Preliminary simulation modelling of kahawai stocks

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1. Executive Summary

Estimates of the range of likely values of virgin biomass, B_0, were made and given B_0, the constant catch which can be taken was estimated. Kahawai are treated as one stock because of the difficulty in estimating immigration to and emigration from the kahawai Fishstocks as they are defined. The non-commercial catch is estimated using the estimates of current recreational harvest and assumptions about the past catch. The catch history is used with a range of upper bounds on fishing mortality in any year to estimate B_0. Maximum Constant Yield is estimated. Some sensitivity analyses are performed.

The following conclusions are drawn.

- A conservative virgin biomass, B_0, calculated using the maximum plausible fishing mortality, is about 100 000 t. A maximum possible B_0 is harder to determine but is possibly about 500 000 t. Assuming the conservative B_0, the current biomass, B_{1994} is up to five times B_{MSY} depending on the value of natural mortality (M) and other productivity parameters. These results depend upon the catch (with an assumed non-commercial catch history) and deterministic recruitment.

- The Maximum Constant Yield is slightly greater than the current total catch if B_0 is at its conservative value (but current biomass is still about three times B_{MSY}).

Note: the results from this modelling are preliminary "ball-park" estimates and should be treated with caution.

2. Review of the fishery

2.1 Catch, landings, and effort data

Early commercial catches of kahawai were low (for example, 102 t in 1965 (Watkinson & Smith 1972)); since the mid 1970s kahawai commercial catch has grown. Purseseining began in the 1970s in New Zealand and began targeting kahawai in the late 1970s when the trevally catches declined. The kahawai fishery around the upper part of the South Island is based on a purseseine fleet and began in about 1977 (James 1983, Kilner 1988).

Estimates of commercial kahawai catch up to the mid 1980s are unreliable as the figures provided are suspected to under-report actual landings. Little is known of the level of traditional and recreational catches until the recreational surveys of the 1990s (Teirney et al. 1995).

2.2 Commercial catch

Reported commercial catches increased in 1986–87 and stayed high until purseseine catch restrictions were imposed in 1990–91 (Table 1). The increase in reported catch in the late 1980s was attributed to fishers attempting to improve their catch histories in the fishery by fully reporting their catches in anticipation of the introduction of a Quota Management System for kahawai. There may not have been an actual increase in kahawai catch. During the early 1980s, reported catches were believed to underestimate the total catches, possibly because of non-recording of bycatch. In addition, kahawai were used for bait, mainly in the Kaikoura rock lobster fishery (Kilner 1988). Up until the early 1980s kahawai were often dumped at sea or landed as "MIX" or "FELIX". Reliable estimates of unreported catch before 1983 are not available, but quantities are believed to have been large in some years (Sylvester 1989, Jones et al. 1992).

2.3 Non-commercial catch

The recent telephone and diary surveys give estimates of recent recreational kahawai catch (Table 2) (Teirney et al. 1995). Recreational fishers are estimated to have caught just under 1.5 million kahawai (somewhat under 2000 t) each year during recent years. In this report, the current non-commercial catch is taken to be the rounded figure of 2000 t. Note that the mean size of kahawai in the recreational catch does vary around New Zealand.

Kahawai were an important traditional food source for the early Maori, and continue to have cultural significance to many tribes. River mouths are popular recreational fishing areas (Allan Kilner, Ministry of Fisheries, pers. comm.) and were fishing areas for Maori. The Motu River mouth in the eastern Bay of Plenty is perhaps the most important. A survey in early 1982 estimated 11 000–26 000 kahawai were taken   from

January to April (Rowe 1983, Kilner 1988). For a mean fish weight of about 1.25 kg these numbers translate to 14–32 t.

Table 1: Reported landings (t) or total commercial catch of kahawai (from Annala 1995)

A: 1970–1982			B: 1983–84 to 1993–94	
Year	Landings		Year	Total catch
1970	294		1983-84	4 266
1971	572		1984-85	4 623
1972	394		1985-86	4 416
1973	586		1986-87	7 525
1974	812		1987-88	9 610
1975	345		1988-89	7 431
1976	729		1989-90	8 466
1977	1 461		1990-91	5 687
1978	2 238		1991-92	5 104
1979	3 072		1992-93	6 639
1980	3 265		1993-94	5 164
1981	3 085			
1982	3 236			

Table 2: Estimated number of kahawai caught by recreational fishers by Fishstock, estimated catches, and the corresponding indicative catch in tonnes (some catch estimates are combined estimates from different fishing years which should not be considered as a single point estimate representative of one year). A tonnage range based on the number c.v. is provided for each catch estimate to reflect the uncertainty in the representative weights. In the North region the range also takes account of different weight estimates. The mid-point of tonnage range has been used for the indicative catch

Fishstock	Survey	Year	Estimated Number	% c.v.	Estimated catch (t)	Indicative catch (t)
KAH 1	North	1993–94	720 000	8	840–1160	1 030
KAH 1	Central	1992–93	19 500	22	25–35	
KAH 9	North	1993–94	250 000	19	220–500	360
KAH 9	Central	1992–93	5 600	54	–	
KAH 2	Central	1992–93	187 000	17	240–340	290
KAH 3	Central	1992–93	213 000	20	105–155	200
KAH 3	South	1991–92	33 000	18	55–85	
Total			1 430 000	n/a		1 880

