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SAGINAW BAY SUCKERS: THEIR DYNAMICS AND POTENTIAL FOR INCREASED UTILIZATION

By

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ABSTRACT

SAGINAW BAY SUCKERS: THEIR DYNAMICS AND POTENTIAL FOR INCREASED UTILIZATION

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Yield potential estimates from underutilized Great Lakes fish stocks are lacking for most species. This investigation was undertaken to determine potential limits on the commercial exploitation of white suckers (Catostomus commersoni) in Saginaw Bay, Lake Huron. Principal data sources included historical fishery catch and effort data along with biological data on the size, sex and age composition of the commercial catch. Fish of different sizes and sexes were sampled for analyses of PCB's and DDT. Commercial fishery cost and revenue data were incorporated into a logistic surplus production model function and used in a rudimentary bioeconomic analysis of the fishery.

Approximately 1,000,000 pounds of white suckers were harvested annually from Saginaw Bay during the first half of the 20th century. Current harvest levels range from 100,000 to 150,000 pounds per year. Catch-effort analyses indicate a general pattern of decreased exploitation and increased abundance of Saginaw Bay suckers since the early 1950's. Cautious interpretation of catch-effort data indicates that

landings could be increased by as much as 500% without danger of stock overexploitation.

Surplus production model estimates of mean exploitable population biomass approximate 4,000,000 pounds. Bio-economic analysis indicates that an ex-vessel price increase of $0.05/lb would generate a short term economic rent of about $11,000 to the commercial fishery. Contaminant analyses indicate that the mean levels of PCB's (0.05 ppm) and ΣDDT (0.015 ppm) in Saginaw Bay white sucker fillets are well below the FDA's 5 ppm tolerance limit for these compounds. Adult white suckers experience low annual growth rates (from 1 to 2 cm in total length), high annual survival rates, S (from 0.59 to 0.72) and long life spans (up to 19+ years old). Females grow faster and larger and, on the average, live longer than males.

The Beverton-Holt dynamic pool model, incorporating a linear age-weight relationship, was used to estimate the equilibrium yield per recruit at different rates of fishing. Optimal utilization of this fishery, in terms of maximizing yield per recruit, can only occur with a six to ten-fold increase in the rate of fishing. The current absence of profitable markets for suckers render immediate increases in the rate of exploitation unlikely.

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CHAPTER I

Introduction

A. Background

The Laurentian Great Lakes contain abundant populations of such commercially underutilized fish as carp (*Cyprinus carpio*), suckers (*Catostomus* and *Moxostoma* spp.), alewives (*Alosa pseudoharengus*) and rainbow smelt (*Osmerus mordax*). The principal reason that these and other so-called rough fish species are underutilized is the absence of dependable and profitable markets for rough fish. Changes in the species composition of the Great Lakes fisheries have had a dramatic negative impact on the size and scope of commercial fishing operations. The survival of the remaining commercial fishery hinges, in part, on the development of abundant stocks of heretofore underutilized fish. Estimates of the yield potential from latent or underutilized Great Lake fish stocks are lacking for most species. This investigation was undertaken to determine potential limits on the commercial exploitation of suckers in Saginaw Bay, Lake Huron.

The species composition of the Great Lakes fisheries has changed markedly over the past forty to fifty years. Formerly plentiful stocks of lake trout (*Salvelinus* *namaycush*), lake whitefish (*Coregonus clupeaformis*), lake herring (*Coregonus artedii*), walleye (*Stizostedion vitreum*), lake sturgeon (*Acipenser fulvescens*) and burbot (*Lota lota*) have been supplanted by abundant stocks of alewives, rainbow smelt, carp and other so-called rough fish species. Commercial overfishing, the introduction and proliferation of such exotic species as the sea lamprey (*Petromyzon marinus*) and alewife, environmental enrichment and pollution have combined to help bring about this transformation in species composition. Documentation and interpretation of the changes which have occurred in the Great Lakes fisheries during the last four to five decades are provided by: Hile and Buettner (1959); Buettner (1968); Smith (1968); Berst and Spangler (1973); Smith (1973); Regier (1973) and Christie (1974).

The virtual elimination of commercially exploitable stocks of lake trout, lake whitefish and lake herring in many areas of the Great lakes has contributed to a substantial reduction in the size and scope of Michigan's Great Lakes commercial fishery over the past twenty to thirty years. Scott (1974) reports a decrease in the number of Michigan commercial fishing licensees from approximately 900 in 1963 to about 660 in 1967. After 1970, according to Borgeson (1972), state-imposed restrictions on gear and entry reduced the total number of Michigan Great Lakes commercial fishermen by an additional 50%. At present, Michigan licenses from 100 to 150 commercial fishermen, exclusive of non-licensed Native American fishermen (Asa Wright, personal communication).

The Michigan Department of Natural Resource's management objectives for Michigan's Great Lakes commercial fishery include restricting new entries and encouraging the exit of marginal fishing operations. The efficient and equitable allocation of Great Lakes fishery resources between sport and commercial fishermen is a complex social, political, economic and biological problem with no immediate satisfactory solution. The principal thrust of Great Lakes fisheries management is currently oriented toward a large, fairly recently established sport fishery for introduced salmonids. Suspicions, real or otherwise, that the commercial fishery poses a threat to the survival of highly prized artificially maintained sport fish stocks have resulted in widespread misunderstandings and feelings of animosity between sport and commercial fishermen. State licensed commercial fishermen are prohibited from using gill nets for capturing fish and must return all designated sport fish (e.g. lake trout, Pacific salmon, walleye pike) and undersized commercial species (e.g. lake whitefish, yellow perch, *Perca flavescens*) to the water in an unharmed condition. The entrapment gear used by non-Indian commercial operators allows for selective exploitation of Great Lakes fishery resources without causing significant damage to the sport fishery. At present, regulations prohibiting the use of gill nets do not extend to non-licensed Native American commercial fishermen operating in Michigan's Great Lakes waters. The unregulated use of gill nets poses a potentially severe threat to the sport fishery, exacerbating the problems of efficient and equitable resource management.

Annual fish production within the Great Lakes represents a large potential source of high quality protein for consumers in the United States and Canada. Only a small proportion of this production finds its way into the marketplace due to the reduced size of current commercial fishery operations and the relative paucity of profitable markets for underutilized rough fish species. The existence of abundant potentially exploitable populations of underutilized fish (e.g. carp, alewives, suckers and smelt) in Michigan's Great Lakes waters is documented by Hile and Buettner (1959), Borgeson (1972), Galloway and Kevern (1976) and Rybicki (1979). With the exception of such local enterprises as the lake whitefish fishery of Northern Lake Michigan, the traditional Great Lakes commercial fishery, which had been based largely upon lake trout, lake whitefish and lake herring, has all but disappeared. The survival of the remaining commercial fishery hinges upon the reestablishment of a viable coregonid fishery and the enhanced development of fisheries for underutilized species.

According to Frick (1965), if the Great Lakes commercial landings are to be maintained in volume and value, then product development, quality improvement and

market promotion are necessary to increase the demand for those species available in abundance. Great Lakes commercial fishermen have been reluctant to change the focus of their operations to underutilized, lesser valued species due to the absence of remunerative markets for these fish. The lack of profitable markets for underutilized fish may, in part, be the fault of the commercial fishing industry itself, since, as Anderson (1973) has pointed out, fishing industries generally lag behind competitors in other food processing industries in developing markets for their products. In recent years it has become evident that assistance from outside the Great Lakes commercial fishing industry is necessary to provide both the incentive and the technological support for increased development of underutilized fishery resources. In response to developmental assistance requests from the commercial fishing industry, a Sea Grant-supported program conducted by Michigan State University's Departments of Fisheries and Wildlife and Food Science has been designed to stimulate the development of underutilized Great Lakes fish resources, primarily via production of a frozen minced fish product (Michigan State University, December 1975 and March 1978).

The development of viable markets for underutilized fish and fish products is, perhaps, the single biggest obstacle confronting potential developers of underutilized Great Lakes fish stocks. According to Anderson (1973), before consumers become adventurous and try unfamiliar species and products, they must be taught to accept fish as a prime food. In 1978, according to the U.S. Department of Agriculture's Economic, Statistical and Cooperative Service, Americans consumed an average of 149.7 pounds of red meat, 57.1 pounds of chicken and turkey and 13.4 pounds of fish per person. This low per capita consumption of fish relative to other meats indicates that Americans, as a whole, may not regard fish as a primary dietary item. If this observation holds, then the initial introduction of underutilized species into the marketplace may be met with a less than enthusiastic response.

Estimates of the net all or none values (social surplus) of Great Lakes sport and commercial fisheries have been made by Talhelm, et al (1979). These estimates indicate that the sport fishery's net all or none value (i.e. approximately $525 million) greatly exceeds the correspondent value of the commercial fishery (i.e. approximately $12 million). These estimates are in terms of constant 1979 dollars. Establishment of new, profitable markets for underutilized fish and fish products could noticeably improve the economic importance of the Great Lakes commercial fishery relative to the Great Lakes sport fishery. Increased exploitation of underutilized Great Lakes fish should not interfere with overall fishery management goals by the State of Michigan and other governmental agencies. It is possible that the controlled harvest and concomitant reduction of large populations of rough fish may favor or enhance the growth and development of some highly valued sport fish stocks.

Large numbers of suckers, predominately white suckers, (Catostomus commersoni) are captured annually by Saginaw Bay commercial fishermen in entrapment gear set for more commercially valuable species (e.g. channel catfish, Ictalurus punctatus, yellow perch, and lake whitefish). Historical catch data summarized by Hile and Buettner (1959) show annual commercial landings of Saginaw Bay suckers averaged approximately 1,000,000 pounds during the late 1800's and up through the 1930's. During this period, fishermen received up to $0.30 per pound for suckers at dockside. This relatively high ex-vessel price for suckers was attributed to the existence of a large, stable Eastern United States market for these fish. After the 1930's, this market disappeared, resulting in markedly decreased per pound revenues to the individual fisherman (i.e. from $0.30 to $0.05 per pound). A large proportion of the suckers sent to the East Coast had been processed into gefilte fish. Changes in traditional ethnic lifestyles or increased availability of acceptable substitutes helped shift the demand for large quantities of Saginaw Bay suckers. From 1968 to 1979, annual landings of Saginaw Bay suckers averaged approximately 120,000 pounds. Conversations with Saginaw Bay fishermen reveal that most (i.e. from 50% to 75%) of the current sucker catch is returned to the water due to the absence of a profitable sucker market. This information, combined with historical sucker fishery catch statistics, reveals a great potential for increased utilization of Saginaw Bay suckers.

B. Purpose of this Investigation

This paper presents results of a two year investigation designed to evaluate the population dynamics of Saginaw Bay white sucker stocks. Samples of the commercial catch revealed that white suckers comprise more than 90% of the total sucker catch in terms of numbers and weight from the waters of eastern Saginaw Bay. Other sucker species present in Saginaw Bay are the longnose sucker (*Catostomus catostomus*) and the redhorse sucker (*Moxostoma* spp.). Information concerning sucker growth and mortality is needed to help estimate the potential for increased utilization of these fish. This study was conducted in conjunction with Michigan State University's Sea Grant-sponsored efforts to stimulate the development of underutilized Great Lakes fish via production of a frozen, mechanically deboned minced fish product.

Aside from commercial fishery catch and effort data, little information is available concerning the population dynamics and abundance of Saginaw Bay suckers. In order to evaluate the potential impacts of increased harvest levels on population stability, baseline data is needed regarding: (1) the size, age and sex composition; (2) age and size specific growth and mortality rates and (3) the relative magnitude of existing stocks. Prior to fishery development,

levels of environmental contaminants in underutilized fish should be determined to insure compliance with applicable governmental health regulations.

The principal question addressed by this investigation is, what are the potential limits on Saginaw Bay sucker exploitation? Crutchfield (1973) cites an urgent need for reasonably accurate yield estimates from latent or underutilized fisheries prior to instigation of multiple objective management policies. The delineation of a reliable production function, relating measurable inputs to corresponding outputs, is one of the most important aspects of any resource development evaluation. Without an accurate production function, application of biological and economic management techniques is much more difficult. Much of the present study involves attempts to relate fishing effort to catch. Additional questions addressed by this study are: (1) what are the magnitudes of the likely benefits to the commercial fishery of increased sucker utilization and (2) what are the levels of the common environmental contaminants, DDT and PCB's, in the usable flesh of Saginaw Bay suckers?

In addition to possible biological constraints, other impediments to the enhanced development of the Saginaw Bay sucker fishery are: (1) the short (less than two day) shelf life of whole iced fish; (2) the large number of small y-bones found in the edible flesh (fillets) of suckers and (3) the generally poor reputation enjoyed by suckers and other rough fish species among the consuming public. Establishment of a dependable and profitable market for suckers would increase the annual landings of these fish and help strengthen the local commercial fishery. A greatly expanded and profitable market for suckers cannot be established unless the existing impediments to sucker fishery development are removed. The short shelf life of iced whole suckers precludes their transport to distant markets. The geographic scope of potential markets could be broadened by adoption of suitable processing techniques (e.g. smoking or mincing). Remediation of the y-bone nuisance could be achieved by a mincing process (Michigan State University, December 1975 and March 1978). A minced product could be more readily packaged, stored, transported and marketed than whole iced or frozen fish. With proper marketing methods, negative consumer attitudes regarding rough fish may be altered.

C. Methods

An ideal fish population dynamics investigation should include a comprehensive mark and recapture study to determine fish movements, distribution and estimates of population density. In addition, timely and accurate catch and effort data for each commercially harvested species must be available. Funding constraints for this project ruled out the possibility of any meaningful mark and recapture program. Fortunately, a long term commercial fishery data base is available for each principal species landed by

Michigan commercial fishermen (Hile, 1962). These catch and effort data, if interpreted carefully, allow an investigator to calculate estimates of relative population abundance. The analysis and interpretation of Saginaw Bay sucker fishery catch and effort data is detailed in Chapter III.

Catch and effort data, along with basic cost and revenue information furnished by individual operators, were used to develop a rudimentary bioeconomic model of the Saginaw Bay commercial sucker fishery. The logistic surplus production model was utilized to estimate a production function for this fishery. Some of the problems associated with the bioeconomic analysis of multi-species fisheries, particularly with regard to optimization of single species harvest levels, are discussed in Chapter IV.

Previous work on samples of the commercial catch from Lake Huron and Saginaw Bay (Zabik, et al, 1978) indicates that the levels of the environmental contaminants, PCB's and DDT, in suckers are within the 5 ppm allowable tolerance limits established by the U. S. Food and Drug Administration for these compounds. Continued monitoring of environmental contaminant levels to insure compliance with applicable health regulations is a necessary component of any fisheries development effort. Samples of the commercial sucker landings, stratified by sex and size, were obtained for analysis of DDT and PCB's. Methods and results of these analyses are presented in Chapter V.

Representative samples of commercially caught suckers from the east central portion of Saginaw Bay were obtained from September 1979 through April 1981. Data from these samples were used to determine the size, age and sex composition and age-specific growth and mortality rates of Saginaw Bay white suckers. Age-specific survival and fecundity data were incorporated into a Leslie Matrix model (Vaughan and Saila, 1976) in an effort to obtain estimates of age 0 survival rates. Estimates of relative yield per recruit were calculated for different, hypothetical rates of fishing via a modification of the dynamic pool model described by Beverton and Holt (1957). This model, incorporating a linear age-weight function, was used to estimate the relative susceptibility of Saginaw Bay sucker stocks to different rates of exploitation. These efforts are described in Chapter VI.

Chapter VII contains a summary of the biological and economic analyses contained in Chapters III through VI. In this section, recommendations for future management of Saginaw Bay sucker stocks are discussed. Problems and deficiencies in the analysis of sucker population dynamics encountered in the preceding chapters are discussed along with recommendations for future work.

CHAPTER II

Saginaw Bay

A. The Physical Setting

The following description of the physical characteristics of Saginaw Bay is taken from the monograph by Beeton, et al, (1967). Saginaw Bay (Figure II-1) is a large indentation on the western shore of Lake Huron (42 km wide at the mouth between Point Aux Barques and Au Sable Point and 82 km long from the midpoint of a line between these points to the mouth of the Saginaw River). The bay narrows to a width of 21 km between Point Lookout on the west shore and Sand Point on the east shore. A broad shoal at this constriction (between Charity Island and Sand Point) effectively divides the bay into outer and inner zones. The total area of 2960 km^2 is divided about equally between the two zones, but the outer zone is considerably deeper (mean depth, 15.6 m, maximum depth, 40.5 m) than the inner zone (mean depth, 4.6 m, maximum depth, 14.0 m) and contains about 70% of the total volume of the bay. The volume of water above the 5.5 m contour is only 32% for the outer bay, but 80% for the inner zone. The east shore of the outer bay is rocky; the west shore has extensive sandy areas, although some rock and clay occur near Point Lookout. The shoal

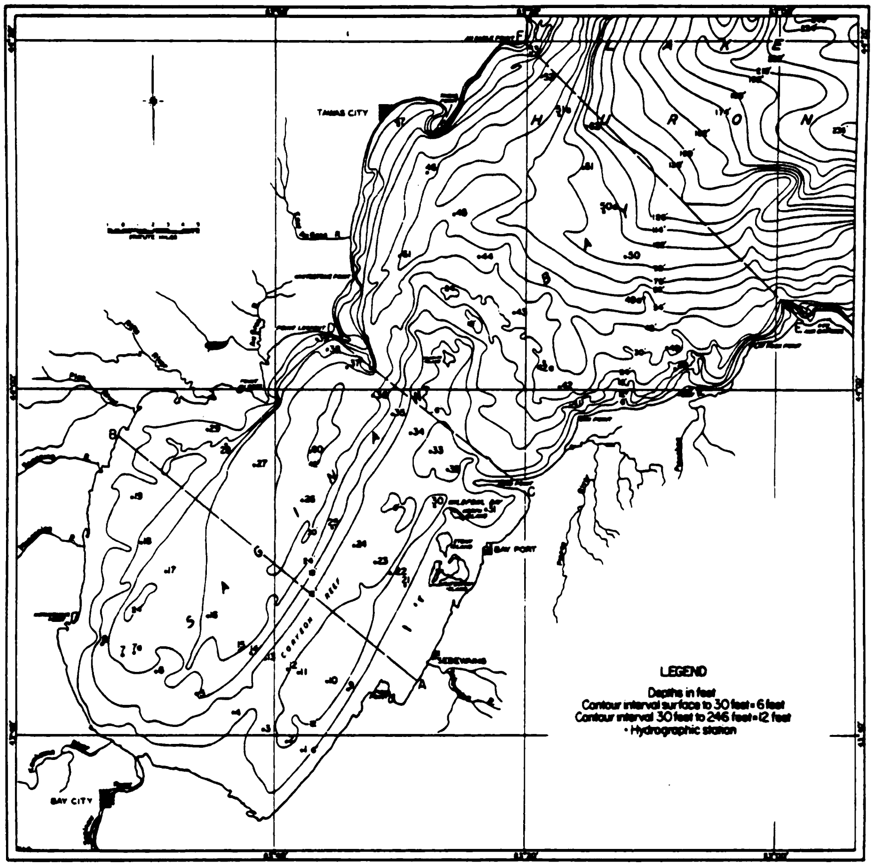


Figure II-1. Saginaw Bay (from Beeton, et al, 1967).

around Charity Island and most of the points in the outer bay are rocky. Tawas Point and Sand Point are sand spits. The inner bay has extensive shallows. A broad sandy flat extends southward from Wildfowl Bay. Another irregular sandy flat extends from the Saginaw River along the west shore to Point Au Gres. Several shallow spits off the mouths of small rivers extend over this flat perpendicular to the shore. The two large flats have extensive marshes near shore. Coryeon Reef is a sand and gravel bar between the shore southeast of the Saginaw River and the Charity Islands. Its ridge is about 1.8 m below the surface and it is separated over most of its length from the sandy flat near shore by water deeper than 3.7 m. The bay has several islands, the most prominent of which is Charity Island. A group of marshy low-lying islands (North, Stony and Katechay) lies southwest of Sand Point. These islands are surrounded by marshy shallows from which there is no clear line of demarcation.

B. Limnology

The most recent comprehensive limnological survey of Saginaw Bay was a cooperative investigation by the Michigan Department of Conservation and the U.S. Bureau of Commercial Fisheries in 1956 reported upon by Beeton, et al, (1967). Federal and State of Michigan monitoring of Saginaw Bay tributary water quality has been sporadic over the past twenty years and is summarized in the U.S. Environmental Protection Agency's STORET data system (Freedman, 1974).

Biological investigations of Saginaw Bay have focused on fish (Carr, 1962, and Eshenroder, 1977) and benthic macroinvertebrates (Schuytema and Powers, 1966, and Schneider, et al, 1969). A summary of existing physical, chemical and biological information on Saginaw Bay is provided by Freedman (1974).

Beeton, et al (1967) report that water circulation within the bay is generally counterclockwise, however, surface circulation patterns are highly variable, depending primarily on the direction of the prevailing winds. Winds from the northeast, east and southeast produce a clockwise circulation whereas winds from the northwest and west generate a counterclockwise surface circulation. Little is known concerning the direction of subsurface circulation patterns within Saginaw Bay. The inner bay (mean depth, 4.6 m) becomes homothermous during late July, according to Beeton, et al, (1967), whereas the outer bay (mean depth, 15.6 m) exhibits a more complex summer thermal stratification, influenced by intrusions of Lake Huron water. Dissolved oxygen concentrations vary according to water temperature and wind velocity. Beeton, et al, (1967) found dissolved oxygen concentration at 9 m in the inner bay at a low value of about 70% of saturation after a period of calm during mid-June. The pH of Saginaw Bay waters increases from approximately 7.8 - 8.1 in June to about 8.4 in July, after which it gradually decreases to lower values. Alkalinity varies from 110 - 125 ppm $CaCO_3$ in the inner bay and from 90 - 110 ppm $CaCO_3$ in the outer bay. A brief summary of some major physicochemical parameters for Saginaw Bay is listed in Table II-1.

According to Freedman (1974), large summertime blooms of blue green algae are a common occurrence in Saginaw Bay. These algal blooms have been attributed to increased concentrations of phosphorus resulting from agricultural activity in the Saginaw Bay watershed. Schneider, et al, (1969) investigated the distribution and abundance of benthic fauna in Saginaw Bay. These workers found that oligochaetes and chironomids dominate the benthic fauna, comprising approximately two thirds of the average standing crop of 4.43 g/m^2. The deeper portions of the inner and outer bays and Wildfowl Bay were found to be the most productive areas in terms of benthic fauna whereas the shallow, sandy Coreyon Reef was the least productive zone. Oligochaetes comprised 50% of the standing crop in the zone closest to the mouth of the Saginaw River while chironomids and amphipods dominated the benthos in the middle and outer portions of the bay, respectively. Pronounced decreases in observed numbers of burrowing mayflies (*Hexagenia* spp.) occurred after the mid-1950's.

C. The Fishery

According to Beeton, et al, (1967), Saginaw Bay supported a prosperous recreational fishery during the first half of the 20th century and also produced about 40% of the U.S. commercial catch from Lake Huron although it

Table II-1

Saginaw Bay Physicochemical Data

Parameter	Value	Source
Climate		
type	maritime	Eshenroder (1977)
latitude (^{o}N)	43^{o} 50'	
avg. max. temp. (^{o}C)		
July	28.6^{o}	
January	0.1^{o}	
annual precipitation	76.6 cm	
growing season	218 days	
Drainage basin		
area	21000 km^2	Freedman (1974)
human population		
1940	0.6 million	
1970	1.2 million	
Effluent streams		
mean discharge		
8 largest streams	115 m^3/s	Freedman (1974)
Saginaw River	96 m^3/s	
Morphometry		
length	83 km	Beeton, et al, (1967)
width at mouth	42 km	
total area	2960 km^2	
mean depth		
inner bay	4.6 m	
outer bay	15.6 m	
maximum depth		
inner bay	14.0 m	
outer bay	40.5 m	
volume	27 km^3	
flushing rate	186 days	
Chemistry		
specific conductance		
inner bay	469 μmhos	Beeton, et al, (1967)
outer bay	253 μmhos	
Saginaw River mouth	800 μmhos	
Lake Huron proper	174 μmhos	
alkalinity		
inner bay	110-125 ppm $CaCO_3$	
outer bay	90-110 ppm $CaCO_3$	
pH		
June	7.8-8.1	
July	8.4	
phosphorus (total)		
inner bay	0.041 ppm	
outer bay	0.018 ppm	

constituted only 5% of the total area of Lake Huron's U.S. waters. During this period the commercial fishery depended upon abundant stocks of lake herring, walleye pike, yellow perch and lake whitefish. Of these species, only yellow perch are currently taken in appreciable quantities by commercial fishermen. The most widely distributed species of fish within Saginaw Bay, according to Carr (1962), are alewives, rainbow smelt, yellow perch and white suckers. Approximately 74 species of fish are known to occur in the bay. At present, Saginaw Bay commercial fishermen rely upon harvests of channel catfish for the major portion of their incomes. Carp, yellow perch, sheepshead (*Aplodinotus grunniens*), quillback, (*Carpiodes cyprinus*) and lake whitefish are the other principal commercially harvested species.

Saginaw Bay is a productive, enriched body of water which supports a thriving recreational fishery and a small, declining commercial fishery. The vast potential of this body of water for fish production was heavily exploited during the latter portion of the 19th century and up through the first half of the 20th century. Changes in the species composition of the fishery have markedly diminished the commercial utilization of the bay's fish producing capability. The future of the commercial fishery hinges upon carefully regulated efforts to capitalize upon the bay's productivity through increased exploitation of underutilized species. Management goals for Saginaw Bay's

latent fisheries should consist of a mixture of biological, economic and social objectives designed to enhance the productive capacity of existing stocks and the region's economic and social well-being. Prior to formulation of an underutilized fishery management policy, we need to know the fishery yield potential. Chapter III is concerned with this problem.

CHAPTER III

Catch and Effort Data Analysis

A. Introduction

The distribution and abundance of commercially exploited fish populations depend upon a set of n genetically regulated physiological and behavioral rate variables, $r_k(t)$, $k = 1,\ldots,n$, which determine a population's ability to respond to changes in environment (biotic and abiotic) and level and pattern of exploitation. Some examples of these rate variables, $r_k(t)$, are: age, size and sex specific growth and mortality; age and size specific fecundity; recruitment; immigration and emigration. The study of fish population dynamics includes obtaining reasonably accurate measurements of these variables and relating this information to past, present and projected future levels of population abundance. Much of the data used to determine the dynamics of commercially exploited fish populations is acquired from: mark and recapture studies; samples obtained from research vessel surveys and commercial landings; and commercial fishery catch and effort records.

The acquisition of biological data constitutes the most costly portion of any fish population dynamics investigation. Most studies of the dynamics of commercially exploited fish populations depend, therefore, to a large extent, upon the information contained in the records of total landed catch, C_t, and nominal effort, f_t, provided at little cost by the commercial fishery. With reliable catch and effort statistics, estimates of relative population abundance can be inferred from the ratio of total catch, C_t, to total effort, f_t. The accuracy of population abundance estimates calculated from catch per unit effort analyses depends, among other things, upon the degree to which records of: (1) total landed catch, C_t, reflect actual catch and (2) nominal effort, f_t, reflect actual fishing-induced mortality.

B. The Basic Theory of Catch and Effort Data Analyses

The change in stock biomass due to mortality during the time interval, Δt, is given by,

III-1 $$dB(t)/dt = -[M(t) + F(t)]\, B(t),$$

where: $B(t)$ = stock biomass at time t

$M(t)$ = instantaneous rate of natural mortality

$F(t)$ = instantaneous rate of fishing mortality.

In practice, $M(t)$, the instantaneous rate of mortality attributable to all factors other than fishing (e.g. predation, disease, parasitism, senescence, etc.) and $F(t)$, the instantaneous rate of mortality attributable to the effects of fishing, are regarded as constants during the time interval, Δt. This is a lumped parameter model which assumes that each unit of biomass within the exploitable portion of a given population is subject to the same rates of mortality, M(t) and F(t), during a given time interval, Δ t.

The solution to equation III-1 when M(t) and F(t) are constant during time, Δt, is given by,

III-2 $$B_t = B_0 e^{-(M + F)\Delta t},$$

where: B_t = stock biomass at t_o

B_0 = stock biomass at t.

The exponential expression in equation III-2 is the probability (S) that a unit of biomass in the portion of the population which is vulnerable to exploitation will survive to the end of the time interval, Δ t, or

III-3 $$S = e^{-(M + F)\Delta t}.$$

Conversely, the probability (A) that a unit of biomass in the exploitable portion of the population will succumb to the forces of mortality during time, Δ t, is

III-4 $$A = 1 - S = 1 - e^{-(M + F)\Delta t}.$$

The proportion of total removals due to fishing during time, Δ t, is given by,

III-5 $$u = FA/(M + F),$$

where u is referred to as the rate of exploitation. Theoretically, total removals due to fishing (i.e. total catch C_t) during time, Δ t, equal the rate of exploitation, u, multiplied by the size of the stock present at the beginning of the time interval or,

III-6 $$C_t = uB_0 = FAB_0/(M + F) = F(1 - S)B_0/(M + F)$$
$$= F[1 - e^{-(M + F)\Delta t}]B_0/(M + F).$$

Now, in accordance with equation III-2, we know that stock biomass decreases exponentially during time, Δt. By integrating equation III-2 with respect to time we obtain an estimate of mean stock biomass during time, Δt,

III-7 $\quad \overline{B}_t = B_0[1 - e^{-(M + F)\Delta t}]/(M + F).$

Substituting equation III-7 into equation III-6 leads to the following expression for total catch, C_t, during time, Δt,

III-8 $\quad C_t = uB_0 = F\overline{B}_t.$

F, the instantaneous rate of fishing mortality, is usually assumed to be directly proportional to the amount of nominal fishing effort, f_t, applied to the fishery during time, Δt,

III-9 $\quad F = qf_t.$

The proportionality constant, q, in equation III-9 is referred to as the catchability constant or the probability that a given unit of fish biomass within the exploited portion of a population will be captured by a unit of nominal fishing effort, f, during time, Δt. The units of q are in terms of f^{-1}.

A production function is a mapping which relates a set of identifiable, measurable inputs (e.g. land, labor, capital, management) to a corresponding set of identifiable, measurable outputs (i.e. goods or services). Perhaps the simplest model of a fishery production function is given by the following equation,

III- 10 $\quad C_t = Q(f_t,\overline{B}_t).$

In this equation, total catch, C_t, during the time interval, Δt, is hypothesized to be a function of the total amount of

nominal effort exerted by the fishery, f_t, and the average size of the exploitable portion of the population, $\overline{B}_t$. In economic analyses of commercially exploited fisheries, the function, $Q(f_t,\overline{B}_t)$, is sometimes represented in the following form (Clark, 1976).

III-11 $\quad C_t = q(f_t)^a(\overline{B}_t)^b,$

where q is the catchability constant and a and b are positive constants.

The well-known assumption that the ratio of catch per unit effort, C_t/f_t, is directly proportional to the mean size of the vulnerable portion of the population present during the period when fishing takes place, $\overline{B}_t$, is described by Beverton and Holt (1957). This assumption leads to the following formulation of equation III-11,

III-12 $\quad C_t = q(f_t)(\overline{B}_t),$

where the constants a and b in equation III-11 are both set equal to one. Equation III-12 is also derived by substituting equation III-9 into equation III-8.

A more general form of a fishery production function, $Q(f_t,\overline{B}_t)$, is given by,

III-13 $\quad C_t = Q(f_t,\overline{B}_t) = q_t{}^x(f_t)^a(\overline{B}_t)^b,$

where catchability, q, is a time varying function and x, a and b are positive constants. The analytical difficulties involved in estimating the parameters of equation III-13 are formidable, so most catch and effort data analyses use equation III-12 to describe the short term production function of a commercially exploited fishery. Equation III-

12 represents the catch, C_t, obtained during time, Δt, by applying f_t units of effort to the fishery. Long term fishery production functions incorporate specific assumptions about stock biomass growth (e.g. logistic growth models) to help describe the assumed long term equilibrium relationships between and among catch, C_t, effort, f_t, and stock biomass, B_t. An example and discussion of a long term fishery production function is contained in Chapter IV.

Nominal effort, f_t, measured in terms of standardized gear lifts or sets, is not a unidimensional measure of effective fishing mortality, F, as may be erroneously inferred from equation III-9. Nominal effort, f_t, is a function of several variables, each of which plays an important role in determining the effective rate of fishing mortality exerted upon an exploited population during time, t. For example, f_t can be represented by,

III-14 $\quad f_t = f(g_1,...,g_m).$

Some of these variables, g_i, $i = 1,...,m$, are: size, capacity and power of the fishing vessels; knowledge and experience of the crews; selectivity of the fishing gear; and per unit harvest costs and prices. The enumeration and quantification of these effort variables, g_i, along with the determination of their exact relationship to effective fishing effort, F, would involve an exceedingly complex form of economic input analysis, the scope of which is probably not justified by the value of most fisheries. Equation III-14 indicates that the assumption of a constant effective fishing mortality rate, F, may be unrealistic for long time periods. The potential difficulties and costs associated with a multi-dimensional analysis of fishing effort lead most fisheries investigators to conditionally accept the assumption that nominal effort, f_t, is a reliable measure of effective fishing mortality, F(t). This assumption will be adopted for the purpose of the present analysis.

In addition to the assumption of constant catchability, q, some additional assumptions upon which equation III-12 is based are: (1) instantaneous fishing and natural mortalities occur uniformly throughout the year and from year to year; (2) fish in the exploitable portion of the population are uniformly distributed throughout the area of exploitation and (3) individual fishing vessels and units of fishing gear are distributed so they are not in direct physical competition with one another.

Mean exploitable population size, $\overline{B}_t$, present during the time interval covered by available catch, C_t, and nominal effort, f_t, data can be calculated from equation III-12 provided a reasonably reliable estimate of catchability, q, can be obtained.

C. <u>The Leslie Model</u>

If a population is fished until enough fish are removed to significantly reduce the catch per unit effort ratio, C_t/f_t, then estimates of catchability, q, and initial population size, B_0, can be obtained from the following relationship between catch per unit effort and cumulative catch, K_t (cf. Seber, 1973, and Ricker, 1975).

III-15 $\quad C_t/f_t = qB_t$.

The population, B_t, present during the period covered by available catch and effort data can be equated to the initial population, B_0, minus the cumulative catch, K_t, or

III-16 $\quad B_t = B_0 - K_t$.

By substituting equation III-16 into equation III-15 we get,

III-17 $C_t/f_t = q(B_0 - K_t) = qB_0 - qK_t$.

Equation III-17 indicates a negative linear relationship between catch per unit effort, C_t/f_t, and cumulative catch, K_t, with slope, -q, and y-intercept, qB_0. This model was first introduced by Leslie and Davis (1939) and subsequently modified by Braaten (1969). The reliability of this method of determining catchability, q, and initial population abundance, B_0 depends upon the following assumptions: (1) the population is closed with respect to recruitment, natural mortality and migrations, or equivalently, these processes are in equilibrium; (2) catchability, q, is constant for all sizes of fish appearing in the catch throughout the time period covered by available catch and effort data; (3) catch and effort records are completely reliable; (4) fishing effort is randomly distributed throughout the range of the population; (5) individual units of fishing effort are independent; (6) the entire catch or most of the catch is captured by the same type of fishing gear and (7) there is no variation in catching efficiency between and among the various units of fishing gear employed by the fishery. The range and severity of the above restrictions greatly reduce the applicability of the Leslie method to commercial fishery population dynamics studies. Despite these severe limitations, however, the Leslie and other similar methods of population enumeration can be used to obtain rough estimates of catchability and mean population size for those fisheries in which: (1) catchability, q, is reasonably constant; (2) catch and effort records are fairly reliable and (3) the fishery is dominated by a single, uniform type of fishing gear.

D. Sources of Commercial Fishery Catch and Effort Data

Since 1929, Michigan's Great Lakes commercial fishermen have been required to submit detailed monthly reports to the Michigan Department of Natural Resources describing, on a daily basis, the total landed weight of each species harvested along with the total number of units of effort employed by each type of fishing gear. A comprehensive description of the current Great Lakes commercial fishery catch and effort data reporting system is provided by Hile (1962).

