S-19

UNITED STATES
DEPARTMENT OF THE INTERIOR
HAROLD L. ICKES, Secretary

FISH AND WILDLIFE SERVICE
IRA N. GABRIELSON, Director

R. F. SHUMAN

Special Scientific Report No. 19

# STUDIES ON THE PACIFIC PILCHARD OR SARDINE

# (SARDINOPS CAERULEA)

## I - Structure of a Research Program to Determine How Fishing Affects the Resource

By

Oscar E. Sette

Chicago
1943

## Explanatory Note

The series, Special Scientific Reports, embodies results of investigations, usually of restricted scope, intended to aid or direct management or utilization practices and as guides for administrative or legislative action. It is issued in limited quantities for the official use of Federal, State or cooperating agencies and in processed form for economy and to avoid delay in publication.

UNITED STATES
DEPARTMENT OF THE INTERIOR
Fish and Wildlife Service
Chicago

# Studies on the Pacific Pilchard or Sardine (*Sardinops caerulea*)

## I - Structure of a Research Program to Determine How Fishing Affects the Resource

By

Oscar E. Sette
Aquatic Biologist, In Charge
Section of South Pacific Fishery Investigations,
Division of Fishery Biology.

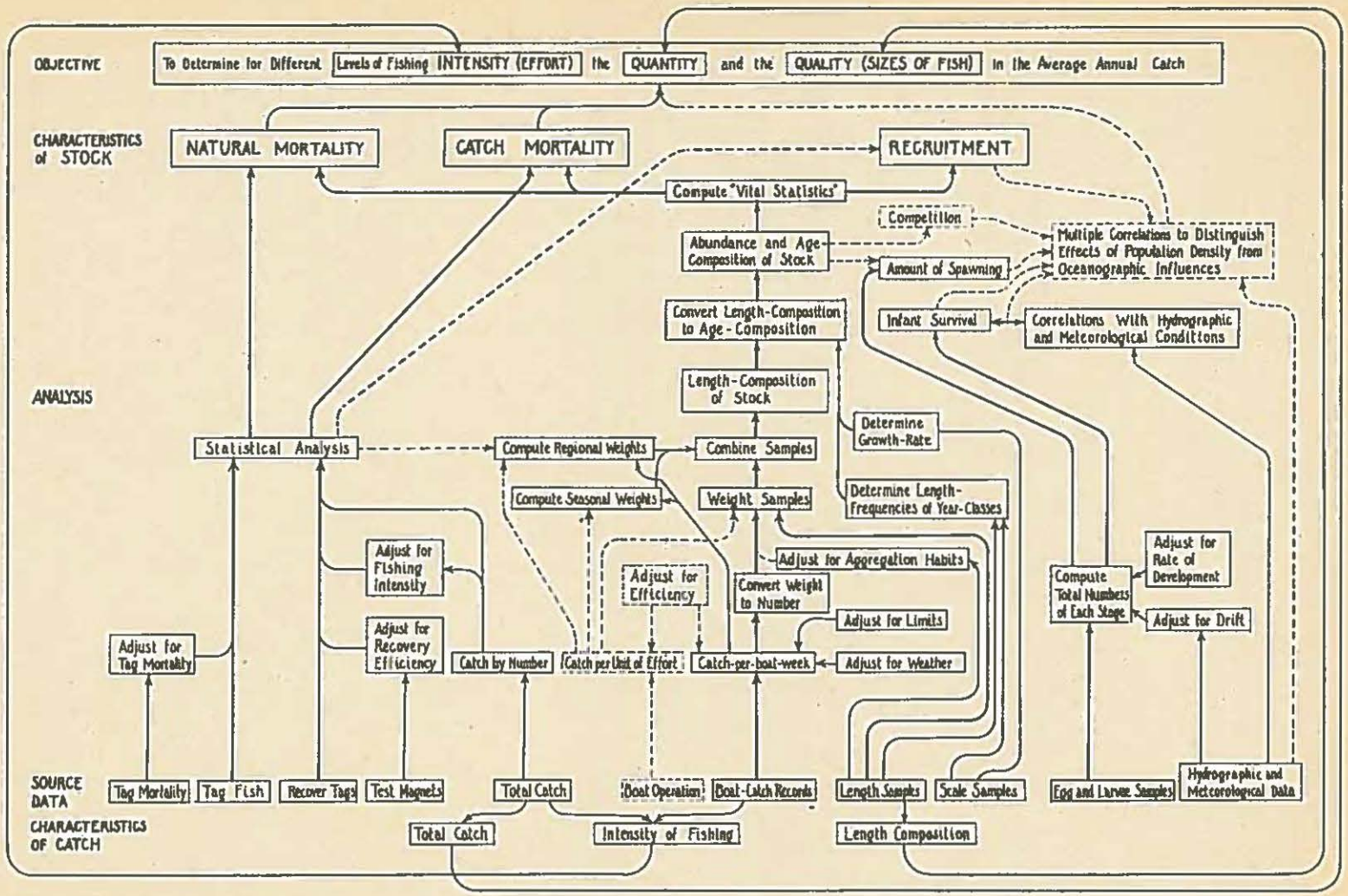
CONTENTS

| | Page |
|---|---|
| Introduction | 1 |
| Objective | 2 |
| Characteristics of catch and stock | 4 |
| Analysis | 5 |
| Vital statistics | 6 |
| Source data | 6 |
| Total catch | 6 |
| Boat operation | 6 |
| Boat-catch-records | 6 |
| Length samples | 6 |
| Scale samples | 7 |
| Analysis | 7 |
| Catch-per-boat-week | 7 |
| Adjust for efficiency | 7 |
| Adjust for weather | 7 |
| Adjust for limits | 8 |
| Convert weight to number | 8 |
| Adjust for aggregation habits | 9 |
| Compute seasonal weights | 9 |
| Compute regional weights | 10 |
| Combine samples | 10 |
| Determine length frequencies of year-classes | 11 |

CONTENTS
(continued)


| | Page |
|---|---|
| Determine growth rate | 12 |
| Convert length-composition to age-composition | 12 |
| Abundance and age composition of stock | 13 |
| Compute "vital statistics" | 13 |
| Recruitment | 13 |
| Natural mortality | 14 |