Kilner (1988) gave a range of rough estimates (2000–10 000 t) of the recreational kahawai catch in the 1980s using the tag return data from the 1981–84 kahawai tagging study (Wood *et al.* 1990). (Kilner warned that his estimates should be treated with extreme caution as they involve several assumptions which are unlikely to be valid.)
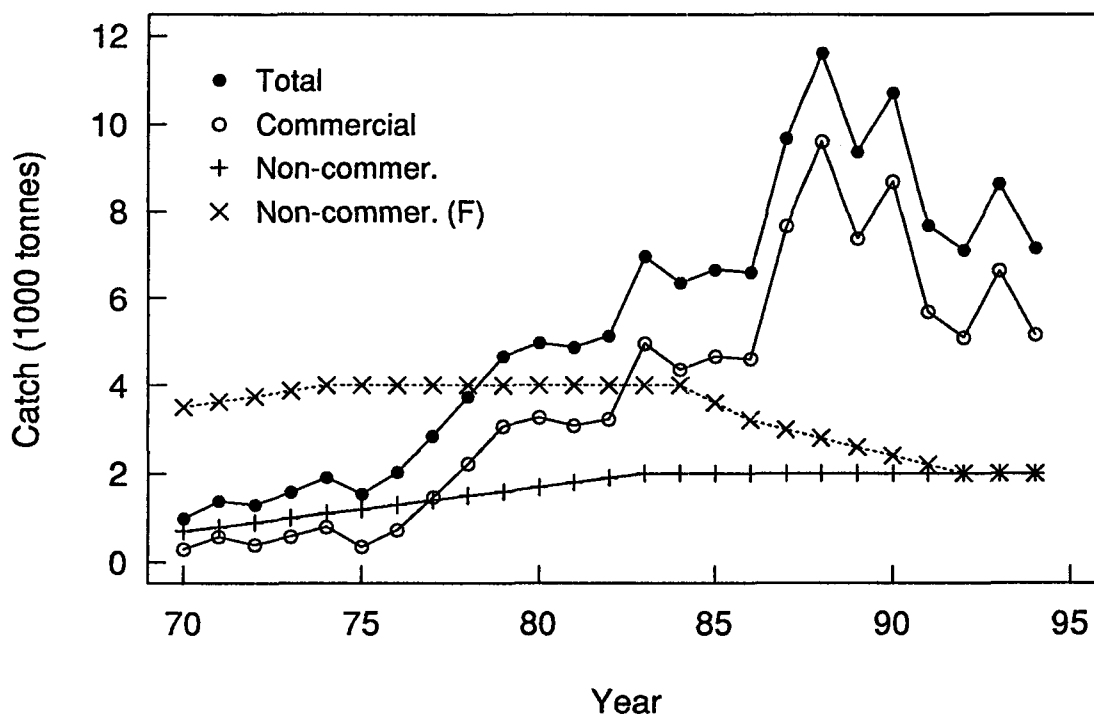

Figure 1: The assumed commercial, non-commercial (non-commer.), and total catch used in modelling in most of Section 5. The non-commer. (F) catch is an alternative estimate of non-commercial catch used in Section 5.2.3

Some recreational (and commercial) fishing for kahawai by Europeans has occurred, presumably since first settlement. Graham (1956) reported little commercial interest in kahawai in the early 1930s in Otago.

Kahawai close inshore have always been vulnerable to fishing. Given that the Maori caught kahawai at several major river mouths (at least) in the North Island and on the South Island east coast, a conservative estimate of the Maori catch in past centuries would be 50–100 t a year. Kahawai are also vulnerable to other shore-based fishing methods including netting. Assuming that European subsistence and recreational fishers gradually merged with the Maori, the inshore non-commercial catch is likely to have increased slowly since last century as the population increased. The recent recreational surveys have shown that shore-based methods (lines and netting) contribute 24% of the catch in KAH 1 (~250 t), 46% of the catch in KAH 9 (~165 t), 53% in the

Central Region (~260 t), and 85% in the South Region (~60 t) which gives an indicative total of 735 t. The KAH 1 and KAH 9 results are from Bradford (1996) and the South and Central Region results are from Allan Kilner (pers. comm.) and were not split by Fishstock. An inshore catch of 700–750 t may be roughly maximal for these fishing methods if the number of kahawai which come inshore at any time is a constant fraction of the population and non-commercial fishers limit their effort when catch rates become low. (It may be possible to model more formally the expected kahawai catch from close inshore using economic, social, and demographic factors and assumptions about kahawai availability.)

At some time, which I have assumed was during the 1970s and early 1980s, greater prosperity and technological changes allowed more of the population to have access to boats from which they could fish safely in offshore waters. This greatly improves the access to kahawai and would lead to a catch increase. "Handlines from trailer boats" is now the most popular fishing method for kahawai in the North Region (Bradford 1996).

I guess that by 1970, when records of commercial catch of kahawai begin, the non-commercial catch of kahawai was at least 500 t but could have been higher. By 1983, the minimum non-commercial catch was probably 1000–3000 t. The current non-commercial catch of about 2000 t may have been at that level for several years. The estimated number of kahawai fishers in the North Region in a 1986–87 recreational survey was 131 730 (Teirney et al. 1991), which agrees well with an estimated number of 123 000 kahawai fishers from the 1993–94 North Region diary survey (unpublished Ministry of Fisheries data).

2.4 Catch used for modelling

The kahawai Fishstocks are treated as a single stock for this preliminary modelling exercise. I have ignored the change from calendar to fishing years in the commercial catch; this assumption should still be accurate enough given the uncertainties in the catch. The assumed non-commercial catch starts from 700 t in 1970 and increases in 100 t steps each year to 2000 t in 1983 and then remains constant at 2000 t until 1994 (Table 3, Figure 1). This is a fairly conservative estimate. The total catch (Table 3) is used in the stock reduction model.

Table 3:   Commercial catch (t), assumed non-commercial (Non-commer.) catch (t), and total catch (t)

Year	Commercial	Non-commer.	Total catch
1970	294	700	994
1971	572	800	1 372
1972	394	900	1 294
1973	586	1 000	1 586
1974	812	1 100	1 912
1975	345	1 200	1 545
1976	729	1 300	2 029
1977	1 461	1 400	2 861
1978	2 228	1 500	3 728
1979	3 072	1 600	4 672
1980	3 265	1 700	4 965
1981	3 085	1 800	4 885
1982	3 236	1 900	5 136
1983	4 965	2 000	6 965
1984	4 365	2 000	6 365
1985	4 667	2 000	6 667
1986	4 606	2 000	6 606
1987	7 667	2 000	9 667
1988	9 608	2 000	11 608
1989	7 377	2 000	9 377
1990	8 696	2 000	10 696
1991	5 687	2 000	7 687
1992	5 104	2 000	7 104
1993	6 639	2 000	8 639
1994	5 164	2 000	7 164

3. Biology

The natural mortality(M) estimate is 0.18 using $M = \log_e(100)/\text{maximum age}$, where the maximum age is the age to which 1% of the population survives in an unexploited stock (Hoenig 1983), taken to be 26 years (Annala 1995).

Little has been published about the age of maturity for New Zealand kahawai. However, Eggleston (1975) estimated the age at maturity to be 4–5 years.

Published estimates of the total mortality, Z, are in Table 4. Values in KAH 3 are known to be biased because the purseseine catch does not sample the kahawai population randomly or representatively; the ranges given may span the true value (Drummond & Wilson 1993). The same comment will apply to the KAH 2 estimate.