According to Hile and Buettner (1959), about 70% of the total Saginaw Bay sucker landings from 1929 to 1956 were obtained with shallow trap nets (i.e. trap nets fishing in water less than 20 feet in depth). During the period from 1960 to 1979, approximately 90% of all commercially landed suckers from Saginaw Bay were captured by shallow trap nets. After the commercial use of gill nets was banned in the

early 1970's, the Saginaw Bay commercial fishery for all species has been exploited almost exclusively by means of shallow trap nets. One unit of nominal effort for this gear corresponds to one net lift.

A uniform analysis of catch and effort data requires that all nominal effort from all types of gear (if more than one type of gear is employed) be standardized against a specific gear (usually the gear which consistently captures more fish than any other type of gear). Prior to analysis of Saginaw Bay sucker fishery catch and effort data, all reported effort was standardized against the shallow trap net as follows,

III-18 $f_t = (C_t)(f_s)/(C_s)$,

where: f_t = total (standardized) effort

C_t = total catch from all types of gear

f_s = total number of units of standard effort (i.e. total number of shallow trap net lifts)

C_s = total catch obtained with the standard gear.

No single gear utilized by any given fishery is likely to be entirely non-selective with respect to the size, sex or age composition of a particular exploited population. Therefore, when obtaining fish samples from the commercial catch for purposes of size, sex and age composition analyses, sampling effort should be stratified, if possible, according to the various types of gear used to capture the species under investigation. Calculations of catch indices, population estimates, growth rates and mortality rates can be biased if all fish sampling is restricted to a single size selective gear.

According to Patriarche (1968), stationary trapping devices are usually selective with respect to the species and sizes of fish they capture and retain. Latta (1959) found the vulnerability of white suckers to trap net capture increased with increasing fish size, however, Laarman and Ryckman (1980) reported that trap net size selectivity was not evident for this same species. Patriarche (1968), observing that good estimates of population dynamics parameters can be systematically biased if certain species exhibit strong tendencies to escape confinement, found that 28% of the total number of white suckers initially captured had escaped from experimental trap nets within 48 hours. The tendency of suckers to escape from trap net confinement is corroborated by Saginaw Bay commercial fishermen, who observe that the absence of suckers in a given trap net's catch often indicates the presence of a hole in the net. Captured suckers work so persistently in exploring possible openings in the trap nets' pot end (i.e. confinement area) mesh that they often abrade away the papillose flesh of their snouts and lips. This phenomenon of snout abrasion is particularly evident in suckers obtained from trap nets which have been set for prolonged periods (e.g. more than 5 days) between lifts.

Since the Saginaw Bay sucker fishery is prosecuted almost exclusively by means of shallow trap nets, any size selective bias for suckers inherent to this gear plus any marked tendency for these fish to escape confinement could significantly bias estimates of population parameters calculated from trap net samples. Determination of possible size selectivity or escape tendencies could be assessed via limited mark and recapture studies. In the absence of such information, the assumption must be made that estimates of growth and mortality rates obtained from samples of the trap net catch are representative only of that portion of the stock which is most vulnerable to trap net capture and confinement.

Saginaw Bay commercial sucker fishery yearly catch and effort data for the period from 1929 to 1956 were obtained from the monograph by Hile and Buettner (1959). Monthly catch and effort report summaries for the period from 1960 to 1979 were obtained from the Michigan Department of Natural Resources' Fisheries Division, Lansing, Michigan.

E. The Saginaw Bay Sucker Fishery

1. Background

For purposes of commercial fishery catch and effort data reporting, the area designated as Saginaw Bay, Lake Huron Statistical District MH-4 (Figure III-1), extends into a wedge-shaped region of Lake Huron proper (Smith, et al, 1961). The adjacent open-lake waters of Lake Huron were included in the Saginaw Bay district, according to Hile (1962), to separate the whitefish grounds off the mouth of

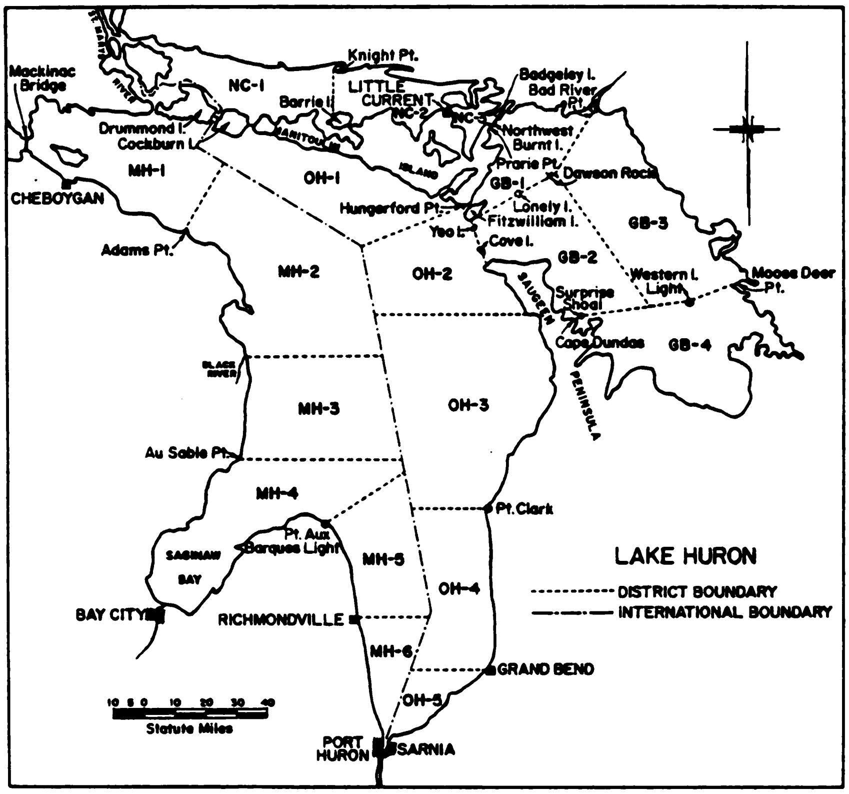


Figure III-1. Lake Huron Statistical Catch Districts (from Smith, et al, 1961)

the bay from the more northerly grounds of the Oscoda area and the southerly grounds of the Harbor Beach region. Almost no suckers are taken from the deep waters of this wedge-shaped region, therefore, reported catch and effort statistics correspond almost exactly to the 2960 km^2 area of Saginaw Bay described by Beeton, et al, (1967).

Multi-species fisheries present a perplexing set of problems to any investigator studying the population dynamics of a particular species' population within such fisheries. The Saginaw Bay trap net fishery is a relatively non-selective harvester of an assemblage of different species including: channel catfish; yellow perch; carp; suckers; lake whitefish; sheepshead (Aplodinotus grunniens); quillback (Carpiodes cyprinus); black crappies (Pomoxis nigromaculatus); white bass (Morone chrysops) and others. The fishery has some ability to target on desired species (e.g. yellow perch and lake whitefish) during specific times of the year. At present suckers represent an incidental catch and are not specifically sought by commercial fishermen. The species composition of the commercial catch varies according to the seasons. For example, lake whitefish, yellow perch and suckers are most available to the fishery in the early spring and late fall whereas carp, sheepshead and quillback are most available during the warm summer months. Availability, as used here, is a term which refers to that portion of a given stock which is actually vulnerable to a fishery during a particular time. If a

species' vulnerability to the fishery varies during different times of the year (e.g. due to temperature-induced behavioral movements), then changes in relative abundance indices (e.g. C_t/f_t) from season to season within a given year are probably unreliable indicators of changing population abundance. In such instances only yearly relative abundance indices are likely to be of any value in assessing population abundance. A particularly vexing problem associated with the analysis of Saginaw Bay sucker fishery catch and effort data is that, due to the poor market for these fish, reported landings are usually a subset of the actual catch. The reliability of catch per unit effort indices calculated from such data is questionable unless it can be assumed that a reasonably constant proportion of the actual catch is landed throughout the fishing season from year to year. With such problems in mind, we will cautiously proceed with an analysis of Saginaw Bay commercial sucker fishery catch and effort data.

2. The Sucker Fishery, 1929 to 1956

An excellent description of the Saginaw Bay commercial fishery for all major species harvested during the period from 1929 to 1956 is provided by Hile and Buettner (1959). Up until the mid-1940's, the principal species harvested by the fishery were lake herring, walleye, suckers, carp and yellow perch. Changes in the species composition of the Saginaw Bay fishery paralleled similar changes which occurred throughout the Great Lakes since the early 1940's.

Declining abundances of highly valued species (e.g. lake herring and walleye) contributed to corresponding reductions in the size of the commercial fishery (cf. Figure III-2). From the group of highly prized species harvested in abundant quantities during the early part of the 20th century, only yellow perch were caught in commercially significant amounts by the mid-1950's. Increased abundances of carp, channel catfish and suckers were observed after the mid-1940's, however, these species remained underutilized due to the absence of sufficiently profitable markets.

For the Great Lakes fisheries, according to Hile (1962), the period from 1929 to 1943 is regarded as the so-called base or reference period of abundance for all commercially harvested species. During this time, the abundances of the principal commercially harvested species populations were considered relatively stable. An index of relative abundance for a given species can be calculated by dividing each year's catch per unit effort ratio, C_t/f_t, by the base period's mean catch per unit effort for that species in a particular catch district. The resulting abundance index, when multiplied by the amount of nominal effort, f_t, expended during a given year, provides a measure of the expected catch for that year (i.e. the catch that would result if the abundance of the current year's stock

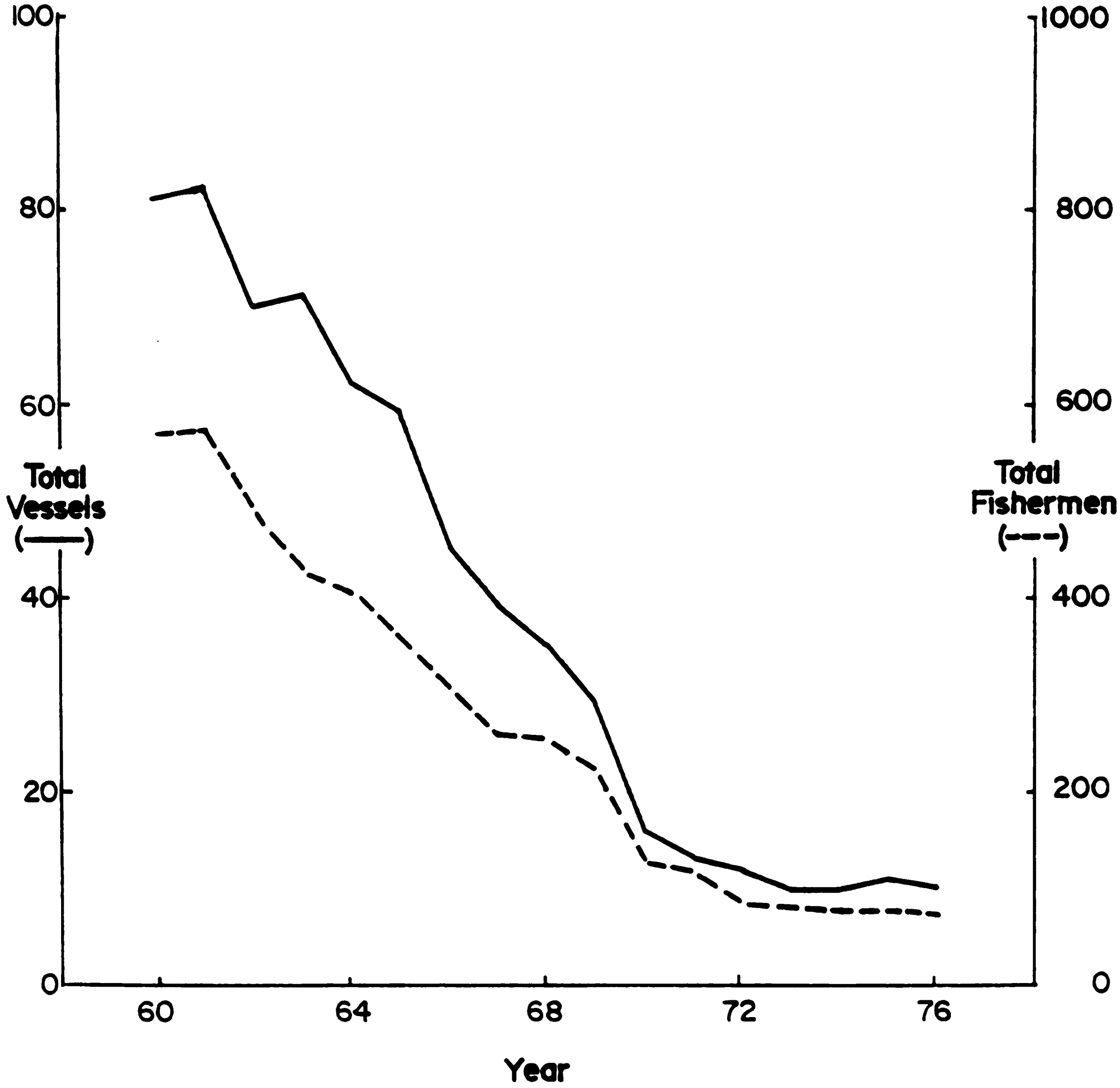


Figure III-2. Participation in the Lake Huron Commercial Fishery (U.S. Waters, 1960-1976).

were equal to the abundance of the stock during the base period). The assumption of constant catchability, q, is implicit in this particular measure of relative abundance.

The years from 1929 to 1956 can be divided into two separate periods, one of lower abundance, from 1929 to 1945, and one of higher abundance, from 1946 to 1956. Table III-1, Table III-2, and Figure III-3 contain summaries of catch, C_t, effort, f_t, and catch per unit effort, C_t/f_t, statistics for these years. The mean catch per unit effort from 1929 to 1943 (i.e. the base period of abundance) was approximately 27.7 pounds of suckers per shallow trap net lift. Figure III-4 depicts the abundance of Saginaw Bay suckers as a percentage of mean 1929 to 1943 catch per unit effort. A period of slightly decreasing relative abundance from 1929 to 1945 is followed by a period of steadily increasing relative abundance from 1946 to 1956.

Equation III-12 can be rewritten as,

III-19 $$C_t = q\bar{B}_t f_t = b(f_t),$$

which suggests that a simple linear regression of total catch, C_t, versus nominal effort, f_t, forced through the origin will yield an estimate (i.e. the slope parameter, b) of mean biomass, $\bar{B}_t$, multiplied by catchability, q. The regression of C_t on f_t for the 1929 to 1945 period resulted in the following,

III-20 $$C_t = b(f_t) = 26.9(f_t);\ r^2 = 0.97.$$

If an independent estimate of catchability, q, could be obtained, we could estimate $\bar{B}_t$ simply by dividing the slope

Table III-1

Saginaw Bay Commercial Sucker Production

(1929-1956)*

Year	Catch (lbs) C_t	Effort f_t**	Catch Per Effort C_t/f_t
1929	1193000	36000	33.1
1930	1687000	53000	31.8
1931	1183000	47000	25.2
1932	1292000	36000	35.9
1933	1069000	32000	33.4
1934	1136000	33000	34.4
1935	803000	40000	20.1
1936	936000	39000	24.0
1937	922000	38000	24.3
1938	780000	29000	26.9
1939	748000	30000	24.9
1940	880000	31000	28.4
1941	820000	29000	28.3
1942	683000	31000	22.0
1943	892000	36000	24.8
1944	740000	37000	20.0
1945	813000	39000	20.8
1946	1214000	34000	35.7
1947	932000	26000	35.8
1948	821000	24000	34.2
1949	630000	19000	33.2
1950	642000	18000	35.7
1951	904000	19000	47.6
1952	941000	21000	44.8
1953	971000	23000	42.2
1954	1060000	19000	55.8
1955	889000	17000	52.3
1956	536000	14000	38.3

* Source: Hile and Buettner (1959)

** Standardized Effort, $f_t = (C_t)(f_s)/(C_s)$

where: C_t = total catch from all types of gear

f_s = total effort with standardized gear

C_s = total catch with standard gear

Note: One unit of standardized effort equals one shallow trap net lift.

Table III-2

Saginaw Bay Sucker Fishery

Summary Statistics, 1929-1956*

Statistics	1929-1945	1946-1956	1929-1956
C_t range (lbs)	683000-1687000	536000-1214000	536000-1687000
$\bar{C}_t$	975000	867000	933000
s_{C_t}	258000	200000	239000
f_t range (shallow trap net lifts)	29000-53000	14000-34000	14000-53000
$\bar{f}_t$	36200	21300	30400
s_{f_t}	6400	5400	9500
C_t/f_t range (lbs per trap net lift)	20.0-35.9	33.2-55.8	20.0-55.8
$\overline{C_t/f_t}$	26.9	41.5	32.6
s_{C_t/f_t}	5.1	7.7	9.5

*Data source: Hile and Buettner (1959)

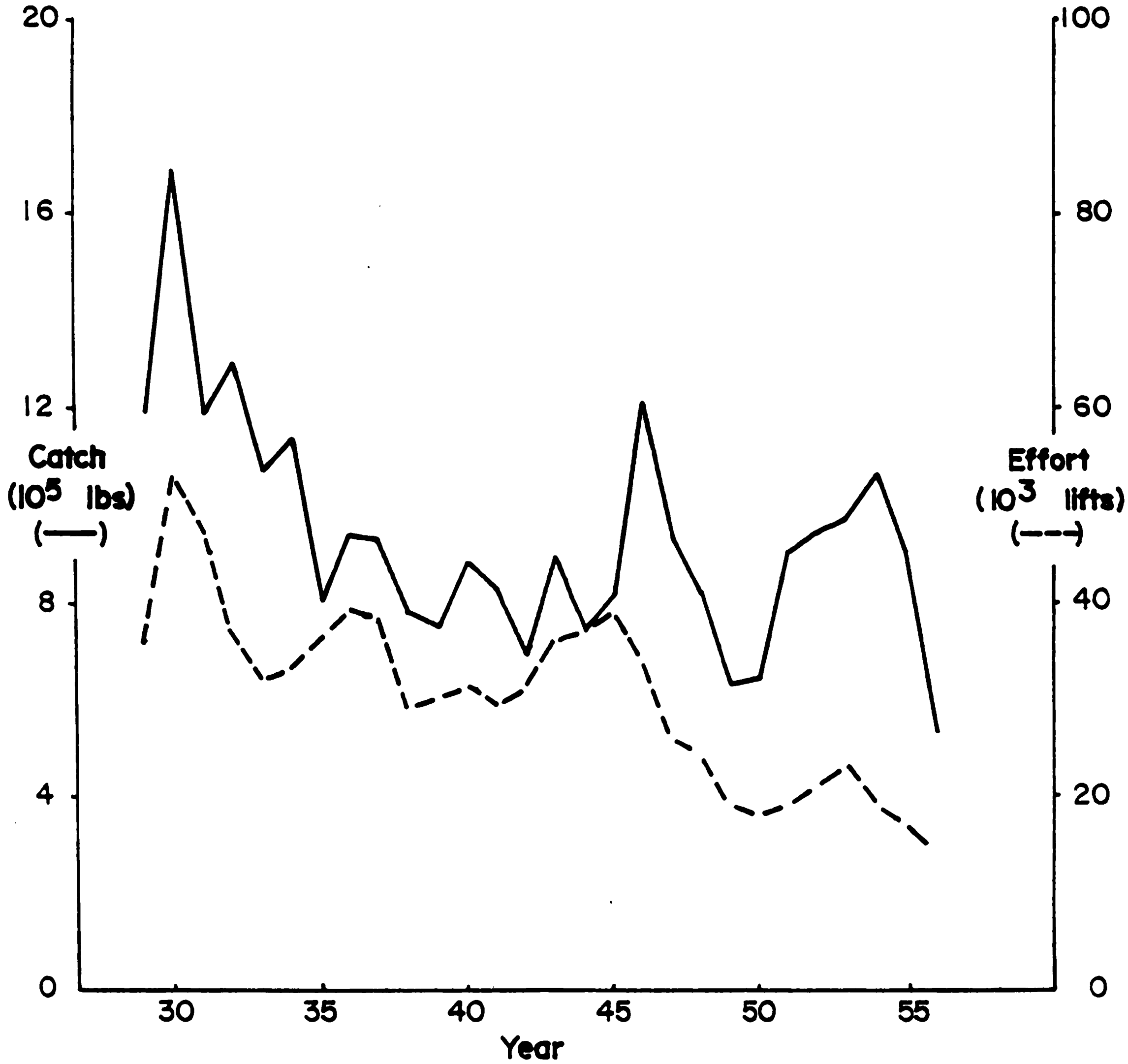


Figure III-3. Saginaw Bay Commercial Sucker Production (1929-1956).

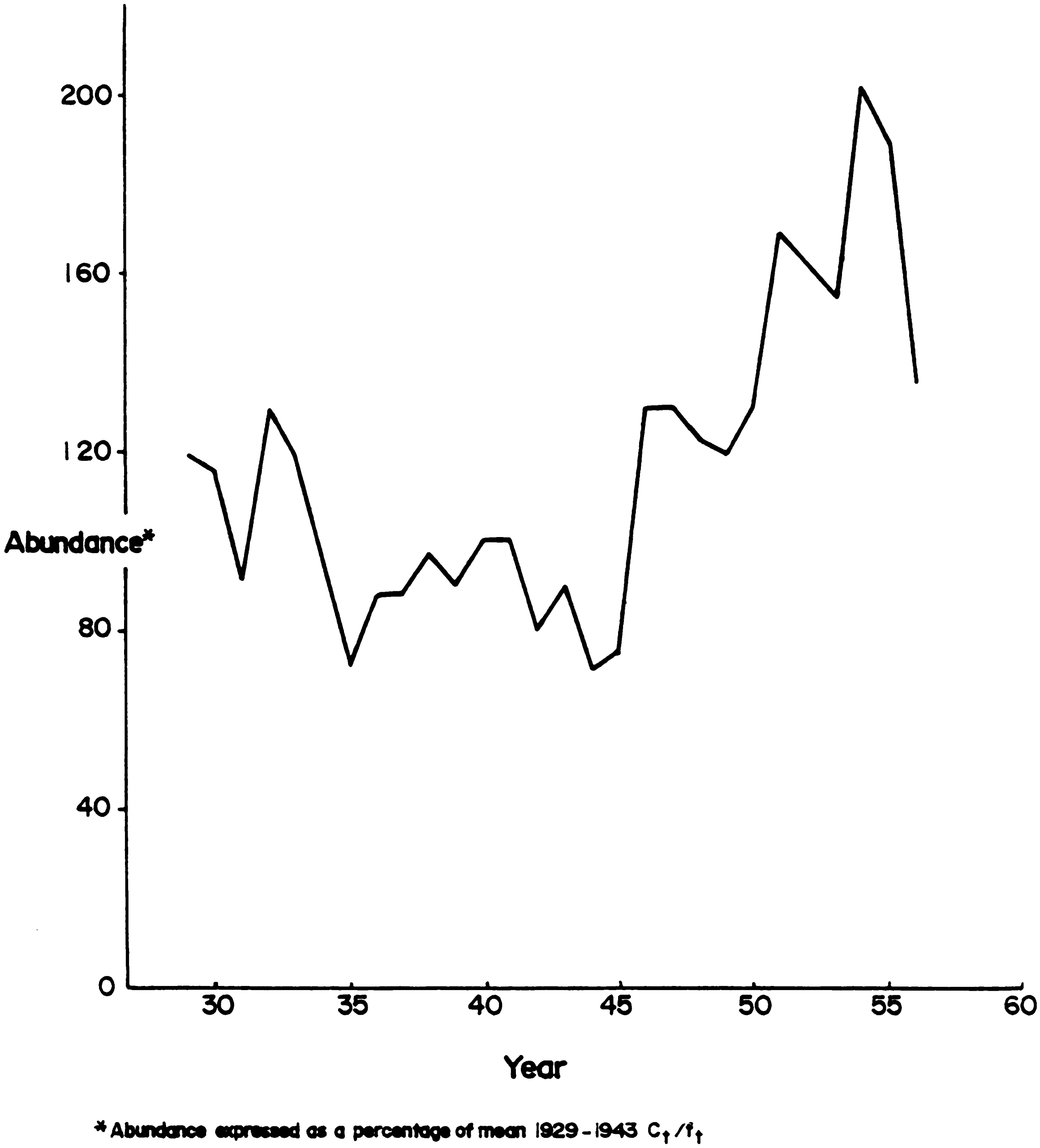


Figure III-4. Saginaw Bay Sucker Abundance (1929-1956).

parameter, b, calculated from equation III-19 by q.

One of the first steps undertaken when examining a time series of commercial fishery catch and effort data is the calculation of the following simple linear regression,

III-21 $C_t = a + b(f_t)$.

A significant positive correlation between catch, C_t, and effort, f_t, indicates that the stock under examination has not been overexploited since, according to Ricker (1975), catch can only increase with an increasing effort if there are reserves of stock to draw upon. Equation III-21, applied to the 1929 and 1945 catch and effort data series resulted in the following,

III-22 $C_t = 1896.69 + 26.86(f_t)$; $r^2 = .45$; $r = .67$*
(p = .01).

According to Ricker (1975), a large significant correlation between catch, C_t, and effort, f_t, indicates that the rate of exploitation, u, has been less than 75% over most or all of the range of efforts represented by the data. Recall equation III-5,

III-5 $u = FA/(F + M) = F(1 - S)/Z = F(1 - S)/(\ln S)$.

u represents the fraction of the total mortality rate, A, attributable to fishing. The upper bound for u, then, is the value of A. By definition, total instantaneous mortality rate, Z, equals F + M, and survival, S, equals $e^{-Z\Delta t}$, during time, Δt. For the sake of convenience, assume that the duration of the time period, Δt, is equal to one. Previous investigations of the dynamics of white sucker populations (e.g. Geen, et al, 1966 and Coble, 1967) plus the present investigation (Chapter VI) indicate that annual white sucker survival rate (S) ranges from 0.50 to 0.75. Taking natural logarithms, we find that Z ranges from approximately .228 to .693. We are now in a position to calculate rough point estimates of instantaneous fishing mortality rate, F.

Case (1)

Assume annual survival rate, S, equals .50. Then, A = 1 - S = .50. The upper bound for rate of exploitation, u = .50. Rearranging equation III-5 we solve for F as follows,

III-23a $$F = u(F + M)/A = u(\ln S)/(1 - S)$$
$$= .50(.693)/(1 - .50)$$
$$= .693.$$

Now, since for S = .50, lnS = Z = F + M = .693, equation III-23a implies that all mortality is attributable to fishing.

If u = .35, we obtain,

III-23b $$F = u(F + M)/A = u(\ln S)/(1 - S)$$
$$= .35(.693)/(1 - .50)$$
$$= .485.$$

If u = .20, we obtain,

III-23c $$F = u(F + M)/A = u(\ln S)/(1 - S)$$
$$= .20(.693)/(1 - .50)$$
$$= .277.$$

Case (2)

If annual survival rate, S, equals .625, then A = 1 - S = .375. The upper bound for rate of exploitation, u = .375. Solving equation III-5 for F we obtain,

III-24a $$F = u(F + M)/A = u(\ln S)/(1 - S)$$

$$= .375(.470)/(1 - .625)$$

$$= .470.$$

If u = .250, we obtain,

III-24b $$F = u(F + M)/A = u(\ln S)/(1 - S)$$

$$= .250(.470)/(1 - .625)$$

$$= .313.$$

If u = .125, we obtain,

III-24c $$F = u(F + M)/A = u(\ln S)/(1 - S)$$

$$= .125(.470)/(1 - .625)$$

$$= .157.$$

Case (3)

Assume annual survival rate, S, equals .75. Then, A = 1 - S = .25. The upper bound for rate of exploitation, u = .25. Solving Equation III-5 for F we obtain,

III-25a $$F = u(F + M)/A = (\ln S)/(1 - S)$$

$$= .25(.288)/(1 - .75)$$

$$= .288.$$

If u = .175, we obtain,

III-25b $$F = u(F + M)/A = u(\ln S)/(1 - S)$$

$$= .175(.288)/(1 - .75)$$

$$= .202.$$

If u = .100, we obtain,

III-25c $F = u(F + M)/A = u(\ln S)/(1 - S)$

$= .100(.288)/(1 - .75)$

$= .115.$

Equation III-23a represents our worst assumptions about survival and exploitation rate while equation III-25c represents our best assumptions about these parameters.

By rearranging equation III-9 we can solve for the catchability constant, q, as follows,

III-26 $q = F/f_t.$

If we substitute mean effort, $\bar{f}_t$ = 36,200 trap net lifts, during the 1929 to 1945 period into equation III-26 along with each of the values for F obtained from equations III-23 through III-25 we obtain a range of possible estimates for catchability, q. Table III-3 contains a summary of these catchability estimates which range from $q = 3.18 \times 10^{-6}$ to $q = 1.91 \times 10^{-5}$. These estimates for q, coupled with the result of equation III-20, enable calculation of rough point estimates of mean biomass, $\bar{B}_t$, ranging from $\bar{B}_t$ = 1,408,000 pounds to $\bar{B}_t$ = 8,459,000 pounds (Table III-3).

Application of Leslie's model (equation III-17) to the 1929 to 1945 catch and effort data resulted in the following,

III-27 $C_t/f_t = qB_0 - qK_t = 33.5044 - .000000715(K_t)$; $r^2 = .42$

where: $q = 7.15 \times 10^{-7}\ \text{lift}^{-1}$

$B_0 = qB_0/q$ = 46,845,000 pounds.

Recall that the prerequisite for application of the Leslie

Table III-3

Catchability and Mean Biomass Estimates

(1929-1945)

Equation	F Estimate	$q = F/\bar{f}_t$*	$\bar{B}_t = b/q$**
III-23a	.693	1.91×10^{-5}	1408000
III-23b	.485	1.34×10^{-5}	2007000
III-23c	.277	7.65×10^{-6}	3516000
III-24a	.470	1.30×10^{-5}	2069000
III-24b	.313	8.65×10^{-6}	3110000
III-24c	.157	4.34×10^{-6}	6198000
III-25a	.288	7.96×10^{-6}	3379000
III-25b	.202	5.58×10^{-6}	4821000
III-25c	.115	3.18×10^{-6}	8459000

* $\bar{f}_t$ = 36,200 trap net lifts

** b = 26.9 (see equation III-20)

model is that enough fish must be removed from the population to significantly reduce the catch per unit effort ratio, C_t/f_t. Examination of the catch per unit effort column in Table III-1 reveals no obvious, consistent decline in C_t/f_t. This indicates that the fundamental prerequisite necessary for application of the Leslie model has not been met. The estimate of catchability, q, obtained from equation III-27 appears to be an underestimate (compared to q estimates listed in Table III-3), the effect of which results in an overestimate of mean stock biomass, $\overline{B}_t$.

The regression of C_t versus f_t, forced through the origin, for the 1946 to 1956 period resulted in the following,

III-28 $$C_t = 40.0(f_t);\ r^2 = 0.97.$$

Equation III-21 applied to the 1946 to 1956 catch and effort data resulted in,

III-29 $$C_t = 297694.46 + 26.78(f_t);\ r^2 = .53;\ r = .73^{*}\ (p = .05).$$

The significant correlation between C_t and f_t for the 1946 to 1956 period indicates the sucker stocks were probably not overexploited.

If we substitute mean annual effort, $\overline{f}_t$ = 21,300 trap net lifts, during 1946 to 1956 into equation III-26 along with each of the values for F obtained from equations III-23 through III-25 we obtain a range of possible catchability estimates. Table III-4 contains a summary of these estimates which indicates catchability ranges from q = 5.40

Table III-4

Catchability and Mean Biomass Estimates

(1946-1956)

Equation	F Estimate	$q = F/\bar{f}_t$*	$\bar{B}_t = b/q$**
III-23a	.693	3.25×10^{-5}	1231000
III-23b	.485	2.28×10^{-5}	1754000
III-23c	.277	1.30×10^{-5}	3077000
III-24a	.470	2.21×10^{-5}	1810000
III-24b	.313	1.47×10^{-5}	2721000
III-24c	.157	7.37×10^{-6}	5427000
III-25a	.288	1.35×10^{-5}	2963000
III-25b	.202	9.48×10^{-6}	4219000
III-25c	.115	5.40×10^{-6}	7407000

* $\bar{f}_t$ = 21,300 trap net lifts

** b = 40.0 (see equation III-28)

x 10^{-6} to $q = 3.25 \times 10^{-5}$. These estimates for q, coupled with the result of equation III-28, enable calculation of rough point estimates of mean stock biomass, $\overline{B}_t$, ranging from 1,231,000 pounds to 7,401,000 pounds (Table III-4).

Application of the Leslie model (equation III-17) to the 1946 to 1956 catch and effort data failed to result in a model of the proper form (i.e. with a negative slope parameter, -q).

In the above analyses of catch and effort data for the periods, 1929 to 1945 and 1946 to 1956, we have seen how the assumption of a constant instantaneous total mortality rate, Z, necessary for calculating point estimates of F via equations III-23 through III-25, resulted in higher estimates of catchability, q, during the latter period than for the earlier period. The apparent increase in relative abundance during 1946 to 1956 (as measured by the increase in mean catch per unit effort over the previous period) could be a result of increased trap net catchability, which, in turn, results in lower estimates of mean population biomass, $\overline{B}_t$, during 1946 to 1956 than during 1929 to 1945. Whether or not such an increase in trap net catchability actually occurred from one period to the next is a matter for conjecture, however, such an idea may be given some credence by the fact that more nets with nylon mesh were used during 1946 to 1956 than during 1929 to 1945, when the mesh of most nets was made from cotton or linen fibers. Different types of fibers exhibit different catchabilities.

Since nylon is stronger and more durable than natural fibers, nylon nets may possess greater catching potential than natural fiber nets.

3. <u>The Sucker Fishery, 1960 to 1979</u>

The Saginaw Bay sucker fishery during the years from 1960 to 1979 can be divided into two periods, one of higher relative abundance, 1960 to 1967, and one of lower relative abundance, 1968 to 1979. Table III-5 and Table III-6 contain summaries of catch, C_t, effort, f_t, and catch per unit effort, C_t/f_t, statistics for these years. Figure III-5 depicts the declining sucker catch from 1960 to 1979. Figure III-6 shows the relative abundance of Saginaw Bay suckers during 1960 to 1979 expressed as a percentage of mean 1929 to 1943 catch per unit effort. A period of steadily decreasing relative abundance from 1960 to 1967 is followed by a more or less stable period of relative abundance from 1968 to 1979.

During 1960 to 1967, 84.5% of the total sucker catch was taken with shallow trap nets, 7.3% was harvested with haul seines, 3.6% was taken with fyke or hoop nets and 4.6% was harvested by a mixture of other, miscellaneous gears. Table III-7 contains a monthly summary of total reported catch, C_t, and nominal effort, f_t, during 1960 to 1967. In terms of total landed catch, the fishing year for this period can be divided into the following quarterly intervals (the percentage of the total catch harvested during each quarter is contained in parentheses); December - February

Table III-5

Saginaw Bay Commercial Sucker Production

(1960-1979)*

Year	Catch (lbs) C_t	Effort f_t	Catch Per Effort C_t/f_t
1960	378700	9350	40.5
1961	517300	10540	49.1
1962	662800	9250	71.7
1963	472100	6730	70.1
1964	392800	6770	58.0
1965	353400	6330	55.8
1966	299300	6040	49.6
1967	219500	5000	43.9
1968	148900	4310	34.5
1969	123200	3740	32.9
1970	137700	3670	37.5
1971	132400	3620	36.6
1972	90600	3640	24.9
1973	144700	4540	31.9
1974	110600	4210	26.3
1975	108600	4360	24.9
1976	124800	3750	33.3
1977	98400	2950	33.4
1978	132000	3480	37.9
1979	107600	2590	41.5

*Source: Mich. Dept. Nat. Res., Fish. Div.

