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MAXIMUM YIELD PER RECRUIT OF SEA SCALLOPS

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The sea scallop (Placopecten magellanicus) fishery in Subarea 5Z has expanded greatly during the past few years. Landings, which had been about 4 million pounds of meats per year just after the war, rose to about 13 million pounds by 1947. Increased effort caused a gradual rise to about 19 million pounds in 1958 (Table 1). Each year since then has shown an increase over the previous year.

Total fishing effort in 5Z has remained about the same since 1957. Although Canadian effort expanded from 1,100 days fished in 1957 to 3,100 days in 1961, United States effort declined from 10,500 to 8,500 days. The great increase in landings during the past three years thus implies a real change in abundance.

TABLE 1. Landings of sea scallop meats (millions of pounds) 1950 - 1961

YEAR	SUBAREA 5Z		OTHER GROUNDS		TOTALS
	U.S.	CAN.	U.S.	CAN.	
1950	13.8	0.0	6.2	0.7	20.7
1951	14.4	0.2	4.3	0.4	19.3
1952	15.2	0.2	3.4	1.1	19.9
1953	19.7	0.3	3.9	1.4	25.3
1954	15.5	0.2	2.1	1.5	19.2
1955	16.8	0.3	5.3	1.4	23.8
1956	16.8	0.7	3.2	1.9	22.6
1957	18.7	1.8	2.3	1.5	24.3
1958	16.4	2.6	2.6	0.7	22.3
1959	20.2	4.4	4.4	0.5	29.5
1960	22.4	7.5	4.2	0.2	34.3
1961	23.6	10.0	2.8	0.5	36.9

Abundance of sea scallops is not directly proportional to landings per day fished since no account is taken of the amount of time actually spent fishing during the day or the average size of the scallops caught. The dredges are only set as often as is necessary to keep the shuckers supplied. This may be only 5-10 percent of the day when scallops are extremely abundant or as much as 60-75 percent when they are less abundant. If the less abundant scallops were larger than the abundant ones, it is possible that the landing per day figure would be greater even though more fishing time was required to catch them.

The major cause of the recent increased abundance seems to be the recruitment in 1959 of an extremely large year class. This is demonstrated by the size distribution of the U.S. landings (Table 2). During 1956, 1957, and 1958 about 50 percent of the landings were made up of scallops less than 110 mm in length. In 1959, this increased to 60 percent, then dropped to 46 percent in 1960 and 34 percent in 1961. The dominant year class has evidently supplied a large fraction of the landings in the last 3 years.

The 33.6 million pounds of meats landed from Subarea 5Z in 1961 by both fleets represents a removal of about 630 million individual sea scallops. The 1958 landings of 19.0 million pounds about 410 million scallops. The numbers removed per year therefore increased only about 54 percent although the landings went up 77 percent in weight. Such are the virtues of fishing on larger scallops when they are abundant.

Maximum yield in a fishery is realized when the required amount of fishing effort is expended during the years when a year class has reached its greatest biomass. The parameters which must be measured are, therefore, the growth rate, the natural mortality rate, and the fishing mortality rate,

TABLE 2. Size Distribution of U.S. Sea Scallop Landings 1956 - 1961

	1956	1957	1958	1959	1960	1961
LENGHT mm.			FREQUENCY IN PERCENT			
80-85	1.3	0.2	0.0	0.0	0.0	0.0
85-90	4.3	4.0	2.5	4.4	0.8	1.6
90-95	8.4	8.3	7.1	14.0	3.0	3.7
95-100	11.2	11.7	13.5	18.5	9.1	8.0
100-105	12.6	11.3	13.5	13.6	15.8	10.4
105-110	14.3	11.6	12.4	9.8	17.6	10.4
110-115	13.2	10.0	11.2	7.5	14.3	10.2
115-120	10.4	9.4	9.6	6.3	12.8	10.3
120-125	8.1	9.5	10.5	6.5	10.5	11.6
125-130	5.7	7.5	7.1	6.4	6.8	11.5
130-135	4.3	5.8	5.3	5.2	4.2	9.7
135-140	3.1	5.5	4.0	3.7	2.9	6.0
140-145	1.5	4.7	3.3	3.5	1.6	3.9
145-150	0.8	0.4	0.0	0.6	0.6	2.7
150-155	0.4	0.1	0.0	0.0	0.0	0.0
155-160	0.4	0.0	0.0	0.0	0.0	0.0
Wt. in Lbs. of 100 Scallops	4.46	4.77	4.62	4.33	4.66	5.31

