A proposal to adjust natural mortality to obtain SY:B relationships consistent with Smith et al (2011).

by

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1 Summary

Smith et al (2011) suggests that a Low-Trophic-Level (LTL) resource biomass target of B/B0=0.75 is a favourable trade-off between loss of yield and the impact on predator populations. The target B/B0=0.75 is now part of the MSC guidelines for the management of LTL stocks. Figure 4 of Smith et al (2011) describes the nature of the trade-off and shows that a loss of yield of 20% relative to MSY corresponds to the target of B/B0=0.75. However, the yield curve in Smith et al (2011) is more flat topped than it is for typical age structured sardine population models, suggesting that the loss of yield at B/B0=0.75 can be as much as 40%. Thus either the trade-off suggested as favourable by Smith et al (2011) needs to be revisited for local sardine population models, or the models need to be adjusted so that their yield curves correspond to that which motivated the Smith et al (2011) trade-off suggestion, and hence the MSC guideline. Here the adjustment option is developed. A method is proposed to adjust natural mortality contingent on the level of depletion of prey stocks in order to get agreement of the yield curve to Figure 4 of Smith et al (2011). This causes a change in, amongst other aspects, the harvest proportion at which at equilibrium B/B0=0.75. The method is applied under deterministic recruitment conditions for the two components of the sardine resource, CTS and WTS. Results compare the harvest proportion for the population model before and after applying the proposed adjustments. They show that the so-called 'multi-species' adjustment, the % increase in the harvest proportion that gives B/B0=0.75 after adjustment c.f. before adjustment, is greatest for the Hockey-Stick relationship, and smaller for Beverton-Holt, and gets smaller as the value of h decreases. These effects played a role in a recent revision of sardine TAC allocations.

2 Smith et al 2011

Figure 4 of Smith et al (2011) provides a plot which integrates results across a number of different ecosystems, viz. a relationship between (i) and (ii) to level of LTL stock depletion (as defined by Smith et al it is the quantity 1-B/B0), where (i) (LH y-axis) is the long term catch as a proportion of the maximum long term catch, and (ii) (RH y-axis) is the proportion of predator groups that are impacted by more than 40% (by the end of a 50 year time horizon):

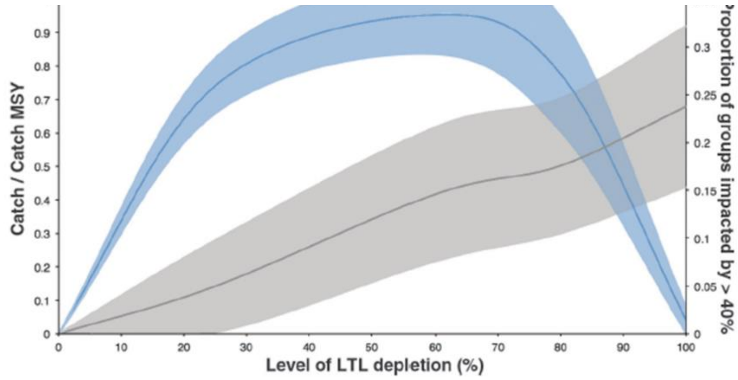

Figure 1. Figure 4 from Smith et al (2011). In this plot the term 'Level of LTL depletion (%)' is 1-B/B0. The unexploited equilibrium state lies at the origin in the bottom left of the plot.

Smith et al (2011) concludes that at B/B0=0.75 the loss of yield relative to MSY is about 20%, and suggests that this may be a favorable trade-off. The B/B0 target of 0.75 is now the basis for the MSC standard for LTL stocks.

Figure 4 of Smith et al (2011) needs to be flipped horizontally to show how the B/B0 = 0.75 suggestion is located on a conventional B/B_0 x-axis. This horizontally reversed version of the relationship is given in Figure 4 below:

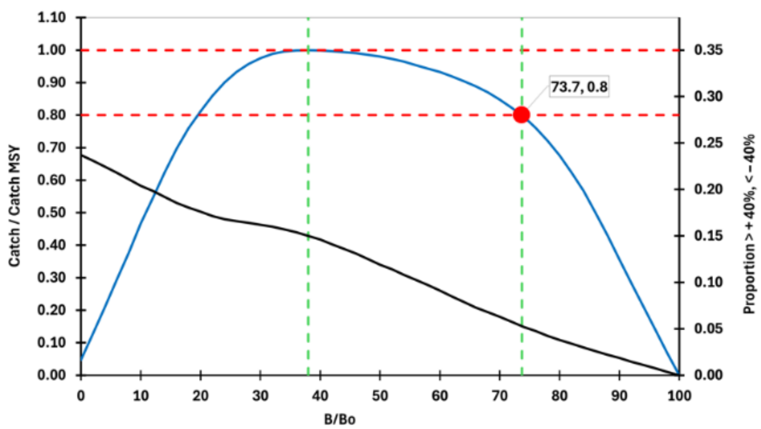

Figure 2. Plots of catch/MSY and the % of species groups impacted by more than 40% (either positively or negatively) vs the LTL prey biomass as a proportion of the unexploited biomass B_0. This figure was obtained by digitizing Figure 4 of Smith et al (2011) and then reversing their plot horizontally.

3 Conventional SY:B relationships

The relationship shown in Figure 2 is characteristically more 'flat-topped' than typical age structured single species models with MSYL < B0/2. *One such relationship* is illustrated by the dashed grey curve in Figure 3 below.

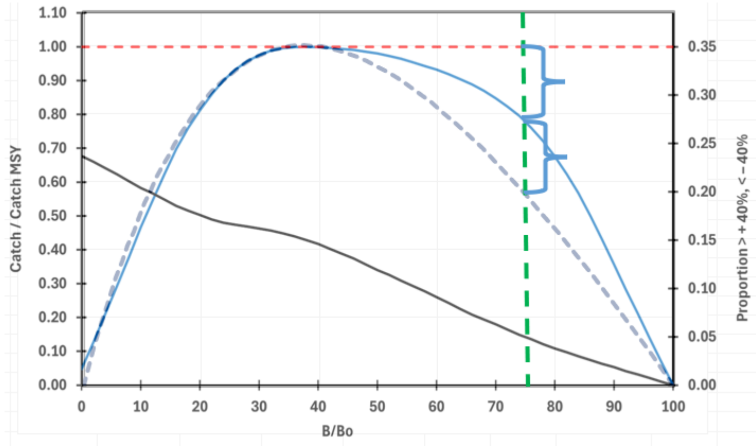

Figure 3. Plots of catch/MSY and % species groups impacted by more than 40% (either positively or negatively) vs the biomass as a proportion of the unexploited biomass B_0. The population model underlying the dashed grey curve is an age-structured population model with a 5+ group, Beverton-Holt stock/recruitment relationship, and parameter values given in the Appendix. The catch equation used is Pope's approximation to the Baranov equation.

In this example, whereas for Figure 4 (Smith et al, 2011) the loss of yield relative to MSY is about 20% at B/B0 ~ 0.75, the loss of yield at B/B0 = 0.75 for the conventional model can be (as in this example) as much as double that amount , i.e. ~40%.

The trade-off suggested as being favorable by Smith et al (2011) must therefore either

(a) be revisited in the context of a conventional sardine population model,

or

(b) the conventional sardine model needs to be revised to conform to Smith et al (2011).

This document proposes (b) and describes a method for doing so.

4 Proposed method for adjusting a conventional population model so that it conforms to the SY:B relationship in Figure 4 of Smith et al (2011)

The basis for the method proposed here is the assumption that the reason that the SY:B relationship in conventional population models may not exhibit the degree of 'flat-toppedness' shown in Figure 4 of Smith et al (2011) is that the latter is derived from predator-prey models (see Smith et al (2011)). These models are assumed to contain prey natural mortality levels that depend on the prey stock depletion level (as opposed to constant natural mortality).

The starting point is the solid blue curve in Figure 1, *shown below as a solid red curve* (see Figure 4).

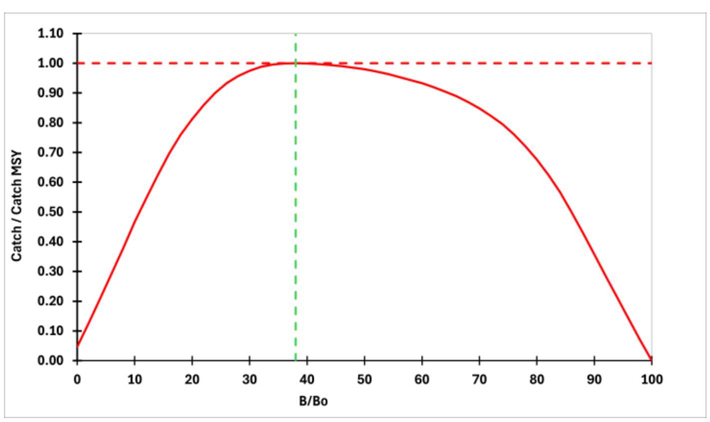

Figure 4. Plots of catch/catch MSY vs the biomass as a proportion of the unexploited biomass B_0, as derived from Figure 4 of Smith et al (2011).