Table III-6

Saginaw Bay Sucker Fishery

Summary Statistics, 1960-1979*

Statistics	1960-1967	1968-1979	1960-1979
C_t range (lbs)	219000-662800	90600-148900	90600-662800
$\overline{C}_t$	412000	121600	237800
s_{C_t}	137500	18500	168700
f_t range (shallow trap net lifts)	5000-10540	2590-4540	2590-10540
$\overline{f}_t$	7500	3740	5240
s_{f_t}	1950	570	2270
C_t/f_t range (lbs per trap net lift)	40.5-71.7	24.9-41.5	24.9-71.7
$\overline{C_t/f_t}$	54.8	33.0	41.7
s_{C_t/f_t}	11.4	5.3	13.6

* Data source: Mich. Dept. Nat. Res., Fish. Div.

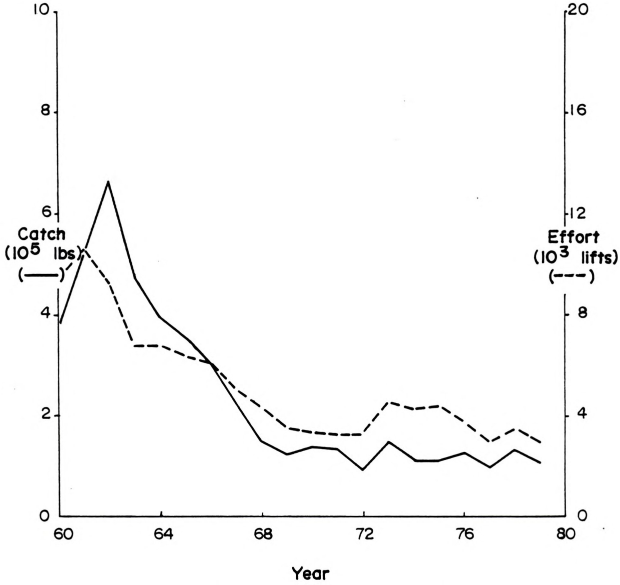
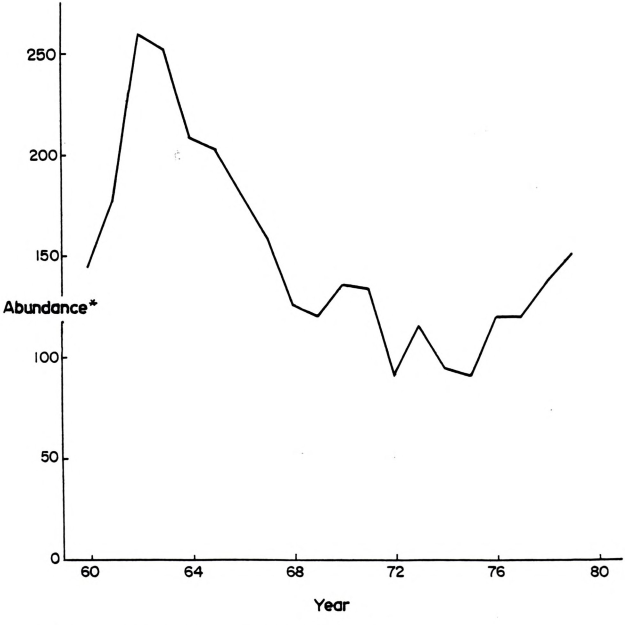


Figure III-5. Saginaw Bay Commercial Sucker Production (1960-1979).



*Abundance expressed as a percentage of mean 1929-1943 C_t/f_t

Figure III-6. Saginaw Bay Sucker Abundance (1960-1979)

Table III-7

Saginaw Bay Monthly Catch and Effort Data

(1960-1967)

Month	Catch (lbs) C_t	Catch Range (lbs)	$C_t/\Sigma C_t \times 100$
January	77248	100- 16605	2.3
February	115375	5635- 29801	3.5
March	402814	20684- 94933	12.2
April	515445	18068-177428	15.6
May	522142	21887- 12552	15.8
June	211581	5636- 47457	6.4
July	64292	3218- 14874	2.0
August	52613	912- 20301	1.6
September	483029	21610- 79989	14.7
October	449336	29296- 82651	13.6
November	338267	13905- 77130	10.3
December	63615	38- 18362	1.9
ΣC_t	3295757		

Month	Standardized Effort f_t	Effort Range (trap net lifts)	$f_t/\Sigma f_t \times 100$
January	1458	74- 336	2.3
February	1481	136- 309	2.4
March	3728	191- 725	5.9
April	7366	381-1400	11.7
May	7772	619-1259	12.4
June	4414	107- 794	7.0
July	2030	173- 430	3.2
August	1290	50- 377	2.1
September	8146	412-1335	13.0
October	13089	933-2615	20.8
November	10296	203-3141	16.4
December	1817	213- 655	2.9
Σf_t	62887		

* Source: Mich. Dept. Nat. Res., Fish. Div.

(7.7%); March - May (43.6%); June - August (10.0%) and September - November (38.6%). Similarly, in terms of the amount of nominal effort expended, the fishing year can be divided into the same quarterly intervals (the percentage of total effort expended is contained in parentheses): December - February (7.6%); March - May (30.0%); June - August (12.3%) and September - November (50.2%).

The regression of C_t versus f_t, forced through the origin, for the 1960 to 1967 data, is,

III-30 $\quad C_t = 54.8(f_t);\ r^2 = 0.96.$

Regression of catch on effort for the 1960 to 1967 catch and effort data results in,

III-31 $\quad C_t = 23008.09 + 51.86(f_t);\ r^2 = .54;\ r = .74^*$

$(p = .05).$

If we substitute mean annual effort, $\bar{f}_t$ = 7,500 trap net lifts, during 1960 to 1967 into equation III-26 along with each of the values for F obtained from equations III-23 through III-25 we obtain a range of possible catchability estimates. Table III-8 contains a summary of these estimates which indicate catchability ranges from $q = 1.53 \times 10^{-5}$ to $q = 9.24 \times 10^{-5}$. These catchability estimates, coupled with the result of equation III-30 enabled calculation of crude point estimates of mean stock biomass, $\bar{B}_t$, ranging from 593,000 pounds to 3,582,000 pounds (Table III-8).

Application of the Leslie model (equation III-17) to the 1960 to 1967 catch and effort data failed to result in a

Table III-8

Catchability and Mean Biomass Estimates

(1960-1967)

Equation	F Estimate	$q = F/\bar{f}_t$*	$\bar{B}_t = b/q$**
III-23a	.693	9.24×10^{-5}	593000
III-23b	.485	6.47×10^{-5}	847000
III-23c	.277	3.69×10^{-5}	1485000
III-24a	.470	6.27×10^{-5}	874000
III-24b	.313	4.17×10^{-5}	1314000
III-24c	.157	2.09×10^{-5}	2622000
III-25a	.288	3.84×10^{-5}	1427000
III-25b	.202	2.69×10^{-5}	2037000
III-25c	.115	1.53×10^{-5}	3582000

* $\bar{f}_t$ = 7,500 trap net lifts

** b = 54.8 (see equation III-30)

model of the proper form (i.e. with a negative slope parameter, $-q$). A glance at the catch per unit effort column in Table III-5 reveals that, for the period from 1962 to 1969, the Saginaw Bay sucker fishery experienced a steady decline in catch per unit effort. Recall that a steady decline in catch per unit effort is a necessary prerequisite for the application of the Leslie model. It would seem instructive, therefore, to apply the Leslie model to the 1962 to 1969 catch and effort data in order to obtain an additional estimate of catchability, q.

III-32 $C_t/f_t = qB_0 - qK_t = 82.2482 - .0000177(K_t)$; $r^2 = .94$

where: $q = 1.77 \times 10^{-5}$ lift^{-1}

$B_0 = qB_0/q = 4{,}647{,}000$ pounds.

These estimates of catchability, q, and biomass, B_0, are close to those obtained from calculations summarized in Table III-8.

During 1968 to 1979, 92.1% of the total sucker catch was taken with shallow trap nets, 4.0% was harvested with haul seines, 1.9% was taken with fyke or hoop nets and 2.0% was harvested by a mixture of other, miscellaneous gear. Table III-9 contains a monthly summary of total reported catch, C_t, and nominal effort, f_t, during 1968 to 1979. In terms of productivity, the fishing year during this period can be divided into the following quarterly intervals (the percentage of the total catch harvested during each quarter is contained in parentheses): December - February (11.4%); March - May (56.1%); June - August (9.7%) and September -

Table III-9

Saginaw Bay Monthly Catch and Effort Data

(1968-1979)*

Month	Catch (lbs)	Catch Range	$C_t / \Sigma C_t$ x 100
January	73348	1150-10166	5.0
February	69533	1167-17687	4.8
March	317826	5120-50985	21.8
April	337652	9474-55466	23.1
May	163011	4558-35305	11.2
June	68998	1851-11820	4.7
July	39799	1003- 6373	2.7
August	34208	614- 5284	2.3
September	113449	5216-18199	7.8
October	149260	6589-18843	10.2
November	69693	2329-10179	4.8
December	22699	15- 5715	1.6
ΣC_t	1459476		

Month	Standardized Effort f_t	Effort Range (trap net lifts)	$f_t / \Sigma f_t$ x 100
January	1235	20-199	2.8
February	1556	33-270	3.5
March	3487	100-616	7.9
April	5661	141-732	12.3
May	3709	150-487	8.4
June	3247	117-414	7.3
July	3720	163-562	8.4
August	4212	49-534	9.5
September	6921	312-941	15.7
October	6286	343-689	14.2
November	3433	168-476	7.8
December	749	1-110	1.7
Σf_t	44216		

* Source: Mich. Dept. Nat. Res., Fish. Div.

November (22.8%). In terms of the amount of effort expended during these years, the fishing year can be divided into the same quarterly intervals (the percentage of total effort expended is contained in parentheses): December - February (11.4%); March-May (56.1%); June - August (25.2%) and September - November (37.7%).

The regression of C_t versus f_t, forced through the origin, for the 1968 to 1979 catch and effort data is,

III-33 $C_t = 32.2(f_t)$; $r^2 = 0.98$.

Equation III-21 applied to these data resulted in,

III-34 $C_t = 66545.16 + 14.73(f_t)$; $r^2 = .21$; $r = .46$ (N.S., p. = .05).

Previous calculations of catchability and mean stock biomass (cf. Tables III-3, III-4 and III-8) depended upon the assumption that the rate of exploitation, u, was less than 75% (refer to the discussion preceding and accompanying equations III-23 through III-25). This assumption, in turn, depended upon a significant positive correlation between catch, C_t, and nominal effort, f_t (Ricker, 1975). The fact that the catch-effort regression described by equation III-34 is not significant (p = .05) could indicate that the rate of exploitation, u, during 1968 to 1979 was greater than that assumed for other periods (i.e. 1929 to 1945, 1946 to 1956 and 1960 to 1967, respectively). This is most unlikely in view of the relatively stable picture of abundance during 1968 to 1979 shown in Figure III-6. To maintain consistency, the method used to calculate point estimates of catchability and mean stock biomass for the 1929 to 1945, 1946 to 1956 and 1960 to 1967 periods will not be used for the 1968 to 1979 period. It seems reasonable, however, to assume that catchability, q, during 1968 to 1979 was not too different from catchability during 1962 to 1969 (as determined by equation III-32). If so, then an estimate of mean stock biomass, $\overline{B}_t$, during 1968 to 1979 can be obtained by dividing the slope coefficient, b, from equation III-33 by the 1962 to 1969 estimated catchability or,

III-35 $\overline{B}_t = b/q = (32.2)/(1.77 \times 10^{-5}) = 1{,}819{,}000$ lbs.

Application of Leslie's model (equation III-17) to the 1968 to 1979 catch and effort data failed to result in a model of the proper form (i.e. with a negative slope parameter,-q). It is interesting to note that Leslie's model, applied to catch and effort data from 1960 to 1979, resulted in the following estimates,

III-36 $C_t/f_t = qB_0 - qK_t = 63.0615 - .00000673(K_t)$; $r^2 = .43$,

with: $q = 6.73 \times 10^{-6}$ lift^{-1}

$B_0 = qB_0/q = 9{,}370{,}000$ pounds.

The following approximate 95% asymptotic confidence limits for B_0 (biomass present at the start of 1960) were calculated after the method described by Ricker (1975),

Lower limit = 6,310,000 pounds

Upper limit = 66,043,000 pounds.

Tending toward the conservative, suppose that the lower limit of approximately 6,310,000 pounds is a reasonable estimate of stock biomass available at the beginning of

1960.

The Saginaw Bay trap net fishery captures a number of species simultaneously. It is reasonable to assume that the relative catching efficiency or catchability, q, of trap nets for two species present in abundance in the commercial catch should be roughly similar. To test this hypothesis, catch and effort data from 1968 to 1975 for yellow perch and suckers were analyzed by means of equation III-17. The following result was obtained for yellow perch,

III-37 $C_t/f_t = qB_0 - qK_t = 79.8146 - .0000128(K_t);\ r^2 = .83.$

The following result was obtained for suckers,

III-38 $C_t/f_t = qB_0 - qK_t = 37.5793 - .0000123(K_t);\ r^2 = .51.$

Comparison of equations III-37 and III-38 reveals that estimated yellow perch catchability ($q = 1.28 \times 10^{-5}$) and estimated sucker catchability ($q = 1.23 \times 10^{-5}$) are very close for the 1968 to 1975 time period.

A reasonable estimate of survival rate for suckers in the vulnerable portion of the population is S = .60 (cf. Chapter VI). This estimate is very close to the survival rate S = .625, assumed by equations III-24. With a constant survival probability, S = .625, and hypothetical rate of exploitation, u = .25, estimates of mean stock biomass, $\overline{B}_t$, for the periods from 1929 to 1945 and 1946 to 1956 are 3,110,000 pounds and 2,721,000 pounds, respectively (cf. Tables III-3 and III-4). The same survival rate and exploitation rate result in a mean biomass estimate of 1,314,000 pounds for the 1960 to 1967 period. An estimate of mean biomass for 1968 to 1979 is provided by equation III-35 and is equal to approximately 1,819,000 pounds. A conservative estimate of mean stock biomass during the 1929 to 1956 period is about 3,000,000 pounds. Similarly, a conservative estimate of mean stock biomass during the 1960 to 1979 period is approximately 2,000,000 pounds. Rearranging equation III-8 we get,

III-39 $F = C_t/\overline{B}_t$.

During 1929 to 1956, mean annual catch, $\overline{C}_t$, equalled about 933,000 pounds. Dividing this by our above estimate of mean biomass (i.e. 3,000,000 pounds) for the same period we arrive at an estimate of effective fishing mortality rate, F or,

III-40 $F = C_t/\overline{B}_t = (933000)/(3000000) = .311$.

This compares favorably with our estimates of F obtained from equations III-23 through III-25. During 1960 to 1979, mean annual catch, $\overline{C}_t$, equalled approximately 238,000 pounds. Dividing this by our above estimate of mean biomass (i.e. 2,000,000 pounds) for the same period we arrive at an estimate of effective fishing mortality rate, F or

III-41 $F= C_t/\overline{B}_t = (238000)/(2000000) = .119$.

This is close to the estimate of F obtained from equation III-25c.

The above estimates of mean annual sucker biomass of 3,000,000 pounds for the 1929 to 1956 period and 2,000,000 pounds for the 1960 to 1979 period are probably overly conservative. In his study of white suckers in South Bay, Lake Huron, Coble (1967) estimated a standing stock of approximately 17.5 kg/hectare for regions less than 36 m deep. If the standing stock of white suckers per hectare in Saginaw Bay is comparable to that of South Bay, then an estimate of standing stock is 17.5 kg/hectare times 2.96×10^5 hectares (the area of Saginaw Bay) or approximately 5.18×10^6 kg (11,396,000 pounds). Suppose that one third (i.e. 3,799,000 pounds) of this estimated standing stock is vulnerable to the commercial fishery. As previously indicated, a plausible estimate of survival rate, $S = .60$ for the vulnerable portion of Saginaw Bay sucker populations. From equation III-5 we calculate a maximum exploitation rate, $u = .40$, which obtains when all mortality is attributable to fishing. If we assume a more realistic exploitation rate, $u = .20$, then a point estimate of effective fishing mortality rate, $F = .255$ which, when multiplied by 3,799,000 pounds, yields an estimate of potential annual catch (i.e. 969,000 pounds). This estimate is very close to the 1929 to 1956 mean annual harvest of 933,000 pounds.

Mean 1968 to 1979 annual reported sucker landings were approximately 122,000 pounds. Discussions with commercial fishermen reveal that up to 75% of the actual sucker catch is regularly returned to the water due to the absence of profitable markets for suckers. If this is so, then annual landings could increase by a factor of some 400% without an apparent increase in nominal fishing effort.

The results of the present analysis of catch and effort data indicate that the Saginaw Bay commercial fishery could, with careful monitoring and regulation, harvest approximately 500,000 pounds of suckers per year. Harvest levels beyond 500,000 pounds per year could probably be obtained only with an expansion of fishing effort. Initial "fishing up" efforts for suckers could effectively reduce the usefulness of the catch per unit effort ratio, C_t/f_t, as an indicator of relative stock abundance. The catch per unit effort ratio is a useful indicator of relative stock abundance when the fishery is not subject to marked fluctuations of its characteristic rate variables, $r_k(t)$ (e.g. exploitation and recruitment). Monitoring of stock responses to changes in exploitation levels during the fishing up stage would probably be best accomplished by observing changes in the size, age and sex composition and growth and mortality rates of the exploited populations.

CHAPTER IV

Fishery Bioeconomics

A. Introduction

The concept of a fishery production function was introduced in Chapter III where equation III-12 was employed to represent the relationship between total catch, C_t, and nominal effort, f_t, assuming constant levels of catchability, q, and mean exploitable population size, $\overline{B}_t$. Recall equation III-12,

III-12 $$C_t = q(f_t)(\overline{B}_t) = q(\overline{B}_t)(f_t),$$

which implies that for each level of mean exploitable population biomass, $\overline{B}_t$, total catch, C_t, is determined directly by the amount of effort, f_t, applied by the commercial fishery. Equation III-12 is a short term, non-equilibrium fishery production function used to describe the effects of changes in effort on total catch during a period of time when mean catchable stock biomass is assumed constant.

Population size, B_t, is a dynamic entity responding to continual changes in its determining rate variables, $r_i(k)$, i = i,.....,n. For an exploited fish stock, the most important of these rate variables, $r_i(k)$, are: growth rate; natural mortality rate; fishing mortality rate; recruitment rate and net migration rate. The rate of change in the size of an exploited fish population can be represented by,

IV-1 $dB_t/dt = G + R - M - F \pm I$,

where: G = rate of stock growth

R = rate of recruitment

M = rate of natural mortality

F = rate of fishing mortality

I = rate of migration (immigration-emigration).

The long term persistence of an exploited fish population depends upon the establishment of some sort of equilibrium relationship between the rates of biomass addition and subtraction. In practice, unless there is evidence to the contrary, the net migration rate, I, can be assumed equal to zero for most freshwater fish populations. Suppose that the rate of population change, dB_t/dt, is equal to zero (i.e. the population is in an equilibrium or steady state). From equation IV-1 we have,

IV-2 $dB_t/dt = G + R - M - F = 0$,

which, when rearranged gives,

IV-3 $F = G + R - M$.

The right side of equation IV-3 indicates that, in equilibrium, the rate of population decrease due to fishing is exactly offset by the aggregate rates of growth, recruitment and natural mortality. In equilibrium, mortality rates are balanced by compensatory changes in the rates of growth and recruitment. The determination of an accurate and realistic functional form for equation IV-3

constitutes one of the most difficult problems confronting an investigator studying the dynamics of exploited fish populations.

B. The Logistic Surplus Production Model

It is usually the case, in studies of the dynamics of exploited fisheries, that precise information concerning rates of growth, natural mortality and recruitment is unavailable. In such instances, investigators are often obliged to use some form of lumped parameter model to describe the rate of change in fish population biomass, dB_t/dt. For example, the so-called logistic growth model is given by the following,

IV-4 $$dB_t/dt = r(B_t)B_t,$$

where $r(B_t)$ is a decreasing function of population size, B_t. In accordance with conventional assumptions regarding density dependent population growth, $r(B_t)$ is given by,

IV-5 $$r(B_t) = r(1 - B_t/K),$$

where: r = the intrinsic population growth rate

K = maximum population size.

Equation IV-5 substituted into equation IV-4 results in,

IV-6 $$dB_t/dt = rB_t(1 - B_t/K),$$

with solution given by

IV-7 $$B_t = B_0 \frac{Ke^{rt}}{K - B_0(1 - e^{rt})}.$$

Now, the rate of change in catch, C_t, during time, Δt, can be described by,

IV-8 $dC_t/dt = qf_tB_t$,

where: q = catchability

f_t = effort during time, Δt.

The integrated form of equation IV-8 is the short term production function represented by equation III-12.

By subtracting equation IV-8 from equation IV-6 we get an expression for rate of change in stock biomass as a function of growth rate, $r(B_t)B_t$, and harvest rate, qf_tB_t, or

IV-9 $dB_t/dt = rB_t(1 - B_t/K) - qf_tB_t$.

At equilibrium, this equals zero, implying that,

IV-10 $qf_tB_t = rB_t(1 - B_t/K)$,

which, upon solving for B_t, results in the following nonzero equilibrium,

IV-11 $B_t = (K/r)(r - qf_t)$.

If we substitute equation IV-11 into equation III-12 we get,

IV-12
$$C_t = qf_tB_t = qf_t(K/r)(r - qf_t)$$
$$= qf_tK - (K/r)(qf_t)^2$$
$$= qK(f_t) - q^2(K/r)(f_t^2),$$

which describes the long term equilibrium relationship between catch, C_t, and effort, f_t. If we differentiate equation IV-12 with respect to effort, f_t, set the result equal to zero and solve for f_t, we obtain,

IV-13 $f_t = r/(2q)$,

which is the amount of fishing effort necessary to produce the maximum sustainable physical yield from the exploited stock. If we substitute equation IV-13 into equation IV-12 we obtain,

IV-14 $$C_t = qKr/2q - q^2(K/r)(r^2/4q^2)$$
$$= Kr/2 - Kr/4$$
$$= rK/4,$$

which is the maximum physical yield or MSY (maximum sustainable yield).

The following linearization procedure, adopted from Jensen (1976), was used to estimate the parameters of equation IV-9. From equation III-12, mean exploitable stock biomass during year t is given by,

IV-15 $$\bar{B}_t = C_t/(qf_t)$$
$$= (1/q)(U_t).$$

where, $U_t = C_t/f_t$.

A rough approximation of the derivative in equation IV-9 is,

IV-16 $$dB_t/dt = (B_{t+1} - B_{t-1})/2$$
$$= (1/q)(U_{t+1} - U_{t-1})/2$$
$$= (1/q)\Delta U_t,$$

where, $\Delta U_t = (U_{t+1} - U_{t-1})/2$.

By substituting equations IV-15 and IV-16 into equation IV-9 we get,

IV-17 $$(1/q)\Delta U_t = (r/q)(U_t)[1 - (U_t)/(qK)] - C_t.$$

By multiplying through by q we obtain,

IV-18 $$\Delta U_t = (rU_t)[1 - (U_t)/(qK)] - qC_t,$$

which can be written as the following linear equation,

VI-19 $$Y_t = a_1X_1 + a_2X_2 + a_3X_3,$$

where: $Y_t = \Delta U_t$; $X_1 = U_t$; $X_2 = (U_t)^2$; $X_3 = C_t$; $a_1 = r$; $a_2 = -r/(qK)$ and $a_3 = -q$. The constants a_1, a_2 and a_3 can be estimated by least squares multiple regression analysis.

The following examples from the fisheries literature are indicative of the widespread use and application of surplus production models to commercially exploited fisheries: Schaefer (1968); Fox (1971); Walter and Hogman (1971); Walter (1973); Fox (1975); Walter (1975); Jensen (1976); Hilborn (1979); McGaw (1980); Deriso (1980); Gatto and Rinaldi (1980); Mohn (1980) and Uhler (1980). Surplus production models, particularly the logistic surplus production model, have been utilized to describe and manage virtually every significant commercially exploited fishery in the world. The attractiveness of surplus production models is attributable to their simplicity and minimal data requirements (i.e. yearly total catch, C_t, and nominal effort, f_t data). The simplicity of these models, however, is overshadowed by the restrictive assumptions necessary for their successful application. Some of the critical assumptions of logistic surplus production models are that: (1) the time lag between spawning and subsequent recruitment has a negligible effect on population growth: (2) each unit of biomass in the exploited stock is identical with respect to growth and mortality factors (i.e. the age structure of the stock is unimportant); (3) the model is applied to a closed homogeneous stock; (4) the exploited stock is in a state of equilibrium with respect to the various factors which affect stock biomass change and (5) the catch per unit effort ratio, C_t/f_t, is an accurate and reliable proxy for population biomass, B_t.

Surplus production model users have, in recent years, identified the need to integrate biological data on the processes of growth, mortality and recruitment with traditional catch and effort statistics. The combination of biological data with catch and effort data is necessary, according to Jensen (1976) and Hilborn (1979), to confirm and expand upon results obtained from surplus production models. Dependence upon the catch per unit effort ratio, in one form or another, as a proxy for biological variables results in models whose independent variables lack sufficient contrasts. The usefulness of multiple regression estimation systems may be severely compromised by the presence of independent variable multicolinearity. Surplus production models estimated by linear or nonlinear techniques continue to enjoy widespread use despite such potential statistical intractabilities.

Deriso (1980) describes a difference equation stock production model which incorporates age-structure, recruitment, survival and growth in an attempt to estimate stock dynamics parameters and optimal harvesting strategies. A similar approach is employed by Gatto and Rinaldi (1980) in their effort to develop a difference equation stock production model for the Gulf of Venezuela commercial fishery. These models are, perhaps, more realistic than other surplus production estimation systems in that they recognize the necessity for including biological information directly into the estimation algorithm. The shortcomings of these efforts stem from the fact that they rely too heavily on the catch per unit effort ratio, C_t/f_t, to approximate the biological processes of growth, survival and recruitment.

The effects of random variability introduced into catch and effort time series data on surplus production model parameter estimates are explored by Fox (1971), Uhler (1980) and Mohn (1980). These studies emphasize the difficulty of obtaining useful results from surplus production models when the data are subject to varying degrees of instability. Stock production model estimates of optimal effort and maximum sustainable yield (MSY) are statistical point estimates and, as such, may not be significantly different from zero. Therefore, when using any of the stock production model variants, according to McGaw (1980), care should be exercised in the interpretation of the results for purposes of fisheries management.

The proper perspective of surplus production model analysis, according to Fox (1975), is that it is little more than a regression model, yet often very useful for making "first estimate" projections of the relationships between the level of exploitation and expected equilibrium yield. The assumption of equilibrium conditions precludes application of surplus production models to either the ascending or descending stages of a fishery. Hilborn (1979) observes that fisheries control systems that utilize catch and effort data frequently fail to provide reasonable estimates of logistic growth model parameters and will produce poor catches, especially when managing long-lived low productivity species. Christie (1974) asserts that catch and effort approaches to population estimation appear to be too slow and retrospective for dynamic systems like those of the Great Lakes. It would seem, then, that the applicability of stock production models to real world dynamic fishery systems is extremely limited. However, due to the all too prevalent lack of comprehensive biological data, these models are often the only available means of obtaining information about exploited stock dynamics. With this in mind, we will proceed to apply the logistic surplus production model to Saginaw Bay commercial sucker fishery catch and effort data.

C. Application of the Logistic Surplus Production Model

Recall equation IV-12,

IV-12 $$C_t = qK(f_t) - q^2(K/r)\ (f_t^{\,2}),$$

which suggests that, under equilibrium conditions, a parabolic relationship exists between equilibrium yield, C_t, and nominal effort, f_t. If we let $a = qK$ and $b = q^2K/r$, then equation IV-12 can be written,

IV-20 $$C_t = a(f_t) - b(f_t^{\,2}).$$

If we divide through by f_t we obtain,

IV-21 $$C_t/f_t = a - b(f_t),$$

which indicates another means of surplus production model estimation (under assumed equilibrium conditions). Differentiating equation IV-20 with respect to nominal effort, f_t, setting the result equal to zero and solving for f_t yields,

IV-22 $$f_{MSY} = a/(2b),$$

which is the optimal level of effort (i.e. the level of nominal effort which results in MSY). By substituting equation IV-22 into equation IV-20 we obtain an expression for maximum sustainable yield (MSY).

IV-23 $$C_{MSY} = a^2/(4b).$$

Recall the linearization procedure (equations IV-15 through IV-19) used to estimate the logistic surplus production model (equation IV-9). In order to estimate population growth parameters from time, t to t+n, catch and effort data is needed from time, t-1 to t+n+1. For example, catch and effort data from 1929 to 1956 is required to obtain growth parameter estimates for the period from 1930 to 1955. In effect, the linearization procedure "swallows" the first and last years' data in order to derive population growth parameter estimates for the intervening years. The equilibrium-centered model represented by equations IV-20 through IV-23 uses all of the available data. For example, catch and effort data from 1929 to 1956 is used to obtain estimates of optimal effort and MSY for the same time period.

Equations IV-19 and IV-21 were applied to catch and effort data from the following time periods: 1930 - 1945; 1946 - 1955; 1930 - 1955; 1961 - 1967; 1968 - 1978 and 1961 - 1978. Population dynamic parameter estimates resulting from these applications are listed in Table IV-1.

1. <u>1930 to 1945</u>

Although both the multiple regression and simple linear regression representations of the logistic surplus production model yielded parameter values with the expected signs, the estimates of f_{MSY} and MSY seem too large when compared to observed mean catch, $\overline{C}_t$, and mean effort, $\overline{f}_t$, during this period. In addition, the estimate of catchability obtained from the linearization method, $q = 2.3 \times 10^{-7}$, appears to be too small when compared to independent estimates of catchability for this period (Table III-3). The surplus production model fails to adequately describe observed catch and effort data from 1930 to 1945.

2. <u>1946 to 1955</u>

The linearization procedure (equation IV-19) failed to generate parameter estimates with the expected signs. Estimates of f_{MSY} and MSY obtained from equation IV-21 were reasonably close to observed mean catch, $\overline{C}_t$, and mean effort $\overline{f}_t$, during this period.

3. <u>1930 to 1955</u>

Both estimation procedures yielded parameter estimates with the expected signs. The estimates of f_{MSY} and MSY obtained from both methods are in relatively close agreement

Table IV-1

Surplus Production Model Results

<u>1930-1945</u>

$\Delta U_t = r(U_t) - r/(qK)(U_t^2) - q(C_t)$

$r = .101186;\ r/(qK) = .003739;\ q = 2.3 \times 10^{-7}$

$K = 117{,}662{,}000$ pounds; $f_{MSY} = r/(2q) = 220{,}000$ lifts

$MSY = rK/4 = 2{,}976{,}000$ pounds

$C_e = qK(f_t) - q^2K/r(f_t^2) = 27.0623(f_t) - .00006151(f_t^2)$

$C_t/f_t = a - b(f_t) = 28.2137 - .00004521(f_t)$

$f_{MSY} = a/(2b) = 312{,}000$ lifts; $MSY = a^2/(4b) = 4{,}402{,}000$ pounds

$\overline{C}_t = 962{,}000$ pounds; $\overline{f}_t = 36{,}300$ lifts

<u>1946-1955</u>

$C_t/f_t = a - b(f_t) = 58{,}3428 - .000075513(f_t)$

$f_{MSY} = a/(2b) = 38{,}600$ lifts; $MSY = a^2/(4b) = 1{,}127{,}000$ pounds

$\overline{C}_t = 900{,}000$ pounds; $\overline{f}_t = 22{,}000$ lifts

<u>1930-1955</u>

$\Delta U_t = r(U_t) - r/(qK)(U_t^2) - q(C_t)$

$r = .092137;\ r/(qK) = .000961;\ q = 1.5 \times 10^{-6}$

$K = 63{,}917{,}000$ pounds; $f_{MSY} = r/(2q) = 30{,}700$ lifts

$MSY = rK/4 = 1{,}472{,}000$ pounds

$C_e = qK(f_t) - q^2K/r(f_t^2) = 95.8762(f_t) - .00156087(f_t^2)$

$C_t/f_t = a - b(f_t) = 54.4734 - .00071726\ (f_t)$

$f_{MSY} = a/(2b) = 38{,}000$ lifts; $MSY = a^2/(4b) = 1{,}034{,}000$ pounds

$\overline{C}_t = 938{,}000$ pounds; $\overline{f}_t = 31{,}000$ lifts

Table IV-1 (cont.)

1968-1978

$\Delta U_t = r(U_t) - r/(qK)(U_t^2) - q(C_t)$

$r = .313292;\ r/(qK) = .001112;\ q = 7.2 \times 10^{-5}$

$K = 3{,}913{,}000$ pounds; $f_{MSY} = r/(2q) = 2{,}200$ lifts

$MSY = rK/4 = 306{,}000$ pounds

$C_e = qK(f_t) - q^2K/r(f_t^2) = 281.7374(f_t) - .06474821(f_t^2)$

$C_t/f_t = a - b(f_t) = 47.7471 - .00404820(f_t)$

$f_{MSY} = a/(2b) = 5{,}900$ lifts; $MSY = a^2/(4b) = 141{,}000$ pounds

$\overline{C}_t = 123{,}000$ pounds; $\overline{f}_t = 3{,}800$ lifts with observed mean catch, $\overline{C}_t$, and mean effort, $\overline{f}_t$, during this period. Figure IV-1 depicts the equilibrium relationship between catch and effort generated by application of equation IV-21. Also shown in Figure IV-1 is the short term production function obtained by applying equation III-19 to this time series of catch and effort data. The surplus production model appears to be a reasonable approximation of the relationship between catch and effort data from 1930 to 1955. From this evidence, one could infer that the Saginaw Bay commercial sucker fishery was in a state of equilibrium during this period. If this calculated relationship reflects potential stock dynamics, then an upper bound (from the standpoint of MSY) for annual sucker harvest from Saginaw Bay is approximately 1,000,000 pounds.

4. 1961 to 1967

Both estimation procedures failed to generate parameter estimates with the expected signs. Realistically, this period is represented by too few data points to warrant the application of surplus production modeling techniques.

5. 1968 to 1978

Both estimation procedures yielded parameter estimates with the expected signs. The estimates of f_{MSY} and MSY obtained from both methods are within the neighborhood of observed mean catch, $\overline{C}_t$, and mean effort, $\overline{f}_t$.

