Depletion-corrected average catch: a simple formula for estimating sustainable yields in data-poor situations

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MacCall, A. D. 2009. Depletion-corrected average catch: a simple formula for estimating sustainable yields in data-poor situations. – ICES Journal of Marine Science, 66: 2267–2271.

The depletion-corrected average catch (DCAC) formula is an extension of the potential-yield formula, and it provides useful estimates of sustainable yield for data-poor fisheries on long-lived species. Over an extended period (e.g. a decade or more), the catch is divided into a sustainable yield component and an unsustainable "windfall" component associated with a one-time reduction in stock biomass. The size of the windfall is expressed as being equivalent to a number of years of sustainable production, in the form of a "windfall ratio". The DCAC is calculated as the sum of catches divided by the sum of the number of years in the catch series and this windfall ratio. Input information includes the sum of catches and associated number of years, the relative reduction in biomass during that period, the natural mortality rate (M, which should be <0.2 year^{-1}), and the assumed ratio of F_{MSY} to M. These input values are expected to be approximate, and based on the estimates of their imprecision, the uncertainty can be integrated by Monte Carlo exploration of DCAC values.

Keywords: data-poor assessment, potential-yield formula, stock depletion, sustainable yield.

Received 5 March 2009; accepted 19 June 2009; advance access publication 5 August 2009.

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Introduction

Unlike the classic fishery problem of estimating maximum sustainable yield (MSY), data-poor fishery analysis must often be content simply to estimate a yield that is likely to be sustainable. Although absurdly low yield estimates would have this property, they are of little practical use. Here, the problem is to identify a moderately high yield that is likely to be sustainable, while having a low probability that the estimated yield level greatly exceeds MSY and hence risks inadvertent overfishing and possible resource depletion before the error can be detected in the course of fishery monitoring and management. The problem of estimating sustainable yields for data-poor fisheries has been heightened in some fishery management systems, such as in the United States where recent legislation has required determination of annual catch limits without regard for adequate supporting data (NMFS, 2009).

Perhaps the most direct evidence for a sustainable yield would be a prolonged historical period during which the average yield has been taken without indication of a change in underlying resource abundance. The estimate of sustainable yield would be nothing more than the long-term average annual catch over that period. However, it is rare that a resource is exploited without some change in underlying abundance. If the resource declines in abundance (which is necessarily the case for newly developed fisheries), a portion of the associated catch stream is derived from that one-time decline and does not represent potential future yield supported by sustainable production. If that non-sustainable portion is mistakenly included in the averaging procedure, the average will tend to overestimate the sustainable yield. This error has been made frequently in fishery management.

Depletion-corrected average catch

Potential yield

Depletion-corrected average catch (DCAC) is based on the potential-yield formula of Alverson and Pereyra (1969) and Gulland (1970). Two approximations used in the traditional potential-yield formula are $B_{\mathrm{MSY}} = 0.5B_0$, and $F_{\mathrm{MSY}} = M$, where B_0 is the unfished vulnerable abundance, B_{MSY} the level of abundance producing MSY, F_{MSY} the fishing rate that produces MSY, and M the natural mortality rate. Mortality rates F and M are expressed in units of year^{-1}. In this and the following calculations, the rates of fishing mortality (F) and exploitation (catch as a fraction of initial year biomass) are treated as roughly equivalent. The original potential yield is given by

$$Y_{\mathrm{pot}} = 0.5MB_0, \tag{1}$$

where Y_{pot} is the potential yield.

The "windfall ratio"

Taking the potential-yield rationale one step farther, it is possible to calculate the one-time "windfall" harvest, W, attributable to reducing the abundance from B_0 to the assumed B_{MSY} level:

$$W = 0.5B_0. \tag{2}$$

After that reduction in biomass, Y_{pot} can be considered a tentatively sustainable annual yield. Under the potential-yield assumptions, the ratio of the one-time windfall yield to the sustainable yield can be calculated as

$$\frac{W}{Y_{\text{pot}}} = \frac{1}{M}, \tag{3}$$

where the unknown quantity B_0 appears in both the numerator and the denominator, and conveniently cancels. The ratio W/Y_{pot} expresses the magnitude of the windfall harvest relative to a single year of potential yield. For example, if M is 0.1 year^{-1}, the estimated windfall harvest is equal to 10 units of the estimated annual sustainable yield.