Growth Rate

The growth rate of sea scallops in Subarea 5Z has been calculated by locating the annual rings on the shells and measuring the distance from the umbo to each ring. The annual formation of these rings has been validated by comparison with the growth of large numbers of tagged and recaptured animals. Using samples collected from various parts of the grounds we have calculated an average growth rate in the form of the Bertallanfy equation:

$$L_t = 148.9 \left(1 - e^{-.26 (t-1)} \right)$$

Using an average length-weight equation to estimate W_∞ we have calculated the corresponding average growth in weight equation

$$W_t = 45.9 \left(1 - e^{-.26 (t-1)} \right)^3$$

Length is in millimeters and weight in grams.

Age	4	5	6	7	8	9	10
Length	80	96	108	118	125	131	135
Weight	7.3	12.9	17.7	22.6	27.0	30.7	33.9

Yield Per Recruit Calculations

An IBM 7090 computer was programed to calculate the points of a series of yield-isopleth diagrams, using the equation of Beverton and Holt (1957), for instantaneous rates of natural mortality (M) from .03 to .42 at intervals of .03. Table 3 gives the estimated ages of first capture corresponding to maximum yield per recruit at various levels of M and fishing mortality rate, F. In this fishery "age at first capture" is not the 50 percent retention size of the gear in use but the 50 percent cull size. At present, this is about 95 to 100 mm. corresponding to about age 5.

A recent survey of the sea scallop fleet showed about 70 percent were using dredges with 3-inch rings in the bags. The other 30 percent were using 4-inch rings. The 50 percent selection point of dredges with 3-inch rings is about 70 mm (Age 3.5), 4-inch rings about 95 mm. Scallops smaller than the cull size are thrown back with, so far as is known, little or no mortality from the experience. The use of the 4-inch rings may serve to reduce whatever mortality does occur among the discards but does not increase age at first capture. Their main effect is to reduce the labor of culling.

TABLE 3. Estimated ages of first capture corresponding to maximum yield per recruit at various levels of fishing mortality rate (F) and natural mortality rate (M).

F \ M	.03	.06	.09	.12	.15	.18	.21	.24
.1	5.7	5.5	5.0	4.5	4.5	4.0	3.5	<3.5
.2	7.0	6.5	6.0	5.5	5.0	5.0	4.5	4.0
.3	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5
.4	9.0	8.0	7.5	7.0	6.0	5.5	5.5	5.0
.5	9.5	8.5	8.0	7.0	6.5	6.0	5.5	5.0
.6	10.0	9.0	8.0	7.5	6.5	6.0	5.5	5.5
.7	10.0	9.5	8.5	7.5	7.0	6.5	6.0	5.5
.8	10.5	9.5	8.5	7.5	7.0	6.5	6.0	5.5
.9	10.5	10.0	8.5	8.0	7.0	6.5	6.0	5.5
1.0	>10.5	10.0	9.0	8.0	7.0	6.5	6.0	5.7
1.1	>10.5	10.0	9.0	8.0	7.0	6.5	6.0	6.0
1.2	>10.5	10.0	9.0	8.0	7.5	6.5	6.5	6.0
1.3	>10.5	10.5	9.0	8.0	7.5	7.0	6.5	6.0
1.4	>10.5	>10.5	9.0	8.0	7.5	7.0	6.5	6.0
1.5	>10.5	>10.5	9.0	8.0	7.5	7.0	6.5	6.0

Tables 4 and 5 give the percent change of yield in weight per recruit if the mean age when the scallops were first subject to fishing mortality were raised from the present 5 to 6 and 7 respectively for various levels of F and M. When M=.09 and F=1.0, for instance, a one year delay would increase the yield of a year class by 18 percent, a two year delay would result in a 29 percent increase. Figure 1 shows the result of leaving age at first capture at 5 but changing the fishing mortality rate. Once fishing effort is large enough to generate a mortality rate of about .4, further increase in effort can lead only to a reduced yield per recruit spread out among more units of effort.

TABLE 4. Percent change of yield in weight if age at first removal were postponed from 5 (96.2 mm) to 6 (108.4 mm).

