Further Information on Sustained Yields from Fluctuating Environments[1]

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ABSTRACT

The conclusions of Ricker (1958) are confirmed in series of 200 generations in which environment effects are simulated. The best constant rate of exploitation is very close to the maximum equilibrium rate when there is no environmental variation. A higher catch is obtained when an optimum portion of the stock is reserved for escapement and the remainder is harvested up to the level of the maximum equilibrium rate. Still higher catches are associated with reserving an optimum portion of the catch for escapement and harvesting all of the remainder. In general, these kinds of benefits are greatest at higher levels of environmental variability.

The observations of Ricker (1958) on maximum sustained yields from fluctuating environments were based on calculations of 28 or fewer "generations" for each of 6 types of populations. This present paper provides confirmation of those results, based on 200 generations. The 6 types of curves were the same as those of Ricker (1958).

Curves A, B, C, employ the relation

$$\mathcal{Z} = We^{a(1-W)}$$

where A is respectively 1, 2, and 2.678. Curve F conforms to Curve B in the ascending limb but where $\mathcal{Z} > 1$ it is put equal to 1. Curve G conforms to Curve A beyond W = 0.4 but below W = 0.4 it is determined by

$$\mathcal{Z} = We^{1.5W}$$

which approximates the exponential form of the empirical curve of Ricker (1958). Curve H is based on the reciprocal relation

$$\mathcal{Z} = \frac{W}{1 + A(W - 1)}$$

where A = 0.9.

Table II gives the catch and escapement characteristics of these curves in their deterministic form.

For simulation of environmental variability random normal deviates as generated in an IBM 1620 subroutine were used. The series of 200 random normal deviates which was used for each run is given in Table I. Scaling of deviates to provide a specified range of extremes was accomplished as in Ricker

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TABLE I. Two hundred random normal deviates produced in IBM 1620 subroutine, and employed to simulate environmental variability. (Read the Table row-wise.)

-.36919000	-1.30248600	-1.61594200	-.62315800	-.29373400
.98673000	-.94336600	-.98162200	-.32163800	.38698600
-.72135000	-.08824600	1.30869800	-.60411800	-.15629400
-.69343000	.06287400	-.94498200	.32940200	-.12357400
-.12951000	.30999400	.05733800	1.27892200	.28514600
.77041000	-.54688600	.11565800	.04444200	-1.13013400
.80633000	-.70776600	1.02997800	1.42596200	1.43058600
-.22175000	1.62735400	-.39970200	.22348200	-1.23269400
-.51383000	1.25847400	-.37338200	1.23700200	-.31997400
.73009000	-1.01440600	-2.09106200	-.73347800	-.03125400
.31001000	-1.39128600	.24725800	-.88795800	.43346600
.02593000	.92783400	.44157800	-.42643800	-2.12581400
-1.32215000	2.74295400	-.70810200	1.45108200	.09090600
.06577000	.85407400	-.40178200	.54460200	-.11637400
-1.01031000	-.93880600	.16053800	.65412200	-.94765400
1.24961000	2.16431400	-1.22114200	.57964200	-.60293400
-.35447000	-.03656600	-.74682200	.12116200	-.28221400
1.97745000	1.25855400	.38349800	1.07868200	.81450600
.04537000	.84967400	-.03018200	.25220200	-.51277400
.64929000	-.46320600	-.18786200	-.55827800	-1.46405400
.58921000	.11991400	-.28954200	-.55275800	1.76066600
.66513000	-.60096600	1.46477800	.06876200	-.03861400
-.32295000	-.82584600	-1.12490200	.10628200	2.93810600
.42497000	-.75472600	-.25858200	1.35980200	-.50917400
-1.29111000	-1.58760600	.86373800	1.62932200	-.58045400
.32881000	-.52448600	.04205800	.71484200	-.47573400
.08473000	1.23463400	.07637800	1.41636200	.60498600
.77665000	.48975400	-.23330200	.53388200	.46170600
.20457000	.04087400	1.91301800	-.13259800	-1.10557400
-.83151000	-.31200600	-.68466200	-.78307800	.70314600
.46841000	-.76888600	-.22634200	.38244200	-.31213400
-1.09567000	-.52976600	1.08797800	-2.83603800	1.64858600
.27625000	.20535400	.05829800	-.63851800	-.61469400
-.61583000	-.76352600	.48461800	.77500200	-1.30197400
.02809000	1.36359400	-1.83306200	2.20452200	-.61325400
2.00801000	-.61328600	-.09474200	2.45004200	.25146600
.12393000	.10583400	.49957800	.31156200	-.90781400
1.17585000	-.67904600	.74989800	.58908200	-.29109400
-.03623000	-1.16792600	-.54378200	-.91739800	-.09837400
-1.71231000	-.56080600	-.58146200	.59212200	.47034600

(1958) by multiplying the deviates by an appropriate factor. The absolute quantity was then augmented by one and the deviates used as multipliers or divisors depending on sign. Level A of variability uses random normal deviates, for which 19 out of 20 lie in the range of effects between $\frac{1}{3}$ and 3 times the mean. Level B provides a comparable range of effects from $\frac{1}{5}$ to 5 times the mean.