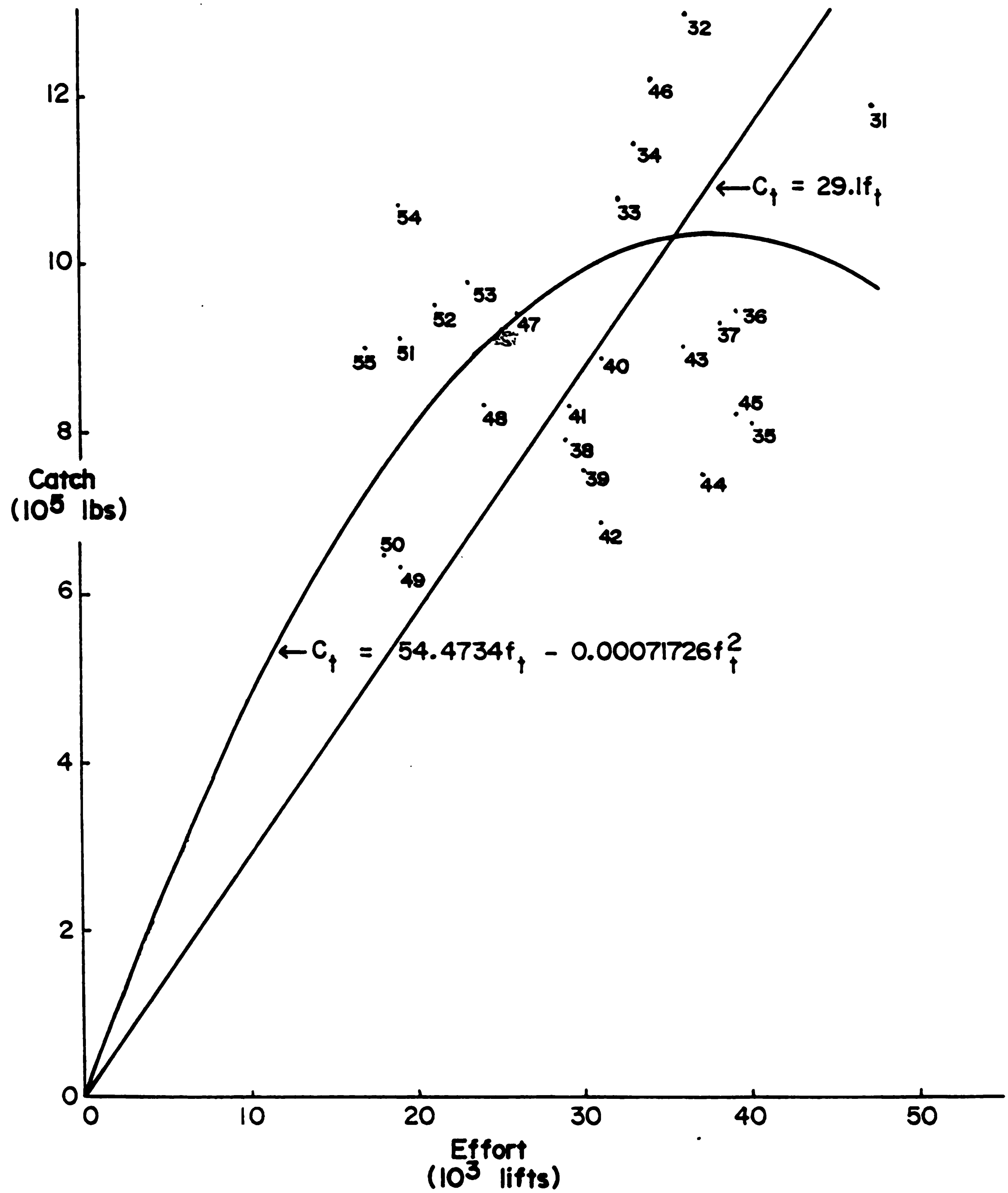


Figure IV-1. Logistic Surplus Production Model (1930-1955).

Interpretation of these results is complicated by the fact that this period is represented by relatively few data points. Figure IV-2 depicts the relationship between catch and effort data generated by the multiple regression linearization procedure. Also shown in Figure IV-2 is the short term production function obtained by applying equation III-19 to these catch and effort data. Three observations can be made about the relationship portrayed in Figure IV-2: (1) the fishery was not in equilibrium; (2) the fishery was overexploited; or (3) the logistic surplus production model is an inappropriate descriptor of stock dynamics for this period.

6. 1961 to 1978

Both estimation procedures failed to generate parameter estimates with the expected signs.

D. Saginaw Bay Sucker Fishery Economics

The preceding analysis of catch and effort data via the logistic surplus production model is an attempt to determine a workable production function which can be used in an economic analysis of the fishery. This section describes a simple bioeconomic fishery management model based upon the logistic surplus production model. The following economic analysis is patterned after the presentations by Fullenbaum and Bell (1974) and Anderson (1977). This analysis depends upon a reasonably accurate determination of the cost and revenue curves for the Saginaw Bay commercial sucker fishery. Cost and revenue data for 1979 were obtained from

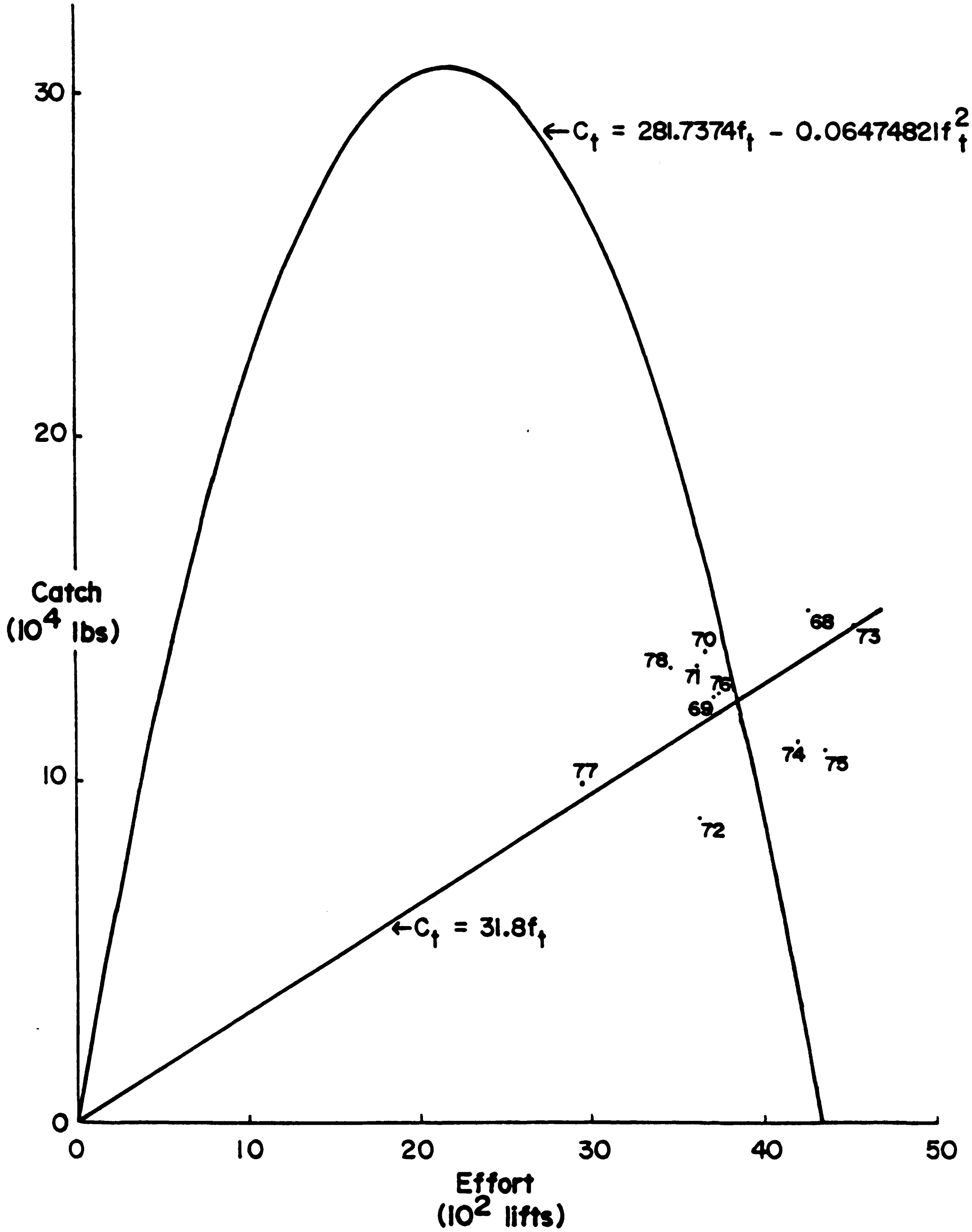


Figure IV-2. Logistic Surplus Production Model (1968-1978).

an eastern Saginaw Bay commercial fishery operation which encompassed two full time fishing vessels.

Table IV-2 contains a description of a typical Saginaw Bay commercial fishery operation for the year, 1979. The total costs of $88,639 represent the operating cost exclusive of operator labor for the two fishing vessels. This operation must earn at least this amount plus a moderate return to the operators' labor and capital or, in the long run, it will be forced to cease fishing. Since this operation fishes 60 trap nets, the average opportunity cost of a trap net is ($88,639/60 nets) or approximately $1,477. During 1979, each vessel was fished an average of 175 days. Approximately 3 nets were lifted per boat day. An estimate of the total amount of nominal fishing effort, f_t, produced by this operation is:

2 boats x 175 days fished/boat x 3 lifts/day fished = 1050 lifts.

An estimated yearly average of 17.5 lifts per trap net is obtained by dividing 1050 lifts by 60 nets. The average cost per net lift is ($1,477/17.5 lifts) or approximately $84. In 1979, suckers comprised about 6% of the total landings (in pounds) of this operation. Assuming that the cost of landing a given species is directly proportional to its percentage composition in the total landed catch, the cost of one trap net lift for suckers is $84 times .06 or about $5.04. The total cost of fishing for suckers can be expressed as a function of nominal fishing effort, f_t:

Table IV-2

Cost and Revenue Data

Description: 2-40 ft. steel-hulled trap net boats; 190 h.p. engines; 60 nylon trap nets (6 ft. and 10 ft.); power spools; net pullers; ship to shore radios; total est. market value: $70,000.

1979 Production (2 boats)

Species	Total Lbs.	Avg. Price/Lb. ($)	Total Return ($)
Catfish	115851	0.50	57925.50
Carp	58162	0.10	5816.20
Quillback	38150	0.15	5722.50
Sheepshead	33158	0.15	4973.70
Perch	22547	0.55	12400.85
Suckers	17655	0.05	882.75
Whitefish	10296	0.90	9266.40
Other spp.	5000	0.30	1500.00
Totals	300819 Lbs.		$98487.90

Variable costs

crewshare; net materials and repair; vessel maint. and repair; fuel and oil; ice; boxes; misc.

$41365.00

Fixed costs

depreciation; license fees; mortgages; utilities; insurance; misc.

$47274.00

Total costs $88639.00

$98487.90
\- 88639.00

Return to labor, management and investment $ 9848.90

IV-24 $TC = \$5.04(f_t)$.

In section C of this chapter we obtained the following estimate of sustainable yield in terms of nominal fishing effort for the 1968 to 1978 period:

IV-25 $C_t = 281.7374(f_t) - .06474821(f_t^2)$.

This relationship was used to describe the dynamics of the Saginaw Bay sucker fishery during 1979.

Average cost in terms of physical yield is calculated by dividing equation IV-24 by equation IV-25;

IV-26 $AC = \$5.04/(281.7374 - .06474821f_t)$.

If we solve equation IV-25 for effort, f_t, by means of the quadratic equation, we obtain:

IV-27 $f_t = (-281.737 \pm (79375.9626 - .2590C_t)^{1/2})/(-.1295)$.

If we substitute equation IV-24 into equation IV-26 we obtain an expression for average cost in terms of physical yield:

IV-28 $AC = \$10.08/(281.7374 \pm (79375.9626 - .2590C_t)^{1/2})$.

By substituting equation IV-27 into equation IV-24 and differentiating the result with respect to C_t we obtain the following expression for marginal cost in terms of physical yield:

IV-29 $MC = \$5.04/(79375.9626 - .2590C_t)^{1/2}$.

Table IV-3 and Figure IV-3 show the relationship between total physical yield, C_t, and average and marginal costs per pound. As the amount of effort applied to the fishery increases, total physical yield eventually falls while average cost per pound increases since more money is

Table IV-3

Average and Marginal Cost Data

Total Catch (lbs)	Nominal Effort (trap net lifts)	Average Cost per Pound ($)	Marginal Cost per Pound ($)
66400	250	.019	.020
124700	500	.020	.023
174900	750	.022	.027
217000	1000	.023	.033
251000	1250	.025	.042
277000	1500	.027	.058
294700	1750	.030	.091
304500	2000	.033	.223
306500*	2176	.036	infinity
306100	2250	.037	-
299700	2500	.042	-
285100	2750	.049	-
262500	3000	.058	-
231700	3250	.071	-
192900	3500	.091	-
146000	3750	.129	-
91000	4000	.222	-
27900	4250	.769	-

* MSY

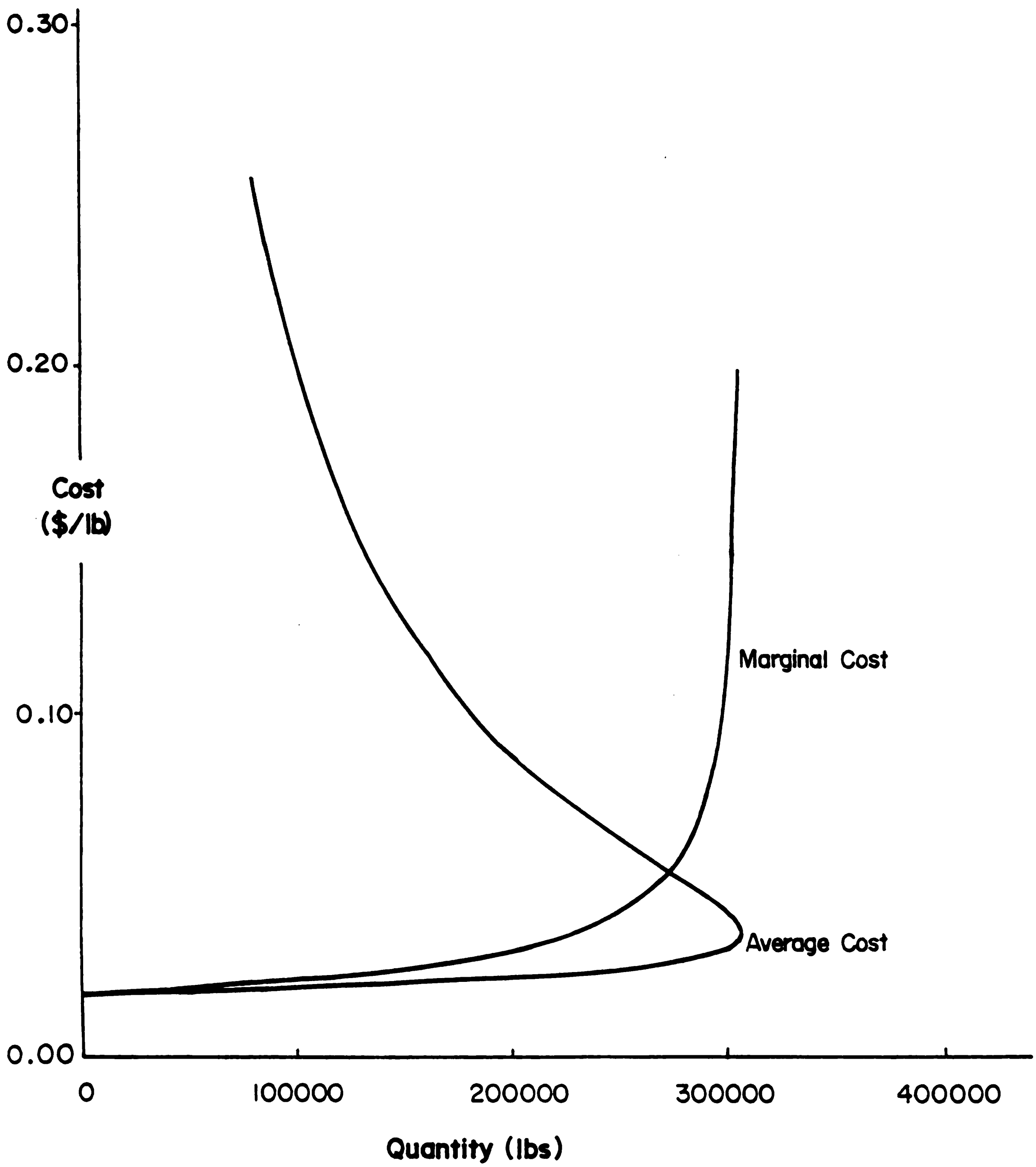


Figure IV-3. Average and Marginal Cost of the Saginaw Bay Commercial Sucker Fishery, 1979.

spent to obtain less yield (Anderson, 1977).

We know from the theory of open access fishery economics that the open access equilibrium or zero economic rent point will occur when the demand curve for suckers intersects the average cost curve. Due to the relative unimportance of the current Great Lakes sucker fishery, adequate information is not available to estimate a reliable sucker demand curve. In such instances, according to Anderson (1977), a simple fixed price model can be used in place of an explicitly derived demand curve. According to data obtained from the Michigan Deparment of Natural Resources' Fisheries Division, the ex-vessel price of suckers from Michigan waters of Lake Huron has remained relatively constant at about $0.05 per pound over the past twenty years. The fixed price of $0.05 per pound will be used in all subsequent bioeconomic calculations concerning the Saginaw Bay commercial sucker fishery.

The P = $0.05 line intersects the average cost curve shown in Figure IV-3 on its backward bending portion where approximate fishery yield is 282,500 pounds. Substituting this figure into equation IV-27 we find that this corresponds to an effort level of approximately 2,800 trap net lifts. This is very close to the 1979 observed level of 2,590 trap net lifts. The expected fishery yield (i.e. 282,500 pounds), however, is more than two and one half times the reported catch of approximately 108,000 pounds. Conversations with commercial fishermen indicate that only one-fourth to one-third of the current sucker catch is landed due to the lack of profitable markets for these fish. If the reported 1979 sucker landings for Saginaw Bay represented approximately one-third of the actual catch, then an estimate of the 1979 total catch is approximately 3 x 108,000 pounds or 324,000 pounds. This figure is very close to the above estimated equilibrium catch of 282,500 pounds.

Maximum economic yield (MEY) occurs at the intersection of the P = $0.05 line with the marginal cost curve shown in Figure IV-3. According to Figure IV-3, MEY occurs when yield is approximately 267,000 pounds. Substituting into equation IV-27 we find that this corresponds to an effort level of approximately 1,400 trap net lifts. The total economic yield at this point is the difference between the selling price (i.e. $0.05/lb) and the average cost (i.e. $0.03/lb) multiplied by the total yield or about $5,340.

The total revenue curve for the 1979 Saginaw Bay commercial sucker fishery is obtained by multiplying equation IV-25 by $0.05:

IV-30 $$TR = .05(281.737f_t - .06474821f_t^2)$$
$$= 14.0869f_t - .00323741f_t^2.$$

Recall equation IV-24:

IV-24 $$TC = 5.04(f_t).$$

Open access equilibrium occurs at the level of effort where total revenue, TR, equals total cost, TC. Equating equations IV-24 and IV-30 and solving for effort, f_t, we

find that open access equilibrium occurs when total fishery effort equals approximately 2,800 trap net lifts. Figure IV-4 depicts the relationship between total revenue and total cost. Maximum economic yield occurs at that effort level where the slope of the total revenue curve equals the slope of the total cost curve. Differentiating equation IV-30 with respect to effort, f_t, and setting the result equal to 5.04, we find that maximum economic yield occurs when effort equals about 1,400 trap net lifts. Substituting this effort level into equations IV-24 and IV-30 and subtracting equation IV-24 from equation IV-30 yields a maximum economic rent estimate of approximately $6,320.

E. Discussion

The preceding abbreviated bioeconomic analysis of the Saginaw Bay commercial sucker fishery is fraught with complications. Recall the multispecies nature of the Saginaw Bay commercial fishery. Any analysis of a single exploited population within a multispecies fishery is contingent upon a number of sweeping assumptions. The assumptions of biological equilibrium conditions, essential to bioeconomic analyses, refer not only to the exploited population of interest, but also to its total environment. The components of an exploited population's environment include: the genetic composition of the population's gene pool; the physical environment; the biological elements of the ecosystem and the commercial fishery. The interactions between an exploited population and its environment

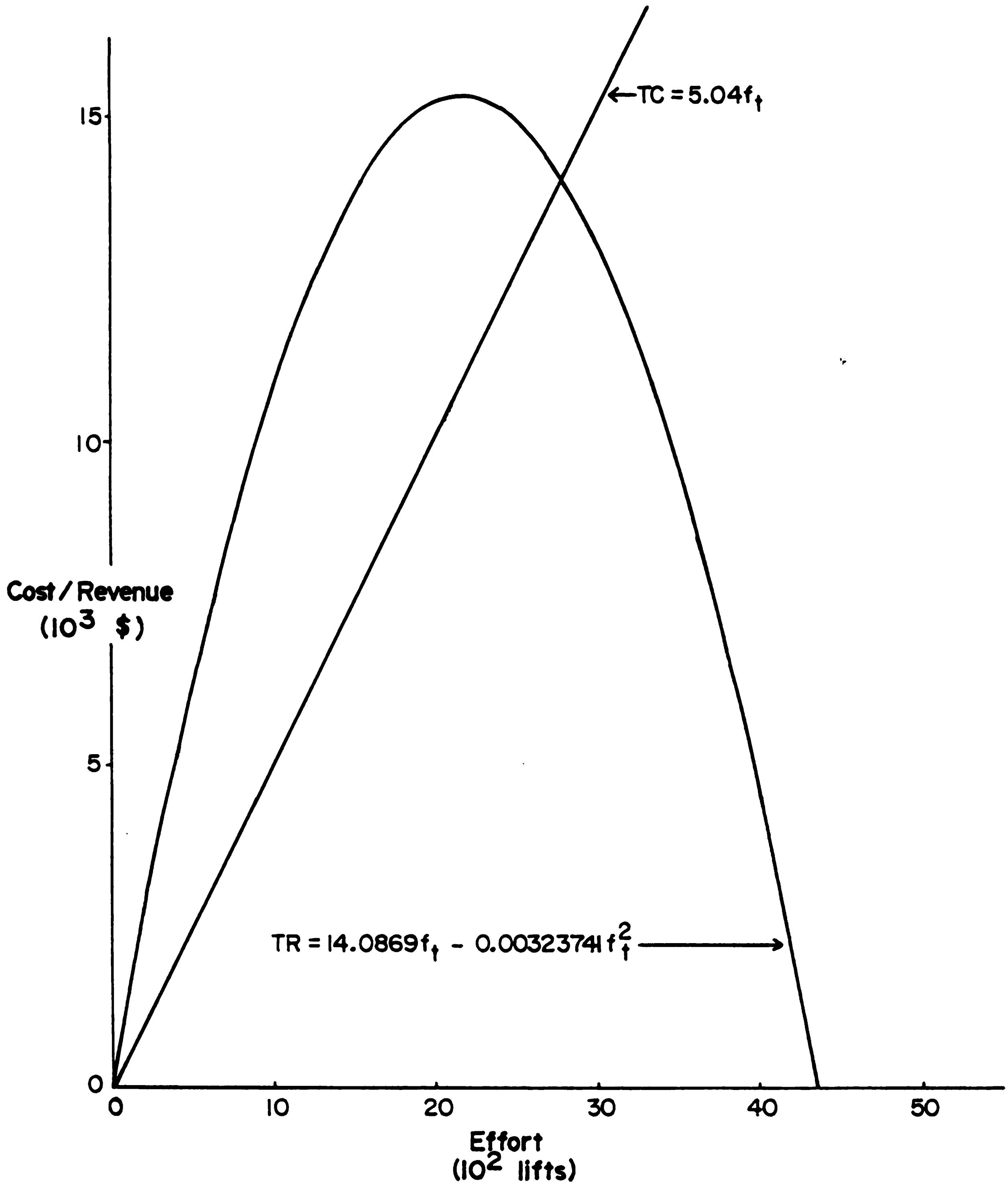


Figure IV-4. Cost and Revenue in Terms of Effort.

determine the aggregate dynamic characteristics of that stock. Bioeconomic analyses of exploited fisheries are often conducted with limited information. Armed only with commercial fishery catch, effort, cost and revenue data plus certain broad generalizations concerning aggregate population biomass growth (e.g. logistic growth), biologists and economists routinely construct simple lumped parameter fishery management models. While such models may reasonably describe the dynamics of single species fisheries in non-fluctuating environments, they almost certainly fail to explain the complex dynamics of multispecies fisheries. Multispecies fisheries require complex methods of analysis. Unfortunately, techniques for biological and economic analyses of multispecies fisheries are poorly developed (cf. Clark, 1976 and Anderson, 1977).

Most efforts to obtain dynamic biological and economic information from multispecies fisheries involve attempts to determine sustainable yield curves for each species within such fisheries (c.f. Walter and Hogman's (1971) study of the Green Bay, Lake Michigan fishery). Frequently, the catch and effort data from one or more exploited species fail to fit the analytical model (e.g. surplus production model) used to describe the fishery. In such cases, independent estimates of MSY and allowable effort obtained by other means are necessary to avoid gaping holes in the analysis. In some instances, individual sustained yield curves calculated for different exploited stocks are combined to generate a single sustained yield curve whose often complex shape defies analytical description. Optimization procedures (e.g. linear and nonlinear programming, linear and nonlinear least squares analysis, gradient analysis) can be utilized in efforts to maximize aggregate biomass yield from multispecies fisheries.

The costs involved in obtaining the requisite biological and economic information necessary for construction of more accurate and reliable fisheries management models are, at least in the case of the Great Lakes commercial fisheries, probably out of proportion to the value of the fishery. Obviously, the analysis and evaluation of multispecies fisheries is an incredibly complex task. With this in mind, what can we say about the reasonableness of our bioeconomic analysis of the Saginaw Bay commercial sucker fishery?

The catch-effort relationship described by equation IV-25 and shown in Figure IV-2 is the basis for our analysis. The reliabiliy of this relationship insofar as it describes assumed equilibrium fishery dynamics is questionable due to the relatively small number of data points used to estimate the equation. The cost and revenue data shown in Table IV-2 are assumed to reflect the average economic condition of the Saginaw Bay commercial fishery. Commercial fishery catch, C_t, and nominal effort, f_t, data are not entirely reliable since they do not reflect actual catch and effort conditions. The propriety of analyzing a single exploited species apart from the other principally exploited species may be questioned.

It is apparent that our bioeconomic analysis of the Saginaw Bay sucker fishery contains several weak links. However, it is possibly one of the few means available to obtain biological and economic information about this fishery, given the type and quality of existing data.

The logistic surplus production model, applied to catch and effort data from 1930 to 1955, indicated a potential sustained annual harvest of approximately 1,000,000 pounds. This estimate should be considered as an upper limit to sucker exploitation since environmental and biological changes which have occurred since the mid-1950's have probably altered the potential productivity of Saginaw Bay suckers. The logistic surplus production model, applied to catch and effort data from 1968 to 1978, indicates a potential sustainable annual harvest of approximately 300,000 pounds. Current annual sucker landings are about 100,000 pounds. Based upon these considerations, and assuming that the market for suckers or sucker products can be expanded, a reasonable projection of annual sucker harvest from Saginaw Bay is about 500,000 pounds.

Assume that an increased market for suckers drives up the ex-vessel price received by fishermen from $0.05/lb to $0.10/lb. This would have the effect of raising the total revenue curve shown in Figure IV-4. In the short run, assuming that costs do not change appreciably and that effort remains at approximately 3,000 trap net lifts, the fishery will experience a net economic rent of approximately $11,000. This represents an additional net annual income of from $1,000-2,000 for each of the current Saginaw Bay commercial fishing operations. A $0.05/lb ex-vessel price increase should result in relatively substantial monetary benefits, in the short run, to Saginaw Bay commercial fishermen. In the long run, under the assumptions of open access equilibrium, this economic rent should be dissipated. The above economic analysis ignores the discount rate, in effect attaching a discount rate of zero to future anticipated fishery revenues. A more thorough dynamic analysis of the Saginaw Bay sucker fishery would consider the maximization of discounted net future revenues. Such considerations are beyond the scope of our simple bioeconomic analysis. The principal reason for the present analysis is to obtain an estimate of expected short term gains to the commercial fishery resulting from a modest (i.e. $0.05 per pound) ex-vessel price increase.

The preceding analysis assumes that it costs the same amount to catch each pound of fish, regardless of species. The principal species currently sought by the Saginaw Bay commercial fishery are channel catfish, yellow perch, lake whitefish and carp, from which most of the fishermen's income is derived. It is reasonable to assume that most or all of the costs associated with fishing should be allocated to these species. Suckers, at present, are always an incidental part of the commercial catch. The additional (marginal) costs associated with landing incidental species are probably negligible. The ex-vessel price for suckers is approximately $0.05/lb. At this price fishermen are just willing to land suckers. Below this price, fishermen would probably not deem it worthwhile to bring in any portion of their sucker catch. A plausible estimate of the marginal cost associated with the Saginaw Bay sucker fishery, then, is $0.05/lb. If current levels of sucker landings are maintained (i.e. from 100,000-150,000 pounds per year), then no economic rent will be generated by the sucker fishery. A $0.05/lb ex-vessel price increase would generate an annual economic rent ranging from $5,000 to $7,500, assuming current levels of sucker use.

As long as suckers remain an incidental part of the total commercial catch (i.e. they are not actively sought by fishermen) the costs associated with landing these fish should remain negligible. If the fishery actively seeks these fish, then the costs associated with their harvest will rise noticeably, necessitating a reevaluation of sucker fishery bioeconomics. The marginal cost of landing suckers is not likely to increase until annual landings approach 400,000 pounds.

CHAPTER V

PCB's and DDT in Saginaw Bay Suckers

A. Introduction

Sporadic attempts to monitor environmental contaminant levels in underutilized Great Lakes fish have been conducted by various state and federal governmental agencies over the past decade. Two of the most prominent ongoing environmental contaminant monitoring programs are conducted by the State of Michigan's Great Lakes Environmental Contaminant Survey (GLECS) and the U.S. Food and Drug Administration. These efforts typically involve obtaining a small number of fish (e.g. one or two individuals) from the commercial catch within a given catch district and analyzing them for a broad spectrum of common organic and heavy metal contaminants. Due to the limited nature of these surveillance sampling programs, resulting data represent litte more than statistical point estimates and, as such, are not amenable to meaningful statistical analyses. More intensive sampling programs are needed to reliably monitor chemical contaminant levels in underutilized fish.

In order to ensure compliance with existing public health standards and regulations, it is necessary to determine the levels of environmental contaminants in underutilized fish prior to increasing the scope of fishing operations for such species. Two of the most widespread environmental contaminants for which allowable tolerance limits have been established are PCB's (polychlorinated biphenyls) and DDT (dichlorodiphenyltrichloroethane). According to the U.S. Food and Drug Administration, Great Lakes fish marketed for human consumption may contain no more than 5 ppm PCB's and 5 ppm DDT and its analogs, DDE and DDD. This investigation included provisions for establishing background information on the levels of PCB's and DDT compounds in Saginaw Bay sucker fillets. The sum of the concentrations of DDE, DDD and DDT is designated by ΣDDT in the following discussions.

Since most halogenated hydrocarbon environmental contaminants are fat soluble, they are usually found concentrated in the fatty tissues of fish and other animals. Accordingly, fish with high amounts of body fat (e.g. lake trout, channel catfish) contain relatively greater amounts of such contaminants than fish with low amounts of body fat (e.g. yellow perch, suckers). Previous investigations (GLECS,1974 and 1975; Dawson, et al, 1978; Zabik et al, 1978) revealed that suckers obtained from Lake Huron had an approximate fat content of 2%. Fat content is not uniform throughout the organism and is often found concentrated in the belly flap tissues and the medial muscle of the lateral line.

B. Sampling Procedures

A total of 25 suckers (4 immatures, 9 females and 12 males) were obtained from the Fall 1979 and Spring 1980 Saginaw Bay commercial sucker landings. These fish were selected to represent the range of sizes commonly found in the commercial catch. Table V-1 contains the size and sex composition of this sample. Fish were transported in ice to the laboratory for processing, usually arriving the day after the catch. Fillets were homogenized in an Osterizer blender, frozen and held in glass jars at -23^{o} C prior to being thawed for contaminant analysis.

C. Analytical Procedures

Analyses of Saginaw Bay suckers for PCB's and ΣDDT were conducted by the Department of Food Science, Michigan State University. The ensuing analytical procedures, described by Zabik, et al, (1978), were followed. Two samples from each fish were extracted separately with hexane-acetone (2:1), partitioned with acetonitrile, and subjected to Florisil-Celite column cleanup. Solids were determined by drying 2-g samples under vacuum at 90^{o}C to constant weight; lipid was estimated by evaporating an aliquot of the hexane extract to dryness at 70^{o} under vacuum. Gas chromatographic analyses were performed with a Tracor 560 gas-liquid chromatograph (GLC) equipped with a ^{63}Ni electron-capture detector and interfaced with a Digital PDP-8e-Pamila GC data system. Instrument parameters and operating conditions follow.

Table V-1

PCB's and ΣDDT in Saginaw Bay Suckers

Sampling Date	Sex	TL(cm)	WGT(g)	PCB's(ppm)	ΣDDT(ppm)
9-6-79	M	32.0	400	0.08	0.010
9-6-79	F	47.9	1220	0.04	0.043
9-26-79	IM	27.5	200	0.03	0.000
9-26-79	F	50.5	1115	0.05	0.020
10-28-79	IM	32.3	550	0.08	0.001
10-28-79	M	36.3	535	0.01	0.003
10-28-79	M	40.5	740	0.03	0.010
10-28-79	F	45.8	1145	0.18	0.010
11-10-79	M	41.5	660	0.02	0.017
11-10-79	F	49.7	1150	0.05	0.007
4-9-80	M	36.8	560	0.04	0.003
4-9-80	M	45.2	985	0.03	0.044
4-9-80	F	44.0	925	0.05	0.012
4-9-80	F	45.7	1100	0.17	0.030
4-26-80	IM	39.6	590	0.06	0.002
4-26-80	M	41.7	830	0.05	0.015
4-26-80	F	44.1	1075	0.05	0.007
5-15-80	IM	38.6	580	0.01	0.005
5-15-80	M	45.8	960	0.02	0.007
5-15-80	M	46.5	940	0.03	0.040
5-15-80	F	49.6	1225	0.01	0.010
6-14-80	M	31.5	355	0.03	0.016
6-14-80	M	33.4	350	0.03	0.004
6-14-80	M	40.9	755	0.03	0.033
6-14-80	F	41.9	625	0.01	0.014
mean				0.05	0.015
std. error				0.0086	0.0027
range				0.01- 0.18	0.000- 0.044

Column:	1.83 m x 4.0 mm ID Pyrex, packed with 3 percent OV-1 on 80-100 mesh Chromosorb W-HP
Temperature:	column 190°C injection port 230°C detector 300°C
Carrier gas:	nitrogen flowing at 40 ml/minute

Standards were prepared with 99+ percent pure recrystallized p,p'-DDT and p,p'-TDE, and Aroclor 1248 in Nanograde hexane. Quantitations were based on peak area for ΣDDT; the area of three peaks was used to quantitate the PCB's. Standards were run every morning and after every eight or nine samples. Recoveries with this method of extraction and quantitation were 85 + 2 percent for PCB's and 92 + 1 percent for DDT compounds; limits of detection were 0.01 ppm for PCB's and 0.001 ppm for DDT compounds.

D. Results

Table V-1 presents the levels of PCB's and ΣDDT found in Saginaw Bay sucker fillets during this investigation. PCB's ranged from 0.01 ppm to 0.18 ppm. ΣDDT ranged from 0.000 ppm to 0.044 ppm. All observed levels are below the tolerance limits for these compounds established by the U.S. Food and Drug Administration. Approximate 95% confidence limits for PCB's are (0.03 ppm, 0.07 ppm). Approximate 95% confidence limits for ΣDDT are (0.009 ppm, 0.021 ppm). In 1974, the Great Lakes Environmental Contaminant Survey analyzed four suckers from Saginaw Bay ranging in total length from 30.5 cm to 45.7 cm and in weight from 320 g to 1,140 g. PCB's ranged from less than 0.02 ppm to 0.84 ppm.

ΣDDT ranged from 0.01 ppm to 0.17 ppm. Zabik, et al, (1978) sampled suckers from Saginaw Bay and Lake Huron from 1975 to 1976. These workers found 0.03 ppm to 0.20 ppm ΣDDT and 0.17 ppm to 0.70 ppm PCB's in mechanically deboned sucker flesh. From this evidence it appears as though the levels of PCB's and ΣDDT are decreasing in Saginaw Bay suckers.

The data presented in Table V-1 can be partitioned into the following categories or "treatments": fall immatures; fall males; fall females; spring immatures; spring males and spring females. For both the PCB and ΣDDT data, one-way analyses of variance were constructed to test for differences between mean contaminant levels. For both contaminants, no significant differences ($p = .05$) were detected between treatment means. The absence of significant differences between the treatment means allowed for pooling of fall and spring data which, in turn, enabled calculation of approximate 95% confidence limits about mean PCB and ΣDDT values. No significant correlations were detected between contaminant levels and fish size (measured by length or weight).

