stock depletion levels in 2017 for different combinations of *M* and *h*. DeplHH stands for the lower depletion expected at the higher *MaxH* and DeplLH for the greater depletion at the lower *MaxH*. The *R0* are the values log(*R0*) that will permit the assumed maximum harvest rate given the known sequence of catches.

M	logR0	DeplHH	logR0	DeplLH	Steepness
0.08	9.64	0.0892	9.98	0.4004	0.6
0.09	9.86	0.1555	10.21	0.4483	0.6
0.1	10.07	0.2164	10.42	0.4858	0.6
0.11	10.26	0.2603	10.62	0.5187	0.6
0.12	10.44	0.2977	10.81	0.5471	0.6
0.08	9.64	0.1452	9.98	0.4317	0.7
0.09	9.86	0.2107	10.21	0.4788	0.7
0.1	10.07	0.2697	10.42	0.5154	0.7
0.11	10.26	0.3124	10.62	0.5474	0.7
0.12	10.44	0.3485	10.81	0.5746	0.7
0.08	9.64	0.1952	9.98	0.4569	0.8
0.09	9.86	0.2586	10.21	0.5030	0.8
0.1	10.07	0.3150	10.42	0.5388	0.8
0.11	10.26	0.3559	10.62	0.5698	0.8
0.12	10.44	0.3903	10.81	0.5960	0.8

Projected Catches by Steepness and Natural Mortality

Table 9: Table of catches at combinations of steepness (columns) and natural mortality (rows), which lead to slow increases in biomass and reductions in depletion level for all log(*R0*) trajectories.

	0.6	0.7	0.8
0.08	25	32	40
0.1	35	40	45
0.12	37	43	48

The catches that just lead to stock increases for all log(*R0*) trajectories are only estimated visually off of the plots (akin to **Figure 6**); hence they are only approximate. Before this approach can be used in practice it would be best to have some more formally agreed way of devising Recommended Biological Catch levels and subsequent TACs.

Discussion

The age-structured stock reduction approach described here, as applied to the east coast seamount Blue-Eye fishery, is a deterministic examination of the implications of an array of different assumptions concerning the fishery. Those assumptions principally revolve around the values taken for natural mortality and the steepness of the Beverton-Holt stock recruitment relationship. These two parameters (in combination with the estimates of growth and maturity) effectively determine the relative productivity of the stock in question. Instead of relying only on single values of steepness and natural mortality, neither of which is known with certainty, by exploring the implications of the exhaustive combinations of ranges of such values the sensitivity of the outcome (an approximate status quo catch-level) can be more fully characterized.

This method generates a table of potential catches that would seem likely to maintain the status quo or eventually lead to a slight increase in the stock size. Presumably for those combinations of parameters that predict the stock to be in a depleted state one would, in practice, recommend a lower catch than that which would lead to the status quo.

The available catches provide information regarding what the minimum biomass must have been to account for the catches for different combinations of the productivity parameters M and h. However, the catches do not provide useful information regarding what the upper bounds on stock size might be. To get any idea of what the upper bounds might be further constraints are required on what constitutes plausible outcomes from the modelling. Such constraints could take the form of some representative index of relative abundance across some years, or a time-series of lengths or ages. Such data are not available for the east coast seamount Blue-Eye fishery so instead a constraint on the maximum annual harvest rate of 0.5 was used. This seemed plausible as fewer than 50% of the seamounts were fished significantly in any one year (assuming the fishing records are spatially accurate). This upper limit is also intended to reflect the fact that fishing so far off-shore would need to maintain a relatively high catch rate to remain economic. To cover the possibility that the fishers would be more sensitive to declines in catch rate than in-shore fishers a lower limit to the maximum harvest rate of 0.25 was also used. Thus, the process involved searching for the unfished recruitment levels, log($R0$), that would generate sufficient biomass that the catches removed would lead to a maximum harvest rate between the 0.25 - 0.5 annual maximum harvest rate.

One thing missing from such an assessment is an acceptable Harvest Control Rule (HCR). The generation of constant catches that should lead to status quo or slight stock increases over 10 years is merely indicative of the range of productivity expected; in this case from 25 t - 48 t.

Fisheries that only have such catch data but that also require management advice are only marginally served by such 'assessment' methods. Such assessments are not usefully updated by including future catch levels if those catch levels came from the predictions of such an assessment. Rather, the application of such methods is effectively an admission that such a fishery remains exploratory. This implies that evidence needs to be gathered concerning any impact the exploratory fishing has upon the stock being fished. At the very least, further constraints could be included into the stock reduction 'assessment'.