EFFECT OF LEVEL A OF VARIABILITY UPON YIELD

Table III confirms the observation that when stocks are harvested at the appropriate rate for maximum equilibrium catch, imposing environmental variability does not influence the mean catch from Curves A, B and C, slightly

TABLE II. Maximum equilibrium catch, rate of exploitation, and size of spawning stock, under conditions of no environmental variability for 6 populations (from Ricker, 1958).

Population	Maximum equilibrium catch	Rate of exploitation at m.e.c.	Size of spawning stock at m.e.c.
		%	
A	0.330	43.3	0.433
B	0.935	72.2	0.361
C	1.656	84.1	0.314
F	0.760	78.3	0.210
G	0.330	43.3	0.433
H	0.520	68.4	0.240

TABLE III. Catch and escapement statistics for 6 populations when subjected to random variability of Level A and when rate of exploitation is that appropriate for maximum equilibrium catch. Figures in parentheses are from Ricker (1958).

	Catch			Escapement		
Population	Mean	Standard deviation	Range	Mean	Standard deviation	Range
A	0.337 (0.33)	0.238	0.04–1.25 (0.09–0.90)	0.441	0.311	0.06–1.63
B	0.940 (0.94)	0.599	0.19–3.04 (0.31–2.13)	0.362	0.231	0.07–1.17
C	1.662 (1.66)	1.067	0.318–5.81 (0.62–3.67)	0.314	0.202	0.06–1.10
F	0.728 (0.71)	0.483	0.12–2.48 (0.22–1.65)	0.202	0.134	0.03–0.69
G	"Extinction" (<.0001) in 10 generations					
H	0.594 (0.58)	0.369	0.13–1.81 (0.20–1.25)	0.275	0.171	0.06–0.88

TABLE IV. Catch and escapement statistics with Level A of environmental variability, where available stock up to the optimum size of spawning population is reserved for escapement, and the fishery can take the surplus but not to exceed the rate of exploitation for maximum equilibrium catch for the stock as a whole. Figures in parentheses are from Ricker (1958).

	Catch				Escapement		
Population	Mean	Standard deviation	Range	Years of no catch %	Mean	Standard deviation	Range
A	0.372	0.309	0–1.370	16	0.613	0.292	0.224–1.794
	(0.36)		(0–0.88)	(21)			
B	1.032	0.756	0–3.773	0.5	0.494	0.215	0.322–1.453
	(1.01)		(0.21–2.33)	(0)			
C	1.826	1.282	0.116–6.605	0	0.424	0.183	0.314–1.249
	(1.79)		(0.47–4.12)	(0)			
F	0.901	0.612	0.051–3.084	0	0.296	0.133	0.210–0.855
	(0.86)		(0.22–1.89)	(0)			
G	0.35	0.309	0–1.370	19	0.592	0.294	0.152–1.794
	(0.36)		(0–0.87)	(21)			
H	0.628	0.441	0–2.110	0.5	0.345	0.156	0.237–0.975
	(0.61)		(0.10–1.30)	(0)			

TABLE V. Catch and escapement statistics with Level A of environmental variability, when available stock up to the optimum size of spawning population is reserved for escapement, and the fishery takes all the remainder. Figures in parentheses are from Ricker (1958).

	Catch				Escapement		
Population	Mean	Standard deviation	Range	Years of no catch %	Mean	Standard deviation	Range
A	0.471	0.524	0–2.573	19	0.416	0.045	0.199–0.433
	(0.45)		(0–1.44)	(33)			
B	1.189	0.960	0–4.742	0.5	0.360	0.002	0.338–0.361
	(1.15)		(0.20–2.87)	(0)			
C	2.042	1.463	0.200–7.450	0	0.314	...	...
	(1.99)		(0.55–4.61)	(0)			
F	0.987	0.741	0.051–3.728	0	0.210	...	...
	(0.92)		(0.21–2.21)	(0)			
G	0.438	0.517	0–2.573	22.5	0.408	0.059	0.152–0.433
	(0.44)		(0–1.45)	(33)			
H	0.670	0.561	0–2.751	0.5	0.240	0.003	0.198–0.240
	(0.65)		(0.09–1.66)	(0)			

decreases that for Curve F, slightly increases that for Curve H, and results in rapid extinction for Curve G. The range in catches, as might be expected, is wider in the series of 200 generations than in the series of 24 given in Ricker (1958). The agreement between the 2 series is otherwise extremely close, and the escapements are accordingly appropriate.

Statistics for partial stabilization of escapement, by harvesting surplus over escapement provided the rate does not exceed that for maximum equilibrium catch are summarized in Table IV. The agreement is again very close, the improvements in annual catch by comparison with those of Ricker (1958) given in parentheses, as follows: Curve A 10.4% (9%); Curve B 9.8% (7%); Curve C 9.9% (8%); Curve F 23.8% (21%); Curve H 5.7% (5%). Curve G is "rescued" from extinction and produces slightly more than what is obtained when there is no environmental variability.