Depletion correction

I now develop a more general form for windfall ratios. The two approximations underlying the potential-yield formula are out of date, and merit reconsideration. Most fishery stock–recruitment relationships (SRRs) indicate that the B_{MSY} of fish tends to be $<0.5B_0$, and $0.4B_0$ has been proposed as a useful proxy for B_{MSY} (Clark, 1991; NMFS, 1998; Restrepo *et al.*, 1998). Although exact values of B_{MSY} can be calculated from particular SRRs, it is unreasonable to assume that the SRR is known in data-poor cases where DCAC would be used. Moreover, even in data-rich stock assessments that support sophisticated statistical analysis of stock and recruitment, there is often no ability to distinguish among alternative candidate SRRs (Dorn, 2002).

The $F_{\text{MSY}} = M$ assumption also requires revision, because fishery experience shows that this often tends to be too high. Therefore, the second of the original potential-yield assumptions can be modified by inserting a tuning adjustment (c), which may have a value of <1. Under the revised assumptions, $B_{\text{MSY}} = 0.4B_0$, and $F_{\text{MSY}} = cM$, and the potentially sustainable yield is

$$Y_{\text{pot}} = 0.4cMB_0. \tag{4}$$

A more flexible accounting for the windfall harvest, W, is based on the relative reduction in vulnerable stock abundance from the first year (FYR) to the last year (LYR) of the catch time-series, i.e. where $W = B_{\text{FYR}} - B_{\text{LYR}}$. In the data-rich case where biomasses have been estimated, the DCAC would simply be $(\Sigma C - W)/n$, but the necessary information is lacking for data-poor cases. However, it may be possible to estimate a relative decline in abundance, Δ, where

$$\Delta = \frac{B_{\text{FYR}} - B_{\text{LYR}}}{B_0}, \tag{5}$$

although the individual quantities on the right side of the equation are unknown except in the most data-rich assessments. Therefore, Δ will usually be a rough estimate of the reduction in vulnerable biomass, expressed as a fraction of unfished vulnerable biomass, and it is not anticipated that Δ can be obtained by direct application of Equation (5). Using the preceding equations, the general windfall ratio is now

$$\frac{W}{Y_{\text{pot}}} = \frac{\Delta B_0}{0.4cMB_0} \quad \text{or} \quad \frac{W}{Y_{\text{pot}}} = \frac{\Delta}{0.4cM}, \tag{6}$$

where the three problematic "data-rich" quantities on the right side of Equation (5) have conveniently disappeared.

The windfall ratio in Equation (6) forms the basis for a depletion correction of average catch. If we make the assumption that, on average, each year produces one unit of annual sustainable yield, the resulting catch stream is the sum of two components, one derived from sustainable annual production, and the other from a one-time windfall harvest. For a catch (C) series of length $n = \text{LYR} - \text{FYR} + 1$, the total cumulative catch (ΣC) consists of n years of sustainable production, plus a windfall equivalent to W/Y_{pot} years of potential yield. The DCAC provides an estimate of the yield that could have been sustained (Y_{sust}) during that period:

$$Y_{\text{sust}} = \frac{\sum C}{n + W/Y_{\text{pot}}}. \tag{7}$$

Note that if there has been no underlying change in abundance, $\Delta = 0$, $W/Y_{\text{pot}} = 0$, and Equation (7) is nothing more than average catch. If there has been an increase in abundance, values of Δ and W/Y_{pot} will be negative, and the estimated sustainable yield is larger than the historical average catch.

The DCAC can easily be calculated as a point estimate using the most likely values of the input quantities, but this practice is not recommended unless it is as a quick approximation. Monte Carlo exploration of DCAC estimates is easily conducted and provides useful information on precision and bias, including estimation of approximate confidence intervals, which are often lacking for data-poor methods. A user-friendly implementation of DCAC, including Monte Carlo estimates of precision, is available from the NOAA Fisheries Toolbox (http://nft.nefsc.noaa.gov). Of course, this exploration still does not incorporate all the possible sources of uncertainty in the estimated yield; uncertainty will therefore always be underestimated and this may convey a false sense of security (Rochet and Rice, 2009).