M	.03	.06	.09	.12	.15	.18	.21	.24
F								
.1	+1	-1	-2	-4	-5	-7	-8	-10
.2	+6	+4	+3	+1	-1	-3	-5	-7
.3	+10	+8	+6	+4	+2	-1	-3	-5
.4	+14	+11	+9	+6	+4	+1	-1	-4
.5	+17	+14	+11	+8	+6	+3	0	-3
.6	+19	+16	+13	+10	+7	+4	+2	-1
.7	+21	+17	+14	+11	+8	+6	+3	0
.8	+22	+19	+16	+13	+10	+7	+4	+1
.9	+23	+20	+17	+14	+10	+7	+4	+2
1.0	+24	+21	+18	+14	+11	+8	+5	+2
1.1	+25	+22	+18	+15	+12	+9	+6	+3
1.2	+26	+23	+19	+16	+12	+9	+6	+3
1.3	+27	+23	+20	+16	+13	+10	+7	+4
1.4	+27	+24	+20	+17	+13	+10	+7	+4
1.5	+28	+24	+21	+17	+14	+11	+8	+5

TABLE 5. Percent change of yield in weight if age at first removal were postponed from 5(96.2 mm) to 7 (117.8 mm).

M	.03	.06	.09	.12	.15	.18	.21	.24
F								
.1	-1	-3	-7	-10	-13	-16	-19	-23
.2	+9	+5	+1	-3	-6	-10	-14	-18
.3	+17	+12	+8	+3	-2	-6	-10	-15
.4	+24	+19	+13	+8	+3	-2	-7	-12
.5	+30	+23	+17	+11	+6	0	-5	-10
.6	+34	+27	+20	+14	+8	+3	-3	-8
.7	+37	+30	+23	+17	+10	+5	-1	-6
.8	+40	+33	+25	+19	+12	+6	0	-5
.9	+42	+35	+27	+20	+14	+8	+2	-4
1.0	+44	+36	+29	+22	+15	+9	+3	-3
1.1	+46	+38	+30	+23	+16	+10	+4	-2
1.2	+48	+39	+32	+24	+17	+11	+5	-1
1.3	+49	+41	+33	+25	+18	+12	+5	0
1.4	+50	+42	+34	+26	+20	+13	+6	0
1.5	+51	+43	+35	+27	+20	+13	+7	+1

