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RESPONSE OF THE BLUEGILL POPULATION AND FISHERY OF MILL LAKE TO EXPLOITATION RATE AND MINIMUM SIZE LIMIT: A SIMULATION MODEL[1]

By James C. Schneider

ABSTRACT

The effects of fishing on a typical, but slow-growing population of bluegills in Mill Lake were simulated. Hypothetical fisheries were generated by varying exploitation rate and age of entry. Corresponding changes in the catch and in the size and structure of the bluegill population were predicted.

Certain combinations of exploitation rate and age of entry (forming the eumetric line) produced the highest sustained yield to the angler. The analysis also showed that minimum size limit should be increased--up to a maximum of 6.0 inches--as exploitation rate increases. Overexploitation, in terms of wasting potential yield or depleting the spawning stock, will not occur if size limits or fishing rates are managed so that the fishery is operating at or above the eumetric line. A bluegill fishery, typical of southern Michigan lakes (μ = 30%, size limit about 5.5 inches), produced a yield of about 7 kg (90 bluegills) per hectare. The numbers of bluegills larger than 5.0 and 7.0 inches which remained in the lake were 77% and 34%, respectively, of the highest number possible.

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Introduction

The bluegill (*Lepomis macrochirus*) population of Mill Lake, Washtenaw County was studied intensively for 5 years (Schneider, 1971). Considerable data on abundance and structure, and rates of growth, mortality and recruitment were obtained. In addition, some insight was gained into how the rate functions responded to increases or decreases in population size. The bluegill population in Mill Lake was relatively large, its structure and mortality rate were normal, growth was slow, and recruitment was highly variable. Natural mortality varied little, and growth only slightly, in response to fluctuations in size of year class.

The purpose of this report is to synthesize this information into a mathematical model and use the model to predict the effects of fishing rate and minimum size limit on the catch and on the bluegill population itself.

Ricker (1958, pp 208-217) has developed a very flexible and useful model suited for this purpose. Given data on natural mortality, fishing mortality and growth, the Ricker model determines the yield (catch) to the fishery and the structure of the fish population when it has come to steady-state (equilibrium) conditions. Results may be expressed in relative terms of yield per fish recruited to the population; however, since the abundance of bluegills in Mill Lake is known, the results of my computations can be expressed in absolute terms.

Ricker (1958) and Patriarche (1968) have used this model to compute yield at various rates of fishing for two other bluegill populations. Ricker also determined the effect of size limit on bluegill yield. Latta (1972) used the model more fully in his commentary on northern pike (Esox lucius) fishing regulations. He explored the effects of closed seasons, size limits, and exploitation rates on both yield and on the size and structure of a hypothetical pike population.

Methods

The basic data needed for the model were given in Table 14 of the report on the Mill Lake fish population (Schneider, 1971). That table has been reproduced here as Table 1. These data apply to a "typical," unexploitated year class of bluegills rather than any one year class in particular, hence, the model has more general applicability.

The number, biomass, and catch from each successive age group was calculated on an annual basis from instantaneous rates of growth, natural mortality, and fishing mortality, according to the method of Ricker (1958). Recruitment was assumed to be constant at 1,580 age-II bluegills per hectare. Age-specific values for growth and natural mortality may be found in Table 1; those for fishing mortality were selected as follows:

Given natural mortality (n), values for annual fishing mortality (m) were selected and rates of fishing (p), annual total mortality (a), instantaneous total mortality (i) and exploitation (μ) were calculated from the formulas of Ricker (1958, p 25). By trial and error, values of m were selected such that the corresponding μ (percent of spring standing crop) would be the same for each age group. Because natural mortality increased with age, the result of holding μ constant was to increase p with age. This was done because anglers (and angling methods) select for larger (and older) bluegills. This causes exploitation to be a relatively constant fraction of each age in typical fisheries.

Rate of exploitation was one of the major variables in the model. I used rates from 11% to over 100%. It was possible for exploitation to exceed spring standing crop because, on the average, some growth takes place during the year a fish is caught. An exploitation rate of 100% by weight was equivalent to 89% by number. For additional reference, 50% exploitation by weight equals 42% by number and 30% by weight equals 25% by number.

The other major variable in the model was age of entry. Age, rather than size, was used because computations were made on an annual basis and growth and mortality rates were age specific. Since for practical reasons fishing regulations are expressed in terms of size, not age, the average length of an age group in the spring will be considered as equivalent to a minimum size limit which would produce the same fishery as that age of entry. For example, entry at age V was roughly equivalent to a 5.5-inch minimum size limit.