With stabilization of escapement to the optimum (Table V), the benefits to catch are confirmed: Curve A 39.8% (36%); Curve B 26.5% (22%); Curve C 22.9% (20%); Curve F 35.6% (30%) and Curve H 12.8% (12%). The effect on Curve G is to increase catch by 30% over that obtained when there is no environmental variability. The greater variability in catch associated with these benefits is apparent, although the years of no catch for Curves A and G are not as frequent as in Ricker's shorter series.

Effect of Level B of Variability Upon Yield

Harvesting at the rate appropriate for maximum equilibrium catch, greater environmental variability does not influence average catch for Curves A, B and C, slightly decreases that for Curve F and, as in the case of a lower level of variability, increases the catch for Curve H (Table VI).

Table VI. Catch and escapement statistics with Level B of environmental variability, when rate of exploitation is fixed at that appropriate for maximum equilibrium catch. Figures in parentheses are from Ricker (1958).

	Catch			Escapement		
Population	Mean	Standard deviation	Range	Mean	Standard deviation	Range
A	0.338 (0.33)	0.382	0.006–2.146 (0.03–1.07)	0.443	0.501	0.008–2.810
B	0.936 (0.93)	0.944	0.058–4.846 (0.14–3.12)	0.360	0.363	0.022–1.866
C	1.654 (1.64)	1.681	0.106–7.732 (0.27–5.72)	0.313	0.317	0.020–1.462
F	0.734 (0.73)	0.783	0.172–4.172 (0.08–2.35)	0.203	0.217	0.005–1.156
G	"Extinction" (<.0001) in 7 generations					
H	0.695 (0.68)	0.656	0.055–3.394 (0.10–1.96)	0.321	0.303	0.025–1.568

The benefits from stabilization of escapement are much greater with the more variable environment. With partial stabilization (Table VII) (which was not included in Ricker (1958) for level B of variability except for Curve G), the mean catch compared to that of Table VI is increased for Curve A 23.7%, Curve B 25.9%, Curve C 26.8%, Curve F 51.9%, Curve H 14.5%. Extinction for Curve G is again avoided.

TABLE VII. Catch and escapement statistics with Level B of environmental variability, when available stock up to the optimum size of spawning population is reserved for escapement, and the fishery can take the surplus but not to exceed the rate of exploitation for maximum equilibrium catch for the stock as a whole. Figures in parentheses are from Ricker (1958).

	Catch				Escapement		
Population	Mean	Standard deviation	Range	Years of no catch %	Mean	Standard deviation	Range
A	0.418	0.495	0–2.273	33	0.683	0.551	0.094–2.976
B	1.178	1.299	0–6.689	13	0.587	0.407	0.081–2.576
C	2.098	2.253	0–11.561	4.5	0.508	0.351	0.053–2.186
F	1.115	1.122	0–5.384	1.5	0.375	0.262	0.150–1.492
G	0.209 (0.33)	0.398	0–2.241 (0–1.30)	64 (42)	0.367	0.492	0.001–2.934
H	0.796	0.807	0–3.773	7.5	0.444	0.314	0.145–1.743

TABLE VIII. Catch and escapement statistics with Level B of environmental variability, when the available stock up to the optimum size of spawning population is reserved for escapement, and the fishery takes all the remainder. Figures in parentheses are from Ricker (1958).

	Catch				Escapement		
Population	Mean	Standard deviation	Range	Years of no catch %	Mean	Standard deviation	Range
A	0.639 (0.59)	0.904	0–4.816 (0–2.15)	39 (42)	0.367	0.010	0.091–0.433
B	1.575 (1.51)	1.765	0–8.549 (0–4.80)	6 (4)	0.357	0.019	0.194–0.361
C	2.647 (2.55)	2.734	0–13.242 (0.24–7.57)	0.5 (0)	0.314	0.001	0.295–0.314
F	1.323 (1.20)	1.412	0–6.801 (0.06–3.67)	1.5 (0)	0.210	0.004	0.153–0.210
G	0.300 (0.44)	0.662	0–3.635 (0–2.15)	68 (42)	0.208	0.186	0.001–0.433
H	0.894 (0.86)	1.025	0–4.982 (0–2.80)	10 (8)	0.235	0.018	0.114–0.240

Complete stabilization of escapement produces even more substantial benefits (Table VIII), the increases, with those of Ricker (1958) in parentheses, being: Curve A 89.1% (79%); Curve B 68.3% (62%); Curve C 60.0% (55%); Curve F 80.3% (64%); Curve H 28.6% (26%). For Curve G there is an increase in catch from partial to complete stabilization of escapement. However, a gain over the condition of no environment variability (catch of 0.330) was not achieved, whereas in Ricker's series a gain was indicated. This is attributable to the difference in the two series of random numbers, which is reflected in the greater percentage of years with no catch. There were 3 long "runs" of no catch in the present series, one of 39 "generations", another of 35 and a third of 23.

REFERENCES

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