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Appendix 1: Age-Structured Model Equations

Initiation of an Age-Structured Model

At equilibrium, in an un-exploited population, the age-structure is assumed to be the result of natural mortality acting alone upon constant average unfished levels of recruitment. The equilibrium result would be a stable age distribution determined by those constant average recruitments and natural mortality. At the start of a time series, let us say in year 1, this is defined as:

Equ. 1:
$$N_{a,1} = \begin{cases} N_{0,1} = R_0 & a = 0 \\ N_{a-1,1}e^{-M} & 1 \leq a < a_x \\ N_{a_x-1,1}e^{-M}/(1-e^{-M}) & a = a_x \end{cases}$$

where $N_{a,1}$ is the numbers of age a, in year 1, a_x is the maximum age modelled (the plus-group), and M is the instantaneous rate of natural mortality. In a pre-exploitation population there is no fishing mortality and the final component the above equation (where a = a_x), is referred to as the plus group because it is the series which combines ages a_x and all older ages that are not modelled explicitly. This requires the inclusion of the $(1- e^{-M})$ divisor to force the equation to be the sum of an exponential series. The $N_{0,1}$ is the constant unfished recruitment level, R_0. Sometimes this also has an e^{-M} term, depending on the timing of spawning. If the natural mortality term is included then the estimated R_0 value will be somewhat higher than if it is omitted (by $1/e^{-M}$), so it is usually simpler to omit it. This stable age distribution can also be obtained by first calculating the numbers-at-age for a recruitment of 1, or the numbers-at-age per recruit, and then multiplying that vectors of numbers by R_0., which is how it is implemented in *simpleSA::dynamics*

Biological Characteristics

Length-at-age of fish is defined by the von Bertalanffy growth function:

Equ. 2:
$$L_a = L_\infty(1 - e^{-k(a-t_0)})$$

where L_a is the mean length at age a, L_∞ is the asymptotic average maximum length, k is the grow rate coefficient, and t_0 is the length at age zero.

The mass-at-age relationship is defined as:

Equ. 3:
$$w_a = W_{aa}L^{W_{ab}}$$

where w_a is the mass at age a, and W_{aa} and W_{ab} are the coefficients that define the power relationship between length and mass.

Spawning Stock Recruitment Relationship

The biomass A_0 can be defined as the mature stock biomass that would develop given a constant recruitment level of one (i.e. $N_{0,1} = 1$ in the above equation). Thus, at a biomass of A_0, distributed across a stable age distribution, the resulting average recruitment level would be $R_0 = 1$. A_0 acts as a scaling factor in the recruitment equations by providing the link between R_0 and B_0

Equ. 4:
$$A_0 = \sum_{a=1}^{a_x} n_{a,1}\, m_a w_a$$

where m_i is the proportion mature at age a, $n_{a,1}$ is the virgin number of animals per recruit of age a in year 1, and w_a is the weight of an animal of age a. The average unfished recruitment level, R_0, is directly related to the virgin mature, or recruited, biomass, B_0

Equ. 5: $$R_0 = B_0/A_0$$

By determining A_0, from a constant recruitment level of one, the recruitment levels from realistic B_0 levels can be obtained by applying the above equation. Once R_0 has been determined the unfished number at age distribution can be obtained by substituting R_0 into the first equation. The spawning stock – recruitment relationship can be described by the deterministic form of the Beverton – Holt relationship:

Equ. 6: $$R_{y+1} = \frac{aB_y^{Sp}}{b+B_y^{Sp}}$$

where B_y^{Sp} is the mature, or spawning biomass in the in year y.