Managing for yield

Equilibrium yields of bluegills from the simulated fisheries have been plotted in Figure 1. Curves were drawn between those combinations of ages of entry and exploitation rates which produced the same yield. The resulting isopleths were semi-elliptical in shape and concentric. The eumetric fishing line, connecting the apexes of the isopleths, denotes which combinations of exploitation rates and ages of entry would produce the greatest yield.

The bluegill fishery in Mill Lake, and other lakes with similar populations, should be managed such that it is operating at or above the eumetric line. Fisheries which operate well below the eumetric line are overexploitative in the sense that potential yield is being wasted; fisheries which operate far below the eumetric line may be overexploitative in the sense that the population may become extinct. Prior to 1965, Mill Lake bluegills were probably being exploited at a rate of 30% or less and anglers usually did not keep bluegills smaller than 6 inches (even though there was no size limit). According to the model, yield was about 6 kg per ha. Yield could have been increased by encouraging higher rates of fishing (up through 100%), or by encouraging anglers to keep bluegills as small as 4.8 inches.

Yields exceeding 12 kg per ha were predicted by the model at exploitation rates exceeding 100% by weight, and 89% by number. Note that under intensive fishing, yields were increased by raising the age of entry to about 5.5 years or 6 inches. In the preceding report I determined that 6 inches was the point in the life history of a cohort of Mill Lake bluegills when biomass was optimal, and that this size (the critical size) was the ideal size for intensive harvest. Since sport fisheries are relatively inefficient and unable to harvest intensively right at the critical size, harvesting should begin at a smaller size and continue through life (as Fig. 1 shows). Obviously a size limit greater than 6 inches will result in a reduction in yield under any fishing rate.

Rather than attempting to maximize yield by adjusting size limits or fishing rates to the eumetric line, a more conservative goal for management could be to balance yield with biological production of the stock being exploited (g times average weight of stock). Such a goal was established, for example, by Mercer Patriarche for the commercial whitefish (Coregonus clupeaformis) fishery in northern Lake Michigan (personal communication).

With entry at age IV (approximately 4.5 inches) bluegill yield would balance bluegill production at 7.7 kg per ha per year when μ = 38%. This exploitation rate falls within the range of 35-57% determined by Patriarche (1968) for another slow-growing bluegill population under a similar (4-inch) size restriction. This fishery is not recommended for Mill Lake, however, because it is slightly below the eumetric line.

With entry at age V (size limit of 5.5 inches) yield and production would balance at 6.5 kg per ha per year when μ = 29%.

This is somewhat lower than the optimal exploitation rate for bluegills in Muskellunge Lake; which, judging from the data of Ricker (1958, p 214), is roughly 40% of the spring biomass. If this difference is real, and not simply an artifact caused by different methods of computation, it may be explained by the much faster growth of the Muskellunge Lake bluegill coupled with a natural mortality rate similar to the Mill Lake bluegill. The result is that a larger fraction of the fast-growing population is of harvestable size.

Delaying harvest until age VI (6.5-inch size limit) would reduce production and yield to 3.6 kg per ha per year when exploitation was 17%. The high natural mortality rate and low productivity of older bluegills make a higher size or age of entry impractical.

Effects of fishing

The model may also be used to examine the abundance and structure of the bluegill population after it has reached a steady-state under various fisheries. Naturally the population would have the greatest biomass and the greatest numbers of large-sized bluegills if it was not fished at all or only "fished for fun" (catch and release). Under either condition (if hooking mortality was negligible) the bluegill population would be as given in Table 1. The structure of the population was converted from an age group basis to a size group (5.0 inches and larger, 6.0 inches and larger, 7.0 inches and larger) basis in Table 2. To illustrate the changes in the bluegill population caused by fishing, the relative numerical abundance of each size group under no harvest has been set at 100%.

Table 2 also contains the fishery and catch, and the population structure which would exist under management strategies of maximizing yield or balancing yield against production rate of the stock being exploited. For each strategy, size limits (actually age of entry) were selected and appropriate statistics were computed. The ideal rates of fishing for maximizing yield could have been read off of Figure 1; however, for convenience I have used calculations made when preparing the figure which are close to the ideal rates. Note that there is no ideal rate for the 6.5-inch size limit since it exceeds the critical size. An additional set of calculations has been added to Table 2 to illustrate the effects of exploitation rate when size limit is a constant 6.5 inches.