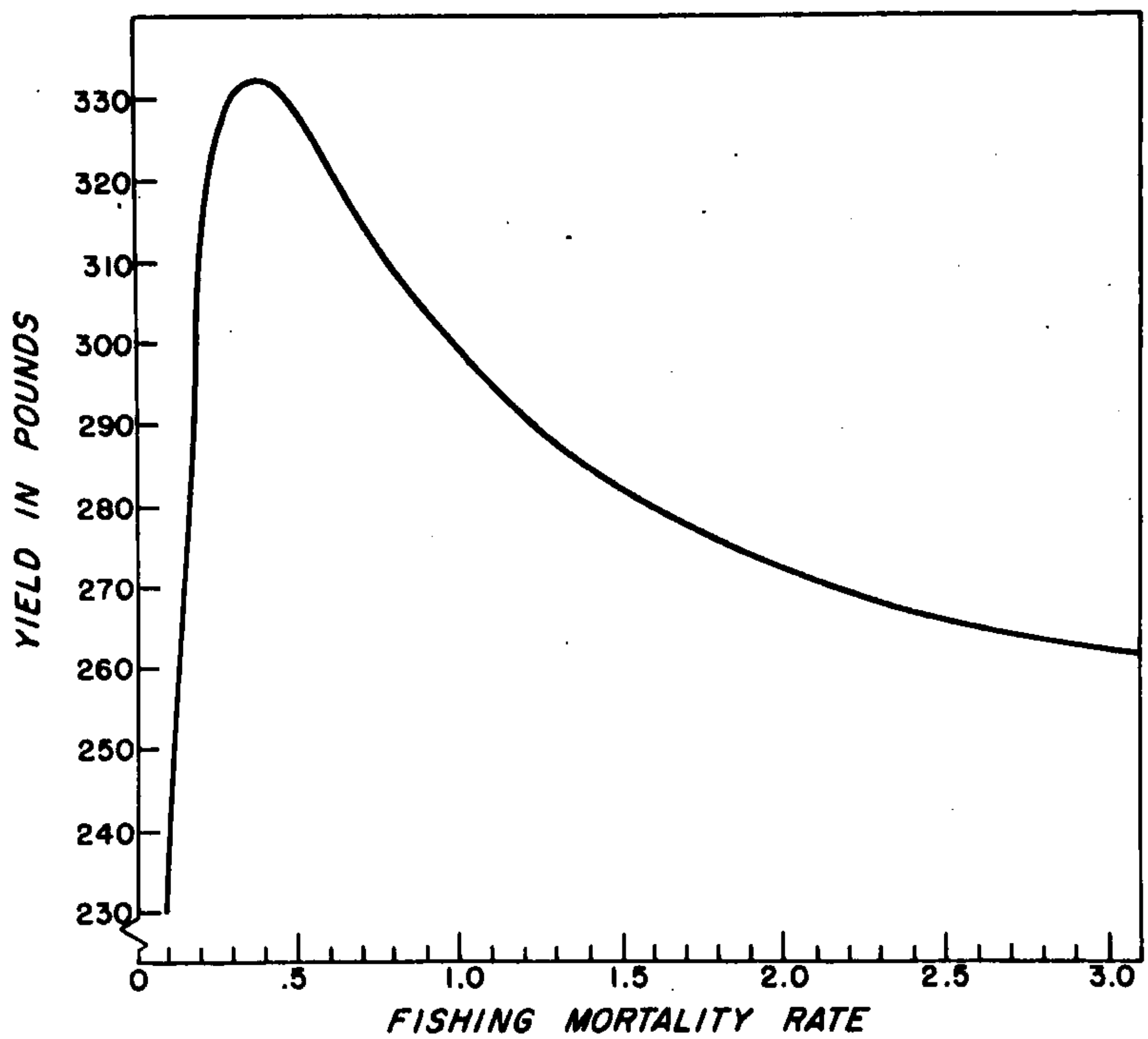

Figure 1. Yield in weight per 10,000 recruits with age at first removal 5 at various levels of fishing mortality. Natural mortality rate of .09.

Mortality Rates

Three survey cruises have been made in Subarea 5Z to collect quantitative samples of the sea scallop population using 2-inch ring gear. About 4-6 10 minute sets were made in each unit area sampled, the catches were pooled and then reduced to a common base of 10,000 square feet dredged. Table 6 gives the catches for 17 unit areas sampled both in May 1960 and May 1961.

Table 7 gives the catches for 22 unit areas sampled both in May 1961 and September 1961. In the tables, N_1 represents the number of scallops over 100 mm in length taken on the first cruise and N_2 the number over whatever size a 100 mm scallop would have reached by the time of the second cruise. The fishing intensity (f) is the number of days fished reported by both the United States and Canadian fleet within each unit area during the time between sampling. Z is the difference of the ~~material~~ natural logarithms of N_1 and N_2

Inspection of tables 6 and 7 shows little correlation between f and Z and many anomalies; i.e., cases where more scallops were found at the second sampling than at the first. The most probable causes of this is sampling error. To reduce the variation, the samples were averaged in groups of five (Table 8). Samples from unit areas which had experienced less than 100 days fishing were discarded since these were probably areas of low total abundance. What scallops were present were probably in isolated patches which the fishermen would find but we would not. The tenth sample in Table 7 (f=72.0 days) was included to gain the fifth group.

TABLE 6. Abundance samples collected in May 1960 (N_1) and May 1961 (N_2). The lapsed time between samples is .92 years.

UNIT AREA		N_1	N_2	f	Z
42-67	F-6	169.9	29.8	894.4	1.741
42-66	A-6	48.4	46.8	442.8	.034
41-66	D-3	321.8	38.8	398.3	2.116
40-67	C-1	40.7	29.7	358.9	.315
40-67	B-2	45.2	39.5	314.7	.135
40-67	E-1	66.1	18.7	272.0	1.263
40-67	A-2	46.6	19.6	235.0	.866
41-66	B-1	35.7	89.0	231.5	-
41-68	B-6	147.4	20.1	216.3	1.992
40-67	D-1	45.9	17.6	211.5	.959
40-67	C-2	41.2	38.2	181.5	.076
41-66	D-1	122.1	76.9	158.6	.462
41-68	A-6	178.6	31.0	154.4	1.751
41-66	E-2	72.3	102.2	126.5	-
41-66	C-1	28.0	54.1	120.6	-
40-67	B-1	8.3	30.7	67.3	-
41-67	E-6	60.6	46.5	30.3	.265

TABLE 7. Abundance samples collected in May 1961 (N_1) and Sept. 1961 (N_2). The elapsed time between samples is .39 years.