Table 4: Estimates of total mortality parameter, Z. KAH 2 and KAH 3 data are sampled from purseseine catches, and KAH 9 data are sampled from trawl bycatch

Fishstock	Estimate	Time sampled	Source
KAH 2	0.24	Nov 92	Drummond (1995)
KAH 3 (Marlborough Sounds)	0.22–0.35	Nov 90–Mar 91	Drummond & Wilson (1993)
KAH 3 (Clifford/Cloudy Bays)	0.19–0.27	Nov 90–Jun 91	Drummond & Wilson (1993)
KAH 3 (Kaikoura)	0.23–0.30	Nov 90–May 91	Drummond & Wilson (1993)
KAH 9	0.11	Feb 91–Mar 91	Jones et al. (1992)

Published estimates of the von Bertalanffy growth parameters are in Table 5.

Table 5: Estimates of the von Bertalanffy growth parameters, k, t_0, and L_∞

Fishstock	Sex	k	t_0	L_∞	Source
KAH 1	Female	0.24	-0.18	56.93	McKenzie et al. (1992)
KAH 1	Male	0.24	-0.20	55.61	McKenzie et al. (1992)
KAH 2	Female	0.33	+0.60	54.23	Drummond (1995)
KAH 2	Male	0.34	+0.58	53.51	Drummond (1995)
KAH 3	Female	0.29	+0.19	55.23	Drummond & Wilson (1993)
KAH 3	Male	0.33	+0.41	53.04	Drummond & Wilson (1993)
KAH 9	Female	0.27	-0.39	55.34	McKenzie et al. (1992)
KAH 9	Male	0.26	-0.65	53.88	McKenzie et al. (1992)

Published estimates of the weight-length relation are in Table 6. The weight-length data collected throughout New Zealand has not been analysed in a unified way.

Table 6: **Estimates of the parameters in the weight-length relation, Weight = a(Length)^b (weight in g, length in cm fork length) in KAH 3**

Method	Sex	a	b	Source
Purseseine	Female	0.035	2.79	Drummond & Wilson (1993)
Purseseine	Male	0.033	2.81	Drummond & Wilson (1993)
All methods	Female	0.0010	3.15	Drummond (1994)
All methods	Male	0.0088	3.18	Drummond (1994)

4. Model

Modelling considers a range of likely parameter values describing the growth, recruitment, catch, and biomass to find which are most important in assessing the stock. We can also set up hypotheses and examine the acceptability of their consequences.

The model used solves by maximum likelihood the following schematic equation:

This year's biomass = Last year's biomass
+ Growth + Recruitment − Catch − Natural mortality

and requires at least biological parameters (*see* Section 4.1 for the values used), a catch history (*see* Table 3, Figure 1), and the range of likely fishing mortalities to estimate the likely range of the virgin biomass (Cordue 1996). An abundance index is required to derive a point estimate of virgin biomass.

The model is age-structured, but all fish 15 years and older are assumed to form a "plus group" and are not treated separately. The Baranov catch equation is assumed to apply, hence the catch is assumed to be taken before natural mortality occurs in each year. I look at changes in the mid-year biomass from year to year. The recruitment is assumed to be deterministic for biomass estimation, but is stochastic for yield estimation.

The model is described in Appendix 1; this is a slightly modified copy of appendix 1 of Francis *et al.* (1995) with some additional material from Francis (1990, 1992). The simpler parts of the model developed for orange roughy (Francis *et al.* 1995) are used.

I make the major assumption that kahawai can be treated as one stock. Tagging experiments (Wood *et al.* 1990, Jones 1995) show that some kahawai move large distances. At this stage, I can not make a realistic estimation of the immigration to and emigration from the individual Fishstocks. The biological information currently available is inadequate to distinguish the Fishstocks.

4.1 Model biological parameters

Table 7 shows the biological parameter values used in the base case model. Both sexes are assumed to have the same growth parameters. This is almost certainly not true and biological parameters will be updated after more age and growth data have been analysed. The von Bertalanffy parameter L_∞ has been taken as 60 cm in all simulations. Other von Bertalanffy parameters were chosen at about the middle of the range of published values (Annala 1995).

Table 7:   Base case biological parameters

Parameter	Symbol	Value (both sexes)
Natural mortality	M	$0.2\,\mathrm{yr}^{-1}$
Age of recruitment	A_r	4 yr
Gradual recruitment	S_r	3 yr
Age at maturity	A_m	5 yr
Gradual maturity	S_m	0 yr
von Bertalanffy parameters	L_∞	60 cm
	k	$0.3\,\mathrm{yr}^{-1}$
	t_0	0 yr
Length-weight parameters	a	0.033
	b	2.80
Recruitment steepness	h	0.95
Recruitment variability (biomass)	σ_R	0
Recruitment variability (yield)	σ_R	0.6

Kahawai recruit to the fishery at all ages, though the younger age classes are less heavily fished. Kahawai differs from most of the assessed New Zealand species in that the recreational fishery forms a substantial part of the total and the kahawai recreational fishery has minimal restrictions imposed on it (a total daily bag limit for all fish species in some areas). Juvenile kahawai are found only in shallow water (Jones 1995) and are easily accessible to recreationalists, particularly in popular areas such as Tasman and Golden Bays, Wellington Harbour, Bay of Islands, Hauraki Gulf, and the Bay of Plenty. Consequently, any model has to allow for some fishing on kahawai from age 1 rather than from about the age of maturity. The use of a gradual recruitment ogive has meant using knife-edge maturity (because of restrictions in the program being used). A knife-edge age at maturity is incorrect for kahawai; it is possible that kahawai become mature at a given length and fish of several ages will have this length.

Kahawai Fishstocks are assumed to be maintained by occasional large year classes rather than by a stock-size dependent recruitment process. Mature kahawai have 60 000 to 750 000 eggs depending on size (Annala 1995). The base case model used a Beverton-Holt stock-recruit relation with steepness parameter $h = 0.95$ to minimise dependence of recruitment on spawning stock size; $h = 0.75$ was used in sensitivity analyses.

5. Biomass estimates for a single kahawai stock

No absolute estimates of abundance are available. Eggleston (1978) estimated the total kahawai stock at 100 000 to 150 000 t using observations from the countrywide aerial sightings surveys started in the mid 1970s and assumptions about the proportions of kahawai schools at the surface at any one time.

5.1 Limiting fishing mortality

Cordue (1996) advocated calculating the minimum and maximum virgin biomasses using the possible range of maximum fishing mortalities.