The section of Table 2 on maximizing yield shows that the highest yield in both weight and numbers occurs under the higher size limit (6.5 inches) when coupled with high fishing rates. If smaller bluegills are acceptable, or exploitation cannot be so intensive, then one of the smaller size limits would be appropriate. Of course, the average size of the fish caught declines also. As might be expected, the bluegill population declines and its structure changes in response to size limit and exploitation rate. Interestingly, the average length of the bluegills over 5.0 inches long is scarsely affected by any of the combinations of size limit and exploitation rate in the table.

The effect of exploitation is more clearly observed when size limit is held constant at 6.5 inches. A light exploitation rate of 12% would produce a catch of 26 bluegills per hectare per year weighing 3 kg and averaging 7.0 inches long. The population of 5.0-inch plus bluegills would drop only slightly--to 95% of their former abundance--and their average length would not change. The number of 7.0-inch plus bluegills would fall to 78% of their maximum abundance. If exploitation increased to 29, 65, and 103%, yield in weight and numbers would increase, and average size of the fish in the catch and population would decrease very slightly. Even at the highest exploitation rate the abundance of 5.0-inch plus bluegills would be 77% of the highest number possible; however, the larger bluegills would decrease to 10% of their former abundance.

Under a management strategy of balancing yield with production rate of the size group being harvested, exploitation rates should be more restrictive: 17% for a 6.5-inch size limit and 30% for a 5.5-inch size limit. The statistics for the 5.5-inch limit and 30% yield are probably typical of current conditions in many Michigan lakes with slow-growing bluegill populations. This fishery has an appreciable effect on the abundance and structure of the bluegill population. The number of 5.0-inch and larger bluegills is 77% of the maximum possible and the number of 7.0-inch plus bluegills is 34% of the maximum.

There would be at least 300 adult (5.0 inches plus) bluegills remaining in the population under any of the fisheries illustrated in Table 2. This seems to be a more than adequate number of spawners to assure recruitment at the assumed rate (1,580 age-II bluegills per year). Even 100 adults would probably be sufficient according to data from ponds (Latta, 1971). In Figure 1 those combinations of age of entry and rate of exploitation which would reduce the residual bluegill population to 100 age-V+ adults per ha are indicated by the "S" line. In any of the fisheries above the S line adequate recruitment seems assured; in any of the fisheries below the S line, recruitment may be impaired and the population would be overexploited in the classical sense. The S line is positioned so low on the graph, however, that size of entry would have to be extremely small (2.5 inches at μ = 32%), or exploitation extremely high (100% at 5 inches) for overexploitation to take place in a sport fishery at Mill Lake.

Evaluation of the model

How well this model simulates the real world is of fundamental importance. A number of assumptions have been made which may have influenced the results. These need to be evaluated carefully before the model can be accepted confidently.

Computations were made in the bluegill model on an annual basis, rather than seasonal (as suggested by Ricker), because the seasonal distribution of natural mortality was not known. Consequently, the estimated yields may not be precise; however, I feel this error is relatively small because the seasonal distributions of growth, natural and fishing mortalities are similar to each other and to the exponential distribution (instantaneous rates are exponential) assumed in the model. Bearing in mind that the computational "year" began in the spring, growth is very high in the early part of the "year" (late spring and early summer) and very low the rest of the "year" (late summer through winter). The seasonal distribution of natural mortality may be similar to that of growth--at least to the extent of being high in the warm seasons and low in the winter (Patriarche, 1968). The seasonal distribution of fishing would also be high early in the "year" and low late in the "year."

There are three assumptions built into the model which have a greater bearing on its predictiveness. I have assumed that rates of growth, natural mortality and recruitment do not change as the population is thinned by exploitation. At Mill Lake I observed that growth remained constant despite shifts in age structure caused by uneven recruitment; however, the standing crop of all bluegills was quite stable. Experiments at other lakes in Michigan indicate that growth will improve if about one-third or more of the total standing crop is removed chemically (Hooper, Williams, Patriarche, Kent, Schneider, 1964). The total standing crop of bluegills in Mill Lake was about 50 kg per ha. Thus, removal of 17 kg per ha ($50 \div 3$) or more should improve growth of the survivors. In order to remove 17 kg per ha, all age VII and older, plus one-half of the VI's, would have to be removed each spring. If fishing is spread out over the year, as is more realistic, then exploitation rates as great as 100% (by weight) would produce yields of only 12 kg per ha and would not affect growth.

Little is known about the relationship between natural mortality and population density but it is thought to be less sensitive than growth (Ricker, 1958, p 205). Observations at Mill Lake suggest that natural mortality may increase slightly as population density declines. Such an increase would counterbalance the tendency for growth to increase.