UNIT AREA	N_1	N_2	f	Z
42-67 F-6	53.0	63.7	351.9	-
41-66 B-1	119.9	30.4	290.1	1.372
42-67 E-6	155.4	99.1	283.5	.450
41-66 E-2	134.8	21.6	267.0	1.831
41-66 D-1	84.8	4.5	264.5	2.935
40-67 C-1	41.8	17.4	245.8	.876
41-66 C-1	75.0	6.0	153.5	2.526
40-67 B-2	42.7	30.7	130.9	.330
41-68 B-6	23.2	26.4	106.4	-
40-67 D-1	22.9	34.3	72.0	-
41-68 A-5	43.4	1.7	60.9	3.240
40-67 B-1	37.6	23.2	56.2	.483
41-66 D-3	54.9	18.6	53.9	1.082
41-68 B-5	12.8	16.0	52.4	-
41-68 A-6	34.9	26.7	32.4	-
41-69 F-6	13.0	56.4	27.0	-
40-67 E-1	25.8	29.4	20.2	-
40-67 C-2	40.6	24.4	17.0	.509
41-66 A-1	23.3	4.0	12.6	1.762
40-67 F-1	32.2	104.6	10.4	-
40-67 A-2	21.8	104.7	8.6	-
40-67 A-1	20.5	30.6	4.7	-

TABLE 8. Serial abundance samples pooled in groups of 5 unit areas ranked by amount of fishing effort between sampling times.

$\bar{f}$	$\bar{N}_1$	$\bar{N}_2$	Z	t	M	F
481.8	125.2	36.9	1.222	.92	.075	1.147
291.4	109.6	43.9	.915	.39	.032	.883
233.3	68.3	33.0	.728	.92	.075	.653
148.3	88.4	60.5	.379	.92	.075	.304
141.7	41.1	23.0	.480	.39	.032	.448

If the rate of natural mortality had been constant and all the samples had been collected at equal time intervals, a plot of Z on f would have an intercept at the value of M. Since the interval between cruises was not equal, a value of M was assumed and the proportionate amount for each time interval subtracted from the calculated Z values. Successive iterations were made until the intercept on the ordinate was nearly zero. Figure 2 shows the final result, using M=.082. The equation of the fitted line is:

$$F = .003 + .00264\, f.$$

Another method we have used to estimate natural mortality is to take the ratio of clapper shells to live scallops and multiply it by the reciprocal of the average time required for the valves to separate. There are several sources of error in this method but most of them tend to cause an overestimate in the rate rather than an underestimate.

The clappers and the live scallops may not be equally catchable. Since the clappers cannot escape the gear either by swimming or closing the valves as the dredge passes over then, they are probably more catchable than the live scallops. The time required for the valves to separate may be inaccurate. We have used .27 years, the result of some tank experiments by Canadian investigators, but some later field experiments have shown somewhat longer times. In a heavily fished area, the number of live scallops will be reduced without reducing the number of clappers, and so result in an artifically high clapper: live ratio.

Accepting all the possible sources of error, we have pooled all samples collected in 1957, 1958, and 1959. These give a ratio of .018; using .33 of a year as the average time for separation gives an estimate of M= .055. In 1960 and 1961 we found certain areas with very high proportions of clapper shells. The valves of both live and clappers from these areas were examined and each clapper assigned to its proper year class. From the amount of shell added after deposition of the last ring it was then possible to fix the approximate date of death. Some of these clappers had died about two years before collection while the average was about one year. Disregarding this evidence for long term persistence of clappers and pooling all data from all cruises including the "graveyards" gives an estimate of M= .20 using .33 year as separation time. Taking account of the evidence for long persistence of clappers and using .66 years as separation time gives an estimate of M = .10.

Discussion

The problem, of course, is to estimate from the available evidence the most probable rates of fishing and natural mortality. Two different methods involving different assumptions give a range in estimate of natural mortality from .06 to .20. Since the clapper method tends to give estimates that are too high, we believe that the best estimabe is about .09 with a possible range of from .06 to .12. The estimation of an average value of the fishing mortality rate for the entire area is more difficult.

Table 9 gives the number of days fished and pounds landed from each exploited unit area in 1961. It is safe to assume that areas not exploited contained few or no scallops of marketable size. It is not safe to assume that unit areas which had low amounts of effort expended within them were subjected to a low rate of fishing mortality. On the contrary it is more likely that total abundance was originally low in these areas and a small amount of fishing quickly reduced the population below fishable densities. Therefore, in calculating the average amount of fishing effort expended to generate the estimated fishing mortality rate, we have eliminated from consideration all unit areas which had less than 150 days fishing during the year. The remaining 21 unit areas supplied 71 percent of the catch with an average of 387 days fished per unit area. From Figure 2, this amount of effort should generate an F=1.0.