I follow a similar procedure and have specified an upper bound on the fishing mortality and then found the virgin biomass (to the nearest 1000 t) for which this fishing mortality is not reached in any year. The maximum upper bound on fishing mortality, F_{UB}, is assumed to be 0.2, based on available Z values and perceptions of commercial fishing pressure and using this value leads to a minimum virgin biomass (thought to be conservative). Substantially higher recreational catches (fishing pressure) than assumed (see Table 3) would increase the maximum possible fishing mortality. Biomass histories are found for 1970 to 1994; reliable figures for later commercial catches were not available.

Table 8: Estimates of B_0 (Est B_0), B_{1994} (mid-year biomass in 1994), F_{1994}, and F_{AV} (average F for 1980 to 1992). $Z_{Est} = M + F_{AV}$. Estimates are for M = 0.2, h = 0.95, and k = 0.3. The upper bound fishing mortality (F_{UB}) is varied

F_{UB}	Est B_0	B_{1994}	F_{1994}	F_{AV}	Z_{Est}
0.20	104 000	50 000	0.145	0.116	0.32
0.15	121 000	68 000	0.106	0.091	0.29
0.10	158 000	105 000	0.068	0.063	0.26
0.05	275 000	223 000	0.032	0.032	0.23
0.04	334 000	283 000	0.025	0.025	0.23
0.03	434 000	383 000	0.019	0.019	0.22
0.02	635 000	584 000	0.012	0.012	0.21

Table 8 shows that B_0 and B_{1994} increase and F_{1994} (current fishing mortality) and F_{AV} (average fishing mortality for years 1970 to 1992) decrease as F_{UB} is decreased. The average fishing mortality, F_{AV}, is about 60% F_{UB}. The estimated Z, defined as $Z_{Est} = M + F_{AV}$ also decreases as F_{UB} is decreased and can be compared with measured values of Z (Table 4). An estimate of the maximum plausible virgin biomass could be determined from the smallest value of F_{UB} thought likely or from the smallest fraction of available fish which is consistent with the catch in the year of maximum catch. No agreement on the values to use was reached. Four small values of F_{UB}, that is, 0.02, 0.03, 0.04, and 0.05 were used assuming the actual possible maximum B_0 will lie within the estimated range. The upper bound on fishing mortality occurs in either

1988 or 1990 (depending on the specific assumptions), that is, in one of the years when the catch was highest (*see* Table 3, Figure 1).

The minimum virgin biomass is roughly 100 000 t. For the maximum virgin biomass, 500 000 t is a round figure estimate within the range 275 000–635 000 t predicted by maximum fishing mortalities of 0.05–0.02 (*see* Table 8).

5.2 Sensitivity analysis

The biomass estimates are uncertain because of uncertainty in the choice of model parameters. The effects of varying some of the parameters are shown below. Uncertainties in other model assumptions, such as the age of maturity and the recruitment ogive, will also lead to uncertainties in the biomass estimates. Perhaps the most important restriction in the model is the use of deterministic recruitment.

Simulated biomass histories where the maximum fishing mortality in any year is constrained to be small, less than 0.05 say, are straining the credibility limits of a model when deterministic recruitment. That is, the changes in biomass when recruitment fluctuates randomly in each year around the mean level predicted from the stock-recruit relation may be much greater than the changes induced by low fishing mortality.

The results in Table 8 show a drop in biomass once any sort of fishing occurs. Further information is required to increase the reliability of the biomass estimation, for example, a relative biomass index. Calculations have been performed for kahawai using assumed sets of biomass indices (Bradford, unpublished results) and show the drop in biomass index which would be consistent with the changes in biomass observed when the fishing mortality is constrained not to exceed a particular level. The probability that the true virgin biomass has been obtained can be simulated for a given biomass index by asking the question, for each of a series of trial B_0 values: "If this were the true B_0, how likely is it that we would get an estimate of virgin biomass greater than B_{0est}?". Such calculations show that as B_{0est} increases, the probability that the we have actually obtained B_0 converges towards 1 only if the relative biomass index has sufficient contrast (when the *c.v*.s on the index points are taken into account).

5.2.1 Effects of changes in productivity on minimum virgin biomass

Virgin biomass (B_0) and other quantities were estimated using different productivity parameters (base case: $M = 0.2$, $h = 0.95$, and $k = 0.3$) with $F_{UB} = 0.2$. Less productive stocks give somewhat higher minimum virgin biomasses, but lower current biomasses than more productive stocks (Table 9). With F_{UB} fixed, Z_{Est} depends mainly on M, and changing M made the biggest change in the estimated minimum virgin biomass. The lack of sensitivity to h occurs because, in these calculations, the spawning biomass remains high and Beverton-Holt stock-recruit relation will be almost flat for both $h = 0.75$ and $h = 0.95$. The current value of biomass is compared with the biomass at maximum

sustainable yield B_{MSY} which is obtained using the Beverton-Holt stock-recruit relation. The current biomass, B_{1994}, approaches B_{MSY} as h and/or k decrease (Table 9); this effect is mainly due to increase in B_{MSY}.

Table 9: Estimates of B_0 (Est B_0), B_{1994} (mid-year biomass in 1994), B_{1994}/B_{MSY}, F_{1994} and F_{AV} (average F for years 1980 to 1992). $F_{UB} = 0.2$. $Z_{Est} = M + F_{AV}$. Estimates are for four values of natural mortality M, two of steepness parameter h, and three of growth parameter k (not all possible parameter combinations)

	M	h	k	Est B_0(t)	B_{1994}(t)	B_{1994}/B_{MSY}%	F_{1994}	F_{AV}	Z_{Est}
	0.10	0.75	0.2	127 000	40 000	110	0.179	0.106	0.21
	0.10	0.75	0.3	121 000	41 000	130	0.176	0.110	0.21
	0.10	0.75	0.4	118 000	43 000	140	0.170	0.111	0.21
	0.10	0.95	0.2	129 000	40 000	140	0.180	0.108	0.21
	0.10	0.95	0.3	123 000	41 000	180	0.175	0.112	0.21
	0.10	0.95	0.4	120 000	43 000	220	0.169	0.113	0.21
	0.20	0.75	0.2	110 000	47 000	150	0.155	0.114	0.31
	0.20	0.75	0.3	105 000	48 000	170	0.149	0.116	0.32
	0.20	0.75	0.4	102 000	50 000	190	0.145	0.117	0.32
	0.20	0.95	0.2	109 000	48 000	230	0.151	0.114	0.31
*	0.20	0.95	0.3	104 000	50 000	300	0.145	0.116	0.32
	0.20	0.95	0.4	101 000	51 000	390	0.141	0.117	0.32
	0.15	0.95	0.3	111 000	46 000	230	0.155	0.115	0.27
	0.25	0.95	0.3	98 000	52 000	390	0.136	0.118	0.37

* Base case

5.2.2 Effects of changing F_{UB} and M

Table 10 compares the estimated virgin (Est B_0) and current biomasses (B_{1994}) with B_{MSY}. B_{1994} has dropped to 30–70% B_0 but may be up to five times B_{MSY}.