The assumption concerning constancy of recruitment is more difficult to evaluate. There is little danger of fishing-out the spawning stock for even at an exploitation rate of 100% there would be a residual population of more than 100 adults per hectare when fishing at or above the eumetric line. The size of the spawning stock becomes critical only when very small bluegills are cropped or fishing is intensive. Possibly the opposite may take place: survival of young bluegills may improve as the adults are exploited due to reduced competition and cannibalism. Consequently their growth may deteriorate so that fewer of them reach exploitable size. This possibility is supported by the observation that recruitment of bluegills in Mill Lake seemed to be more sensitive to changes in the population structure than did growth. On the other hand, observations elsewhere suggest that there is little correlation between recruitment and adult stock at densities where growth is satisfactory. The problem is complicated further by density independent factors which may cause extremely large fluctuations in recruitment. However, within the lower, typical, ranges of exploitation rates the assumption that recruitment remains constant is probably valid, and since the assumptions concerning growth and natural mortality are also reasonable, the bluegill model is realistic.

Resume

This model has quantified the relationship between yield, population size, minimum size limits and fishing rates. Numerous management strategies are possible depending, fundamentally, on how small a bluegill is acceptable for harvest, how intensive fishing is or can be, and how large a residual bluegill population is desired.

The analysis shows that protection of the spawning stock would not be a concern for the Mill Lake bluegill population under ordinary sport fisheries since the "S" line was far below the eumetric fishing line. Appropriate management would have the fishery operate on or above the eumetric line at all times. Fortunately, careful monitoring of the fishery is not necessary because few anglers exploit small bluegills. If fishing pressure should become very intensive in the future, a 6.0-inch minimum size limit would be appropriate to prevent overharvest and protect the spawning stock.

The model shows that normal levels of fishing (about 30%) have only a small impact on the total standing crop of bluegills, their growth, or the number of bluegills larger than 5 inches long. The number of bluegills larger than 7 inches, however, would be only about one-third the maximum possible under no harvest. It is likely that angler success would change proportionately (Schneider, 1973).

Thus anglers would catch about the same number of bluegills (if 5-inch fish are vulnerable to the gear) but only half as many large bluegills. If desired, managers could increase (or decrease) the number of larger bluegills with predictable results by manipulating exploitation rate or size limit as the model indicates.

The model constructed for Mill Lake would apply to any other population with the same characteristics of growth and natural mortality. In a subsequent paper I will extend the analysis to hypothetical populations with growth rates equivalent to the Michigan average and faster.

Table 1. Population statistics of a "typical," unexploitated, year class of bluegills in Mill Lake

	Spring estimates				Annual statistics			
Age group	Fish per ha	Mean length (mm)	Mean weight (g)	Standing crop (kg/ha)	Growth (g)	Natural mortality (n)	Natural mortality (q)	Production (kg/ha)
II	1,580	64	3.4	5.37	1.174	0.781	1.52	5.33
III	346	91	11.0	3.80	0.820	0.226	0.26	4.18
IV	267	117	25.0	6.69	0.588	0.231	0.26	4.66
V	206	140	45.0	9.27	0.470	0.260	0.30	4.74
VI	152	163	72.0	10.97	0.298	0.410	0.53	2.91
VII	90	178	97.0	8.72	0.135	0.656	1.07	0.76
VIII	31	185	111.0	3.43	0.301	0.810	1.66	0.57
IX	6	203	150.0	0.88	--	--	--	--

Table 2. Predicted annual harvest and predicted bluegill populations in relation to size limits and exploitation rates (μ) under management strategies of maximizing the population, maximizing the yield, and balancing yield with production. Also included are the effects of exploitation on the harvest and population with a 6.5-inch size limit.

Fishery					Spring population by inch groups						
Limit (in.)	μ (%)	Catch per ha kg	Catch per ha No.	$\bar{L}$[1] (in.)	No. per ha 5+	No. per ha 6+	No. per ha 7+	Relative No. (%)[2] 5+	Relative No. (%)[2] 6+	Relative No. (%)[2] 7+	$\bar{L}$[1] 5+
Maximum population											
No harvest					485	279	82	100	100	100	6.2
Maximum yield											
6.5	103	13	149	6.8	373	167	8	77	60	10	5.9
5.5	50	9	128	6.3	317	111	15	65	40	18	5.9
4.5	25	6	111	5.9	302	141	29	60	51	35	6.0
Yield = production											
6.5	17	4	37	6.9	453	247	58	93	89	71	6.2
5.5	30	7	90	6.5	372	166	28	77	60	34	6.0
Effect of exploitation											
6.5	12	3	26	7.0	461	255	64	95	91	78	6.2
	29	5	58	6.9	435	229	45	90	82	55	6.1
	65	10	107	6.8	395	189	20	81	68	24	6.0
	103	13	149	6.8	373	167	8	77	60	10	5.9

[1] Mean length in inches

[2] The number of bluegills in the exploited population divided by the maximum population.