| Catch mortality | 14 |
| Reliability | 15 |
| Tagging research | 16 |
| Source data | 16 |
| Tag fish | 16 |
| Tag mortality | 16 |
| Recover tags | 16 |
| Test magnets | 17 |
| Analysis | 17 |
| Adjust for tagging mortality | 17 |
| Adjust for recovery efficiency | 18 |
| Adjust for intensity of fishing | 18 |
| Statistical analysis | 19 |
| Recruitment research | 19 |
| Source data | 21 |
| Egg and larvae samples | 21 |
| Hydrographic and meteorological data | 21 |
| Analysis | 22 |
| Compute total numbers of each stage | 22 |
| Adjust for drift | 22 |
| Adjust for rate of development | 22 |
| Infant survival | 23 |
| Amount of spawning | 23 |
| Correlations with hydrographic and meteorological conditions | 23 |
| Multiple correlation to distinguish effects of population density from oceanographic influences | 23 |
| Structure of the recruitment diagram | 24 |
| Discussion of the recruitment diagram | 24 |
| Discussion of an abbreviated recruitment analysis | 24 |
| Summary | 26 |
| Literature cited | 26 |

STRUCTURE OF A PROGRAM FOR PACIFIC SARDINE RESEARCH



## INTRODUCTION

The fishery for Sardinops caerulea, known as "sardine" in California and "pilchard" in the Pacific Northwest, became important during the war of 1914-1918 and has since grown to be the largest in North America. It started in California and reached its greatest development here. As early as 1919, research on the fishery was under way by the California State Fisheries Laboratory, an agency of the California Division of Fish and Game. More recently, as the fishing spread into northern waters, Oregon, Washington, and British Columbia have engaged in research and, since 1937, the U. S. Bureau of Fisheries, later becoming a part of the U. S. Fish and Wildlife Service, has also participated. With five agencies working together, this has become a cooperative research program, in the best sense. In the spring of 1936 and annually since then, the biologists have met to discuss the problems of this fishery and to coordinate their efforts to solve them.