The points used to plot the red curve in Figure 4 were obtained by digitizing Figure 4 of Smith et al (2011) – the actual values are given in Table 6. There are 51 points in that table.

The aim is to alter the natural mortality relationships in the population model so that its SY:B relationship, after suitable scaling of Figure 4, lies on top of the red solid line in Figure 4.

4.1 Proposed scaling and adjustment procedure

Both the x and y-axis values in Figure 4 and Table 6 are proportions. The x-axis is the population biomass divided by the unexploited equilibrium value B0, and the y-axis is the sustainable yield divided by the maximum long term catch. The latter, based as it is on catches at the end of a 50 year time horizon, are assumed to be equivalent to MSY.

The population model to be adjusted produces 'unscaled' values of equilibrium biomass and sustainable yield for different values of fishing mortality F. In particular the model produces a value of MSY (when $F=F_{MSY}$) and a value of B0 (when F=0).

The proposed scaling adjustment procedure is the following:

1. Calculate the **MSY(p)** and **B0(p)** values for the population model.
2. Multiply all B/B0 values in Table 6 by **B0(p)**, and multiply all SY/MSY values in Table 6 by **MSY(p)**. **<u>These scaled quantities are the points $(B(s),SY(s))_j$</u>**. They correspond to the 51 points in Table 6.
3. For each of the 50 scaled points **<u>$(B(s),SY(s))_j$</u>** , determine which values of F_j and k_j result in $(B(p),SY(p))_j = (B(s),SY(s))_j$, where F_j is the fishing mortality and k_j is the natural mortality adjustment factor associated with value j from Table 6.

We now have a revised adjusted population model and SY:B relationship, albeit at discrete values of F. The adjustment process is illustrated below, where the green dashed line for the LH panel is the SY:B relationship of the original population model, and in the RH panel it is the SY:B relationship for the adjusted population model. For both panels the solid red curve is the scaled version of the (reversed) plot from Figure 4 of Smith et al (2011):

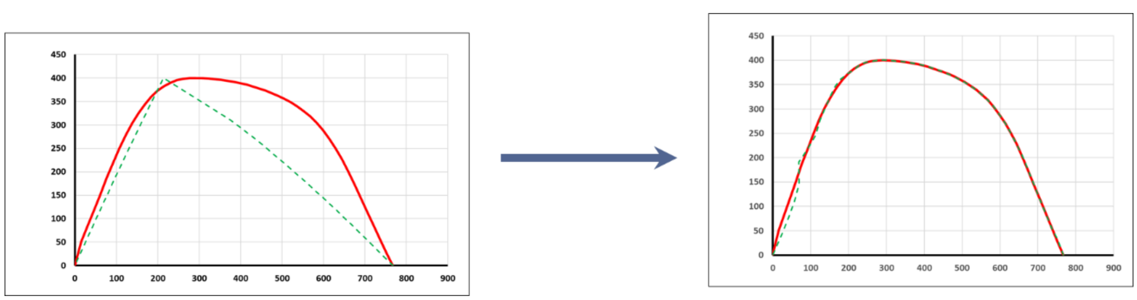

Figure 5. The green dashed line for the LH panel is the SY:B relationship of the original population model, and in the RH panel it is the SY:B relationship for the adjusted population model. For both panels the solid red curve is the scaled version of the (reversed) plot from Figure 4 of Smith et al (2011). The stock/recruitment relationship is a Hockey-Stick relationship in which some slight curvature has been given to the descending portion of the curve to allow for the calculation of SY to the left of the MSYL.