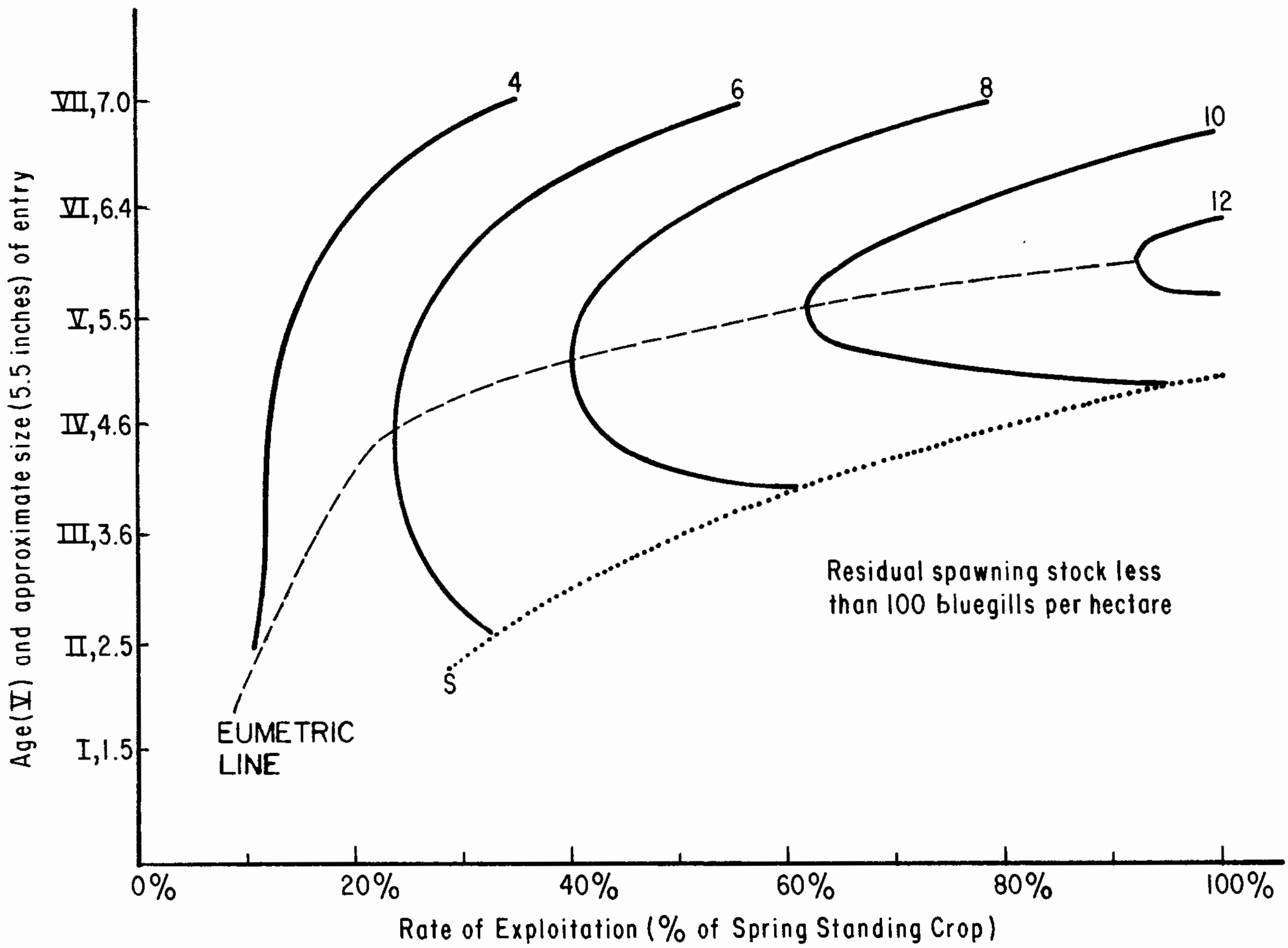

Figure 1. Predicted yields in kilograms per hectare of bluegills from Mill Lake as a function of age of entry and exploitation rate. (To obtain pounds per acre, multiply kg per ha by 0.89.)

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