The results obtained from the present investigation, along with previous work conducted by the Great Lakes Environmental Contaminant Survey and by Zabik, et al, (1978) indicate that Saginaw Bay suckers do not contain harmful amounts of the environmental contaminants, PCB's and ΣDDT relative to the upper tolerance limits for these substances mandated by governmental agencies. If other environmental

contaminants are present in comparably low amounts, then the enhanced development of the Saginaw Bay sucker fishery should not be hindered by high levels of potentially harmful pollutants. Continued monitoring of a broad spectrum of environmental contaminants in all Great Lakes fish marketed for human consumption is essential for the health and welfare of the fish-consuming public.

CHAPTER VI

Saginaw Bay Sucker Population Dynamics

A. Introduction

Historical catch records and commercial fishery catch sampling reveal that white suckers comprise more than 90% of the total Saginaw Bay sucker landings. Accordingly, the present study was designed to evaluate the population dynamics of Saginaw Bay white suckers. Sampling from the commercial catch was restricted to the east central Saginaw Bay fishery and was conducted from September 1979 through April 1981. A sample consisted of the entire sucker catch from one or two shallow trap nets. Samples were preserved in crushed ice until they could be worked up (usually the day after the catch). Each fish was sexed, measured to the nearest 0.1 cm (total length), weighed to the nearest 5 grams on an Accu-Weigh spring loaded single pan scale, and examined for obvious morphological anomalies (e.g. sea lamprey scars). In addition, the state of maturity of each fish was noted and a pectoral fin was taken for age determination via the fin ray technique. Sampling was concentrated during the spring (April through early June) and fall (September through November) fishing seasons when suckers were most readily available to the commercial

fishery. All sucker samples were landed at the facilities of the Bayport Fish Company, Bayport, Michigan. The pot end mesh in the shallow trap nets used to obtain the sucker samples was approximately 1 1/2 inches (stretch mesh).

B. A Brief Review of White Sucker Biology

Concise and informative reviews of white sucker biology are provided by Scott and Crossman (1973) and Eddy and Underhill (1974) from whom much of the following is taken. White suckers are widely distributed throughout North American lakes and rivers and, when present, are usually found in abundance. Spawning occurs from late April to early June in tributary streams and, at times, in the margins of lakes adjacent to principal spawning streams. Geen, et al, (1966) observed the beginning of spring spawning migrations when stream temperatures reached 10^{o} C. Barton (1980) found that both water temperature and stream discharge were important factors contributing to spring spawning migrations. From 20,000 to 50,000 demersal eggs are scattered along the stream substrate. Spent females return to the lake before spent males. Fry begin migrating downstream to the lake about one month after spawning. According to Geen, et al, (1966), survival from egg to migrating fry may be as little as 0.3%.

Male and female growth rates are comparable up to the time of maturity, after which there is a marked difference in growth rates with females growing faster and larger than males. After the first year of life, growth is extremely variable, ranging from 0-2 cm per year. Males usually mature one year before females. In Ontario, according to Scott and Crossman (1973), sexual maturity is normally attained by the third or fourth year. Both sexes begin spawning in appreciable numbers after reaching sexual maturity. Spawning mortality is often low, usually less than 20%. Maximum total length approaches 60.0 cm while maximum weight approaches 3,000 g. Maximum age is 17-19 years. Females usually live longer, on the average, than males.

According to Lalancette (1977), the diet of white suckers varies with the size of the fish, time of the year and size of the food organism. Young of the year feed mainly on plankton and small copepods and crustaceans. After fish reach about 7.5 cm in total length, they change to adult (bottom) feeding habits. Adults consume a variety of crustaceans, insects, vegetation and detritus. Maximum food consumption and growth rates occur during June through August. Adults do not feed during spawning.

White sucker adult survival is high. Olson (1963) reported a 0.87 annual survival rate for adults in a 695 hectare Minnesota lake while Coble (1967) calculated a 0.70-0.75 annual survival estimate for adult white suckers in South Bay, Lake Huron. Coble (1967) correlated a steady decrease over time in numbers of large white suckers with increasing numbers of sea lampreys in South Bay. In a study of 552 white suckers obtained with experimental trap nets in

Northern Lake Huron, Hall and Elliott (1954) reported that 71% of all fish over 38.0 cm (total length) bore at least one sea lamprey scar.

Until white suckers reach approximately 30.0 cm (total length) they serve as an important source of food for large piscivorous fish and fish eating birds. After reaching adult size, white suckers appear to have few natural enemies other than man and the sea lamprey.

C. Saginaw Bay White Sucker Characteristics

1. Fall 1979

During the Fall 1979 fishing season (September through November) five samples consisting of 45 immature, 392 male and 358 female white suckers were obtained from the east central Saginaw Bay commercial fishery. Table VI-1 contains summary statistics for the composite sample. The total length (cm) and weight (g) statistics are self-explanatory. Females are larger and more variable in size than males which, in turn, are larger and more variable in size than immatures.

Figure VI-1 shows the length-frequency distributions of immature, male and female white suckers. For the purpose of this analysis, fish are grouped into 1.9 cm length classes (i.e. 28.0-29.9 cm, 30.0-31.9 cm, etc.). Figure VI-1 depicts the size distribution differences between male and female white suckers.

The bottom portion of Table VI-1 shows the calculated weight-length relationships for immatures, males and

Table VI-1

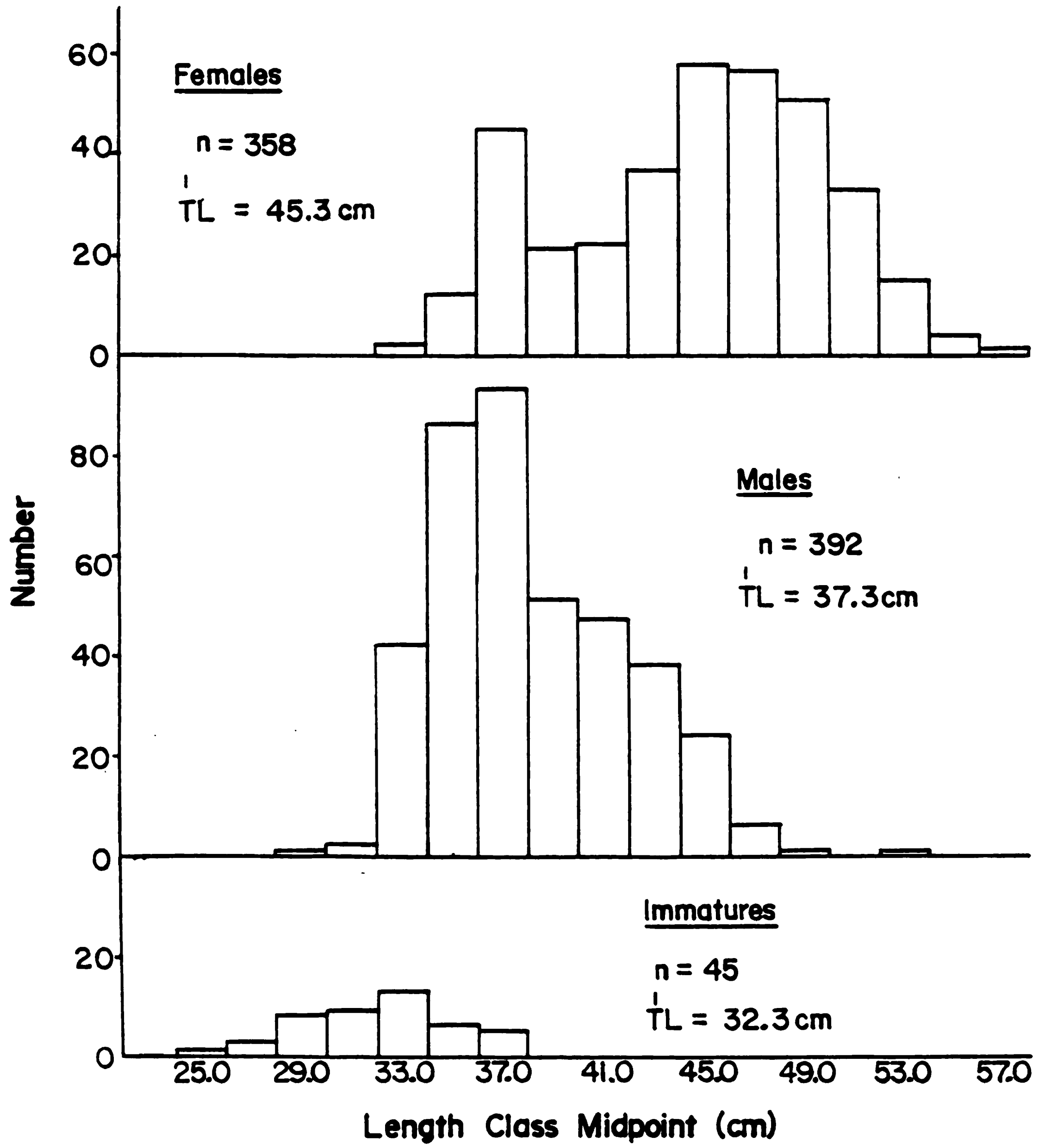
Fall 1979 Summary Statistics

Statistic	Immatures	Males	Females
Sample size (n)	45	392	358
$\overset{\shortmid}{TL}$ (cm)	32.3	37.3	45.3
$\overline{TL}$ (cm)	32.0	38.0	44.6
s_{TL} (cm)	2.980	3.719	5.121
TL range (cm)	25.7- 37.0	29.9 52.7	32.8 58.2
$\overline{WGT}$ (g)	380	635	1030
s_{WGT} (g)	105.149	169.560	314.700
WGT range (g)	170- 570	340- 1480	370- 1795
$\overline{K}_r$	0.94	0.99	1.02
s_{K_r}	0.094	0.132	0.110
K_r range	0.76- 1.35	0.46- 2.20	0.55- 1.84
$WGT = a(TL)^b$			
a	0.013	0.144	0.038
b	2.968	2.300	2.680
r^2	0.90	0.78	0.90

$\overset{\shortmid}{TL}$ = median total length (cm)

$\overline{TL}$ = mean total length (cm)

s_{TL} = standard deviation total length (cm)



Note. TL denotes median total length (cm).

Figure VI-1. Fall 1979 Length-Frequency Distributions.

females. The weight-length relationships are described by,

VI-1 $$WGT = a(TL)^b,$$

where: WGT = weight (g)

TL = total length (cm).

The Fall 1979 population weight-length regression (which includes all 795 fish from the composite sample) is given by,

VI-2 $$\text{Ln WGT} = -3.5140 + 2.7379 \text{ Ln TL}; \ r^2 = 0.92.$$

Analysis of covariance (Snedecor and Cochran, 1967) reveals significant differences ($p<.005$) between the slopes and elevations of the male and female weight-length regressions, underscoring the disparity between male and female growth patterns indicated in Table VI-1 and Figure IV-1.

Carlander (1969), discusses condition factors used by biologists to describe the condition, plumpness or well-being of a fish. The plumper the fish, the higher its condition factor. The condition of a given fish is subject to change from season to season (e.g. due to factors associated with growth, maturity, spawning and temperature-induced feeding changes). The following index of condition, K, can be used to compare weight and length between individuals of roughly similar lengths within a given sample or season,

VI-3 $$K = (WGT)/(TL)^3 \times 100,$$

where: WGT = weight (g)

TL = total length (cm).

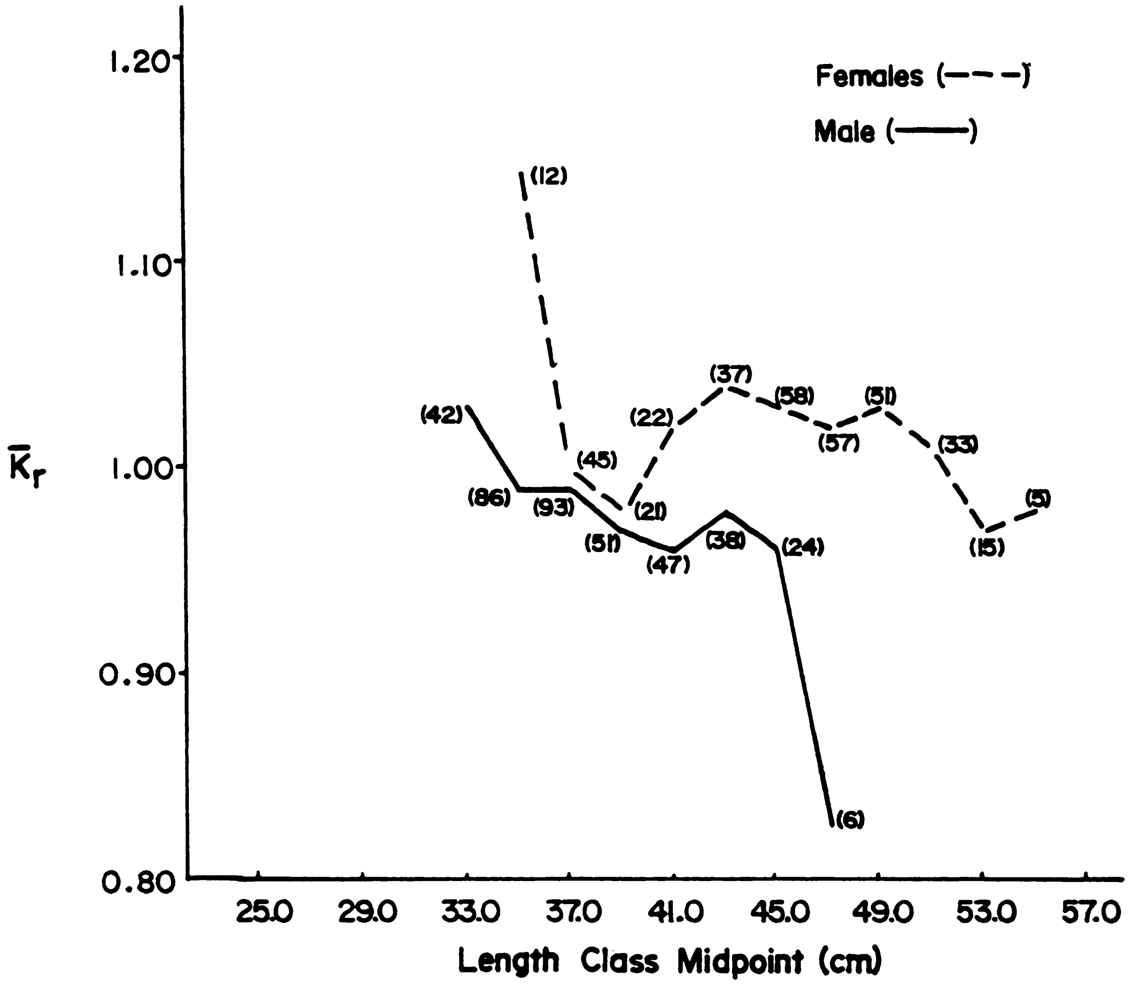
The following relative condition factor, K_r , is used in this study to eliminate possible trends in condition associated in increases in length,

VI-4 $$K_r = (WGT)/(aTL^b).$$

The relative condition factor, K_r, is calculated by dividing the observed weight of a given fish by its expected weight (as computed from the population weight-length regression).

Table VI-1 shows an increase in mean relative condition, $\bar{K}_r$, from immatures to males to females. Figure VI-2 depicts mean relative condition, $\bar{K}_r$, as a function of length for males and females. Both sexes exhibit a general decrease in $\bar{K}_r$ with increasing length. Males exhibit a more precipitous decline in $\bar{K}_r$ toward the end of their length range than females.

Age determinations were made by examining 0.5 mm cross sections of pectoral fin rays under a compound microscope. The cross sections were made by a specially designed microtome provided by the Michigan Department of Natural Resources. Fin ray annuli are detected as regions of lesser optical density than surrounding bony tissue. Only the first three pectoral fin rays are suitable for aging by this method. Cross sections must be obtained from as close to the base of the fin ray as possible in order to provide readable sections. This method of aging white suckers is detailed by Beamish and Harvey (1969) and Beamish (1973) who observed gross inconsistencies in the scale method of sucker aging. Scale samples from all immature and smaller (i.e.



Note. Numbers in parentheses refer to the number of individuals in each length class.

Figure VI-2. Fall 1979 Relative Condition Factors.

less than 35.0 cm total length) fish were obtained to verify the position of the first fin ray annulus. Scales were obtained from the lateral line region directly below the anterior base of the dorsal fin.

Approximately one out of every three fish from the Fall 1979 sample were aged via the fin ray method. This subsample was selected to represent the size-frequency distribution of male and female fish (i.e. the number of fish aged from each 1.9 cm length class was roughly proportional to the total number of fish in that length class). Appendix Tables A1 through A3 describe the size-age characteristics of the Fall 1979 age sub-sample (n = 260). Fall ages, designated by n+, indicate that a fish of age n is in its n+1 year of life. For the purpose of this investigation it is assumed that Saginaw bay white suckers undergo annulus formation during the winter season (i.e. from January to March). A fish of age n+ in the fall will become age n+1 by the following spring. Ages greater than or equal to 13+ for fall samples and greater than or equal to 14 for spring and summer samples were pooled because of the slow growth exhibited by these older fish and also because fish older than 13 years were extremely difficult to age.

The Fall 1979 female age subsample showed a progressive increase in mean total length ($\overline{TL}$) and mean weight ($\overline{WGT}$) with age. The male age subsample, however, exhibited a more irregular size-age increment, especially after age 7+.

Figure VI-3 depicts the Fall 1979 male and female length-age relationships. The vertical lines are approximate 95% confidence limits about the mean total lengths ($\overline{TL}$) at each age. The male length-age relationship was calculated by omitting age 12+ due to the small sample size (n = 2) representative of this age. The $\overline{K}_r$ - age relationship for both males and females did not exhibit any obvious patterns.

2. Spring 1980

During the Spring 1980 fishing season (April through May) four samples consisting of 41 immature, 95 male and 206 female white suckers were obtained. Table VI-2 contains summary statistics for the composite sample. The number of males in this spring sample was considerably less than the number of females. This phenomenon could be attributed to the observation by Geen, et al, (1966), who noted that spent females return to the lake before spent males, who have a tendency to linger in the spawning streams. As was observed in the Fall 1979 sample, females are larger than males which, in turn, are larger than immatures. Comparison of the length and weight statistics contained in Tables VI-1 and VI-2 reveals that the Spring 1980 fish are larger than the Fall 1979 fish. This could be due to springtime concentrations of large spawning individuals.

On 4-9-80, none of the 15 males or 21 females sampled had spawned. On 4-26-80, none of the 16 males but 12 of the 28 females sampled had spawned. By 5-3-80, 12 of the 15 males and all 92 of the females sampled had spawned. From

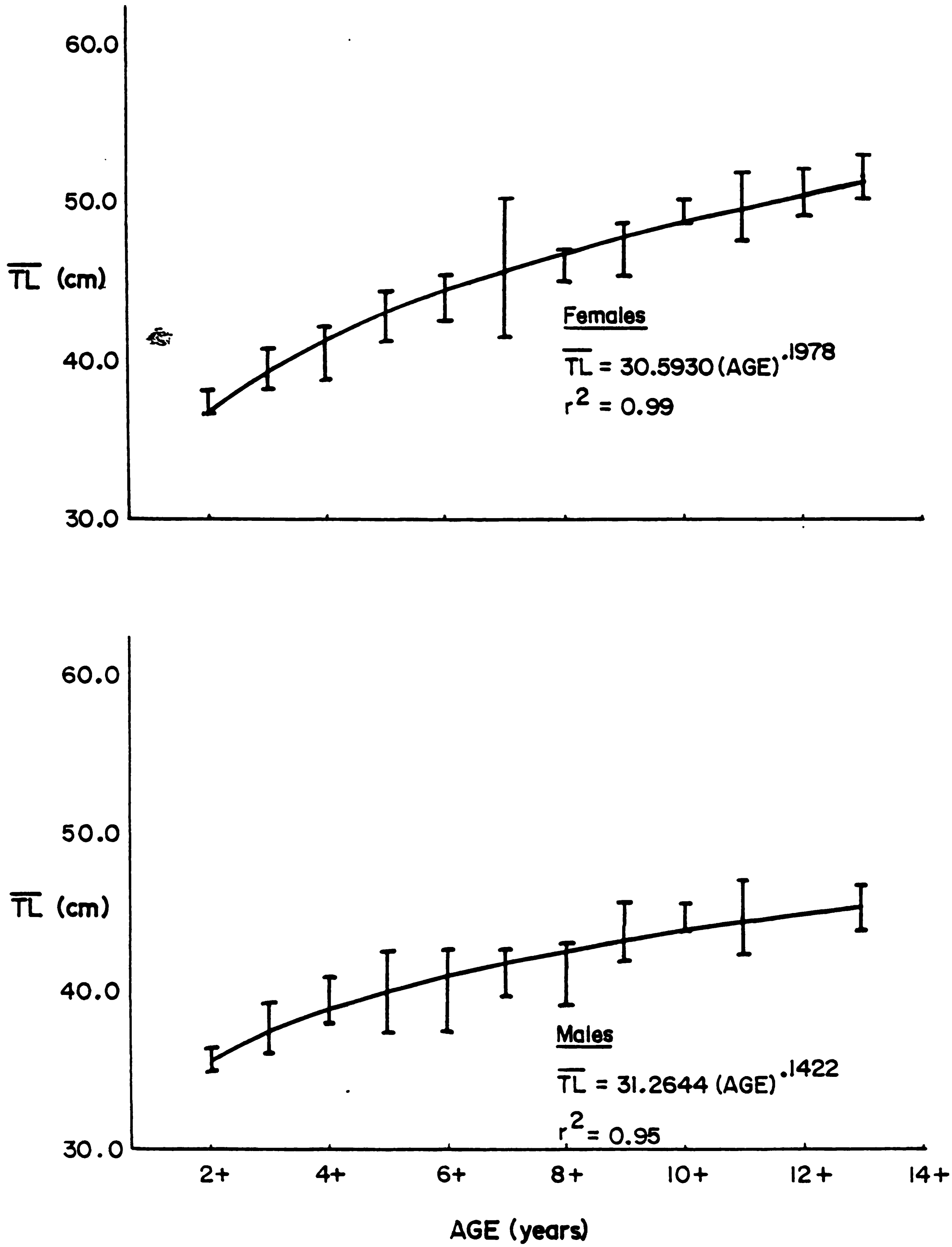


Figure VI-3. Fall 1979 Length-Age Relationships.

Table VI-2

Spring 1980 Summary Statistics

Statistic	Immatures	Males	Females
Sample Size (n)	41	95	206
$\acute{TL}$ (cm)	36.4	40.5	47.4
$\overline{TL}$ (cm)	36.7	40.2	47.3
s_{TL} (cm)	2.589	3.634	3.563
TL range (cm)	29.1- 42.6	32.6- 46.5	37.7- 55.1
$\overline{WGT}$ (g)	530	670	1045
s_{WGT}(g)	92.783	152.437	207.171
WGT range (g)	255- 720	400- 1000	620- 1730
$\overline{K}_r$	0.98	0.98	1.02
s_{K_r}	0.068	0.089	0.103
K_r range	0.86- 1.14	0.78- 1.18	0.80- 1.34
$WGT = a(TL)^b$			
a	0.060	0.132	0.161
b	2.516	2.305	2.274
r^2	0.88	0.85	0.77

these observations, it appears that Saginaw Bay white suckers spawn during the latter week of April and the early portion of May.

Figure VI-4 shows the length-frequency distributions of immature, male and female white suckers. Note that the largest Fall 1979 length class for females (i.e., from 44.0-45.9 cm) has moved into the 46.0-47.9 cm length class, which represents the largest springtime female length class.

Weight-length relationships for immatures, males and females are shown at the bottom of Table VI-2. The Spring 1980 population weight-length regression (which includes all 343 fish from the composite sample) is,

VI-5 $\quad \text{Ln WGT} = -2.9235 + 2.5545\ \text{LnTL};\ r^2 = 0.86.$

Mean total length ($\overline{TL}$) and mean relative condition ($\overline{K}_r$) of unspent females were 44.6 cm and 1.14, respectively. The unspent female (n = 41) weight-length regression is,

VI-6 $\quad \text{Ln WGT} = -2.5745 + 2.4964\ \text{LnTL};\ r^2 = 0.92.$

Mean total length ($\overline{TL}$) and mean relative condition ($\overline{K}_r$) of spent females were 47.9 cm and 0.99, respectively. The spent female (n = 165) weight-length regression is,

VI-7 $\quad \text{Ln WGT} = 3.1285 + 2.6031\ \text{LnTL};\ r^2 = 0.83.$

Analysis of covariance reveals a significant difference ($p<.01$) between the slopes of the unspent and spent female weight-length regressions. This is reflected by the difference between unspent and spent female mean relative condition factors.

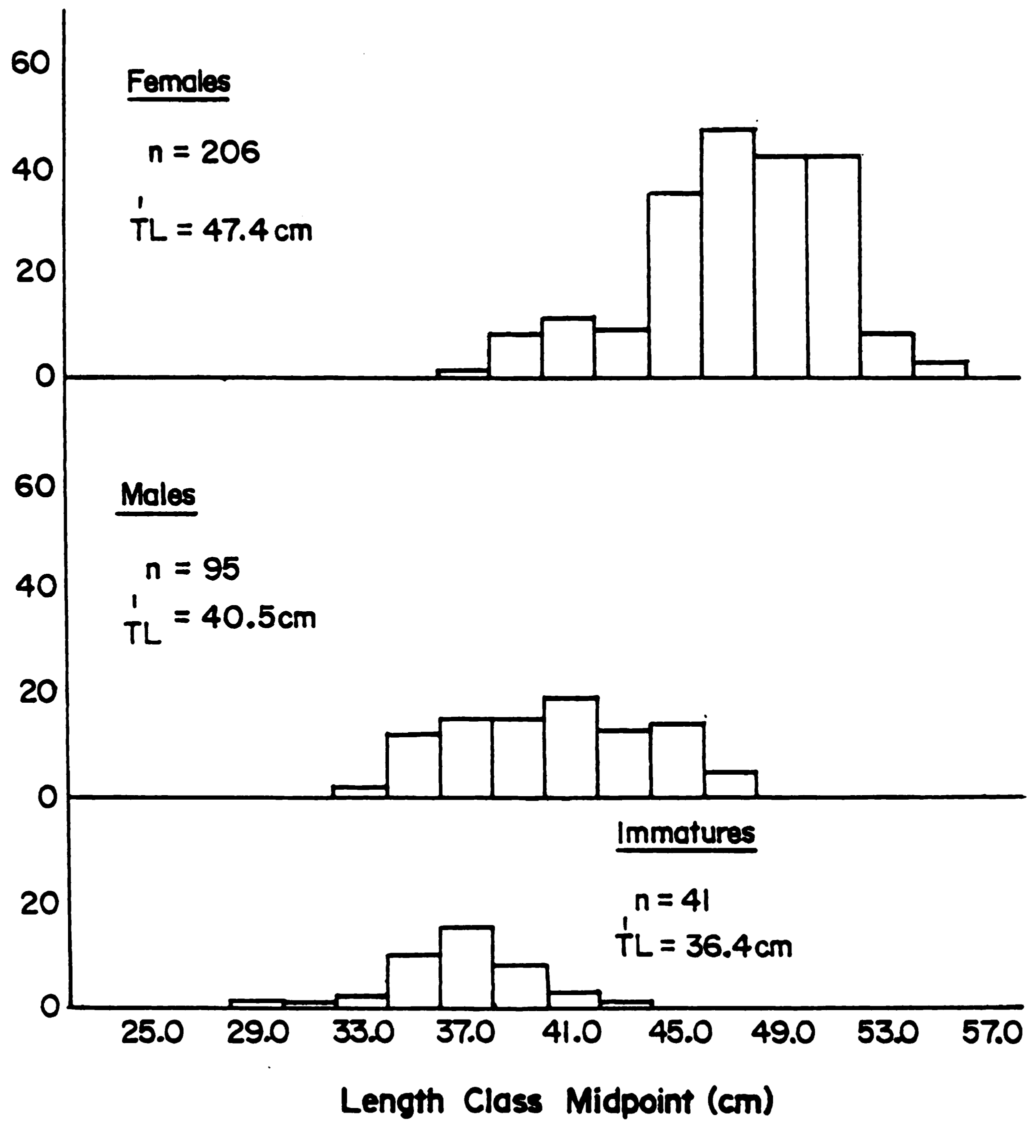


Figure VI-4. Spring 1980 Length-Frequency Distributions.

Mean total length ($\overline{TL}$) and mean relative condition ($\overline{K}_r$) of unspent males were 38.3 cm and 1.05, respectively. The unspent male (n = 35) weight-length regression is,

VI-8 $$\text{Ln WGT} = -3.1170 + 2.6200\ \text{LnTL};\ r^2 = 0.92.$$

Mean total length ($\overline{TL}$) and mean relative condition ($\overline{K}_r$) of spent males were 41.3 cm and 0.94 respectively. The spent male (n = 60) weight-length regression is,

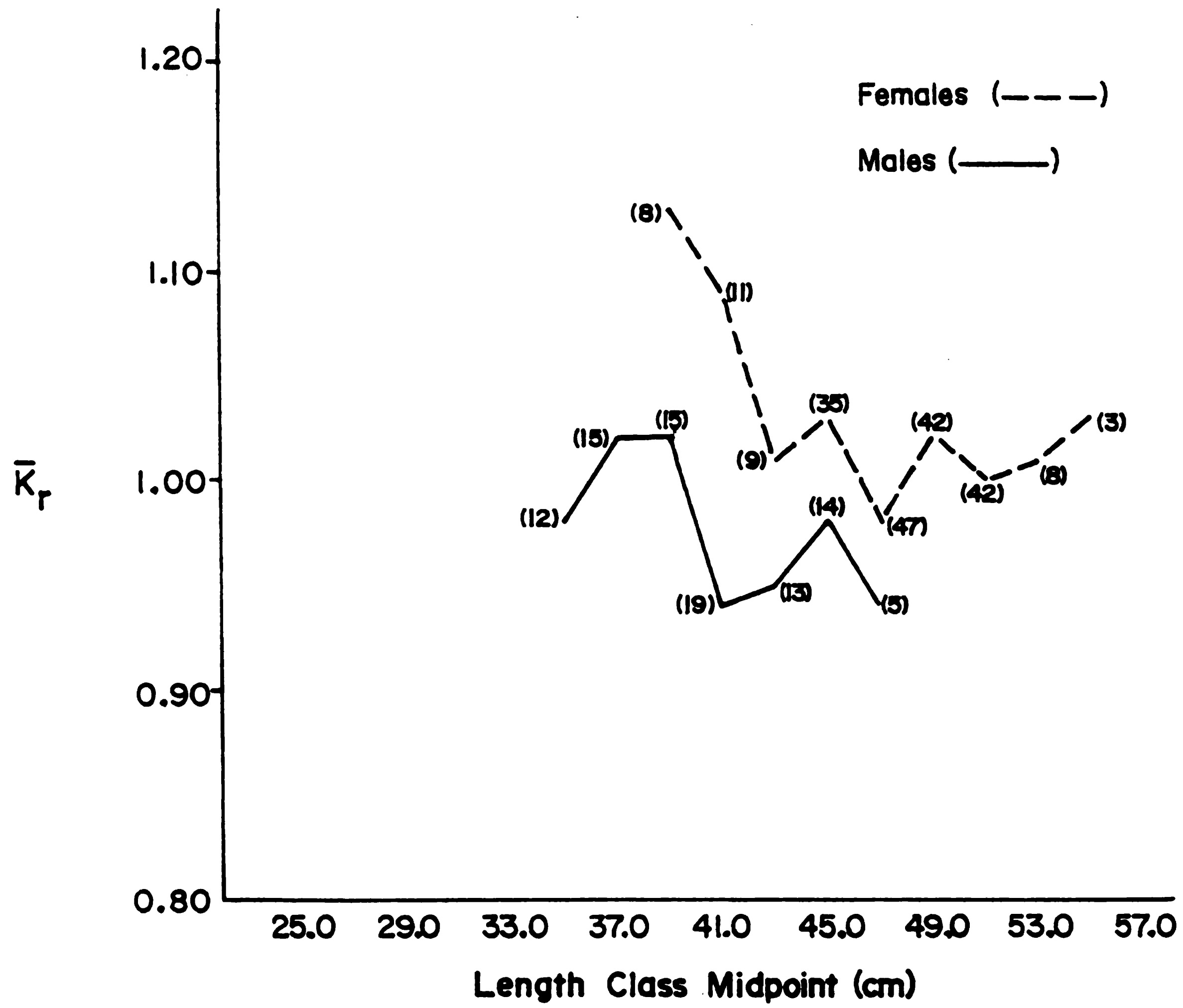
VI-9 $$\text{Ln WGT} = -2.6311 + 2.4600\ \text{Ln TL};\ r^2 = 0.86.$$

Analysis of covariance indicates no significant difference (p = .05) between the slopes of the unspent and spent male weight-length regressions.

Figure VI-5 depicts mean relative condition, $\overline{K}_r$, as a function of length for males and females. Males and females exhibit a similar $\overline{K}_r$ pattern for length classes marked by the 39.0 cm to 47.0 cm midpoints.

Appendix Tables A4, A5 and A6 describe the size-age characteristics of the Spring 1980 age subsample (n = 313). All of the 41 immature fish were aged as were all but one of the 95 males. Females were aged until the length coefficient of variation for each age class approached a value of approximately 0.05.

The female age subsample (n = 178) demonstrated a progressive increase in mean total length ($\overline{TL}$) with age. The male age subsample (n= 94), however, exhibited a more irregular size-age relationship, similar to that represented by the Fall 1979 male age subsample. Figure VI-6 depicts the Spring 1980 male and female length-age relationships.



Note. Numbers in parentheses refer to the number of individuals in each length class.

Figure VI-5. Spring 1980 Relative Condition Factors.

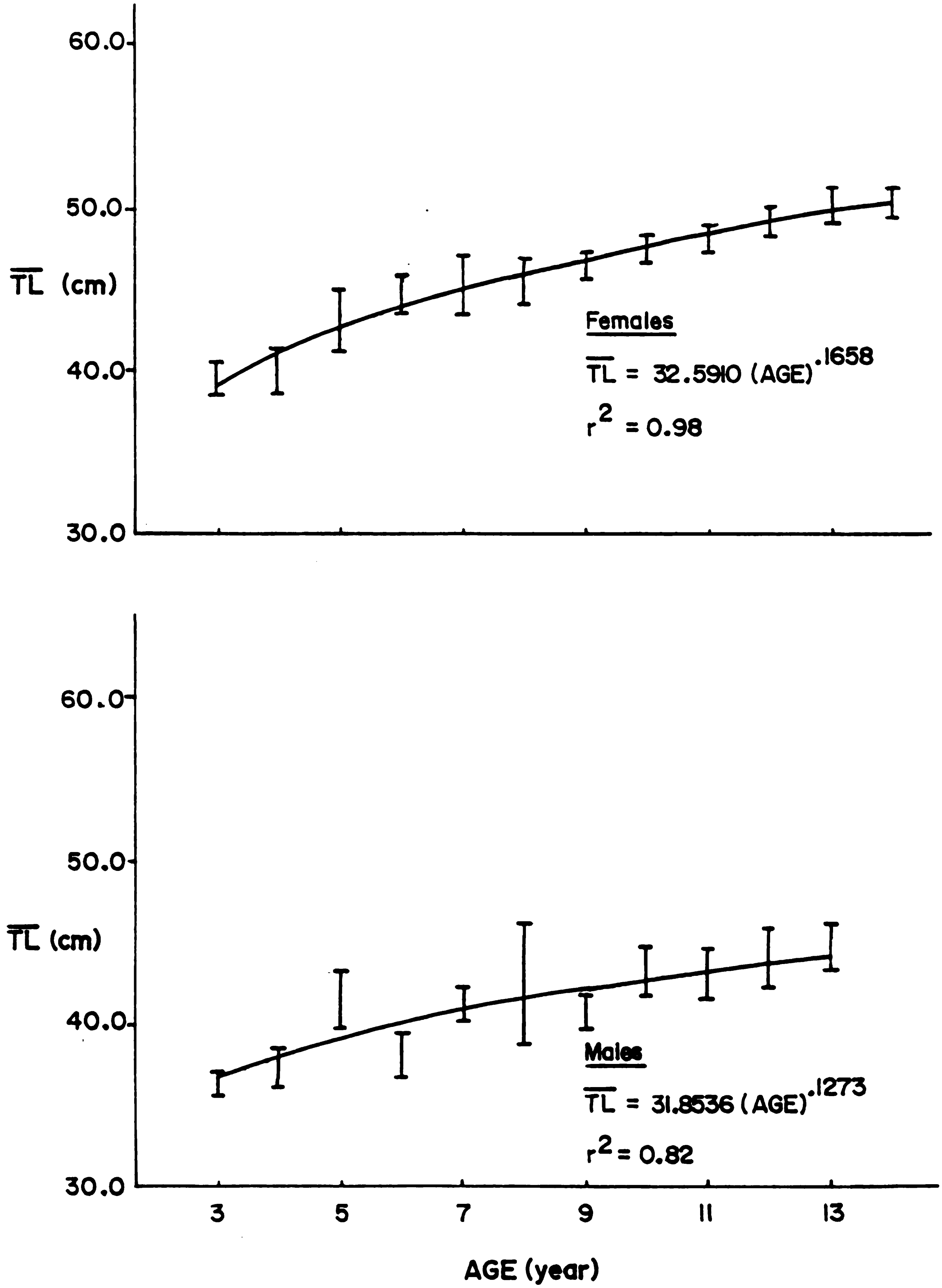


Figure VI-6. Spring 1980 Length-Age Relationships.