Table 10: Estimates of B_0 (Est B_0) and current (B_{1994}) biomasses compared with B_{MSY}. $h = 0.95$ and $k = 0.3$. F_{AV} is the average F for 1980 to 1992. $Z_{Est} = M + F_{AV}$. F_{UB} and M are specified

F_{UB}	M	F_{AV}	Z_{Est}	Est B_0(t)	B_{MSY}/B_0%	B_{1994}/B_0%	B_{1994}/B_{MSY}%
0.1	0.15	0.062	0.21	165 000	18.1	61.7	340
0.1	0.20	0.063	0.26	158 000	15.8	66.8	420
0.1	0.25	0.063	0.31	153 000	13.5	70.9	520
0.2	0.15	0.115	0.26	111 000	18.1	41.0	230
0.2	0.20	0.116	0.32	104 000	15.8	48.1	300
0.2	0.25	0.117	0.37	98 000	13.5	53.2	390
0.3	0.15	0.160	0.32	94 000	18.1	29.4	160

5.2.3 Effects of higher past recreational catch on estimated B_0

Mark Feldman (pers. comm.) suggested using 4000 t as the average recreational catch between 1974 and 1984. Using this suggestion, the minimum virgin biomasses (assuming $F_{UB} = 0.2$) were calculated for a range of productivity parameters. Higher catches in the past lead to higher estimates of minimum virgin biomass. The ratio B_{1994}/B_{MSY} in Table 11 is almost the same as that in Table 9 for corresponding parameter values.

Table 11: Estimates of B_0 (Est B_0), B_{1994} (mid-year biomass in 1994), B_{1994}/B_{MSY}, F_{1994} and F_{AV} (average F for 1980 to 1992). $F_{UB} = 0.2$. Estimates are for two values of M, two of h, and three of k. A larger recreational catch in the past is assumed; the model is run from 1945 to 1994

M	h	k	Est B_0(t)	B_{1994}(t)	B_{1994}/B_{MSY}%	F_{1994}	F_{AV}	Z_{Est}
0.1	0.75	0.2	160 000	46 000	100	0.160	0.121	0.22
0.1	0.75	0.3	152 000	48 000	120	0.151	0.123	0.22
0.1	0.75	0.4	146 000	49 000	130	0.150	0.126	0.23
0.1	0.95	0.2	156 000	47 000	140	0.155	0.123	0.22
0.1	0.95	0.3	148 000	50 000	180	0.146	0.124	0.22
0.1	0.95	0.4	143 000	51 000	220	0.145	0.127	0.23
0.2	0.75	0.2	128 000	54 000	150	0.138	0.130	0.33
0.2	0.75	0.3	120 000	55 000	170	0.133	0.131	0.33
0.2	0.75	0.4	116 000	56 000	190	0.129	0.132	0.33
0.2	0.95	0.2	124 000	54 000	230	0.133	0.130	0.33
0.2	0.95	0.3	117 000	57 000	310	0.129	0.131	0.33
0.2	0.95	0.4	113 000	58 000	390	0.126	0.132	0.33

As this suggestion meant quite large 1970s catches, the calculations were extended back to 1945 (catches during the Second World War were likely to be low). Hence, the non-commercial catch (including traditional catch and some commercial catch in the years before 1970) was taken as: 375 to 4000 t in steps of 125 t for 1945 to 1974; constant at 4000 t from 1975 to 1984; then 3600, 3200, 3000 dropping to 2000 t (in 1992) in steps of 200 t, 2000 t in 1993–94 (*see* Figure 1). (I believe that 10 years of recreational kahawai catch at 4000 t would have resulted in reduced recreational catch rates by the early 1980s, which is contrary to recreational perceptions.)

6. Yield estimates

The Maximum Constant Yield (MCY) is defined here as the percentage of B_0 that can be taken indefinitely without reducing the population below 20% B_0 more than 10% of the time (Francis *et al.* 1995). Similarly, E_{CAY} is defined here as the exploitation rate producing maximum average yield without reducing the population below 20% B_0 more than 10% of the time. Both MCY and E_{CAY} depend on the productivity of the stock and the recruitment variability but not the actual value of B_0. The method of estimation of MCY and E_{CAY} is given in Appendix 1. The calculations use a deterministic calculation of B_0 and an assumed relative biomass index as a starting point. The values of MCY (expressed as a percentage of B_0) and E_{CAY} do not depend on the biomass index used in their generation.

6.1 Effects of changes in recruitment variability and mortality on yield

The recruitment variability, σ_R, is taken as 0.6 in the base case and the last two columns show the change in MCY when the recruitment variation changes (Table 12). The MCY increases when $\sigma_R = 0.4$ and decreases when $\sigma_R = 0.8$.

Table 12: Estimates of Maximum Constant Yield (MCY) as a percentage of B_0 (t), and exploitation rate producing maximum average yield (E_{CAY}) for four values of natural mortality, M, two of steepness parameter h, and three of growth parameter k. Recruitment variability (σ_R) is varied for the MCY estimates

	M	h	k	E_{CAY}	σ_R 0.6 MCY	0.4 MCY	0.8 MCY
	0.10	0.75	0.2	0.131	2.595	2.709	2.413
	0.10	0.75	0.3	0.147	2.924	3.090	2.683
	0.10	0.75	0.4	0.157	3.176	3.378	2.878
	0.10	0.95	0.2	0.163	3.191	3.325	2.967
	0.10	0.95	0.3	0.183	3.701	3.903	3.408
	0.10	0.95	0.4	0.198	4.094	4.347	3.756
·	0.20	0.75	0.2	0.215	4.629	4.983	4.171
	0.20	0.75	0.3	0.242	5.285	5.760	4.690
	0.20	0.75	0.4	0.260	5.762	6.345	5.086
	0.20	0.95	0.2	0.266	5.514	5.933	5.020
*	0.20	0.95	0.3	0.300	6.430	6.979	5.772
	0.20	0.95	0.4	0.324	7.128	7.807	6.307
	0.15	0.95	0.3	0.248	5.033	5.430	4.785
	0.25	0.95	0.3	0.352	7.606	8.427	6.603

* base case

Table 13 has MCY values for σ_R between 0.2 and 1.2 using $M = 0.2$, $h = 0.95$, and $k = 0.3$ (base case parameters). The decrease in MCY as σ_R increases was found by Francis

(1992) for other Fishstocks. Recruitment variability may be high for kahawai and a recruitment index would give one means of improving the biomass estimates.