Since it is only the region of the graph to the right of MSYL which is relevant to the target of B/B0=0.75, only this region need be plotted and considered, as highlighted by the following figure:

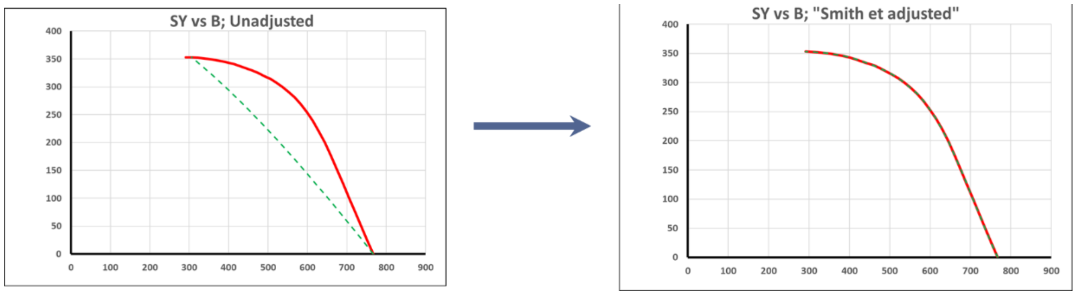

Figure 6. A version of Figure 5 which focusses only on the region of the SY:B curve to the right of the MSYL.

The associated values of k_j for this example are shown in the following plot:

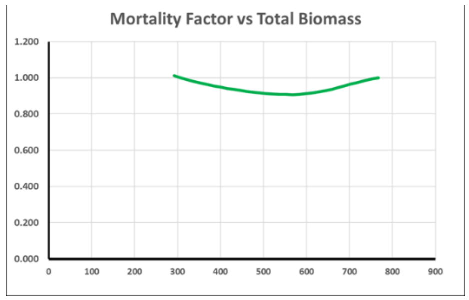

Figure 7. Natural mortality adjustment factors k_j for the SY:B curve depicted in Figure 6.

Although the adjustment process described here can be developed further by, for example, defining the function that relates k_j to B/B0, the model in the form following steps (1) - (5) can be used to estimate the harvest proportion SY/B at which B/B0=0.75, and to compare this harvest proportion to that of the unadjusted population model. This was the main focus at the time that this method was first proposed.

5 An example and some results

Results have been produced for two components of the sardine population, WTS and CTS, treated as stand-alone single species populations. Results have been produced for Hockey-Stick and Beverton-Holt stock-recruitment relationships for different values of the hinge point and for different values of the steepness parameter h (refer to background documents). Only results for deterministic recruitment are shown here and are given in Table 1, Table 2, Table 3 and Table 4.

Table 1. Deterministic results for the CTS sardine component, viewed as a single standalone species. The upper block of three rows of the table summarises results for the Hockey-Stick recruitment relationship, with different hinge point values i.t.o. spawning biomass, 50,100 or 200 thousand MT, while the bottom block of four rows summarises results for the Beverton-Holt recruitment relationship with values of the steepness parameter h of 0.548, 0.3, 0.5 and 0.7. The second column gives the other parameter for the Hockey-Stick relationship. Column 3 gives the harvest proportion as C/B under equilibrium conditions for the unadjusted population model for equilibrium conditions B/B0=0.75. C is the equilibrium catch and B is the start of year equilibrium total resource biomass. Column 4 gives the C/B to achieve B/B0=0.75 for the adjusted population model, denoted as 'multi-species'. Column 5 is the ratio of the Column 4 values to the Column 3 values. The last column, 6, gives a variant of Column 4 values in which the SY has been scaled down by 6%, roughly 1 standard error on Figure 4 of Smith et al (2011), a sensitivity test requested by the PWG (Pelagic Working Group). The values of k_r associated with this table are given in Table 7.

bR	CTS aR	C/B single species	C/B "multi-species"	{C/B "multi-species"}/ {C/B single species}	C/B "multi-species" - 1 SD
50	13.87	0.220	0.395	1.795	0.375
100	15.47	0.220	0.350	1.591	0.330
200	18.06	0.220	0.260	1.182	0.250
h=0.548	n/a	0.160	0.200	1.250	0.190
h=0.3	n/a	0.070	0.078	1.114	0.073
h=0.5	n/a	0.140	0.182	1.300	0.170
h=0.7	n/a	0.180	0.260	1.444	0.245

Table 2. This is a version of Table 1 which uses the mid-year resource biomass Bexp instead of the start of the year equilibrium total biomass B.