Inputs to DCAC

The precision of estimated catches varies widely among fisheries and species, but catches of data-poor species generally are known less precisely than those of data-rich species. However, the quantity needed for DCAC is the cumulative catch over many years, and the variability of catches among individual years does not matter to the calculation. The precision of the sum may be difficult to estimate, but to the extent that individual years' catches are independent estimates, the relative precision may improve with the length of the time-series. Any consistent bias in catches, such as incomplete reporting, tends to be passed through as a similar bias in estimated DCAC.

In terms of natural mortality rate (M), the use of DCAC is not recommended if M is greater than $\sim$0.2 year^{-1}, above which the depletion correction becomes small. Two commonly used regression methods of obtaining approximate rates of M are those of Pauly (1980) and Hoenig (1983). The first of these methods gives a standard error of 0.56 for estimated $\ln(M)$ based on growth and temperature (note: this value has been converted from the original value of 0.245, which was based on $\log_{10}$). Hoenig's (1983) relationship between total mortality rate (Z) and maximum observed age did not include an estimate of precision, but re-analysis of his original data for fish (Hoenig, 1982) reproduces the original regression parameters and gives a standard error of 0.50 for $\ln(Z)$.

For a lognormal distribution, the coefficient of variation (CV) is closely related to the standard error (σ) of the log-transformed variate. Johnson *et al.* (1994) give the relationship as $CV =$

$(\exp(\sigma^2) - 1)^{\frac{1}{2}}$. For values of σ of 0.5 and 0.56, the corresponding *CV*s are 0.53 and 0.61. Based on these two examples, I suggest that an assumed $CV(M)$ of 0.5 could be used as a minimal default value. There seems to be widespread belief that M is known more precisely than this, but this impression may be based on experience with data-rich cases. For data-poor stocks, there appears to be no justification for assuming a $CV < 0.5$ unless additional information exists to improve the estimate.

Hoenig's (1983) relationship does not apply strictly to natural mortality rate, but in practice it is often used as a method for estimating M directly. In a comparison of 443 fish stocks, Punt *et al.* (2005) concluded that Hoenig's (1983) method was more reliable than Pauly's (1980) method for the purposes of estimating M. Of course, if there is supplementary information on the magnitude of the fishing mortality rate (F), that value could be subtracted from Hoenig's (1983) estimated Z to obtain an improved estimate of M. However, subtracting a constant does not reduce the variance of the estimate. If anything, it would increase the variance if the estimate of the subtracted quantity (F) was imprecise, which is very likely in data-poor cases. Moreover, the "improved" estimate of M would be smaller than the original Hoenig-based estimate of Z, so even if the variance is unchanged, the resulting *CV* would necessarily be >0.5.

For the ratio between F_{MSY} and M (c), Restrepo *et al.* (1998) observed that "M has often been considered to be a conservative estimate of F_{MSY}", but also that this view is now being revised towards lower rates of productivity, and $c = 1$ may be a target or even an upper limit. They note that in some data-poor cases, values of c as low as 0.8 and 0.75 have been suggested as upper limits. Walters and Martell (2004) suggest that the coefficient c is commonly $\sim$0.8, but may be 0.6 or less for vulnerable stocks. It seems likely that there are systematic differences in appropriate values of c, based both on taxonomic groups and geographic regions, and the subject would benefit from meta-analysis. A standard error of 0.2 is suggested as the default estimate of precision.