The vertical lines are approximate 95% confidence limits about the mean total length ($\overline{TL}$) at each age. The male length-age relationship was calculated by omitting age 13 due to the small sample size (n = 2) representative of this age. The $\overline{K}_r$ - age relationships listed in Appendix Tables A4 through A6 indicate that the younger age classes (i.e. from 3-7 years old) were in better condition than the older age classes.

3. Summer 1980

During the Summer 1980 fishing season (June through August) two samples consisting of 31 immature, 71 male and 71 female white suckers were obtained. Table VI-3 contains summary statistics for the composite sample. Once again, the previously observed size relationship among immatures, male and females is maintained. The fish from the summer sample, however, are considerably smaller than fish from the Fall 1979 and Spring 1980 samples (c.f. Tables VI-1 and VI-2).

Figure VI-7 shows the length-frequency distributions of immature, male and female white suckers. The diminished sizes of these summer immature, male and female fish may reflect the fact that larger white suckers move offshore into deeper, colder waters during the summer months where they are less available to the commercial fishery (which operates in relatively shallow waters during this time).

Weight-length relationships for immatures, males and females are shown at the bottom of Table VI-3. The Summer

Table VI-3

Summer 1980 Summary Statistics

Statistics	Immatures	Males	Females
Sample size (n)	31	71	71
$\overset{\vert}{TL}$ (cm)	30.5	35.3	38.9
$\overline{TL}$ (cm)	30.4	35.4	39.8
s_{TL} (cm)	3.351	2.605	4.662
TL range (cm)	24.3- 39.2	29.0- 42.5	30.8- 55.8
$\overline{WGT}$ (g)	300	450	650
s_{WGT} (g)	95.567	96.536	219.909
WGT range (g)	145- 580	240- 755	310- 1380
$\overline{K}_r$	1.00	1.00	1.04
s_{K_r}	0.135	0.087	0.105
K_r range	0.42- 1.22	0.82- 1.18	0.77- 1.33
$WGT = a(TL)^b$			
a	0.065	0.043	0.047
b	2.458	2.593	2.578
r^2	0.72	0.83	0.90

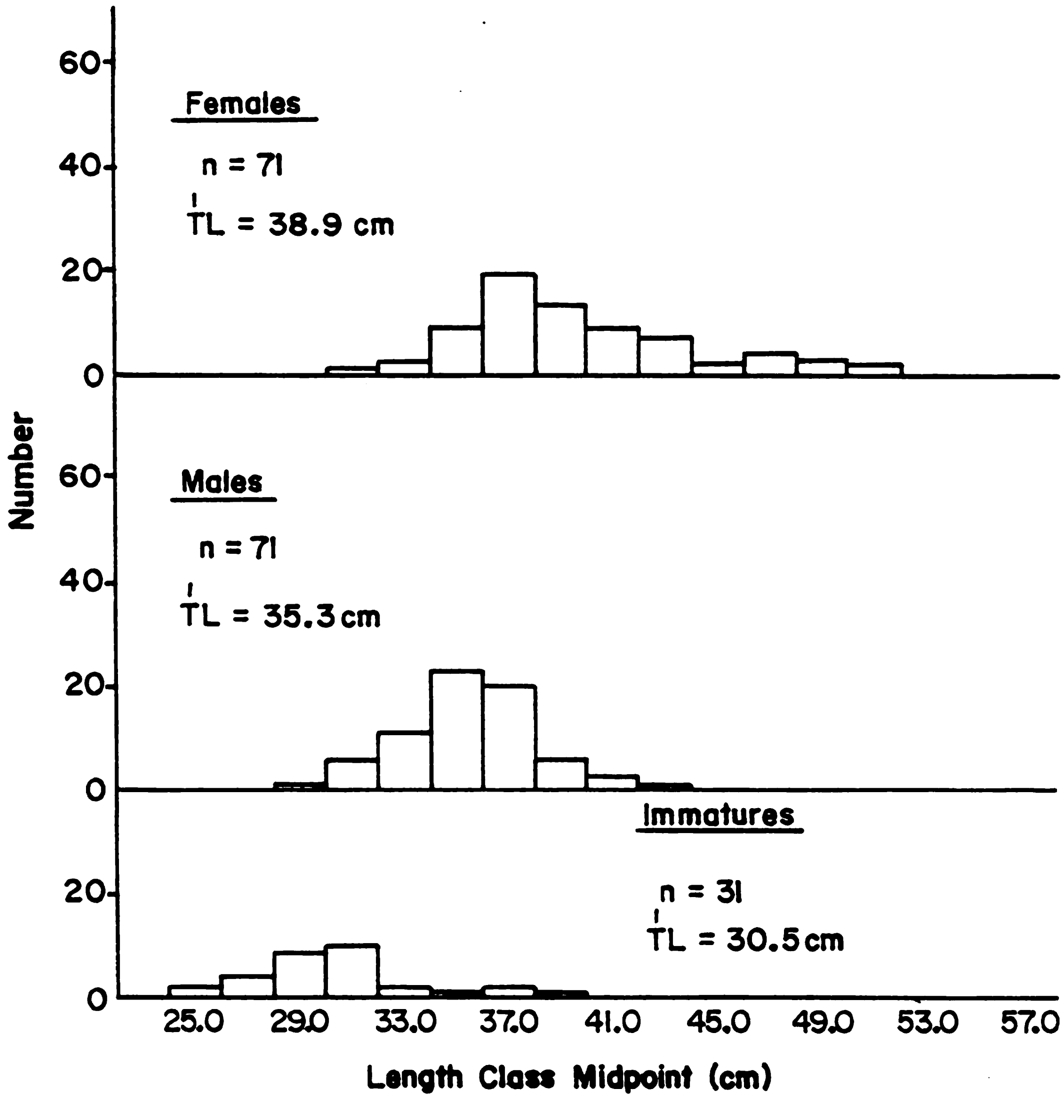


Figure VI-7. Summer 1980 Length-Frequency Distributions.

1980 population weight-length regression (which includes all 173 fish from the composite sample) is,

VI-10 $$\text{Ln WGT} = -3.6797 + 2.7429\ \text{LnTL};\ r^2 = 0.92.$$

Analysis of covariance reveals no significant difference ($p = .05$) between the slopes of the male and female weight-length regressions.

Figure VI-8 depicts mean relative condition, $\overline{K_r}$, as a function of length for males and females. No obvious trends in $\overline{K_r}$ are evident.

Appendix Tables A7, A8 and A9 describe the size-age characteristics of the Summer 1980 age subsample. Fin rays were not collected during the second of two summer sampling periods (which accounts for the poor age class representation for both males and females). Length-age relationships were not calculated for the summer subsample due to this inadequate age distribution.

4. Fall 1980

During the Fall 1980 fishing season (September through November) five samples consisting of 76 immature, 113 male and 153 female white suckers were obtained. Table VI-4 contains summary statistics for the composite sample. The size statistics calculated from this sample are similar to the Fall 1979 size statistics (c.f. Table VI-1).

Figure VI-9 shows the length-frequency distributions of immature, male and female white suckers. The Fall 1979 sample (Figure VI-1) indicated that the dominant male size class was from 36.0 -37.9 cm. Figure VI-9 shows the

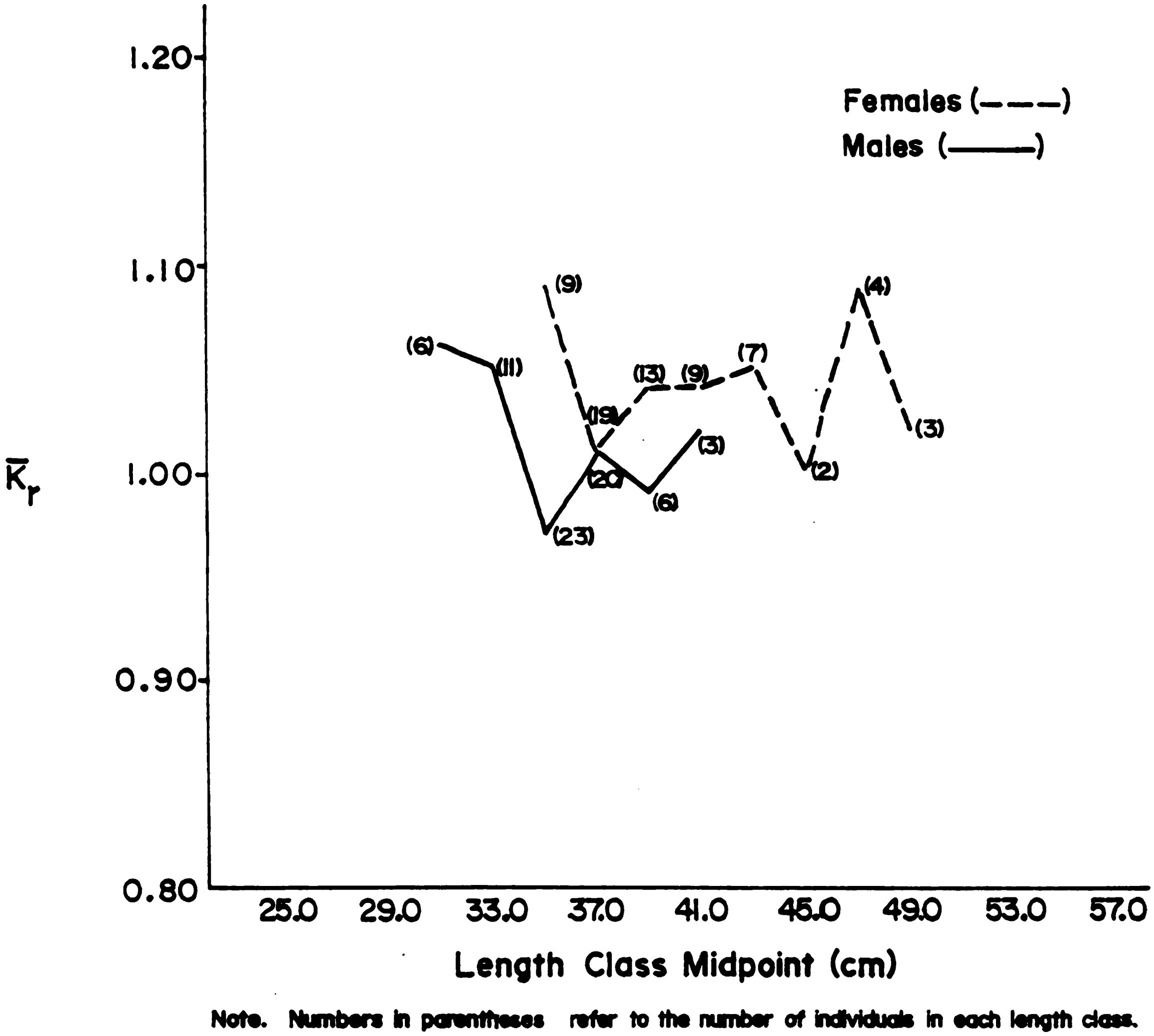


Figure VI-8. Summer 1980 Relative Condition Factors.

Table VI-4

Fall 1980 Summary Statistics

Statistic	Immatures	Males	Females
Sample size (n)	76	113	153
$\tilde{TL}$ (cm)	33.2	39.2	43.7
$\overline{TL}$ (cm)	32.6	39.6	44.0
s_{TL} (cm)	4.174	3.367	4.288
TL range (cm)	23.4- 40.4	32.6- 50.8	34.6- 53.1
$\overline{WGT}$ (g)	365	645	920
s_{WGT} (g)	124.396	149.493	254.140
WGT range (g)	125- 635	350- 1230	460- 1580
$\overline{K}_r$	0.96	0.99	1.02
s_{K_r}	0.076	0.099	0.097
K_r range	0.65- 1.12	0.68- 1.30	0.75- 1.35
$WGT = a(TL)^b$			
a	0.017	0.077	0.033
b	2.854	2.451	2.701
r^2	0.96	0.83	0.89

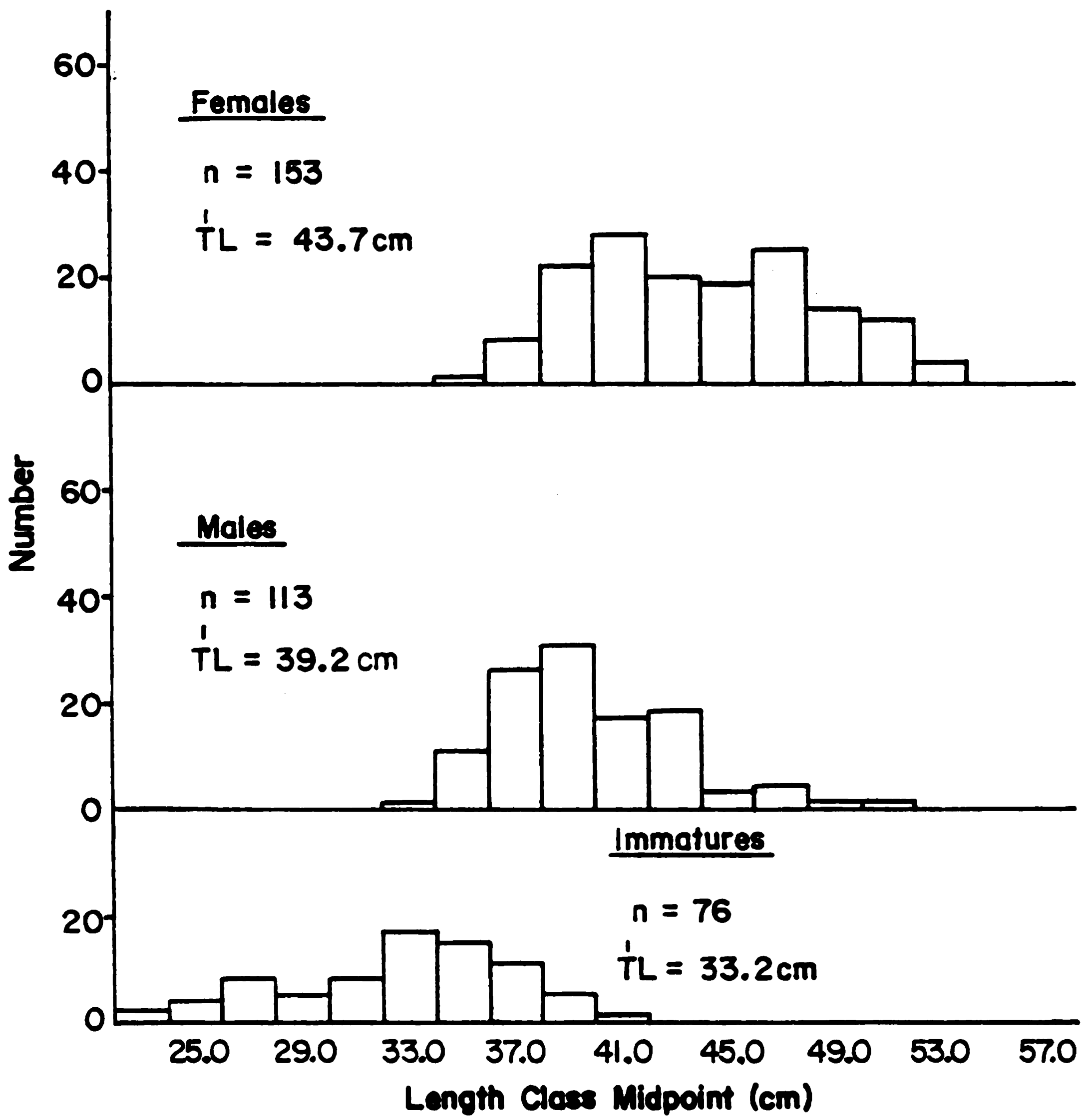


Figure VI-9. Fall 1980 Length-Frequency Distributions.

dominant Fall 1980 male size class to be from 38.0-39.9 cm. This could reflect the movement of a dominant year class through the fishery.

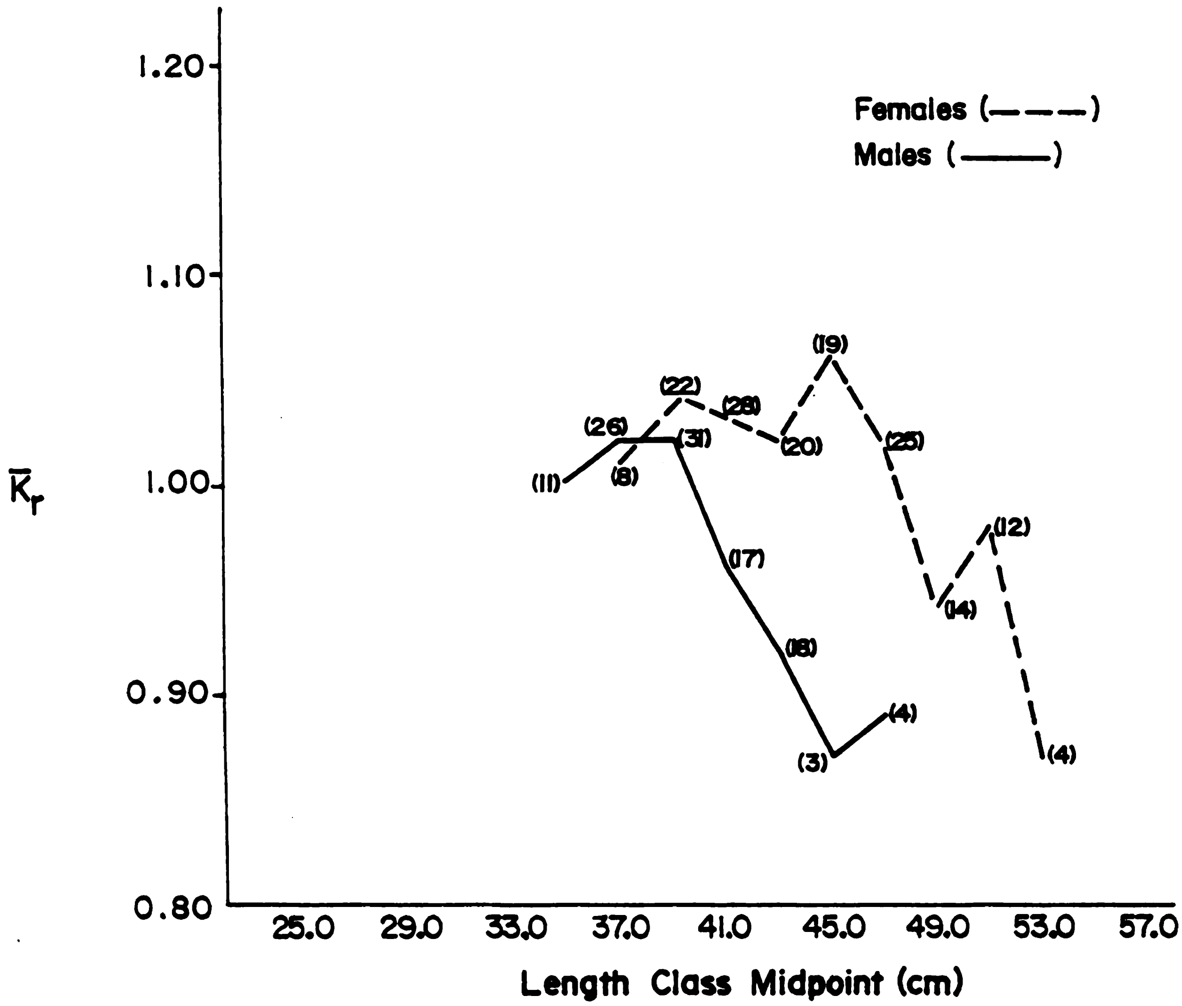
The bottom portion of Table VI-4 shows the calculated weight-length relationships for immatures, males and females. Analysis of covariance indicates no significant difference ($p = .05$) between slopes of the Fall 1979 female and Fall 1980 female weight-length regressions. Comparison of the slopes of the Fall 1979 male and Fall 1980 male weight-length regressions reveals a significant ($p = .05$) difference. The Fall 1980 population weight-length regression (which includes all 342 fish from the composite sample) is given by,

VI-11 $$\text{Ln WGT} = -4.4351 + 2.9629 \text{ LnTL}; \; r^2 = 0.96.$$

Analysis of covariance revealed no significant difference ($p = .05$) between the slopes of the male and female weight-length regressions.

Figure VI-10 depicts mean relative condition, $\overline{K}_r$, as a function of length for males and females. Figure VI-10 shows that $\overline{K}_r$ decreases with increasing length for both males and females.

Appendix Tables A10, A11 and A12 describe the size-age characteristics of the Fall 1980 age subsample ($n = 341$). Figure VI-11 depicts the Fall 1980 male and female length-age relationships. The vertical lines are approximate 95% confidence limits about the mean total lengths ($\overline{TL}$) at each age. Analysis of covariance reveals no significant



Note. Numbers in parentheses refer to the number of individuals in each length class.

Figure VI-10. Fall 1980 Relative Condition Factors.

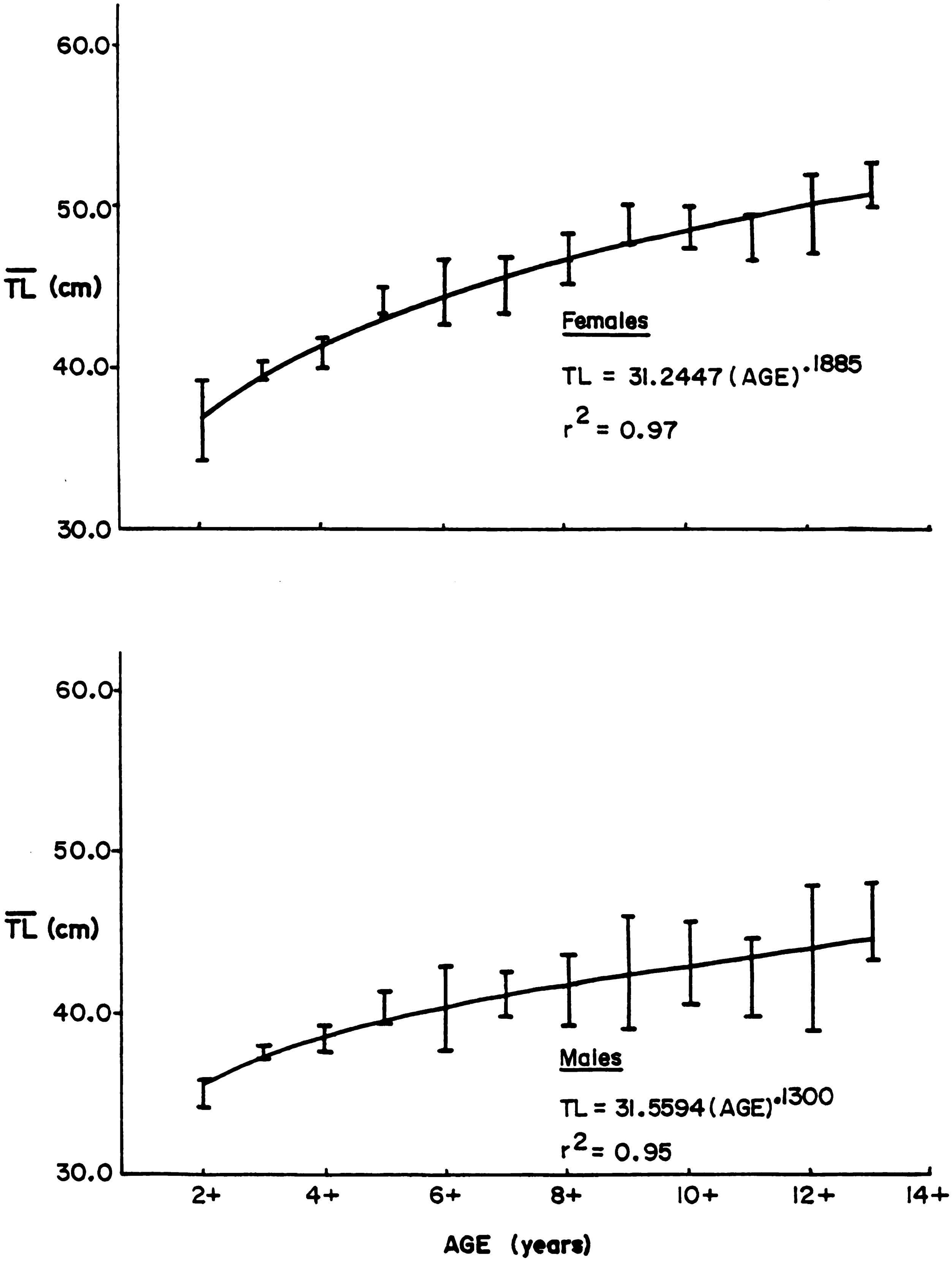


Figure VI-11. Fall 1980 Length-Age Relationships differences (p = .05) between the slopes or elevations of the Fall 1979 male and Fall 1980 male length-age regressions. Similarly, analysis of covariance reveals no significant differences (p = .05) between the slopes or elevations of the Fall 1979 female and Fall 1980 female length-age regressions. The $\overline{K}_r$ - age relationships for both males and females (Appendix Tables A10 and A11) indicate that the younger fish are generally in better condition than the older fish.

5. Spring 1981

During April 1981 two samples, consisting of 12 immature, 33 male and 106 female white suckers were obtained. Table VI-5 contains summary statistics for the composite sample. This sample was obtained to provide additional information about spring spawning periods and female size-fecundity relationships. Meaningful comparisons between Spring 1980 and Spring 1981 summary statistics are difficult due to the limited scope of the Spring 1981 sampling program. On 4-8-81, none of the 21 males or 22 females sampled had spawned. On 4-24-81, 6 of the 12 males and 77 of the 84 females had spawned. These observations parallel similar trends noted during the Spring 1980 season. Saginaw Bay white sucker spawning occurs during the latter portion of April and the early part of May. Females return to the bay before males (as is reflected by the Spring 1980 and 1981 sample sex composition).

Table VI-5

Spring 1981 Summary Statistics

Statistics	Immatures	Males	Females
Sample size (n)	12	33	106
$\tilde{TL}$ (cm)	34.4	38.0	46.9
$\overline{TL}$ (cm)	34.8	38.7	45.2
s_{TL} (cm)	1.480	3.724	4.668
TL range (cm)	32.8- 38.1	30.9- 47.4	34.1- 55.7
$\overline{WGT}$ (g)	440	595	925
s_{WGT} (g)	53.165	139.760	251.562
WGT range (g)	345- 570	330 975	400 1850
$\overline{K}_r$	0.97	0.99	1.03
s_{K_r}	0.087	0.088	0.099
K_r range	0.85- 1.18	0.73- 1.18	0.83- 1.31
$WGT = a(TL)^b$			
a	0.376	0.174	0.077
b	1.990	2.221	2.460
r^2	0.49	0.86	0.88

Figure VI-12 shows the length-frequency distribution of immatures, males and females. The 46.0-47.9 cm length class is the dominant female length class (as was also the case during the preceding spring).

Figure VI-13 depicts mean relative condition, $\bar{K}_r$, as a function of length for males and females. Relative condition is optimal for both sexes at an intermediate size, after which it experiences a progressive decline.

The Spring 1981 population weight-length regression (which includes all 151 fish in the composite sample) is,

VI-12 $$\text{Ln WGT} = -3.0070 + 2.5721 \text{ LnTL}; \; r^2 = 0.93.$$

Analysis of covariance reveals no significant difference (p= .05) between the slopes of the spent and unspent female weight-length regressions. No significant differences (p= .05) were indicated between the slopes or elevations of Spring 1980 and Spring 1981 spent female weight-length regressions. Similarly, no significant differences were indicated between the slopes or elevations of Spring 1980 and Spring 1981 unspent female weight-length regressions.

Appendix Tables A13, A14 and A15 contain immature, male and female size-age statistics. Figure VI-14 depicts the Spring 1981 female length-age relationship. The vertical lines are approximately 95% confidence limits about the mean total lengths at each age. A length-age regression was not calculated for Spring 1981 males due to the small sample

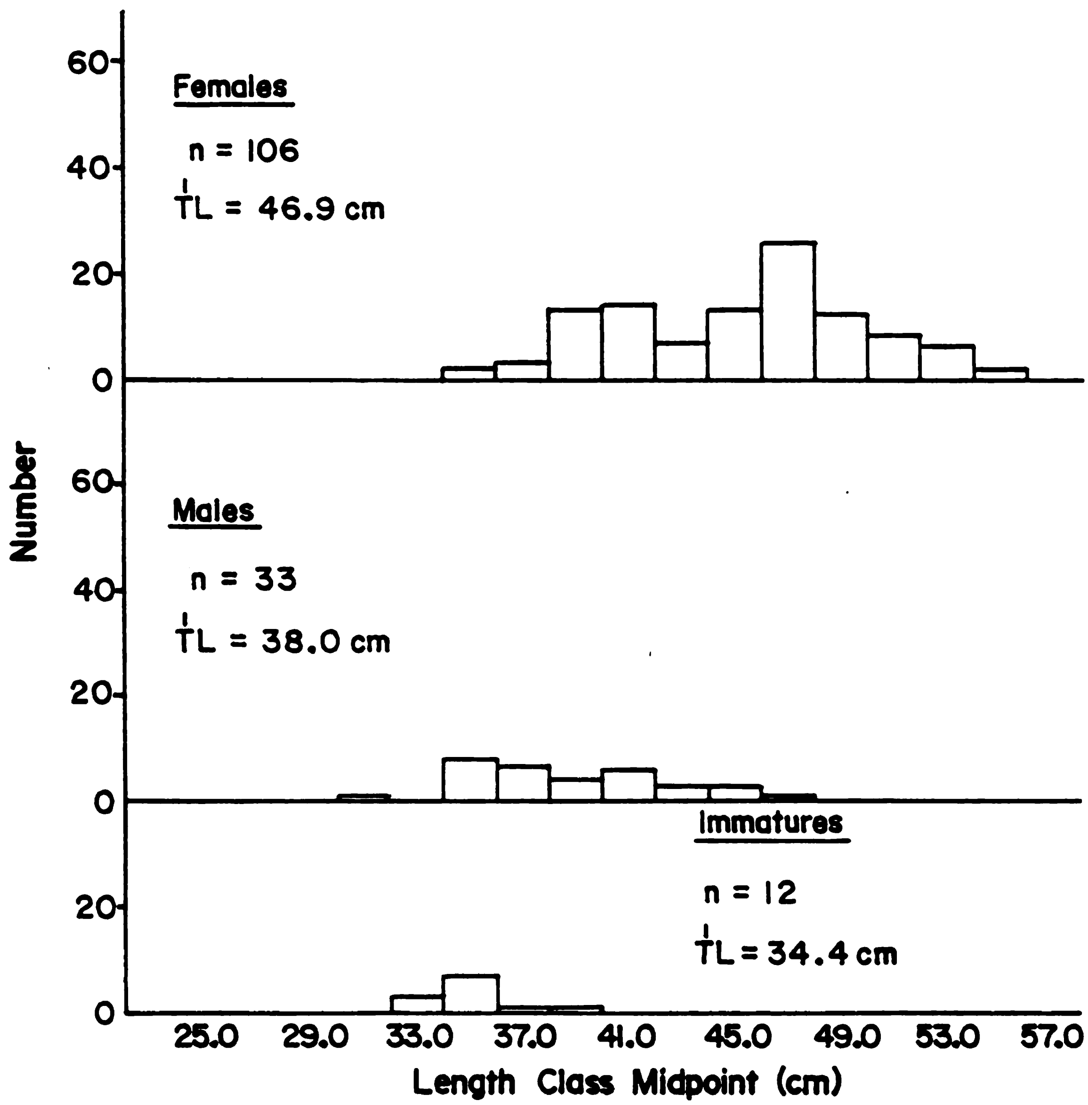


Figure VI-12. Spring 1981 Length-Frequency Distributions.

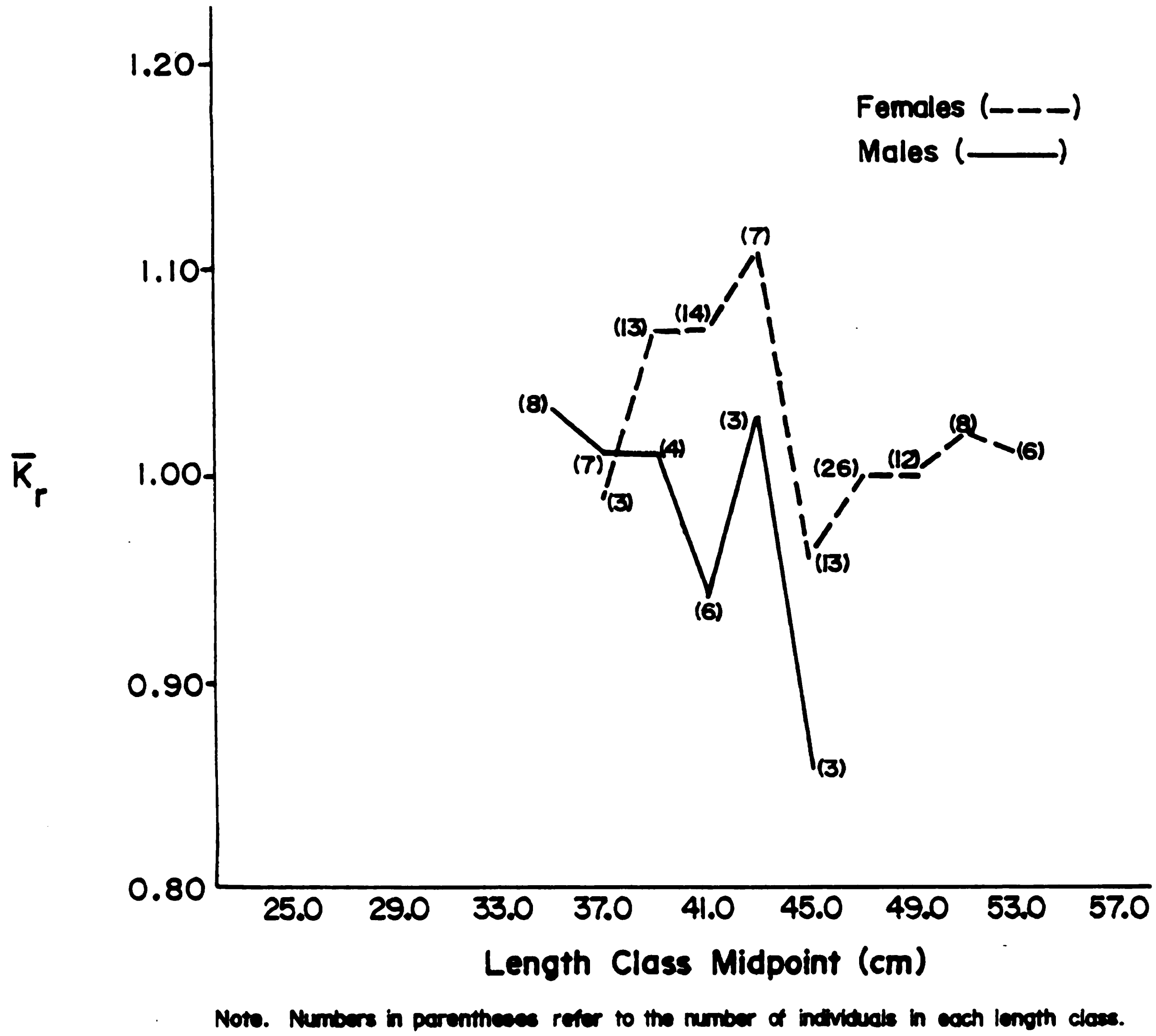


Figure VI-13. Spring 1981 Relative Condition Factors.