Out of the research activities and from these meetings there came evidence of the complexity of the problem of research on the sardine and of the need for clarifying relations between various phases of the research. These have been discussed periodically and at length within the staff of the South Pacific Investigations of the U. S. Fish and Wildlife Service. At one of these staff meetings was drafted a statement of objectives and of the information required to attain them. As the time for the 1942 conference approached, Dr. Richard Van Cleve, Chief of the Bureau of Marine Fisheries of the California Division of Fish and Game, suggested the desirability of a formulated outline as a guide for discussion. In collaboration with Vernon Brock of the Oregon Fish Commission, such an outline was drawn, following a procedural diagram which I constructed at the same time, and embodying results from our Service staff meetings and the suggestions of Dr. Van Cleve and Mr. Brock. The diagram mentioned ( opposite ) thus represents the ideas of a number of persons. It was distributed and discussed at the 1942 meeting of the five agencies without eliciting demands for important revisions. While the program is thus the product of a number of persons, the exposition given herewith is that of the Fish and Wildlife Service laboratory at Stanford University and includes argument on what may be considered controversial topics. It is appropriate, then, that the responsibility for the exposition be assumed by the author who hastens to add that the program is subject to constant revision.

This discussion is mainly an elaboration and justification of the diagram, which by itself is somewhat cryptic, owing to the compression of complicated ideas into short phrases. In the outline the titles of procedures or projects either under way or rather fully planned are enclosed in solid-line rectangles and connected with the others by solid lines. Those recognized as desirable or essential but not yet integrated into the working program are indicated by broken lines. Heavier lines follow the main procedural path and lighter ones connect tributary adjustments with the main procedural lines. The titles at the left margin,

not enclosed by rectangles, refer to material to the right of each. To preserve the closest possible connection between text and diagram, the exact phraseology used in the diagram is repeated as headings in the text, even though, in some instances, it results in rather awkward context.

## Objective

Underlying the investigations of the U. S. Fish and Wildlife Service on the Pacific sardine or pilchard are certain ideas or theories, the discussion of which will clarify that of objectives. In the first place, it is recognized that before fishing took place the sardine population had filled its ecological niche and that, apart from fluctuations such as occur among all organisms, the deaths, on the average, equaled the births and the population was in equilibrium, i.e. neither increasing nor decreasing in total numbers. Moreover, the deaths under these conditions were all due to "natural" causes. Predators were, of course, responsible for a substantial portion of the natural mortality; but the basic influence tending to keep the population in check must have been competition within the population. This competition may have been of many different forms, all, however, connected with the density of the population itself. It might be failure in reproduction which could arise from the overabundance of spawners, the debilitating effects of which might affect the viability of their eggs; or if the viability of eggs were unaffected, simple spread into marginal spawning grounds with consequent failure of eggs to hatch would keep the population in check. Or the competition might simply increase mortality through division of a limited food supply among more mouths. Or the pilchard population, grown to maximal size, might so well supply predators with food that they would multiply to an extent which would check further increase of the pilchards. Whatever the mechanism, the existence of a depressing effect of population size on population increase is implicit in the idea of natural population equilibrium. It also involves negation of the idea that a fishery can ultimately destroy a population.