bR	CTS aR	C/Bexp single species	C/Bexp "multi-species"	{C/Bexp "multi-species"}/ {C/Bexp single species}	C/Bexp "multi-species" - 1 SD
50	13.87	0.170	0.288	1.694	0.273
100	15.47	0.170	0.250	1.471	0.246
200	18.06	0.170	0.205	1.206	0.191
h=0.548	n/a	0.126	0.160	1.270	0.152
h=0.3	n/a	0.061	0.065	1.066	0.062
h=0.5	n/a	0.110	0.145	1.318	0.138
h=0.7	n/a	0.150	0.200	1.333	0.191

Table 3 Results for WTS. As described in Table 1.

b_R	WTS a_R	C/B single species	C/B "multi-species"	{C/B "multi-species"}/ {C/B single species}	C/B "multi-species" - 1 SD
50	40.76	0.28	0.48	1.71	0.450
75	44.16	0.28	0.48	1.71	0.450
125	44.6	0.28	0.48	1.71	0.450
h=0.3					
h=0.5	n/a	0.18	0.229	1.27	0.215
h=0.7					

Table 4. Results for WTS, as described in Table 2.

b_R	WTS a_R	C/Bexp single species	C/Bexp "multi-species"	{C/Bexp "multi-species"}/ {C/Bexp single species}	C/Bexp "multi-species" - 1 SD
50	40.76	0.195	0.31	1.59	0.293
75	44.16	0.195	0.31	1.59	0.293
125	44.6	0.194	0.31	1.60	0.293
h=0.3					
h=0.5	n/a	0.13	0.165	1.27	0.156
h=0.7					

6 References

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Bergh, M. 2025b. The feasibility of applying Smith et al's (2011) trade-off suggestion to a conventional sardine population model. FISHERIES/2025/SEP/EIMTG/11.

Bergh, M. 2025c. Varying natural mortality to obtain SY:B relationships which are consistent with Smith et al. (2011). FISHERIES/2025/SEP/EIMTG/13.

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Smith, A.D., Brown, C.J., Bulman, C.M., Fulton, E.A., Johnson, P., Kaplan, I.C., Lozano-Montes, H., Mackinson, S., Marzloff, M., Shannon, L.J., 2011. Impacts of fishing low-trophic level species on marine ecosystems. Science 333, 1147–1150, http://dx.doi.org/10.1126/science.1209395.

7 Appendix A. The population model

The basic model is an age-structured population model with a 5 year plus group, Beverton-Holt recruitment dynamics, and the use of Pope's catch equation. This is a well-documented model structure. It is only applied here in its equilibrium form. Relevant equations for resource dynamics by age are as follows.

$$N_0^* = R^*(F) \tag{A.1}$$

$$N_{a+1}^* = \left(N_a^* e^{-M_a/2} - C_a^*\right) e^{-M_a/2} \quad \text{for } 0 \le a \le m-2 \tag{A.2}$$

$$N_m^* = \left(N_{m-1}^* e^{-M_{m-1}/2} - C_{m-1}^*\right) e^{-M_{m-1}/2} + \left(N_m^* e^{-M_m/2} - C_m^*\right) e^{-M_m/2} \tag{A.3}$$

$$C_a^* = F S_a N_a^* e^{-M_a/2} \tag{A.4}$$

where

N_a^* is the number of fish of age *a* under equilibrium conditions;

$R^*(F)$ is the equilibrium recruitment level;

$m = 5$ is the maximum age considered (taken to be a plus-group);

M_a denotes the natural mortality rate on fish of age *a*; and

C_a^* is the equilibrium number of sardine of age *a* caught.

F is the fishing mortality of a fully selected age class;

S_a is the commercial selectivity for age class a.

7.1 Recruitment

A deterministic Beverton-Holt relationship is used, parameterized by the "steepness" of the stock-recruitment relationship, h, the pre-exploitation equilibrium spawning biomass K, and the pre-exploitation recruitment, R_0:

$$R^*(F) = \frac{4hR_0 SSB(F)^*}{K(1-h)+(5h-1)SSB(F)^*} \quad \text{(A.5)}$$

$SSB(F)^*$ is the equilibrium spawning biomass, viz.:

$$SSB(F)^* = \sum_{a=1}^{m} f_a \, w_a N_a^* \quad \text{(A.6)}$$

$$K = SSB(F=0)^* \quad \text{(A.7)}$$

$$R_0 = R^*(F=0) \quad \text{(A.8)}$$

and where

w_a is the beginning of year mass of fish of age *a*;

f_a is the proportion of fish of age *a* that are mature

7.2 Sustainable yield

The sustainable yield is

$$SY = \left[\sum_{a=0}^{m} w_{y,a+1/2} \; C_a^*\right] = \left[\sum_{a=0}^{m} N_a^* e^{-M_a/2} F S_a\right] \quad \text{(A.9)}$$

where

$w_{y,a+1/2}$ is the mid-year weight-at-age for age a.