Table 13: **Estimates of MCY (as a percentage of B_0) with M = 0.2, h = 0.95, and k = 0.3 and a range of values of σ_R**

σ_R	0.2	0.4	0.6	0.8	1.0	1.2
MCY	7.389	6.979	6.430	5.772	4.995	4.160

6.2 Maximum constant yield in tonnes at largest likely Z_{Est}

Table 14 repeats part of Table 10 for those entries where Z_{Est} is a little greater than 0.3 since the maximum likely Z is somewhat larger than 0.3 (Table 4). Input numbers to the estimations are given suitably rounded values in recognition of the model and measurement inaccuracies, so the Z_{Est} estimates are slightly different. The summary data in Table 14 are thought to represent conservative estimates. Current estimates (Annala 1995) suggest that M is about 0.2 and, as several kahawai of about 20 years have been aged (Drummond & Wilson 1993), M is unlikely to be as high as 0.25. Also, F_{UB} is unlikely to be as high as 0.3, or M as low as 0.15.

Table 14: **Estimates of F_{AV}, Z_{Est}, B_0, the formulae for estimating MCY, MCY (t), B_{1994}/B_{MSY}. h = 0.95 and k = 0.3. Estimates are calculated for the specified F_{UB} and M**

F_{UB}	M	F_{AV}	Z_{Est}	Est B_0	Formula	MCY (t)	B_{1994}/B_{MSY}%
0.3	0.15	0.160	0.32	94 000	5.03%B_0	4 700	160
0.2	0.20	0.116	0.32	104 000	6.43%B_0	6 700	300
0.1	0.25	0.063	0.31	153 000	7.61%B_0	11 600	520

The estimated catch (Table 3) in the past 10 years falls within the range of MCY yields given in Table 14.

7. Discussion

The preliminary simulation modelling described in this report estimates a conservative virgin biomass for kahawai throughout New Zealand at about 100 000 t, which agrees with the best estimate made by Eggleston (1978). The biomass and other values obtained depend upon the catch history (which includes an assumed non-commercial catch) and the use of deterministic recruitment and upper bounds on fishing mortality in any year. An estimate of the maximum virgin biomass proved difficult to obtain but is perhaps about 500 000 t.

At the conservative B_0, assuming a maximum fishing mortality of 0.2, steepness (h) of 0.95, natural mortality (M) of 0.2, and growth rate parameter (k) of 0.3, the catch will have exceeded the MCY in some years in the past and the current catch is slightly greater than MCY. However, the estimated biomass in 1994 (B_{1994}) is about three times B_{MSY} when using the parameter values in this paragraph.

The calculations have indicated some areas where more information is needed to develop a complete stock assessment for kahawai.

- A recruitment index would improve the predictions of how much kahawai can be harvested in the future. A recruitment index would also give a measure of recruitment variability.

- A properly substantiated abundance index is required. A relative biomass index needs to be precise or have a lot of contrast to be useful.

- Better knowledge of the biological parameters, particularly M, will improve the accuracy of the calculations. The further analysis of the available biological data will help in this regard.

- The correct stock structure is required to attempt calculations by Fishstock, including knowledge of the movement patterns of kahawai as immigration to and emigration from Fishstocks may need to be considered.

The non-commercial catch in the past had to be guessed from the current estimate of recreational harvest (Teirney et al. 1995), reports of fishing activity in the past, and a probable increase in non-commercial fishing activity. It might be possible to model the likely kahawai non-commercial catch in the past taking into account economic, social, and demographic factors, and how many kahawai might have been accessible to non-commercial fishers.

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Appendix 1: Stock reduction model

The stock reduction model and associated decision analysis has been developed by Chris Francis for the orange roughy assessment (Francis 1990, 1992, Francis *et al.* 1995). Only the simpler aspects of the techniques are used here. This description of the model comes from Francis (1995); however, the model has been developed further than is used here. The calculations done in this report are more in the spirit of Francis (1990) than Francis *et al.* (1995).

Table 15: Data required, and corresponding model notation, for stock reduction and decision analysis

Parameter	Description
Subscripts	
s	sex (1 = male, 2 = female)
y	year
j	indexes the jth series of biomass indices
Biological parameters	
M_s	instantaneous natural mortality (y^{-1})
A_{rs}	age at 50% recruitment (y)
S_{rs}	recruitment ogive width parameter (y)
A_{ms}	age at 50% maturity (y)
S_{ms}	maturity ogive width parameter
$L_{\infty s}$	von Bertalanffy maximum length (cm)
k_s	von Bertalanffy growth rate parameter (y^{-1})
t_{0s}	von Bertalanffy constant (y)
a_s, b_s	length–weight parameters: $W = aL^b$, L in cm W in g
σ_R	recruitment variability
h	stock recruit steepness (Beverton & Holt equation)
A_{max}	maximum age in the model (y) (there is a plus group at this age)
F_{max}	maximum possible exploitation rate
Biomass indices	
O_{yj}	value of jth index in year y
c_{yj}	coefficient of variation of O_{yj}
Catch history	
C_y	catch (historical or projected) in year y

The aim of stock reduction analysis is to estimate past and present biomass for a fishery. Three types of input data are required (Table 15): biological parameters, abundance indices, and a complete catch history. For decision analysis, the catch history

is extended into the future by adding proposed future catch levels, and evaluating the likely response of the fishery to these catch levels by estimating various measures of risk or fishery performance.

The mean virgin biomass (B_0) is determined by running the stock reduction model with deterministic recruitment.