A re-parameterization of the Beverton-Holt parameters in terms of steepness, h, and B_0 is to specify a and b such that:

Equ. 7: $$a = \frac{4hR_0}{5h-1} \quad \text{and} \quad b = \frac{B_0(1-h)}{5h-1}$$

Using this re-parameterization the the number of recruits produced in year y from the spawning biomass in year $y-1$ is:

Equ. 8: $$N_{0,y} = \frac{4hR_0B_{y-1}^{Sp}}{(1-h)B_0+(5h-1)B_{y-1}^{Sp}}.$$

Stock dynamics

To describe the dynamics subsequent to population initiation (i.e. the generation of $N_{a,y}$, the number at age a in year y, for years other than 0), requires the inclusion of the stock recruitment relationship and the impact of fishing mortality. Not all age classes are necessarily fully selected, thus the fishing mortality term must be multiplied by the selectivity associated with the fishing gear for age a, s_a, described by a logistic curve:

Equ. 9: $$s_a = \frac{1}{\left(1+e^{\left(\frac{a-a_{50}}{\delta}\right)}\right)}$$

where a_{50} is the age at which 50% of individuals are selected by the fishing gear, and δ is a parameter that determines the width or steepness of the selectivity ogive. Such logistic curves are also used to describe the development of maturity within he population but in such a case the a_{50} refers to the age at 50% maturity.

A term is also needed for the recruitment in each year (stock-recruit relationship above), and this is assumed to be a function of the spawning biomass of the stock at the end of the previous year y, B_y^{Sp}.

The spawning biomass for a year y is:

Equ. 10: $$B_y^{Sp} = \sum_{a=0}^{a_x} w_a\, m_a N_{a,y}$$

If this is applied to the unfished stable age distribution this would provide an estimate of the unfished spawning biomass-per-recruit. When using difference equations (rather than continuous differential equations) the dynamics of the fishery, in terms of the order in which growth, natural, and fishing mortality occur, are important when defining how the numbers at age change. If the transition of numbers at age in year y into numbers at age in year $y+1$ is made in a number of steps this simplifies the calculation of internally consistent estimates of exploitable biomass, catch rates, and harvest rates. If it is assumed that the dynamics of a population entails that fish first grow from year $y-1$ to year y, then undergo half of natural mortality before they are fished and only then undergo the final half of natural mortality this would imply two steps to define the transition from one year to the next. The first step entails recruitment, growth from each age class to the next, and the application of the effect of half of natural mortality:

Equ. 11:
$$N_{a,y^*} = \begin{cases} N_{0,y} & a = 0 \\ N_{a-1,y-1}e^{-M/2} & 1 \le a < a_x - 1 \\ \left(N_{a_x-1,y-1} + N_{a_x,y-1}\right)e^{-M/2} & a = a_x \end{cases}$$

where $N_{0,y}$ is defined by the stock - recruit relationship, ages 1 to a_x-1 are modelled by adding 1.0 to the previous year's ages 0 to a_x – 2 and imposing the survivorship from half the natural mortality, and the plus group (a_x) is modelled by adding 1.0 to the previous year's age a_x - 1 and adding those to the numbers in the previous year's age a_x and then applying the survivorship from half the natural mortality. The above equation thus leads to the mid-year exploitable biomass (mid-year being the reason for the $e^{-M/2}$) in year y being defined as:

Equ. 12:
$$B_y^E = \sum_{a=0}^{a_x} w_a\, s_a N_{a,y^*}$$

The dynamics within any year are completed by the application of the survivorship following fishing mortality across all ages (expressed as an annual harvest rate), followed by the survivorship following the remainder of natural mortality. Natural mortality is not applied directly to the new recruits until they grow into the next year:

Equ. 13:
$$N_{a,y} = \begin{cases} N_{0,y^*} & a = 0 \\ N_{a,y^*}\left(1 - s_a\,\hat{H}_y\right)e^{-M/2} & 1 \le a \le a_x \end{cases}$$

In the above equation, the $N_{a,y}$ refer the numbers in age a at the end of year y (i.e. after all the dynamics have occurred). The predicted harvest rate, ., given an observed or recommended catch level in year y, C_y, is estimated as

Equ. 14:
$$\hat{H}_y = \frac{C_y}{B_y^E}$$

where B_y^E is defined above. The catch at age, in numbers, is therefore defined by:

Equ. 15:
$$C_{a,y}^N = N_{a,y^*} s_a\,\hat{H}_y$$

and the total catch by mass is the sum of the separate catches at age multiplied by their respective average weights for all ages:

Equ. 16:
$$C_y = \sum_{a=0}^{a_x} w_a\, C_{a,y}^N$$

Predicted catch rates also derive from the exploitable biomass and the average catchability coefficient, q:

Equ. 17:
$$I_y = qB_y^E.$$

Appendix 2: R code for age-structured stock reduction

The following code is sourced into the R environment once the simpleSA R package is loaded as a library.

```
#' @title asmreduction conducts an age-structured stock reduction
#'
#' @description asmreduction conducts an age-structured stock
#'     reduction based on R functions out of the simpleSA package.
#'
#' @param inR0 the trial value of unfished recruitment R0
#' @param fish a data.frame containing the year and catch in each year
#' @param glb  the global variables defined in the data structures for
#'     simpleSA
#' @param props the biological properties of the species, including
#'     length-, weight-, maturity-, and selectivity-at-age
#' @param limitH a vecotr of two numbers denoting the lowest and
#'     highest values of the maximum harvest rate the stock is
#'     assumed to have experienced.
#' @param projyr number of years fo projecting at a constant catch. If
#'     set to 0 the contents of constC are ignored
#' @param constC the constant catch to apply in the projections
#'
#' @return a list containing a summary matrix, and the full results
#'     for fully selected harvets rate, the spawning biomass, the
#'     depletion, and the explotiable biomass in each trajectory.
#' @export
#'
#' @examples
#' \dontrun{
#' print("To be developed once an example dataset is included.")
#' }
asmreduction <- function(inR0,fish,glb,props,limitH=c(0,1),
                         projyr=0,constC=0.0) {
   steps <- length(inR0)
   year <- fish[,"year"]
   yrs <- c((year[1]-1),year)
   norigyr <- length(yrs)
   if (projyr > 0) {
      endyr <- tail(year,1)
      addyrs <- (endyr+1):(endyr+projyr)
      yrs <- c(yrs,addyrs)
      fish <- as.data.frame(cbind(year=yrs[2:length(yrs)],
                          catch=c(fish[,"catch"],rep(constC,projyr))))
   }
   nyrs <- length(yrs)
   columns <- c("R0","B0","depl","MaxH")
   answer <- matrix(0,nrow=steps,ncol=length(columns),dimnames=list(in
R0,columns))
   fullh <- matrix(0,nrow=nyrs,ncol=steps,dimnames=list(yrs,inR0))
   spawnb <- matrix(0,nrow=nyrs,ncol=steps,dimnames=list(yrs,inR0))
   exploitb <- matrix(0,nrow=nyrs,ncol=steps,dimnames=list(yrs,inR0))
   depl <- matrix(0,nrow=nyrs,ncol=steps,dimnames=list(yrs,inR0))
```

```
   for (i in 1:steps) { # step through inR0   i=1
      fishery <- dynamics(inR0[i],infish=fish,inglb=glb,inprops=props)
      answer[i,] <- c(inR0[i],getB0(exp(inR0[i]),glb,props),
                      fishery[35,"Deplete"],max(fishery[,"FullH"],na.r
m=TRUE))
      fullh[,i] <- fishery[,"FullH"]
      spawnb[,i] <- fishery[,"SpawnB"]
      depl[,i] <- fishery[,"Deplete"]
      exploitb[,i] <- fishery[,"ExploitB"]
   }
   maxH <- apply(fullh[1:norigyr,],2,max,na.rm=TRUE) # max H in each t
rajectory
   pickL <- which.closest(limitH[1],maxH)  # pick low H
   pickH <- which.closest(limitH[2],maxH)  # pick high H
   pickR <- pickH:pickL  # pick rows
   out <- list(answer=answer,fullh=fullh,spawnb=spawnb,depl=depl,
               pickR=pickR,yrs=yrs,inR0=inR0,limitH=limitH,
               projyr=projyr,constC=constC)
   return(out)
} # end of asmreduction

#' @title plotreduction generates a summary plot of a stock reduction
#'
#' @description plotreduction generates a summary plot of the output
#'     from an age-structured stock reduction produced by the
#'     asmreduction function, which in turn relies on the dynamics
#'     function from the aspm within the simpleSA package.
#'
#' @param inreduct the list object generates by asmreduction
#' @param defineplot boolean which determines whether a par statement
#'     is made or not. default = TRUE.
#'
#' @return nothing, but it does produce a 3,1 plot of FullH, spawning
#'     biomass, and depletion for the input stock reduction
#' @export
#'
#' @examples
#' \dontrun{
#' print("To be developed once an example dataset is included.")
#' }
plotreduction <- function(inreduct,defineplot=TRUE) {
   yrs <- inreduct$yrs
   nyrs <- length(yrs)
   pickR <- inreduct$pickR
   if (length(pickR) <= 1)
      stop("Lowest R0 value not low enough to achieve lowest limH \n")
   steps2 <- length(pickR)
   projyr <- inreduct$projyr
   if (defineplot) {
      par(mfrow=c(3,1),mai=c(0.25,0.45,0.05,0.05),oma=c(1.0,0,0.0,0.0)
)
      par(cex=0.85, mgp=c(1.35,0.35,0), font.axis=7,font=7,font.lab=7)
   }
   fullh2 <- inreduct$fullh[,pickR]
   ymax <- getmaxy(fullh2)
   plot(yrs,fullh2[,1],type="l",ylim=c(0,ymax),lwd=1,col="grey",
```

```
        ylab="FullH",panel.first=grid(),yaxs="i")
   for (i in 2:steps2) lines(yrs,fullh2[,i],lwd=1,col="grey")
   if (projyr > 0) abline(v=(inreduct$yrs[nyrs - projyr]+0.5),col=3)
   spawnb2 <- inreduct$spawnb[,pickR]
   ymax <- getmaxy(spawnb2)
   plot(yrs,spawnb2[,1],type="l",ylim=c(0,ymax),lwd=1,col="grey",
        ylab="Spawning Biomass (t)",panel.first=grid(),yaxs="i")
   for (i in 2:steps2) lines(yrs,spawnb2[,i],lwd=1,col="grey")
   if (projyr > 0) abline(v=(inreduct$yrs[nyrs - projyr]+0.5),col=3)
   depl2 <- inreduct$depl[,pickR]
   ymax <- getmaxy(depl2)
   plot(yrs,depl2[,1],type="l",ylim=c(0,ymax),lwd=1,col="grey",
        ylab="Depletion",panel.first=grid(),yaxs="i")
   for (i in 2:steps2) lines(yrs,depl2[,i],lwd=1,col="grey")
   abline(h=c(0.2,0.48),col=c(2,3))
   if (projyr > 0) abline(v=(inreduct$yrs[nyrs - projyr]+0.5),col=3)
   label <- paste0("H = ",inreduct$limitH[1])
   text(max(yrs)-5,0.9*ymax,label,pos=4,cex=1.1,font=7)
   label <- paste0("H = ",inreduct$limitH[2])
   text(max(yrs)-5,0.05*ymax,label,pos=4,cex=1.1,font=7)
   mtext("Year",side=1,outer=T,line=0.0,font=7,cex=1.1)
} # end of plotreduction
```