Figure 3 shows the yield isopleth diagram for a natural mortality rate of .09. At a fishing mortality rate of 1.0 it shows a yield per 10,000 recruits of 299 pounds for first capture at age 5, 352 pounds for age 6, 386 pounds at age 7, and 403 pounds at age 8. Table 5 shows that, with M=.09, even if there is a ± 20 percent error in F=1.0, the range of benefit to be predicted for postponing first capture for 2 years is only from 25-32 percent.

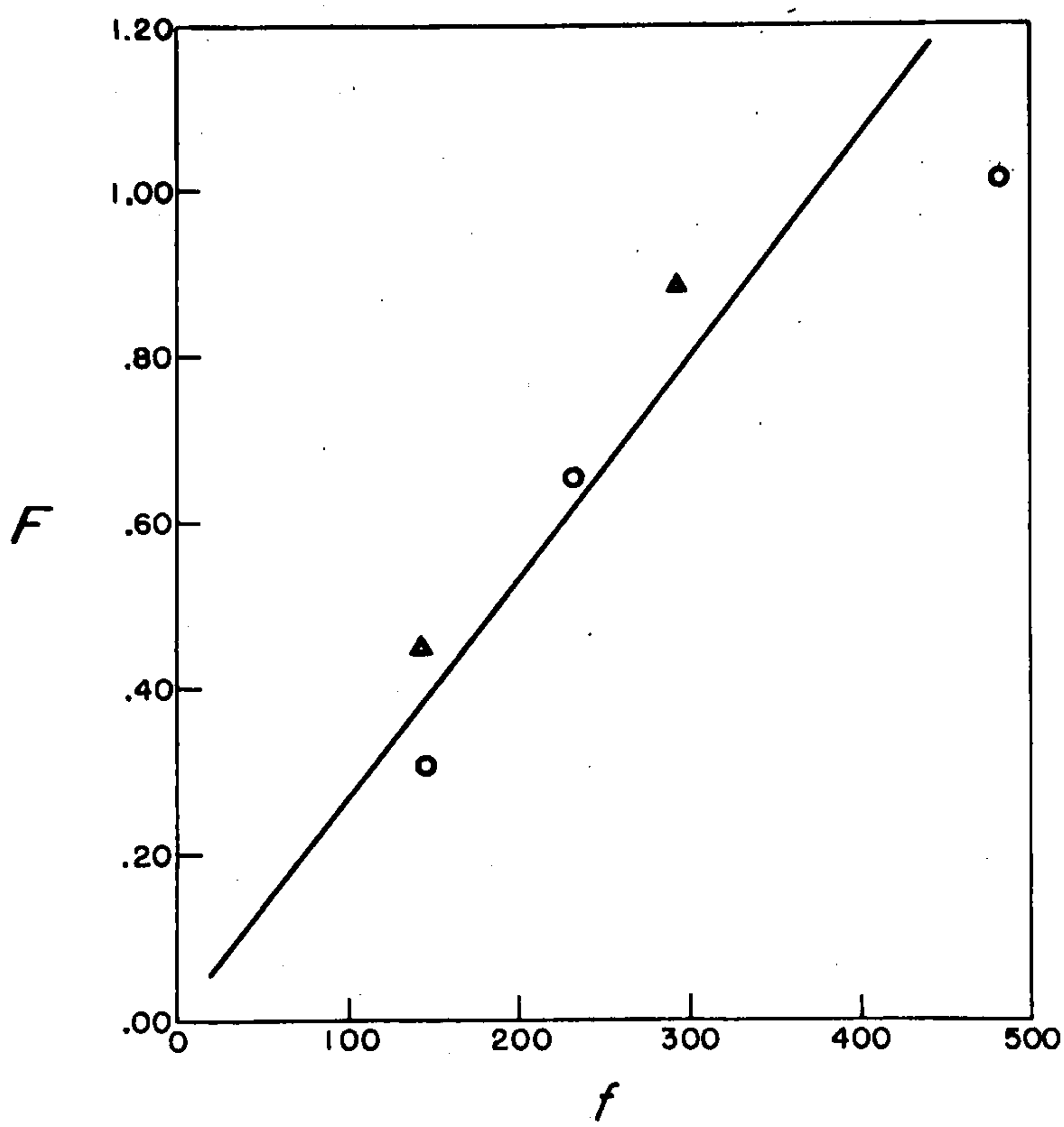

Figure 2. Relationship of F as measured from serial abundance samples as a function of f, the fishing effort. M taken as .082..