The population model

Given input data (Table 15) and a value for B_0, the population model first calculates values for the derived parameters (Table 16) as follows.

$$A_{r,lo} = int(A_{rs} - S_{rs}) \tag{1}$$

$$A_{r,hi} = int(A_{rs} + S_{rs} + 0.999) \tag{2}$$

where $int(x)$ returns the largest integer less than or equal to x.

$$r_{is} = \begin{cases} 0 & 1 \leq i < A_{r,lo} \\ 1/[1 + 19^{(A_{rs}-i)/S_{rs}}] & A_{r,lo} \leq i \leq A_{r,hi} \\ 1 & A_{r,hi} < i \leq A_{max} \end{cases} \tag{3}$$

$$p_{is} = \frac{1 - r_{is}}{1 - r_{i-1,s}} \tag{4}$$

$$L_{is} = L_{\infty s}[1 - e^{k_s(i-t_{0s})}] \tag{5}$$

$$w_{is} = 10^6 a_s L_{is}^{b_s} \tag{6}$$

$$\theta_s = \sum_i r_{is} w_{is} e^{-M_s i} + \frac{r_{A_{max}^S} w_{A_{max}^S} e^{-M_s(A_{max}+1)}}{1 - e^{-M_s}} \tag{7}$$

$$\bar{R}_0 = \frac{2B_0}{\sum_s \theta_s} \tag{8}$$

$$\alpha = 0.5\theta_2 \left(1 - \frac{h - 0.2}{0.8h}\right) \tag{9}$$

$$\beta = \frac{h - 0.2}{0.8h\bar{R}_0} \tag{10}$$

Recruitment to the fishery happens at a specified age (taken to be age 1 for kahawai) and involves parameters A_{rs}, S_{rs}, N_{yis}^r, r_{is}, p_{is}, $A_{r,lo}$, and $A_{r,hi}$. Recruitment to the population happens at age 1 and involves parameters σ_R, h, $\bar{R}_y$, R_y, and ϵ_y.

Table 16: Description and notation for model parameters and variables (in addition to those in Table 15). These are given in the order in which they are introduced in the text. Subscripts s, y, and j are as defined in Table 15

Parameter   **Description**

Subscripts

i — age (y)

Derived parameters

$A_{r,lo}$, $A_{r,hi}$	range of ages for which there is partial recruitment/maturity
r_{is}	proportion of fish (of age i and sex s) that are recruited (= mature) in the virgin population
p_{is}	proportion (of fish of age $i - 1$ and sex s that were not recruited in one year) that will still not be recruited in the next year
L_{is}	mean length of fish of age i and sex s
w_{is}	mean weight of fish of age i and sex s
θ_s	constant used in calculating $\bar{R}_0$
$\bar{R}_0$	mean virgin recruitment (at age 1)
α, β	Beverton & Holt stock-recruit relationship parameters

Variables calculated at each model iteration

$\bar{R}_y$	expected recruitment (at age 1) in year y
N_{yis}	number of fish (age = i, sex = s) in year y
ϵ_y	recruitment deviate for cohort that recruits (at age 1) in year y
R_y	actual recruitment (at age 1) in year y
N^r_{yis}	number of recruited fish (age = i, sex = s) in year y
N^u_{yis}	number of unrecruited fish (age = i, sex = s) in year y
B^1_{ys}	beginning-of-year biomass for sex s in year y
B^2_{ys}	pre-fishing biomass for sex s in year y
B^3_{ys}	mid-year biomass for sex s in year y
B^4_{ys}	end-of-year biomass for sex s in year y
F_y	exploitation rate in year y
$\bar{L}_y$	mean length in year y

The model then initialises the population structure by generating a vector of standard normal variates $\{\epsilon_{1-i} : 1 \leq i \leq A_{max}\}$ and calculating the numbers at age as follows. (For most cases used here, deterministic recruitment is assumed and ϵ is a constant.)

$$R_{1-i} = \bar{R}_0 \exp[\epsilon_{1-i}\sigma_R - 0.5\sigma_R^2] \qquad 1 \leq i \leq A_{max} \tag{11}$$

$$N_{0is} = \begin{cases} 0.5 R_{1-i} \exp[-M_s(i-1)] & 1 \leq i < A_{max} \\ 0.5\bar{R}_0 \frac{\exp[-M_s(A_{max}-1)]}{1-\exp[-M_s]} & i = A_{max} \end{cases} \tag{12}$$

$$N_{0is}^r = N_{0is}r_{is} \tag{13}$$

$$N_{0is}^u = N_{0is}(1 - r_{is}) \tag{14}$$

An iterative procedure is used to calculate numbers at age for each successive year. At each step, a standard normal variate, ϵ_y, is generated, and the following equations evaluated.

$$\bar{R}_y = \frac{B_{y-1,2}^3}{\alpha + \beta B_{y-1,2}^3} \tag{15}$$

$$R_y = \bar{R}_y \exp[\epsilon_y\sigma_R - 0.5\sigma_R^2] \tag{16}$$

$$N_{yis}^u = \begin{cases} 0.5 R_y & i = 1 \\ N_{y-1,i-1,s}^u e^{-M_s} & 2 \leq i < A_{r,lo} \\ N_{y-1,i-1,s}^u p_{is} e^{-M_s} & A_{r,lo} \leq i \leq A_{r,hi} \\ 0 & A_{r,hi} < i \leq A_{max} \end{cases} \tag{17}$$

$$N_{yis}^r = \begin{cases} 0 & 1 \leq i < A_{r,lo} \\ N_{y-1,i-1,s}^r e^{-M_s}(1 - F_{y-1}) + N_{y-1,i-1,s}^u e^{-M_s}(1 - p_{is}) & A_{r,lo} \leq i \leq A_{r,hi}+1 \\ N_{y-1,i-1,s}^r e^{-M_s}(1 - F_{y-1}) & A_{r,hi}+1 \leq i < A_{max} \\ (N_{y-1,i-1,s}^r + N_{y-1,i,s}^r)e^{-M_s}(1 - F_{y-1}) & i = A_{max} \end{cases} \tag{18}$$

The biomasses, exploitation rate, and mean length associated with each year are calculated using the following equations.

$$B_{ys}^1 = \sum_i N_{yis}^r w_{is} \tag{19}$$

$$B_{ys}^2 = B_{ys}^1 e^{-M_s} \tag{20}$$

$$B_{ys}^3 = B_{ys}^2 (1 - 0.5 F_y) \tag{21}$$

$$B_{ys}^4 = B_{ys}^2 (1 - F_y) \tag{22}$$

$$F_y = \begin{cases} \dfrac{C_y}{\sum_S B_{ys}^2} & \text{if } \dfrac{C_y}{\sum_S B_{ys}^2} < F_{max} \\[2ex] F_{max} & \text{otherwise} \end{cases} \tag{23}$$

$$\bar{L}_y = \frac{\sum_{is} N_{yis}^r L_{is}}{\sum_{is} N_{yis}^r} \tag{24}$$

Calculation of likelihood

This section shows how the likelihood associated with (B_0, ϵ) and the indices O_{yj} is calculated.