For Δ, if an index of abundance such as catch per unit effort were available, construction of a conventional production model should be possible, and the use of DCAC might not be necessary. In data-poor circumstances where such an index is not available, it can be especially difficult to estimate the fractional depletion over the duration of a catch series. However, it may be possible to obtain a useful value by direct questioning experienced fishers or by expert opinion. In those data-poor cases, the estimate of Δ will necessarily be imprecise, and the additional difficulty of scaling it in units of B_0 can also be reflected in the stated precision of this quantity. If it is thought that there has been little or no change in abundance, the depletion correction is not required, but there still may be uncertainty about the possible range of Δ, and Monte Carlo integration including the uncertainty in Δ can provide useful confidence intervals for estimated sustainable yield. Alternatively, if nothing at all is known about the value of Δ, it may be appropriate to assume a value (e.g. 0.5) for precautionary purposes. Unlike the other parameters, the precision of Δ is entirely dependent on the data and method used in its estimation, and there is no clear value of precision that can serve as a default.

Examples

The following two examples are drawn from cases where full age-structured stock assessments have been conducted. They provide a basis for comparing DCAC results with independently derived estimates of MSY.

Widow rockfish

About 1981, the widow rockfish (*Sebastes entomelas*) fishery began harvesting an unexploited stock off the west coast of the United States, and for the first 3 years fishing was nearly unrestricted (Gunderson, 1984). Reliable estimates of sustainable yield based on the conventional stock assessments were not available for several years thereafter. The stock assessment in 1988 concluded that abundance was "at or above" B_{MSY} (Lenarz and Hightower, 1988; PFMC, 1988), and in 1989 the assessment concluded that abundance was "at" B_{MSY} (Hightower and Lenarz, 1989; PFMC, 1989). As of 1988, the historical average annual catch (uncorrected) was 15 900 t, and the Pacific Fishery Management Council (PFMC) established a catch quota of 12 100 t for 1989 in the belief that it would be an appropriate reduction in allowable catch.

Application of DCAC to widow rockfish indicates good performance of the formula within a few years of the beginning of the fishery. Calculations of DCAC, as it would have been parameterized at the time, are given for 1988 and 1989 in Table 1. The Monte Carlo distribution of DCAC values shows that the PFMC's catch levels would have been inadvisable (Figure 1). Even now, however, after nearly three decades, the value of MSY for widow rockfish is still unclear, partly because of low-frequency

Table 1. Application of DCAC to the developing widow rockfish fishery, using parameter values that would have been assumed at the time.

Parameter	**Value in 1988**	**Value in 1989**
Fishery performance		
Post 1981 catch (t)	127 000	139 000
Number of years	8	9
Average catch (t)	15 900	14 900
Stock assessment and management		
B relative to B_{MSY}	"at or above"	"at"
Estimated MSY (t)	9 500	8 300
Recommended catch in year + 1	12 400	7 900
Adopted catch in year + 1	12 100	12 400
DCAC		
Assumed M (year^{-1})	0.15	0.15
Standard deviation ln(M) (year^{-1})	0.50	0.50
Assumed Δ	0.5	0.6
Standard deviation Δ	0.15	0.15
Assumed c	1	1
Standard deviation c	0.2	0.2
DCAC point estimate (t)	7 776	7 316
Percentile of point estimate (%)	57	58
Monte Carlo results (n = 10 000)		
Monte Carlo mean (t)	7 408	6 938
Percentiles (%)		
1	2 669	2 515
5	3 708	3 545
10	4 381	4 162
20	5 339	4 982
50	7 308	6 849
80	9 438	8 820
90	10 476	9 803
95	11 367	10 582
99	13 013	12 055

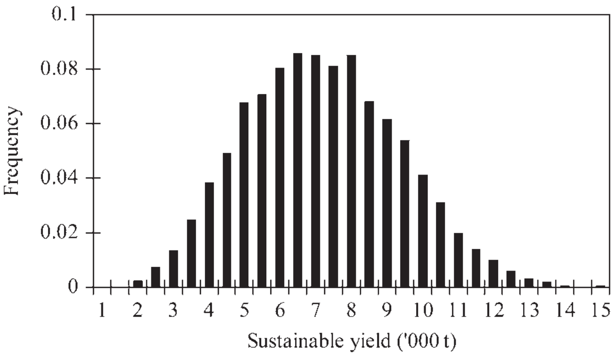

Figure 1. Frequency distribution of DCAC results for widow rockfish in 1989, based on Monte Carlo sampling of parameter values.

environmental variability in reproductive success. One recent estimate is near 2000 t per year (He *et al.*, 2007), but this value may be influenced by a prolonged period of poor recruitment during the 1990s. Also, assumed values of some DCAC parameters have changed since the 1980s. For example, M is now thought to be 0.125 year^{-1}, and c could be assumed to be 0.6, which appears to be typical of *Sebastes* spp. on the US west coast (pers. obs.). These changes produce DCAC values that are ~33% lower than those in Table 1.