The population parameter values that were used are those given in Table 5.

Table 5. The values of natural mortality, beginning and mid-year masses, fishing selectivity and proportion mature at age used in the modelling work carried out in this document. Note the natural mortality values are base values used for the unexploited equilibrium only, for other values of biomass they are adjusted by a factor k_r as described in the main text.

CTS Parameter Values						
a	**0**	**1**	**2**	**3**	**4**	**5+**
M	1.00	1.00	1.00	1.00	1.00	1.00
wb	0.000	25.688	69.414	**91.609**	99.625	102.287
wm	12.937	47.551	80.511	**95.617**	100.956	102.287
s	0.20	1.00	1.00	**1.00**	1.00	1.00
fc	0.00	0.50	1.00	**1.00**	1.00	1.00

WTS Parameter Values						
a	**0**	**1**	**2**	**3**	**4**	**5+**
M	1.25	1.25	1.25	1.25	1.25	1.25
wb	0.00	30.26	71.83	83.09	90.13	92.15
wm	16.17	51.05	77.46	86.61	91.14	92.15
s	0.20	1.00	1.00	1.00	1.00	1.00
fc	0.00	0.50	1.00	1.00	1.00	1.00

Table 6. Values of B/B_0 and SY/MSY obtained by digitizing Figure 4 of Smith et al (2011).

j	B/B_0	SY/MSY	j	B/B_0	SY/MSY
1	**1.000**	**0.000**	26	**0.500**	**0.980**
2	0.980	0.068	27	0.480	0.985
3	0.960	0.139	28	0.460	0.991
4	0.940	0.212	29	0.440	0.994
5	0.920	0.283	30	0.420	0.997
6	0.900	0.356	31	0.400	0.999
7	**0.880**	**0.430**	32	0.380	1.000
8	0.860	0.500	33	0.360	0.999
9	0.840	0.567	34	0.340	0.996
10	0.820	0.624	35	0.320	0.988
11	**0.800**	**0.676**	36	0.300	0.975
12	0.780	0.721	37	0.280	0.957
13	0.760	0.761	38	0.260	0.933
14	**0.740**	**0.796**	39	0.240	0.900
15	0.720	0.823	40	0.220	0.860
16	0.700	0.848	41	0.200	0.812
17	0.680	0.870	42	0.180	0.760
18	0.660	0.889	43	**0.160**	**0.697**
19	0.640	0.905	44	0.140	0.624
20	0.620	0.919	45	0.120	0.545
21	0.600	0.933	46	0.100	0.466
22	0.580	0.943	47	**0.080**	**0.377**
23	0.560	0.954	48	0.060	0.294
24	0.540	0.964	49	0.040	0.210
25	0.520	0.973	50	0.020	0.127
			51	**0.000**	**0.000**

Table 7. The values of k_j associated with the results given in Table 1, Table 2, Table 3 and Table 4