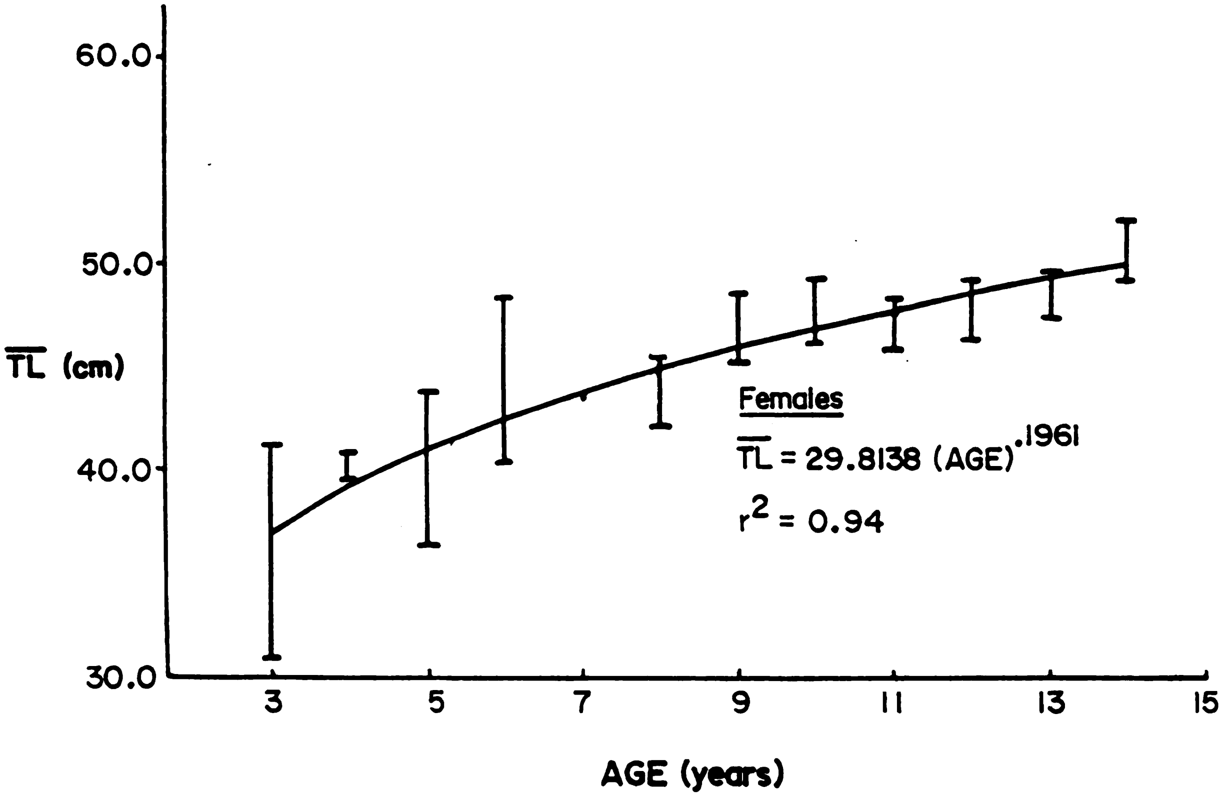


Figure VI-14. Spring 1981 Female Length-Age Relationship.

size represented by this sex. Analysis of covariance revealed no significant differences (p = .05) between the slopes or elevations of Spring 1980 and Spring 1981 female length-age regressions.

6. Composite Length-Frequency Distributions

Figure VI-15 represents the composite female, male and immature length-frequency distributions obtained by combining all samples (n = 1803) obtained during this investigation. This figure depicts the size selective scope of the Saginaw Bay trap net fishery for white suckers.

7. White Sucker Fecundity

The size-fecundity relationship for Saginaw Bay white suckers was determined as follows. Ovaries from 45 ripe females sampled during April 1980 and 1981 were removed and weighed to the nearest 5 grams. The ovaries from 13 of these ripe females were placed in glass jars and transported in ice to the laboratory. In the laboratory, a subsample of 50 eggs from each of the 13 ovaries was weighed to the nearest 0.1 mg on a Mettler single pan analytical balance, with the result divided by 50 to obtain an estimate of mean egg weight. The resulting 13 mean egg weight estimates ranged from 3.6 to 5.3 mg and averaged 4.5 mg. An estimate of the total number of eggs produced by each female was obtained by dividing the total ovary-egg complex weight (in grams) by 4.5 mg. The following size-fecundity regression was calculated,

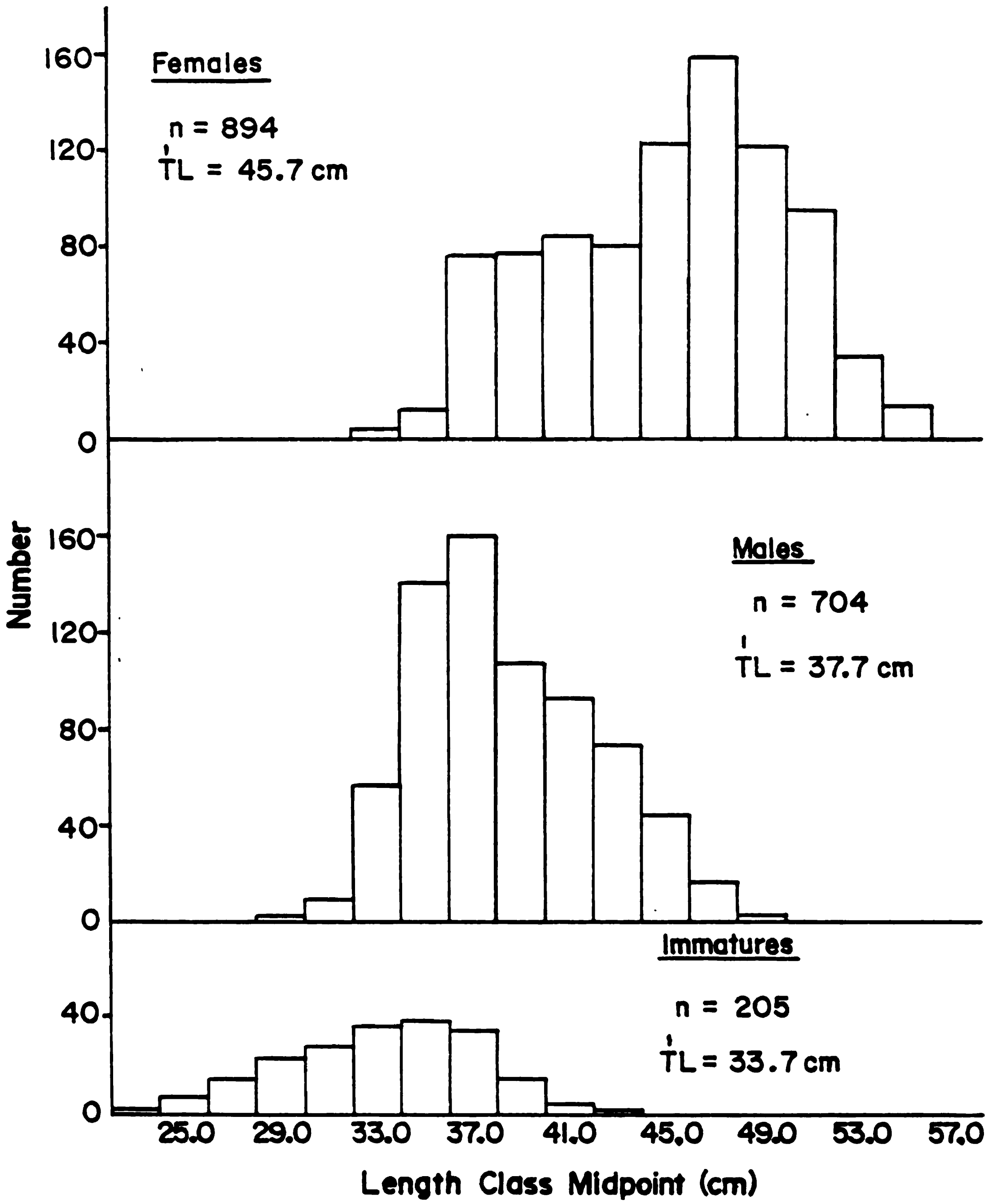


Figure VI-15. Composite Length-Frequency Distributions.

VI-13 $$m = a(TL)^b,$$

where: m = total number of eggs

TL = total length (cm).

The fecundity-size relationship for the combined sample of 45 ripe females sampled during April 1980 and 1981 is,

VI-14 $$\ln m = -0.0195 + 2.7355 \ln TL; \; r^2 = 0.49.$$

Fecundity computations obtained by applying equation VI-14 overestimate actual fecundity since the fraction of the total ovary-egg complex which is ovary is not subtracted from the total ovary-egg weight in the estimation process. This positive bias in estimating fecundity is not considered important for current descriptive purposes since more than 90% of the total ovary-egg weight consists of eggs.

The ovary-egg mass of the above 45 ripe females averaged approximately 14.9% of the total female weight and ranged from 9.8-20.5% of the total weight. In contrast, the testes-sperm mass of 22 ripe males sampled during April 1981 averaged 5.7% of the total male body weight, ranging from 3.7-9.1% of the total weight. The reproductive investment of female white suckers is considerably greater than that of males and is consistent with similar observations made by Lalancette (1975) in his investigation of white suckers in a 12.3 hectare Quebec lake.

8. Miscellaneous Observations

Previous investigations of white suckers in Lake Huron (i.e. Hall and Elliott, 1954 and Coble, 1967) indicated that the sea lamprey was an important factor regulating the size composition of white sucker populations. The current study found 11 out of 894 sampled females bore noticeable lamprey wound scars. All but 1 of these scarred females were greater than or equal to 45.0 cm in total length. Only 1 out of the 704 males sampled bore a noticeable lamprey scar. The sea lamprey does not appear to play a major role as a predator of Saginaw Bay white suckers unless it kills the vast majority of the individuals it attacks.

A number of large fish of both sexes were afflicted with a severe degenerative fungal-like disease of the anal or caudal fins. Several larger fish collected during the fall and spring seasons had parasitic roundworms embedded in their paired fins. A few individuals contained massive abdominal tumors which constituted up to 20% of their total body weight.

The maximum observed ages for females and males were 17+ and 19+ years old, respectively. Aging of individuals greater than 13+ or 14 years old was very difficult since fin ray annuli formed during later years were extremely close together and often undiscernible.

Food habit studies of Saginaw bay white suckers were precluded in this study by the fact that most samples, although well-preserved on ice, were more than 24 hours old.

A rapid degeneration of the digestive tract contents occurred within 24 hours after the fish were captured. Those digestive tracts observed contained large amounts of detritus and plant material and, especially in the fall, were often engorged with amphipods.

Perhaps the most notable aspect of Saginaw Bay white sucker biology, as inferred from samples obtained during the course of the present investigation, is the marked difference between male and female growth patterns as evidenced by the weight-length and length-age regressions. Analysis of covariance reveals no significant differences ($p = .05$) between slopes or elevations of the Fall 1979, Spring 1980 or Fall 1980 male length-age regressions. Covariance analysis indicates no significant differences ($p = .05$) between slopes of the Fall 1979, Spring 1980, Fall 1980 or Spring 1981 female length-age regressions. The differences between male and female length-age regressions, however, were significant ($p = .05$) for the Fall 1979, Spring 1980 and Fall 1980 samples. Insufficient numbers of Spring 1981 males were collected to justify calculation of the length-age regression, therefore no comparisons could be made between male and female Spring 1981 growth patterns.

9. Saginaw Bay Adult White Sucker Survival

A catch curve is a plot of the $\log_e$ frequency of occurrence of fish in each age class, from a given sample or samples, versus age. The typical form of a catch curve (Ricker, 1975) has a relatively steeply ascending left limb, a somewhat dome-shaped or flat upper portion, and a long descending right limb. The difference between natural log frequencies of fish in successive age classes in the descending portion of the catch curve is the negative quantity, -Z, where Z equals the instantaneous total mortality rate. The annual survival rate, S, between age classes is equal to e^{-Z}. Estimates of annual survival rate, S, between age classes can be calculated from the descending portions of catch curves. Ricker (1975) outlines the following assumptions upon which catch curve analyses depend: (1) annual survival rate, S, is uniform with age, over the range of age classes in question; (2) the instantaneous rates of fishing mortality, F, and natural mortality, M, are uniform; (3) mortality rate is time invariant; (4) the age sample is taken randomly from the age groups involved; and (5) the age classes in question were equal in numbers at the time each was recruited into the fishery.

The assumption of uniform recruitment from year to year is unrealistic since most fisheries experience frequent fluctuations in recruitment patterns, resulting in differences in year class strength. Differences in year class strength (i.e. unequal recruitment) alter the shape of the descending right limb of a catch curve. Ricker (1975) suggests that a good way to reduce catch curve irregularities caused by unstable recruitment is to combine samples of successive years. Male and female white sucker

age-frequency distributions observed during each seasonal sampling period exhibited marked irregularities. Accordingly, the combined male and female Fall 1979 and Fall 1980 observed age-frequency distributions were used to construct a catch curve (Figure VI-16) to estimate adult white sucker survival.

The ascending left limb of the catch curve shown in Figure VI-16 reaches a peak at age 3+, which indicates that fish are fully recruited into the fishery by this age. From age 3+ until age 7+ the curve experiences a steady decline, after which it rises until age 10+. The gradual rise in the curve from age 7+ to age 10+ could be due to non-random sampling or could reflect the influence of 3-4 consecutive strong year classes. After age 10+, the combined male and female catch curve declines more or less regularly until age 16+. The slope of the curve from age 3+ to age 7+ equals approximately -0.322 which yields a 0.72 survival rate estimate. The slope of the curve from age 10+ to age 16+ is about -0.422, which results in a 0.66 survival rate estimate. Due to the irregular ascending central portion of the curve (i.e. from age 7+ to age 10+), survival rate estimates could not be obtained for ages 8+ and 9+.

Figure VI-17 is the catch curve obtained by combining the male and female Spring 1980 and Spring 1981 age-frequency distributions. The ascending left limb of this catch curve reaches a peak at age 4. From age 4 until age 7

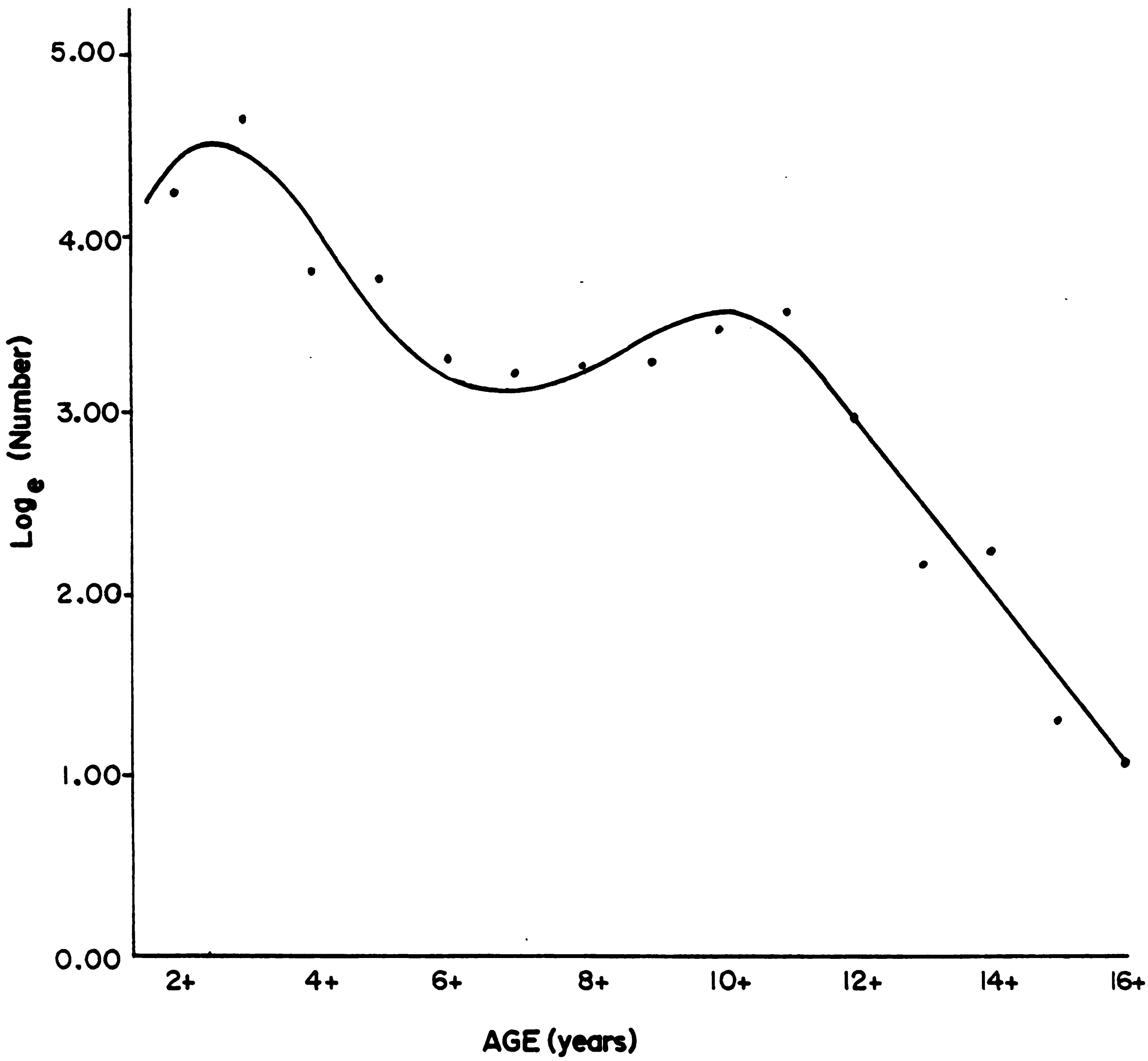


Figure VI-16. Combined Fall 1979 and Fall 1980 Catch Curve.

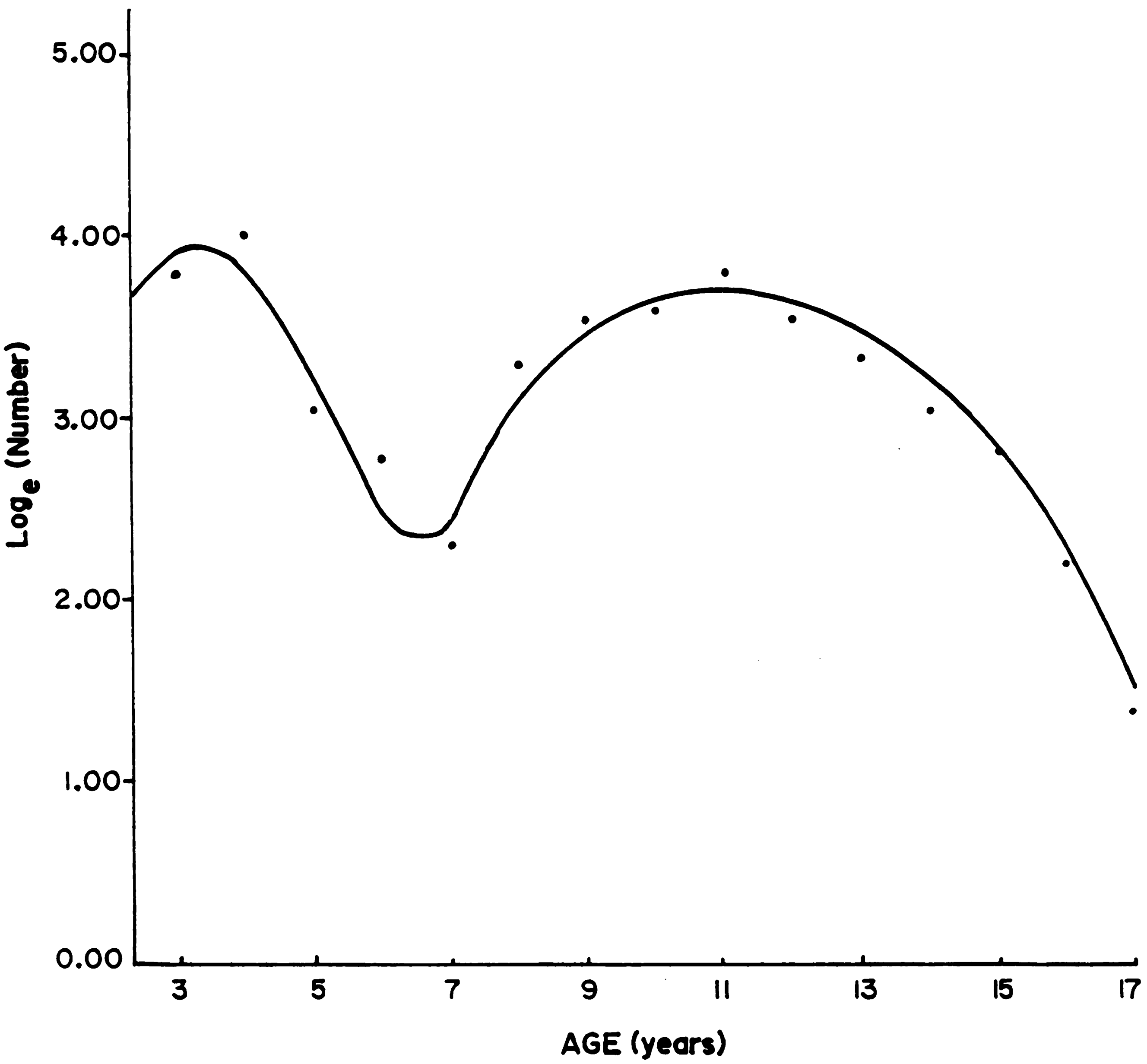


Figure VI-17. Combined Spring 1980 and Spring 1981 Catch Curve.

the curve declines steadily, after which it rises until age 11. After age 11, the curve declines steadily until age 17. The slope of the curve from age 4 to age 7 is approximately -0.533 which gives a 0.59 survival rate estimate. The slope of the curve from age 11 to age 17 is about -0.377, which results in a 0.69 survival rate estimate. Survival rate estimates could not be obtained for ages 8 - 10.

Estimates of annual survival rate, S, obtained by analyzing the catch curves shown in Figures VI-16 and VI-17 indicate that annual survival of adult white suckers in Saginaw Bay ranges from approximately 0.59 to 0.72. Coble (1967) in his study of white suckers in South Bay, Lake Huron, estimated that annual adult survival, S, ranged from 0.70 to 0.75. These investigations indicate that the survival rate of white suckers in Lake Huron is relatively high, reflecting the longevity and absence of signficant commercial exploitation of this species.

D. Estimation of Yield from a Given Recruitment

The decline in numbers of individuals after hatching is given by,

VI-15 $$dN/dt = -M(N),$$ with solution given by,

VI-16 $$N_t = N_o e^{-Mt},$$

where: N_o = the initial number of fish (i.e. fertilized eggs)

M = instantaneous natural mortality rate.

The number of individuals which survive to recruitment, R, is given by,

VI-17

$$R = N_o e^{-Mt_R}, \text{ where } t_R = \text{age of recruitment.}$$

After the age of recruitment, fish are subject, not only to the probability of death due to natural causes, M, but also to the probability of death due to fishing, F. At time, t (where $t > t_R$), the original number of recruits, R, is reduced to,

VI-18

$$R_t = Re^{-Z(t - t_R)}, \text{ where } Z = \text{total instantaneous mortality rate (i.e. } M + F).$$

The mean number of individuals from a given year class present during a given time period is obtained by integrating equation VI-18 with respect to time,

VI-19 $$N_t = \int_{t=tr}^{t=tm} Re^{-Z(t - t_R)}dt,$$ where t_m = maximum age attained. The catch in numbers from a year class after recruitment is obtained by multiplying the instantaneous rate of fishing mortality, F, times equation VI-19. By multiplying equation VI-18 by an expression for weight as a function of age and integrating with respect to time we obtain an expression for the sum of the yearly mean biomass of all fish in a year class, for all the years that it contributes to the fishery,

VI-20 $$\overline{B}_t = \int_{t=tr}^{t=tm} (WGT)_t Re^{-Z(t-t_R)}\, dt,$$

where WGT_t = weight as a function of age. The total yield in weight, C_t, from a year class after recruitment is obtained by multiplying the instantaneous rate of fishing mortality, F, times equation VI-20,

$$C_t = F\int_{t=tr}^{t=tm} (WGT)_t Re^{-Z(t-t_R)}\, dt. \qquad \text{VI-21}$$

To avoid specificiation of a recruitment function (which is usually much more complex than that implied by equation VI-17) equation VI-21 is often divided by R, which results in an expression for average yield per recruit, C_t/R, as a function of fishing mortality rate, F,

$$C_t/R = F\int_{t=tr}^{t=tm} (WGT)_t\, e^{-Z(t - t_R)}\, dt. \qquad \text{VI-22}$$

Equation VI-22 is referred to as the Beverton-Holt dynamic pool model and was introduced by Beverton and Holt (1957). If an investigator has information concerning: age at recruitment; maximum attainable age; instantaneous rate of natural mortality, M; and the relationship between weight and age, then equation VI-22 can be used to calculate the effects of different rates of fishing on the average yield per recruit. A given fishery can then be managed so as to produce a specified optimal yield per recruit by adjusting the rate of fishing, F. Of course, if the relationship between spawning stock size and subsequent number of recruits is known, then equation VI-21 can be used to estimate the effects of different rates of fishing on the total yield from the fishery.

When using either equation VI-21 or equation VI-22 to calculate equilibrium yield or yield per recruit, it is not

necessary to know the form of the growth function prior to the age of recruitment. All that is necessary is to find a function which describes weight as a function of age from $t = t_R$ to $t = t_m$. The historical development and use of the dynamic pool model assumed that fish growth was described by a Von Bertalanffy-type growth equation, which assumes asymptotic growth in length. There is no a priori reason to assume that the pattern of growth demonstrated by any given fish population is necessarily asymptotic. A better growth equation, which is directly applicable to the population under investigation, can often be obtained by relating the observed sizes of fish to their corresponding ages via some form of linear functional relationship. This is the suggestion put forward by Roff (1980) who advocates abandoning the use of the Von Bertalanffy growth function in fisheries applications.

Weight at age data for ages 2+ through >13+ from the Fall 1979 samples were used to determine a linear weight-age relationship for both males and females. Fish greater than 13+ years old demonstrated very little growth, therefore they were pooled with the age 13+ fish. For the purposes of these and other size-age calculations, fish aged as n+ were designated as age n.5 (i.e. a fish aged 3+ was treated as though it were age 3.5, etc.). The following simple linear regression model was used to describe the relationship between mean weight and age for both males and females,

VI-23 $$\overline{WGT} = a + b\,(AGE).$$

The female weight-age relationship is given by,

VI-24 $$\overline{WGT} = 426.3141 + 81.3462(AGE);\ r^2 = 0.99.$$

The male weight-age relationship is given by,

VI-25 $$\overline{WGT} = 475.6294 + 38.6713(AGE);\ r^2 = 0.87.$$

By substituting equation VI-23 into equation VI-22 we get,

VI-26 $$C_t/R = F\int_{t=tr}^{t=tm} (a + bt)e^{-(F + M)(t - t_R)}\, dt,$$

where t = AGE.

Integration of equation VI-26 results in,

VI-27 $$C_t/R = \frac{aF}{-(F+M)}\left[e^{-(F + M)(t_m - t_R)} - 1\right] + \frac{bF}{-(F+M)}\left[t_m e^{-(F + M)(t_m - t_R)} - t_R\right] + \frac{bF}{-(F+M)^2}\left[e^{-(F + M)(t_m - t_R)} - 1\right].$$

As mentioned previously, growth (in terms of length and weight) is negligible for both males and females after about age 13+. Therefore, for the purposes of the present analysis, t_m = 13+ (i.e. 13.5 years) for both sexes. Catch curve analyses indicate that adult white sucker survival, S, ranges from 0.59 to 0.72. If all mortality were attributable to natural factors, then these annual survival rates would indicate that instantaneous natural mortality, M, ranges from about 0.329 to 0.528. The results of Chapter III indicate that the current rate of fishing, F, is small (i.e. less than 0.1), implying that most of the Saginaw Bay adult white sucker mortality is probably attributable to natural causes. Assume a constant natural mortality rate of 0.4 for both males and females. The weight-age regression parameters, a and b, are obtained directly from equations

VI-24 and VI-25 for females and males, respectively. Catch curve analyses show that, although significant numbers of fish of age 2+ in the fall and of age 3 in the spring are captured by the fishery, full recruitment does not occur until fish are about age 3+ (for fall fish) and age 4 (for spring fish). We now have all of the parameters necessary to estimate equilibrium yield per recruit via equation VI-27.

Figure VI-18 depicts equilibrium yield per recruit for males and females at different rates of fishing, F, for two possible ages of recruitment, $t_R = 2.5$ and $t_R = 3.5$. The yield per recruit for females is higher than that for males at all levels of fishing, F, reflecting the differences between male and female growth rates. Optimal utilization of Saginaw Bay white suckers (in terms of maximization of equilibrium yield per recruit) under the conditions implied by Figure VI-18 should occur at rates of fishing, F, ranging from 0.6 to 1.2. This would involve a substantial increase in nominal fishing effort, f_t, from current levels, which are on the order of 3,000 shallow trap net lifts per year. The equilibrium yield per recruit curves shown in Figure VI-18 indicate that, at present rates of fishing (i.e. F less than or equal to 0.10), the potential productivity of Saginaw Bay sucker stocks is greatly underutilized. Recall the relationship between rate of fishing, F, and nominal effort, f_t,

III-9 $F = qf_t$, where q = catchability.

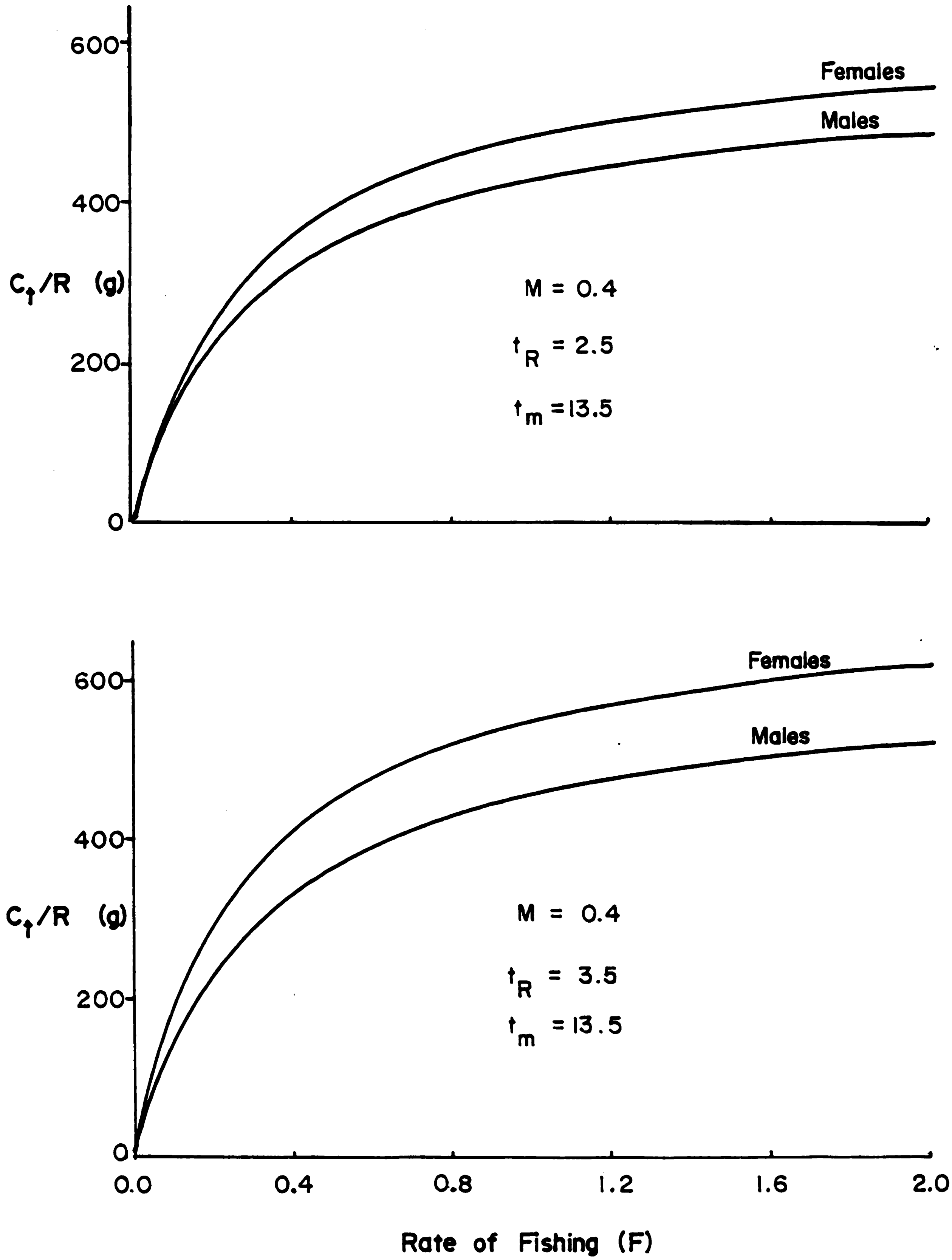


Figure VI-18. Equilibrium Yield Per Recruit at Different Rates of Fishing.

If catchability remains constant, then F can only increase with increasing nominal effort, f_t. If the current rate of fishing, F is approximately 0.1, then a six-fold expansion in nominal effort, f_t, would be necessary to raise the rate of fishing to 0.6. It is doubtful that the present commercial fishery has the capability to expand its effort by the amount necessary to attain optimal utilization of the sucker fishery.

E. Estimating Mortality Rates of Pre-recruits

One of the most important aspects of population dynamics research is the determination of age-specific rates of survival. Representative sampling (e.g. of the commercial catch) of the adult portion of a population enables an investigator to obtain post-recruit survival estimates via catch curve analyses. Unfortunately, difficulties and costs associated with sampling younger life stages usually preclude direct survival rate estimation of pre-recruit age classes.

Perhaps the most fundamental problem facing fisheries managers and investigators is the determination of the spawning stock - recruit relationship (i.e. the so-called recruitment curve). Knowledge about the recruitment process helps fisheries managers exert more precise control over the fisheries relegated to their stewardship. Compensatory recruitment mechanisms, if properly delineated, describe potential fluctuations in year class strength. Knowledge about year class strength enables fisheries managers to

adjust the rates of fishing, F, to take advantage of exceptionally strong year classes or to protect the fishery during a series of poor recruitment years. Recruitment curve delineation depends upon knowledge of pre-recruitment survival rates, particularly of the age 0 year class.

Vaughan and Saila (1976) describe an indirect method for determining age 0 survival rates via application of the Leslie Matrix. This method depends upon the following assumptions: (1) mortality rates are constant over time; (2) fishing mortality is zero for the age 0 year class; (i.e. the population age structure is stable); and (3) the population is in equilibrium (i.e. is neither growing nor declining in size). Any one element of the Leslie Matrix can be indirectly determined if the remaining age-specific fecundity and survival relationships are known. The assumption of an equilibrium population implies that the dominant eigenvalue of the Leslie Matrix is equal to 1. Let F_x be the number of females born in the interval, t to t + 1, per female of age x to x + 1 at time t who will be alive in the 0th age class at time t + 1 or,

VI-28 $$F_x = S_x m_{x+1},$$

where: S_x = the probability that an individual reaching age x will survive to age x + 1

m_{x+1} = the number of females born per female of age x + 1.