The formal structure of the output from *asmreduction* is:

```
## List of 13
##  $ answer : num [1:136, 1:5] 9.5 9.51 9.52 9.53 9.54 9.55 9.56 9.57
9.58 9.59 ...
##   ..- attr(*, "dimnames")=List of 2
##   .. ..$ : chr [1:136] "9.5" "9.51" "9.52" "9.53" ...
##   .. ..$ : chr [1:5] "logR0" "B0" "Bcurr" "depl" ...
##  $ fullh  : num [1:35, 1:136] NA 0.00787 0.01019 0.04341 0.12486 ..
.
##   ..- attr(*, "dimnames")=List of 2
##   .. ..$ : chr [1:35] "1983" "1984" "1985" "1986" ...
##   .. ..$ : chr [1:136] "9.5" "9.51" "9.52" "9.53" ...
##  $ spawnb : num [1:35, 1:136] 868 862 853 818 721 ...
##   ..- attr(*, "dimnames")=List of 2
##   .. ..$ : chr [1:35] "1983" "1984" "1985" "1986" ...
##   .. ..$ : chr [1:136] "9.5" "9.51" "9.52" "9.53" ...
##  $ depl   : num [1:35, 1:136] 1 0.992 0.983 0.942 0.831 ...
##   ..- attr(*, "dimnames")=List of 2
##   .. ..$ : chr [1:35] "1983" "1984" "1985" "1986" ...
##   .. ..$ : chr [1:136] "9.5" "9.51" "9.52" "9.53" ...
##  $ pickR  : int [1:35] 15 16 17 18 19 20 21 22 23 24 ...
##  $ yrs    : num [1:35] 1983 1984 1985 1986 1987 ...
##  $ inR0   : num [1:136] 9.5 9.51 9.52 9.53 9.54 9.55 9.56 9.57 9.58
9.59 ...
##  $ limitH : num [1:2] 0.25 0.5
##  $ projyr : num 0
##  $ constC : num 0
##  $ M      : num 0.08
##  $ h      : num 0.6
##  $ catches: num [1:34] 7 9 38 105 210 174 243 181 60 38 ...
```