Table 9. U.S. and Canadian landings in thousands of pounds and effort in days for each unit area fished for sea scallops in 5Z during 1961. Ranked by amount of effort.

UNIT AREA	CATCH	EFFORT
41-66 B-1	2365	862.5
42-67 F-6	2568	831.0
42-66 A-6	2493	789.6
42-66 B-6	1847	564.8
40-67 C-1	1306	558.0
41-66 E-1	1650	554.5
42-67 E-6	1542	488.5
41-66 E-3	1083	391.2
42-66 C-6	1135	341.6
41-66 D-1	1083	332.6
41-66 E-2	863	292.6
41-66 C-1	810	274.9
41-66 D-3	726	273.8
41-66 D-4	740	244.7
42-67 D-6	806	235.8
41-66 F-2	647	230.4
41-68 B-6	470	191.7
40-67 D-1	460	191.1
41-67 E-1	506	171.5
41-66 C-4	432	160.9
40-69 F-1	395	151.3
40-67 E-1	333	147.4
40-67 B-2	343	145.8
41-67 D-1	370	130.0
40-68 A-1	293	116.7
41-67 F-1	347	115.6
41-69 E-6	308	115.3
41-68 B-5	320	111.4
41-68 C-6	278	109.8
40-67 B-1	243	101.2
41-66 D-2	267	98.7
41-66 F-1	270	90.5

Table 9 (Continued)

UNIT AREA	CATCH	EFFORT
41-68 A-5	247	84.0
41-66 C-2	201	82.2
40-68 F-2	165	76.8
41-68 D-4	195	76.7
40-67 A-2	165	72.5
42-66 D-6	235	71.7
41-66 A-1	202	68.0
42-67 C-6	171	62.7
40-69 E-1	169	56.1
41-68 A-6	142	54.6
40-68 B-3	103	54.2
41-68 D-3	147	52.6
40-69 E-2	192	52.2
41-66 C-5	159	50.7
41-68 C-5	129	48.2
41-67 A-1	102	48.1
41-67 E-6	90	45.5
41-66 B-2	142	43.2
41-69 F-6	114	42.0
40-67 D-2	106	41.9
41-66 D-5	143	40.9
40-68 B-1	87	37.5
40-68 A-3	84	36.2
40-68 C-3	84	35.4
40-68 A-2	86	35.2
41-67 D-2	83	29.9
41-69 F-5	95	29.5
41-68 E-2	76	28.5
41-67 F-6	57	27.6
41-69 D-4	78	27.0
41-66 B-6	64	26.8
40-67 C-2	62	25.9
41-69 E-5	65	24.8
41-68 F-2	52	24.4
40-67 C-3	59	20.7
41-66 B-4	56	19.9
40-67 F-1	47	19.6
40-68 E-2	66	18.8

Table 9 (Continued)

UNIT AREA	CATCH	EFFORT
41-69 D-5	56	18.8
41-66 A-6	50	18.7
41-67 D-6	38	18.3
41-68 C-4	27	17.5
41-66 E-4	51	17.4
40-68 C-1	28	15.8
41-66 C-3	34	13.0
41-67 E-5	34	14.5
41-68 D-6	40	14.3
41-68 D-5	28	14.3
40-67 A-1	34	14.2
40-67 B-3	34	14.2
41-68 E-4	38	13.2
40-68 F-3	33	13.2
41-67 F-5	30	12.8
41-67 C-1	48	11.4
40-69 F-2	29	10.2
40-68 D-1	31	10.1
40-69 D-1	36	9.7
41-66 B-5	19	8.5
41-66 A-3	27	8.0
40-68 E-1	15	7.2
40-67 E-2	13	7.0
40-68 B-2	20	6.1
40-68 D-2	22	6.0

Table 9 (Continued)

UNIT AREA	CATCH	EFFORT
41-68 F-1	18	6.0
41-68 C-3	8	6.0
41-66 A-2	20	5.5
41-68 F-6	12	5.2
40-68 F-1	10	4.7
41-67 F-3	11	4.0
41-68 B-4	7	4.0
40-69 F-3	6	3.5
40-68 C-2	6	2.9
41-67 E-2	5	2.0
40-68 B-4	4	1.6
40-68 C-4	4	1.6
41-68 F-3	4	1.5
41-67 B-1	4	1.4
41-66 D-6	3	1.0