Define the Leslie Matrix as follows,

$$\underline{L} = \begin{bmatrix} F_0 & F_1 & F_2 & \cdots & F_{k-2} & F_{k-1} \\ S_0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & S_1 & 0 & \cdots & 0 & 0 \\ 0 & 0 & S_2 & \cdots & 0 & 0 \\ \cdot & \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & \cdot & & \cdot & \cdot \\ 0 & 0 & 0 & \cdots & S_{k-2} & 0 \end{bmatrix}$$

Define the population state vector, N(t) as follows:

$$\overrightarrow{N(t)} = \begin{bmatrix} n_0(t) \\ n_1(t) \\ \cdot \\ \cdot \\ \cdot \\ n_{k-1}(t) \end{bmatrix}$$

where $n_x(t)$ equals the number of individuals (females) of age x at time t. The population state vector at time t + 1 is,

VI-29 $\overrightarrow{N(t+1)} = \overrightarrow{\underline{L}N(t)}$.

Equation VI-29 is a special case of the following first order linear homogeneous difference equation,

VI-30 $\overrightarrow{N(t)} = \underline{L}^t N(0)$.

The dominant positive eigenvalue, R, of $\underline{L}$ is obtained by solving,

VI-31 $|\underline{L} - \underline{R}\,\underline{I}| = 0$, where $\underline{I}$ = the identity matrix.

A scalar R is called an eigenvalue of $\underline{L}$ if there exists a non-zero vector $\vec{X}$ such that,

VI-32 $\underline{L}\vec{X} = R\vec{X}$.

If R = 1 (i.e. the population is in equilibrium) age 0 survival rate, S_0, is determined from,

VI-33 $$|\underline{L}-\underline{I}| = 0, \text{ or}$$

VI-34 $$S_0 = (1 - F_0)/(F_1 + S_1F_2 + S_1S_2F_3 + \ldots + S_1 \ldots S_{k-2}F_{k-1}).$$

Table VI-6 contains the basic data necessay for constructing a Leslie Matrix for female Saginaw Bay white suckers. Analysis of covariance indicates no significant differences (p = .05) between slopes of the Fall 1979, Spring 1980,or Fall 1981 female total length-age regressions. The length at age column in Table VI-6 is derived by pooling the Fall 1979, Spring 1980, Fall 1980 and Spring 1981 female length-age regressions which results in,

VI-35 $$TL = 31.1073(AGE)^{.1862}.$$

Catch curve analysis of the combined Fall 1979 and Fall 1980 age samples indicates that annual survival rate, S, from age 3+ to age 7+ is about 0.72 and from age 10+ to age 16+ is approximately 0.66. These survival rate estimates were used as guidelines for the age-specific survival rates listed in Table VI-6 for ages 3+ to 13+. Since survival rates of pre-recruits are almost certainly less than adult survival rates, estimates of age 1 and 2 survival are S = 0.30 and S = 0.50, respectively. Recall the size-fecundity relationship described by equation VI-14.

VI-14 $$m_x = .9807(TL)^{2.7355}.$$

Assuming a 1-1 sex ratio (i.e. the number of male and female eggs produced are equal) the size-fecundity relationship

Table VI-6

Female Age-Specific Fecundity and Survival Rates

Age	TL(cm)	S_x	m_x	F_x
0			0	0
1		0.30	0	0
2		0.50	0	0
3		0.70	0	8451
4	40.3	0.70	12073	9463
5	42.0	0.70	13518	10350
6	43.4	0.70	14786	11221
7	44.7	0.70	16030	11992
8	45.8	0.65	17132	11814
9	46.8	0.65	18175	12517
10	47.8	0.65	19257	13098
11	48.6	0.60	20151	12643
12	49.4	0.60	21072	13211
13+	50.2	0.00	22018	

shown in Table VI-6 is given by,

VI-36 $$m_x = (.5) \times .9807(TL)^{2.7355}.$$

The Leslie Matrix constructed from the data contained in Table VI-6 is a 13 x 13 square matrix. Age 0 survival rate is obtained by application of equation VI-35 to the Table VI-6 data,

VI-37 $$S_0 = (1 - 0)/(4816.08) = 2.076 \times 10^{-4}.$$

According to equation VI-37, approximately 2 females out of 10,000 fertilized eggs survive the first year of life. The preceding Leslie Matrix calculations assume that Saginaw Bay female white suckers first spawn at age 4. The weakest links in the age-specific survival and fecundity data listed in Table VI-6 are the estimates of age 1 and age 2 annual survival rates, for which no concrete data could be obtained.

In Chapter IV, application of the logistic surplus production model to commercial fishery catch and effort data from 1968 to 1978 resulted in an estimated carrying capacity of approximately 3,913,000 lbs (i.e. 1,779,000 kg). This is an estimate of the total catchable biomass of white suckers in Saginaw Bay. The percentages of the combined weight of all the samples obtained during this study as immatures, males and females were 5.85%, 31.52% and 62.63%, respectively. If we multiply these percentages by 1,779,000 kg, we obtain rough estimates of the total weight of catchable immatures, males and females (i.e. 104,072 kg immatures; 560,741 kg males; 1,114,188 kg females). The mean weights of immatures, males and females obtained during this investigation were 395 g, 620 g and 970 g, respectively. By dividing total weight estimates of catchable immatures, males and females by mean individual weights, we obtain estimates of the total numbers of catchable immatures, males and females (i.e. 263,000 immatures; 904,000 males; 1,149,000 females). Assume, for the present purposes, that white suckers are catchable once they reach age 2. Also assume that age 13 is the maximum attainable age. The total number of exploitable females is given by,

VI-38 $$N(t) = \sum_{i=2}^{13} n_i(t), \text{ where } n_i(t) = \text{no. in age class } i.$$

Now, the absolute number of females in age class i is,

VI-39 $$n_i(t) = n_0 \prod_{j=0}^{i-1} S_j, \text{ where } S_j = \text{prob. of survival from age } t \text{ to age } t+1.$$

Substituting equation VI-39 into equation VI-38 we obtain,

VI-40 $$N(t) = \sum_{i=2}^{13} (n_0 \prod_{j=0}^{i-1} S_j) = n_0 \sum_{i=2}^{13} \prod_{j=0}^{i=1} S_j.$$

Solving equation VI-40 for n_0 we get,

VI-41 $$n_0 = N(t)/(\sum_{i=2}^{13} \prod_{j=0}^{i-1} S_j).$$

With the estimate of age 0 survival obtained from equation VI-37 coupled with the annual survival rate estimates listed in Table VI-6 we obtain the following value for the denominator of equation VI-41,

$$\sum_{i=2}^{13} \prod_{j=0}^{i-1} S_j = 0.0001622982943.$$

The numerator for equation VI-41 is our previous estimate of to total number of catchable females (i.e. 1,149,000).

Dividing 1,149,000 by 0.0001622982943 we obtain an estimate of the total number of female eggs produced (i.e. 7,079,557,000). Assuming a 1-1 sex ratio, the total number of eggs produced would equal about 14,159,114,000. If the average female ($\overline{TL}$ = 44.8 cm) produces $.9807(44.8)^{2.7355}$ = 32,300 eggs, then the total number of spawning females is approximately 438,000.

Jensen (1974) describes a Leslie Matrix approach to fishery yield estimation as follows,

VI-42 $$\vec{C}_t = \underline{F}\underline{W}\underline{L}^t\overrightarrow{N(0)},$$

where: $\vec{C}_t$ = total catch (harvest) vector

$\underline{F}$ = a diagonal k x k matrix with age-specific rates of fishing on the diagonal and zeroes elsewhere

$\underline{W}$ = a diagonal k x k matrix with age-specific weights on the diagonal and zeroes elsewhere

$\underline{L}$ = the Leslie Matrix

$\overrightarrow{N(0)}$ = the initial population state vector.

Equation VI-42 and similar discrete time population harvest models could be useful predictors of future harvest levels from age-specific rates of fishing, F_i, provided a reliable estimate of the population state variable, $\overrightarrow{N(0)}$, is available. The present investigation obtained a rough estimate of the age class distributions of males and females greater than or equal to 2+ years old. The contribution of 2+ year old fish to these age class distributions is underestimated since fish are not fully recruited into the fishery until they reach age 3+. Indirect estimates of the size of age class 0 depend upon the assumption of an equilibrium population. Insufficient data is available to substantiate this assumption although it seems reasonable as a first approximation, in light of the absence of information to the contrary. No estimates of the size of age class 1 are available. In short, the lack of a reliable measure of the Saginaw Bay white sucker population state variable, $\overrightarrow{N(0)}$, precludes meaningful application of equation VI-42.

CHAPTER VII

Summary and Recommendations

A. Recapitulation

This investigation was undertaken to determine potential limits on the commercial exploitation of Saginaw Bay suckers. Three species of suckers (i.e. white, longnose and redhorse suckers) occur commonly in the waters of Saginaw Bay. The white sucker dominates the species composition of the commercial sucker catch, accounting for more than 90% of all landings. Accordingly, the major portion of this study involved determining the population dynamics of Saginaw Bay white suckers.

Population dynamics data (e.g. catch and effort records, age and growth information) were considered representative of a single homogeneous stock of fish. This may be a rather sweeping assumption, considering the large area (2960 km^2) of Saginaw Bay and the observations by Olson and Scidmore (1963) and Coble (1967), which indicate that white suckers typically exhibit little in the way of long range movements. Refer to Figure II-1 which shows at least 10 tributary streams and rivers emptying into Saginaw Bay. Each of these tributaries may accommodate the spring spawning run of a distinct stock of white suckers. For present purposes, however, it is assumed that available data reflect the average characteristics of several possible white sucker stocks.

The description and analysis of commercial fishery catch and effort data is central to this investigation's study of white sucker population dynamics. Chapter III contains an in-depth analysis of Saginaw Bay sucker fishery data from 1929-1956 and from 1960-1979. In general, these data reflect decreasing rates of exploitation and increasing levels of abundance of Saginaw Bay sucker stocks. Current annual sucker harvests approximate 100,000-150,000 pounds, which is about an order of magnitude less than historical maximum harvest levels. The analysis of recent (1960-1979) catch and effort data is complicated by the fact that, in recent years, only a fraction (i.e. from one-fourth to one-third) of the actual catch has been landed, reflecting the absence of a remunerative market for Great Lakes suckers. A cautious interpretation of these data indicates that up to 500,000 pounds of suckers could be harvested annually without overexploiting the stocks.

Chapter IV contains a simple bioeconomic analysis of the current Saginaw Bay commercial sucker fishery. The logistic surplus production model is used as the production function for this analysis. The reliability of this production function may be questioned since it was derived for a period of time (1968-1978) represented by relatively few data points. A similar production function, representing a longer time frame (1930-1955) was not used since it was assumed these earlier data no longer describe current fishery dynamics. According to this analysis, an ex-vessel price increase from \$0.05/lb to \$0.10/lb would generate a short term economic rent of approximately \$11,000 to the commercial fishery.

According to the U.S. Food and Drug Administration, Great Lakes fish marketed for human consumption may contain no more than 5 ppm PCB's and no more than 5 ppm ΣDDT (i.e. DDT and its analogs, DDD and DDE). Chapter V summarizes the results of PCB and ΣDDT analyses on samples of 25 white suckers obtained from the Fall 1979 and Spring 1980 commercial landings. These analyses indicate that the mean levels of PCB's (0.05 ppm) and ΣDDT (0.015 ppm) in the edible fish (fillets) of Saginaw Bay white suckers are well below the FDA tolerance limits for these compounds. These results are encouraging with respect to future development of the Saginaw Bay sucker fishery since they indicate that organic chemical contaminants should not be limiting factors to enhanced sucker utilization.

One of the primary objectives of this investigation was the establishment of a preliminary data base regarding: the size, age and sex composition and age-specific growth and mortality rates of Saginaw Bay white sucker stocks. This information is presented in Chapter VI and constitutes, perhaps, the most important aspect of this study. Adult white suckers in Saginaw Bay experience low growth rates (from 1-2 cm in total length per year), high annual survival rates, S (from 0.59 to 0.72) and long life spans (up to 19+ year old). Females grow faster and larger and, on the average, live longer than males. These characteristics are diagnostic of an underexploited fishery. An increased rate of fishing, F, should result in increased growth rates as the stocks compensate for increased mortality rates. Increased levels of exploitation should change the age and size composition of the stocks as older and larger individuals are removed from the fishery.

In Chapter VI, a modification of the Beverton-Holt dynamic pool model was used to estimate the equilibrium yield per recruit at different rates of fishing, F. In this model, the age-weight relationship was described by a simple linear function, which allowed for a simple closed form solution of the dynamic pool equation without the assumption of a Von Bertalanffy-type growth form. This analysis indicates that optimal utilization (in terms of maximum yield per recruit) of the Saginaw Bay sucker fishery can only occur with a comparatively large increase in the rate of fishing (i.e. from 6 to 10 times current levels).

The Saginaw Bay sucker fishery is a greatly underexploited resource. Current harvest levels could probably be safely increased by as much as 500% without risk of overexploitation. Increased sucker utilization, however, depends upon establishment of dependable and profitable markets for suckers and sucker products.

B. Recommendations

Future investigations of the dynamics of Saginaw Bay suckers stocks should include a comprehensive mark and recapture study to obtain estimates of population size and information about fish movements and distribution within the bay. Catch-effort methods of population size estimation as used in Chapter III are not the most reliable means of determining the magnitude of the population state variable $\overrightarrow{N(t)}$. In Chapter VI, a Leslie Matrix approach to yield estimation (Jensen, 1974) was suggested, but was not utilized due to the lack of a reliable estimate of $\overrightarrow{N(t)}$. This could prove to be a fruitful approach in future investigations of the dynamics of Saginaw Bay sucker stocks.

This investigation concentrated on white sucker population dynamics. Future studies should include efforts to obtain population dynamics information about the other commercially harvested sucker species, longnose and redhorse suckers. This information is needed to help insure the rational exploitation of all sucker species within Saginaw Bay.

Management of the Saginaw Bay sucker fishery solely by means of commercial fishery catch and effort statistics should be avoided, if possible, since these data are not entirely reliable. Catch-effort data analyses depend upon the assumption of equilibrium conditions with respect to the various factors influencing population growth. In the short term, fishery expansion upsets these equilibrium conditions, thereby destroying the predictive utility of the catch per unit effort ratio, C_t/f_t, at least until the fishery reaches a new equilibrium. Increased development of this fishery should be monitored by a spring and fall commercial catch sampling program designed to ascertain the size, age and sex distribution of the exploited populations. Information obtained from such sampling efforts could be used to monitor the response of the sucker stocks to changing rates of fishing, F. For example, marked shifts in stock size or age composition toward smaller sizes and younger ages could indicate overfishing, in which cases appropriate controls on fishing effort could be instituted.

The difficulties associated with the economic analysis of a single species fishery within the framework of a multi-species fishery are discussed in Chapter IV. Additional economic information (e.g. costs and revenues associated with harvesting all commercially utilized species) would be helpful. This information would be used to place the developing sucker fishery in its proper perspective relative to the entire fishery.

Periodic assessments of the levels of potentially harmful environmental contaminants should be undertaken to insure continuing compliance with applicable governmental tolerance limits. Such efforts should probably be conducted every second or third year, funding permitted.

Management expenditures incurred to monitor the size, age and sex composition of Saginaw Bay sucker stocks should

be relatively minor, particularly if similar information on other exploited species (e.g. yellow perch, channel catfish, lake whitefish) is concurrently obtained.

C. Critique

Often, when analyzing dynamic ecological and economic systems, we presuppose the existence of more or less stable equilibria around which the behavior of these systems is centered. All of the analyses of Saginaw Bay white sucker population dynamics contained in this report assume the existence of equilibrium conditions. In light of available information, we have no way of knowing whether or not such assumptions are justified.

APPENDICES

Table A1

Fall 1979 Female Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	TL(cm)
2+	20	37.3	1.443	35.0 - 41.7	37.1
3+	12	39.4	2.003	36.5 - 42.6	39.8
4+	10	40.4	2.334	37.2 - 44.0	40.4
5+	7	42.7	1.718	39.8 - 44.4	43.5
6+	12	43.9	2.139	38.8 - 47.8	43.9
7+	4	45.8	2.765	42.5 - 49.0	45.9
8+	7	46.0	1.049	44.8 - 48.0	45.8
9+	8	47.0	2.047	44.3 - 50.5	47.1
10+	9	49.5	0.866	48.4 - 50.7	49.6
11+	11	49.8	3.281	44.6 - 54.5	49.8
12+	10	50.7	2.057	47.3 - 53.3	51.0
≥13+	10	51.7	2.017	48.6 - 55.6	51.5

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2+	20	590	84.722	450 - 830
3+	12	715	111.017	570 - 910
4+	10	780	151.416	550 - 995
5+	7	905	105.503	720 - 1010
6+	12	960	151.130	590 - 1220
7+	4	1095	95.656	970 - 1195
8+	7	1115	104.100	995 - 1260
9+	8	1150	142.422	925 - 1385
10+	9	1305	181.311	1045 - 1550
11+	11	1370	271.605	970 - 1700
12+	10	1435	200.042	1125 - 1795
≥13+	10	1505	136.541	1260 - 1795

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2+	20	0.98	0.096	0.75 - 1.21
3+	12	1.02	0.067	0.93 - 1.17
4+	10	1.03	0.102	0.92 - 1.26
5+	7	1.03	0.050	0.95 - 1.10
6+	12	1.01	0.067	0.88 - 1.09
7+	4	1.04	0.081	0.94 - 1.12
8+	7	1.04	0.069	0.95 - 1.15
9+	8	1.01	0.125	0.81 - 1.23
10+	9	0.99	0.119	0.82 - 1.16
11+	11	1.02	0.107	0.80 - 1.21
12+	10	1.02	0.087	0.94 - 1.22
≥13+	10	1.02	0.070	0.88 - 1.11

TABLE A2

Fall 1979 Male Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	TL'(cm)
2+	34	35.6	1.863	32.0 - 40.5	35.7
3+	17	37.6	3.110	34.4 - 48.5	37.7
4+	7	39.3	1.670	37.4 - 42.4	38.8
5+	5	39.9	2.066	37.5 - 42.2	40.8
6+	5	40.0	2.064	38.0 - 43.0	39.6
7+	5	41.1	1.199	39.7 - 42.0	41.8
8+	5	41.0	1.598	39.4 - 43.5	40.5
9+	6	43.7	1.819	41.5 - 46.2	43.8
10+	6	44.7	0.857	43.5 - 45.6	44.9
11+	5	44.6	1.903	42.5 - 47.6	44.0
12+	2	42.9		42.5 - 43.2	
≥13+	7	45.2	1.649	43.8 - 47.8	44.4

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2+	34	520	80.597	375 - 740
3+	17	570	67.064	450 - 655
4+	7	660	75.986	600 - 815
5+	5	720	126.125	545 - 840
6+	5	725	158.493	485 - 900
7+	5	800	81.670	690 - 870
8+	5	805	82.417	730 - 910
9+	6	935	148.683	790 -1180
10+	6	915	93.113	810 -1030
11+	5	965	75.033	860 -1060
12+	2	845		825 - 860
≥13+	7	960	123.741	820 -1190

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2+	34	0.97	0.058	0.82 - 1.07
3+	17	0.93	0.115	0.51 - 1.01
4+	7	0.94	0.044	0.90 - 1.04
5+	5	0.98	0.067	0.89 - 1.07
6+	5	0.98	0.121	0.76 - 1.05
7+	5	1.02	0.031	0.96 - 1.04
8+	5	1.03	0.043	0.99 - 1.09
9+	6	1.01	0.114	0.79 - 1.10
10+	6	0.92	0.071	0.83 - 1.01
11+	5	0.99	0.112	0.79 - 1.06
12+	2	0.96		0.95 - 0.96
≥13+	7	0.94	0.079	0.84 - 1.04

Table A3

Fall 1979 Immature Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{'}{TL}$(cm)
1+	13	28.5	1.634	25.7 - 30.8	28.5
2+	21	33.5	1.903	30.8 - 37.0	33.0
3+	2	35.7		34.9 - 36.5	

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
1+	13	265	57.641	170 - 350
2+	21	430	80.668	315 - 570
3+	2	500		455 - 545

Age	n	$\overline{K}_r$	s_{Kr}	Kr range
1+	13	0.91	0.100	0.76 - 1.06
2+	21	0.95	0.110	0.81 - 1.35
3+	2	0.93		0.90 - 0.96

Table A4

Spring 1980 Female Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{\mid}{TL}$(cm)
3	9	39.5	1.218	37.7 - 41.6	39.1
4	6	39.9	1.256	38.0 - 41.5	40.1
5	11	43.1	2.787	38.9 - 48.5	43.0
6	7	44.6	1.172	42.5 - 45.7	44.3
7	3	45.3	0.723	44.5 - 45.8	45.7
8	17	45.4	2.814	40.6 - 50.4	45.0
9	21	46.5	1.821	43.3 - 50.8	46.4
10	18	47.6	1.768	44.3 - 50.2	47.3
11	27	48.2	2.154	42.9 - 52.0	47.7
12	17	49.0	1.813	45.1 - 51.7	49.3
13	14	50.4	1.924	47.3 - 54.4	50.5
≥14	28	50.5	2.306	46.7 - 55.1	50.6

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
3	9	705	65.865	620 - 830
4	6	745	58.195	640 - 820
5	11	895	162.500	720 - 1140
6	7	945	172.354	740 - 1200
7	3	980	169.730	830 - 1165
8	17	915	160.438	685 - 1300
9	21	940	130.512	720 - 1230
10	18	1050	135.916	820 - 1360
11	27	1070	144.571	850 - 1500
12	17	1160	125.716	1010 - 1470
13	14	1220	155.599	1060 - 1630
≥14	28	1240	200.988	865 - 1730

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
3	9	1.09	0.093	0.93 - 1.22
4	6	1.12	0.073	1.04 - 1.21
5	11	1.10	0.118	0.93 - 1.26
6	7	1.08	0.175	0.87 - 1.28
7	3	1.07	0.176	0.89 - 1.24
8	17	0.99	0.079	0.80 - 1.09
9	21	0.96	0.060	0.87 - 1.04
10	18	1.01	0.083	0.91 - 1.21
11	27	1.00	0.101	0.84 - 1.34
12	17	1.02	0.078	0.90 - 1.19
13	14	1.01	0.083	0.83 - 1.13
≥14	28	1.02	0.124	0.87 - 1.34

Table A5

Spring 1980 Male Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\tilde{TL}$(cm)
3	29	36.3	1.789	32.6 - 39.8	36.2
4	8	37.3	1.441	35.2 - 39.6	37.1
5	5	41.6	1.369	40.1 - 43.5	41.0
6	4	38.1	0.854	37.0 - 39.0	38.3
7	6	41.3	0.967	39.8 - 42.8	41.3
8	4	42.5	2.347	39.5 - 44.5	43.0
9	6	40.8	0.937	39.7 - 42.2	40.6
10	12	43.3	2.322	40.0 - 46.5	42.7
11	6	43.1	1.479	41.5 - 45.2	42.9
12	5	44.2	1.440	42.7 - 45.8	44.5
13	2	46.2		45.8 - 46.5	
≥14	7	44.4	1.419	42.0 - 46.0	44.5

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
3	29	530	80.017	420 - 740
4	8	575	102.913	470 - 750
5	5	700	76.518	600 - 780
6	4	600	53.600	530 - 660
7	6	690	79.587	635 - 840
8	4	820	149.129	635 - 1000
9	6	675	69.839	600 - 790
10	12	770	139.069	595 - 1000
11	6	755	118.677	640 - 985
12	5	790	109.396	625 - 900
13	2	950		940 - 960
≥14	7	860	95.250	700 - 960

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
3	29	1.01	0.081	0.84 - 1.16
4	8	1.02	0.126	0.78 - 1.16
5	5	0.95	0.083	0.84 - 1.08
6	4	1.01	0.056	0.97 - 1.09
7	6	0.95	0.067	0.88 - 1.06
8	4	1.05	0.095	0.95 - 1.14
9	6	0.96	0.074	0.89 - 1.07
10	12	0.94	0.101	0.75 - 1.07
11	6	0.93	0.086	0.86 - 1.08
12	5	0.91	0.091	0.79 - 1.01
13	2	0.99		0.96 - 1.02
≥14	7	0.97	0.053	0.90 - 1.06

Table A6

Spring 1980 Immature Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	TL'(cm)
2	2	33.7		31.9 - 35.5	
3	28	36.7	2.407	29.1 - 40.3	36.6
4	7	36.4	2.307	34.2 - 40.7	35.9
6	2	36.2		34.9 - 37.5	
7	2	41.7		40.7 - 42.6	

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2	2	395		340 - 450
3	28	525	83.826	255 - 690
4	7	530	90.501	450 - 695
6	2	535		480 - 590
7	2	695		670 - 720

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2	2	0.91		0.91 - 0.92
3	28	0.97	0.068	0.86 - 1.14
4	7	1.01	0.070	0.89 - 1.09
6	2	1.03		1.02 - 1.04
7	2	0.94		0.92 - 0.96

Table A7

Summer 1980 Female Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{\prime}{TL}$(cm)
2	1	33.0			
3	17	37.3	1.900	34.0 - 40.8	37.3
4	4	39.5	1.239	38.0 - 40.5	39.7
5	7	42.4	2.480	39.1 - 46.5	41.9
6	1	42.5			
7	3	42.5	2.339	39.8 - 43.9	43.8
9	1	43.2			
11	2	47.4		46.8 - 48.0	
≥13	3	52.6	3.601	48.7 - 55.8	53.3

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2	1	420		
3	17	550	86.674	410 - 690
4	4	655	62.099	600 - 710
5	7	825	241.451	570 - 1220
6	1	805		
7	3	730	90.875	630 - 805
9	1	840		
11	2	1125		1055 - 1190
≥13	3	1185	197.547	985 - 1380

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2	1	1.15		
3	17	1.06	0.103	0.85 - 1.29
4	4	1.09	0.032	1.04 - 1.11
5	7	1.11	0.180	0.89 - 1.33
6	1	1.10		
7	3	1.00	0.038	0.96 - 1.03
9	1	1.10		
11	2	1.13		1.10 - 1.16
≥13	3	0.90	0.122	0.77 - 1.01

Table A8

Summer 1980 Male Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{\mid}{TL}$(cm)
2	7	31.9	1.490	30.0 - 33.9	31.7
3	35	35.2	1.713	29.0 - 37.9	35.0
4	2	39.0		38.6 - 39.4	
5	3	39.5	1.217	38.7 - 40.9	38.9
7	1	40.0			
9	2	41.0		39.5 - 42.5	
11	1	41.0			

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2	7	360	45.539	300 - 420
3	35	445	80.844	240 - 620
4	2	580		565 - 595
5	3	625	132.571	490 - 755
7	1	580		
9	2	630		580 - 680
11	1	650		

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2	7	1.08	0.036	1.04 - 1.14
3	35	1.01	0.101	0.84 - 1.22
4	2	1.00		
5	3	1.04	0.150	0.87 - 1.15
7	1	0.94		
9	2	0.95		0.93 - 0.97
11	1	0.98		

Table A9

Summer 1980 Immature Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	TL'(cm)
2	21	29.3	3.055	24.3 - 39.2	29.0
3	2	37.0		36.7 - 37.2	

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2	21	260	65.938	145 - 385
3	2	540		495 - 580

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2	21	0.98	0.150	0.45 - 1.22
3	2	1.08		0.97 - 1.18

Table A10

Fall 1980 Female Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	TL'(cm)
2+	4	36.7	1.555	34.6 - 38.0	37.0
3+	37	39.9	1.596	36.2 - 43.0	40.0
4+	24	40.9	2.137	36.7 - 45.8	41.1
5+	21	44.2	1.762	38.9 - 46.4	44.5
6+	8	44.7	2.340	41.7 - 49.2	43.8
7+	9	45.1	2.398	40.1 - 48.7	45.5
8+	8	46.8	1.962	43.6 - 50.4	46.7
9+	10	49.0	1.623	46.5 - 51.2	49.4
10+	12	48.8	2.093	45.9 - 52.8	48.8
11+	9	48.2	1.869	45.4 - 51.4	47.9
12+	4	49.7	1.593	47.4 - 51.0	50.1
≥13+	6	51.5	1.375	49.4 - 53.1	51.9

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2+	4	545	99.875	460 - 685
3+	37	680	89.570	530 - 845
4+	24	755	133.274	530 - 1070
5+	21	935	130.274	650 - 1140
6+	8	965	141.911	740 - 1210
7+	9	955	134.508	775 - 1150
8+	8	1085	172,730	885 - 1310
9+	10	1270	179.679	1010 - 1580
10+	12	1160	151.544	870 - 1350
11+	9	1185	128.916	1000 - 1360
12+	4	1165	179.141	1000 - 1410
≥13+	6	1310	192.319	1040 - 1510

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2+	4	1.04	0.108	0.95 - 1.19
3+	37	1.02	0.068	0.90 - 1.18
4+	24	1.05	0.064	0.90 - 1.19
5+	21	1.03	0.097	0.82 - 1.22
6+	8	1.04	0.068	0.94 - 1.11
7+	9	1.00	0.077	0.92 - 1.15
8+	8	1.02	0.169	0.78 - 1.35
9+	10	1.04	0.127	0.84 - 1.17
10+	12	0.96	0.120	0.78 - 1.18
11+	9	1.02	0.104	0.90 - 1.17
12+	4	0.91	0.080	0.84 - 1.02
≥13+	6	0.92	0.140	0.75 - 1.14

Table All

Fall 1980 Male Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{|}{\text{TL}}$(cm)
2+	12	35.0	1.310	32.6 - 37.5	35.0
3+	38	37.5	1.313	34.4 - 40.0	37.5
4+	6	38.3	0.756	37.1 - 39.4	38.2
5+	11	40.3	1.479	37.9 - 42.8	39.0
6+	5	40.2	2.109	38.0 - 43.3	40.5
7+	8	41.2	1.679	39.3 - 43.9	41.0
8+	7	41.4	2.400	38.4 - 46.0	41.3
9+	4	42.4	2.195	39.2 - 44.3	43.0
10+	6	43.0	2.490	39.8 - 46.0	42.4
11+	3	42.1	0.950	41.2 - 43.1	42.1
12+	5	43.2	3.652	40.5 - 49.5	42.0
≥13+	8	45.4	2.911	42.2 - 50.8	44.2

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2+	12	455	64.542	350 - 620
3+	38	565	65.241	440 - 690
4+	6	620	19.937	585 - 645
5+	11	720	68.500	650 - 850
6+	5	610	128.287	390 - 700
7+	8	685	69.424	605 - 790
8+	7	760	120.963	600 - 970
9+	4	755	94.692	620 - 840
10+	6	765	40.794	705 - 820
11+	3	765	137.961	660 - 920
12+	5	790	267.432	550 - 1230
≥13+	8	850	173.303	700 - 1120

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2+	12	1.00	0.070	0.90 - 1.12
3+	38	1.01	0.071	0.85 - 1.16
4+	6	1.06	0.082	0.96 - 1.20
5+	11	1.06	0.124	0.86 - 1.30
6+	5	0.89	0.134	0.68 - 1.00
7+	8	0.94	0.073	0.77 - 0.99
8+	7	1.02	0.072	0.96 - 1.17
9+	4	0.95	0.025	0.93 - 0.98
10+	6	0.93	0.126	0.78 - 1.12
11+	3	0.97	0.127	0.85 - 1.10
12+	5	0.91	0.083	0.79 - 0.98
≥13+	8	0.87	0.055	0.82 - 0.98

Table A12

Fall 1980 Immature Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{\prime}{TL}$(cm)
1+	22	27.4	2.536	23.4 - 33.1	27.0
2+	45	34.2	2.154	29.0 - 38.9	34.0
3+	7	37.1	3.071	32.4 - 40.4	37.8
4+	2	38.0		36.2 - 39.7	

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(cm)
1+	22	215	59.978	125 - 345
2+	45	415	77.029	265 - 635
3+	7	500	118.864	355 - 645
7+	2	405		385 - 425

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
1+	22	0.96	0.049	0.86 - 1.06
2+	45	0.97	0.066	0.81 - 1.13
3+	7	0.92	0.086	0.80 - 1.04
7+	2	0.71		0.65 - 0.77

Table A13

Spring 1981 Female Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{\shortmid}{TL}$(cm)
3	3	36.0	2.074	34.1 - 38.2	35.6
4	28	40.1	1.667	36.0 - 43.0	40.1
5	4	40.0	2.319	37.8 - 42.7	39.8
6	3	44.3	1.617	42.6 - 45.8	44.6
7	1	43.5			
8	5	43.8	1.404	41.5 - 44.7	44.7
9	5	46.9	1.404	45.3 - 48.1	47.7
10	6	47.7	1.550	45.9 - 49.6	47.7
11	11	47.0	1.863	44.6 - 51.0	47.0
12	12	47.7	2.298	45.7 - 52.3	46.7
13	11	48.5	1.577	46.5 - 51.5	48.3
≥14	17	50.6	2.944	46.5 - 55.7	51.1

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
3	3	460	62.517	400 - 525
4	28	710	105.457	470 - 930
5	4	660	127.435	490 - 795
6	3	890	62.517	820 - 935
7	1	740		
8	5	790	75.614	675 - 865
9	5	950	81.056	860 - 1040
10	6	960	117.757	830 - 1090
11	11	960	137.647	770 - 1170
12	12	1045	153.669	910 - 1340
13	11	1075	114.342	890 - 1310
≥14	17	1245	255.615	930 - 1850

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
3	3	0.94	0.121	0.84 - 1.07
4	28	1.09	0.096	0.93 - 1.26
5	4	1.01	0.106	0.88 - 1.13
6	3	1.06	0.145	0.96 - 1.23
7	1	0.92		
8	5	0.97	0.025	0.95 - 1.01
9	5	0.97	0.026	0.93 - 1.00
10	6	0.94	0.040	0.90 - 1.00
11	11	0.97	0.070	0.86 - 1.12
12	12	1.02	0.102	0.92 - 1.31
13	11	1.01	0.075	0.89 - 1.11
≥14	17	1.04	0.084	0.87 - 1.26

Table A14

Spring 1981 Male Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	TL′(cm)
2	1	30.9			
3	6	35.2	0.668	34.7 - 36.5	35.0
4	12	37.0	1.221	35.0 - 39.1	
5	1	38.4			
6	2	41.7		40.8 - 42.6	
8	1	40.7			
9	3	41.0	1.079	40.2 - 42.2	40.5
11	2	42.5		41.0 - 44.0	
12	1	44.7			
13	1	45.5			
≥14	1	47.4			

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
2	1	330		
3	6	480	36.560	440 - 540
4	12	535	50.142	435 - 640
5	1	610		
6	2	750		600 - 900
8	1	685		
9	3	605	106.888	485 - 690
11	2	735		720 - 750
12	1	690		
13	1	795		
≥14	1	975		

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
2	1	0.99		
3	6	1.03	0.047	0.97 - 1.09
4	12	1.01	0.059	0.91 - 1.12
5	1	1.05		
6	2	1.03		0.88 - 1.18
8	1	1.01		
9	3	0.87	0.127	0.73 - 0.96
11	2	0.98		0.91 - 1.05
12	1	0.80		
13	1	0.88		
≥14	1	0.97		

Table A15

Spring 1981 Immature Size-Age Statistics

Age	n	$\overline{TL}$(cm)	s_{TL}(cm)	TL range(cm)	$\overset{|}{TL}$(cm)
3	12	34.8	1.480	32.8 - 38.1	34.6

Age	n	$\overline{WGT}$(g)	s_{WGT}(g)	WGT range(g)
3	12	440	53.165	390 - 570

Age	n	$\overline{K}_r$	s_{Kr}	K_r range
3	12	0.97	0.087	0.85 - 1.04

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