Redfish

Redfish (*Sebastes fasciatus*) in the Gulf of Maine and Georges Bank area experienced a long and intense fishery, beginning in the 1930s, leading to severe depletion of the resource by the 1980s. A recent age-structured stock assessment of redfish by Miller *et al.* (2008) produced an estimated MSY of 8951 t, but some participants in the assessment review doubted whether the MSY was that low, given that the historical fishery continued at over twice that level for nearly two decades. Assuming near-total depletion of the resource ($\Delta = 0.95$), an M of 0.05 year^{-1} (also used in the assessment), and $c = 1$, the sustainable yield estimated by DCAC (Table 2), based on the catches from 1934 to 1988, would be 9152 t. This value is close to that derived from the stock assessment and supports the interpretation that a large portion of the historically high catches was supported by a one-time reduction in stock biomass. Use of $c = 0.6$ (as for west coast rockfish) produces a DCAC that is ~25% lower, but it is unclear if North Atlantic stocks of *Sebastes* exhibit the low productivity of Northeast Pacific stocks.

Table 2. Application of DCAC to the Gulf of Maine and Georges Bank redfish.

Parameter	Value
Fishery performance	
Catch 1934–1988 (t)	1 010 230
Number of years	55
Average catch (t)	18 368
Stock assessment and management	
Estimated MSY (t)	8 951
DCAC	
Assumed M (year^{-1})	0.05
Standard deviation ln(M) (year^{-1})	0.50
Assumed Δ	0.95
Standard deviation Δ	0.01
Assumed c	1
Standard deviation c	0.2
DCAC point estimate	9 856
Percentile of point estimate	61%
Monte Carlo results ($n = 10\,000$)	
Monte Carlo mean (t)	9 152
Percentiles (%)	
1	4 040
5	5 374
10	6 125
20	7 149
50	9 155
80	11 164
90	12 132
95	12 857
99	14 112

Discussion

Despite DCAC being derived from the assumptions used in the potential-yield formula, its properties are quite different. Traditional potential yield is a function of two highly uncertain quantities, M and B_0. In contrast, DCAC is primarily a function of catches, which tend to be known comparatively well. In DCAC, M is used only in the depletion correction, so its importance is related to the size of Δ. The estimate of unfished abundance (B_0) nearly disappears from the equations, except in its use as a scaling factor in expressing the value of Δ.

In effect, DCAC is a one-parameter production model that is made possible by supplementary information on quantities such as M and Δ. It provides an estimated yield that is likely to be sustainable, if the stock is maintained near the levels of abundance experienced during the historical period from which the catches were derived. The estimated yield is not necessarily maximal, but in practice seems often to be near MSY. In Equation (7), it does not matter when during the time-series the reduction in abundance actually occurs because, unlike a conventional production model, the assumed production is not an explicit function of biomass. However, a practical interpretation is that the estimated sustainable yield is associated with "typical" stock abundances during the interval FYR to LYR. If there has been a substantial change in abundance, such as severe depletion, during that time interval, the stock conditions at the end of the period (LYR) may no longer correspond to those typical conditions. Although the estimated yield may have been sustainable during the historical time interval, the same yield may no longer be sustainable, because of depletion. Therefore, DCAC is not directly suitable for specifying catches in a stock-rebuilding plan.

Acknowledgements

I thank Mike Jones for programming DCAC for use in the National Fisheries Toolbox, Xi He and Dvora Hart for the example applications, and Chris Legault, Steve Ralston, John Field, an anonymous reviewer, and the editor for useful comments on various versions of the manuscript.

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doi:10.1093/icesjms/fsp209