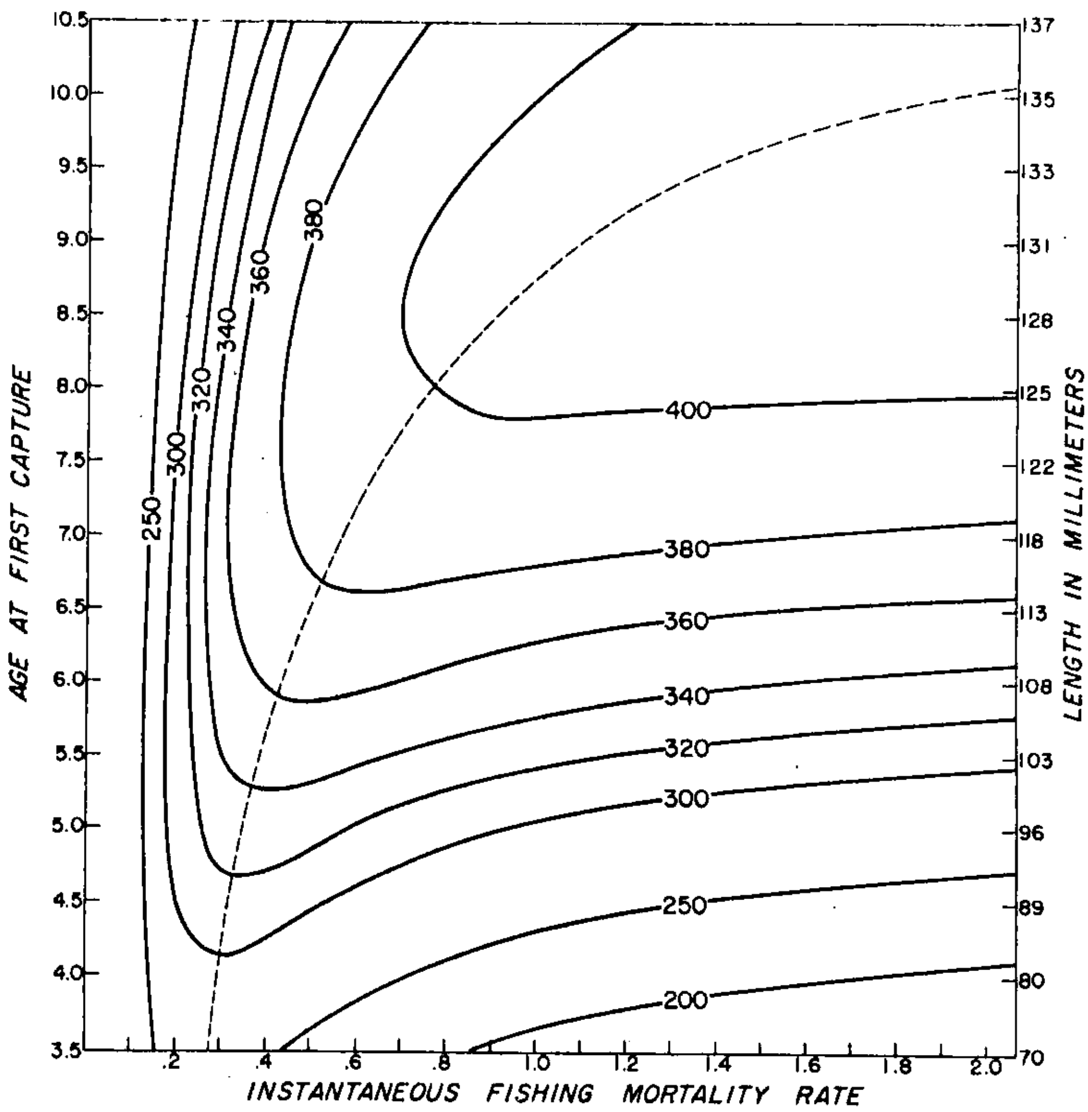

Figure 3. Yield isopleths for 10,000 recruits at age 3.5 with a natural mortality rate of .09/

Literature Cited

Beverton, R. J. H. and S. J. Holt, On the dynamics of exploited fish population. Fishery Investigations Series II, Vol. XIX.