	CTS							WTS					
	bR			h				bR			h		
B/B0	**50**	**100**	**200**	**h=0.548**	**h=0.3**	**h=0.5**	**h=0.7**	**50**	**75**	**125**	**h=0.3**	**h=0.5**	**h=0.7**
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000		1.000	
0.980	0.991	0.993	0.997	0.998	1.000	0.998	0.996	0.993	0.994	0.993		0.999	
0.960	0.981	0.986	0.994	0.995	1.000	0.996	0.992	0.985	0.985	0.985		0.997	
0.940	0.971	0.977	0.990	0.992	0.999	0.994	0.987	0.976	0.976	0.976		0.994	
0.920	0.960	0.969	0.987	0.989	0.999	0.991	0.981	0.967	0.968	0.967		0.992	
0.900	0.948	0.960	0.982	0.985	0.998	0.988	0.976	0.958	0.957	0.958		0.989	
0.880	0.936	0.950	0.978	0.981	0.997	0.984	0.969	0.948	0.948	0.948		0.986	
0.860	0.924	0.941	0.973	0.977	0.996	0.981	0.963	0.938	0.938	0.938		0.983	
0.840	0.912	0.932	0.970	0.973	0.995	0.978	0.957	0.929	0.929	0.929		0.980	
0.820	0.903	0.925	0.968	0.971	0.994	0.976	0.953	0.922	0.922	0.922		0.978	
0.800	0.895	0.919	0.966	0.969	0.994	0.974	0.950	0.916	0.916	0.916		0.976	
0.780	0.889	0.915	0.966	0.967	0.994	0.973	0.948	0.912	0.912	0.912		0.976	
0.760	0.885	0.913	0.968	0.967	0.994	0.973	0.946	0.909	0.909	0.909		0.975	
0.740	0.881	0.911	0.970	0.967	0.994	0.973	0.946	0.907	0.907	0.907		0.976	
0.720	0.880	0.912	0.974	0.968	0.995	0.974	0.947	0.907	0.907	0.907		0.977	
0.700	0.880	0.913	0.978	0.970	0.996	0.976	0.948	0.908	0.908	0.908		0.978	
0.680	0.880	0.915	0.983	0.971	0.996	0.977	0.950	0.910	0.910	0.910		0.980	
0.660	0.881	0.918	0.989	0.974	0.997	0.979	0.952	0.913	0.913	0.913		0.982	
0.640	0.884	0.921	0.996	0.976	0.998	0.982	0.956	0.916	0.916	0.916		0.984	
0.620	0.886	0.926	1.003	0.979	0.999	0.984	0.959	0.920	0.920	0.920		0.986	
0.600	0.889	0.930	1.011	0.981	1.000	0.986	0.962	0.925	0.925	0.925		0.988	
0.580	0.893	0.936	1.017	0.984	1.000	0.989	0.966	0.930	0.930	0.930		0.991	
0.560	0.897	0.942	1.008	0.987	1.001	0.991	0.969	0.936	0.936	0.936		0.993	
0.540	0.901	0.947	0.998	0.989	1.001	0.993	0.973	0.942	0.942	0.942		0.995	
0.520	0.906	0.954	0.987	0.991	1.002	0.995	0.976	0.948	0.948	0.948		0.996	
0.500	0.912	0.961	0.976	0.994	1.002	0.996	0.980	0.955	0.955	0.955		0.998	
0.480	0.918	0.969	0.963	0.996	1.002	0.998	0.984	0.963	0.963	0.963		0.999	
0.460	0.925	0.978	0.950	0.998	1.001	0.999	0.987	0.971	0.971	0.971		1.000	
0.440	0.932	0.987	0.936	0.999	1.001	1.000	0.991	0.980	0.980	0.980		1.001	
0.420	0.939	0.997	0.920	1.000	0.999	1.001	0.994	0.990	0.990	0.990		1.001	
0.400	0.947	1.007	0.903	1.000	0.998	1.000	0.997	1.000	1.000	1.000		1.000	
0.380	0.956	0.984	0.883	1.000	0.996	0.999	0.999	1.011	1.011	1.011		0.998	
0.360				0.999	0.994	0.997	1.000					0.996	
0.340				0.997	0.991	0.995	1.002					0.993	
0.320				0.995	0.988	0.992	1.003					0.990	
0.300				0.993	0.985	0.990	1.006					0.987	
0.280				0.992	0.981	0.987	1.009					0.983	
0.260				0.990	0.978	0.984	1.013					0.979	
0.240				0.990	0.975	0.983	1.020					0.977	
0.220				0.992	0.972	0.984	1.030					0.976	
0.200				0.995	0.969	0.984	1.041					0.975	
0.180				0.998	0.967	0.985	1.054					0.974	
0.160				1.005	0.966	0.989	1.072					0.976	
0.140				1.017	0.966	0.999	1.099					0.983	
0.120				1.032	0.967	1.010	1.129					0.992	
0.100				1.043	0.967	1.017	1.157					0.997	
0.080				1.064	0.970	1.034	1.200					1.012	
0.060				1.070	0.966	1.036	1.225					1.011	
0.040				1.053	0.953	1.019	1.223					0.989	
0.020				0.934	0.908	0.910	1.077					0.863	
0.000				1.473	0.893	1.355	1.928					1.385	