For all indices, it is assumed that O_{yi} is either normally (for mean length and older biomass versions) or lognormally (for biomass) distributed with mean $q_j E_{yj}$ and coefficient of variation c_{yj}. The c_{yj} are assumed known, the q_j is to be estimated, and the E_{yj} are calculated from the population model as mid-season biomass $(B_{y1}^3 + B_{y2}^3)$. Note that the program also allows the calculation of E_{yj} as $\bar{L}_y$, but this is not appropriate at this stage for kahawai.

If the recruitment deviates ϵ, are such that the historical catches could not have been caught, the likelihood, L, is set to zero. Otherwise, it is calculated as

$$L = \exp \sum_j \lambda_j \tag{25}$$

where the value of λ_j, the log-likelihood associated with the O_{yj}, depends on whether the O_{yj} are assumed to be normally or lognormally distributed.

When the O_{yj} are normally distributed

$$\lambda_j = -m_j \ln q_j - \sum_y \ln E_{yj} - 0.5 \sum_y c_{yj}^{-2} - \sum_y \ln c_{yj} + \frac{0.5 S_1}{q_j} \tag{26}$$

where

$$q_j = \frac{(S_1^2 + 4 M_j S_2)^{0.5} - S_1}{2 m_j} \tag{27}$$

$$S_1 = \sum_y \left(\frac{O_{yj}}{E_{yj} c_{yj}} \right) \tag{28}$$

$$S_2 = \sum_y \left(\frac{O_{yj}}{E_{yj} c_{yj}} \right)^2 \tag{29}$$

and m_j is the number of years for which there is an observation in the jth series of biomass indices (throughout this section all sums over the indices y are assumed to cover only these years).

Where the O_{yj} are lognormally distributed

$$\lambda_j = 0.5m_j - \sum_j \ln(O_{jy}s_{yj}) - \sum_y \frac{0.5}{s_{yj}^2} \left(\ln \left(\frac{O_{yj}}{q_j E_{yj}} \right) + 0.5s_{yj}^2 \right)^2 \tag{30}$$

where

$$q_j = \exp[(S_1 + 0.5m_j)/\sum_j s_{yj}^{-2}] \tag{31}$$

$$S_1 = \sum_y \left(s_{yj}^{-2} \ln \left(\frac{O_{yj}}{E_{yj}} \right) \right) \tag{32}$$

$$s_{yj} = (\ln(1 + c_{yj}^2))^{0.5} \tag{33}$$

Fishery performance measures

All performance measures are expressed as probabilities and calculated as proportions.

Simple estimation algorithm for calculating B_0

The method proceeds according to the following steps (Francis 1990).

1. Choose a trial value of B_0.

2. Given B_0, calculate the biomass values, E_{yj}, corresponding to each biomass index, O_{yj}, using the catch history and the age-structured model.

3. Calculate the best value of the catchability, q_j, for this B_0; that is, the value of q_j that gives the best match between the calculated biomass values and the sequence of biomass indices divided by q_j.

4. Calculate the log-likelihood, λ_j, for these values of B_0 and q_j.

5. Repeat steps 1 to 4 with a range of trial B_0 values to find the value of B_0 that maximises the likelihood.

Estimation of confidence interval for B_0

Suppose B_{0est} is the maximum likelihood estimate derived above. A series of simulations may be used to estimate a confidence interval for B_{0est}, given a value of c_{yj} (c.v.

on biomass index). These simulations answer the question for each series of trial B_0 values, "If this were the true B_0, how likely is it that we would get an estimate of virgin biomass greater than B_{0est}?".

The procedure is as follows.

1. Pick a trial value of B_0.

2. Calculate the biomasses, E_{yj}, using the age structured model with this value of B_0.

3. Generate simulated biomass indices, O_{yj}, (assuming O_{yj} is normal with mean E_{yj} and coefficient of variation c_{yj}).

4. Calculate the maximum likelihood estimate B_0 for the simulated O_{yj}.

5. Repeat steps 3 and 4 100 times and calculate the proportion, p, of the B_o that are greater than B_{0est}.

6. Repeat steps 1 to 6 for a range of trial B_0 values.

7. Graph p against the trial B_0 values and draw a smooth line through the points.

8. The 95% confidence interval for B_{0est} is the range of trial B_0 values on the graph for which $0.025 < p < 0.975$.

Estimation of Maximum Constant Yield and Current Annual Yield

These calculations are described in Francis (1992); the description of the calculation below comes from that report.

The age structured model used in the simulations is as described above. In this model two parameters describe the stock-recruit relationship: the steepness, h (= the mean recruitment at $S = 20\%S_0$, expressed as a fraction of the virgin recruitment) and recruitment variability, σ_R (= the standard deviation of the natural logarithm of the recruitment).

The aim is to estimate, for each level of harvesting (with constant catch or constant F), the mean catch and the probability that S is less than $20\%S_0$. This probability is taken to be a long-term value, that is, the probability calculated after the population had reached a (stochastic) equilibrium under a particular harvesting level.

The following initialisation procedure is used to obtain approximate equilibrium starting conditions. First calculate f_r, the equilibrium biomass (expressed as a fraction of B_0) associated with the given harvest level when recruitment was deterministic. If the given harvest level was not sustainable with deterministic recruitment, f_r was set equal to the equilibrium recruited biomass (expressed as a fraction of B_0) associated with F_{MSY}. The pre-recruit biomass, f_u is calculated as the recruitment (expressed as

a fraction of the virgin recruitment) predicted by the (deterministic) stock-recruit relationship when $S = f_r S_0$. Next, a virgin population is generated assuming stochastic recruitment. The the numbers at age in this population are multiplied by f_r (for recruited fish) or f_u (for pre-recruit fish) to reduce the population to the approximate size expected for the given harvest level. Finally, the model is run for A_l years to stabilise, where A_l is the approximate maximum age of the species, defined by $A_l = \log_e(100)/M$.

The model is run for a further A_l years and the whole procedure repeated 500 times. The mean catch (as a percentage of B_0) and the proportion of years in which S is less than $20\% S_0$ are recorded.

Estimates of biomass are required for both the MCY and CAY rules. It is assumed that these estimates are unbiased and normally distributed with a coefficient of variation of 20% in all cases.

The MCY rules require an estimate of B_0. It is assumed here that what is estimated is the initial biomass, that is, the biomass at the time the fishery started (1970 for the calculations in this report). This may be greater or less than B_0 depending on whether recent recruitment has been above or below average. Thus, in each simulation run with constant catch, the estimate of B_0 is taken as the size of the virgin population generated in the above initialisation procedure, plus a random estimation error (as described above).