What, then, happens when an important amount of fishing takes place? There is an added cause for deaths. These deaths are largely among adults, and to the extent that catch mortality goes beyond replacing natural mortality, that is, to the extent that fishermen take fish that would not be eliminated by sharks and other predators, the number of adults in the population is reduced and the size composition is changed in the direction of fewer large individuals. But the fact that the population grows lesser in numbers and its individuals smaller in size, is no proof that the fishery is taking more than it ought to take, for another thing is happening at the same time. The depressing effect of population-size on population-increase is diminishing. If internal competition had been strongest among the commercial sizes, catch mortality would largely replace natural mortality and the population decrease would be slight. If it had been strongest among pre-commercial sizes or between commercial sizes on the one hand and pre-commercial sizes on the other hand, then replenishment of the commercial population would increase somewhat in proportion to the amount of "thinning out."

So far the argument has been speculative. But it is not necessary to rest on this. There have been many experiments in which populations have been reared under laboratory conditions. These have involved such diverse forms as yeast, diatoms, protozoans, insects, and even fishes. In all of them the rate of increase was rapid while the population was small and slowed down as it grew larger, finally reaching a size beyond which there was no increase. Initially, when the population is small, even though the reproductive rate is high, relatively few individuals are added because there are only a few producers. Finally, when the population is at its maximum and there are many reproducers, there are also relatively few individuals added, either because the reproductive rate has become depressed or because mortality has become so high as to offset the additions from reproduction. Usually both a depressed birth rate and increased mortality operate together to keep the net increase in numbers of individuals at a minimum. In contrast to the small increase in population-size at both low and high population densities, is the large increase that takes place when the population is about midway between these extremes. Then, the population is large enough to have many reproducers and small enough so that the reproductive rate has not been greatly lowered and mortality has not yet been intensified. In this state, the increase in numbers of individuals per unit of time is large.

The lesson is obvious. A population has its maximum increase when it is neither at maximum, nor minimum, size, but when middling in size; and that is the level at which the most individuals can be regularly removed and still be fully replenished by the population's inherent tendency to grow.

Of course, with a population of fishes in their natural habitat, things are not as simple as in these experiments. With the pilchard it is almost beyond question that predation would be a large influence. Fortunately, there have been population experiments that included the element of predation. In these it has been shown that the predator population increases as the prey increases - with a time lag, to be sure. Therefore, holding a prey population at a middling size would similarly limit its predators, especially with a species like the pilchard which is in a dominant position among prey fishes. So the factor of predation should not greatly alter the fact that replacement will be maximal in a medium-sized population. The time lag in the growth curves of composite predator-prey populations does introduce fluctuations and may disturb not only the general level but also the precise level at which the prey-population would otherwise have its maximal replacement. This, however, does not affect the general concept.

According to this idea, the optimal amount of fishing would be that which lowers the population numbers to a level at which maximum increase takes place. Such a fishery will remove only as many fish as will be replaced and the number removed will be the largest number that can be regularly removed without further disturbing the population-size.

However, there are things to be desired in a commercial fishery beyond merely a continuing yield of maximal numbers of fish. The stock must be sufficiently abundant to be economically fishable and the sizes of fish in the catch should be economically desirable.

At the present stage of research on the pilchard population, we do not have any notion of the level at which maximum replacement would take place, nor as to whether the abundance at that level would be an economic one or whether the size composition would be commercially desirable. We can, however, be confident that the replacement, the abundance, and the size composition will be affected by the fishing intensity; and we can be sure also that we shall want the replacement to be equal to the catch so that no continuous decrement will ensue.

Therefore, for the time being, the objective is "to determine at various levels of fishing intensity the quantity and quality (sizes of fish) in the average annual catch." Choice of the optimum intensity can then be made among the consequences of the various fishing intensities according to what is economically and socially desirable. That will undoubtedly involve other than biological considerations.

It should be noted particularly that it is not an objective to determine whether abundance is decreasing. The population can be expected to decrease long before maximal yield is reached. It is not along an objective to determine whether the average size of the fish is decreasing. This probably will be the finding but is not of itself a sufficient indicator of a desirable or undesirable situation. No mention is made of protection of spawners or of spawning grounds, or of size limits, or of closed seasons, or of wasteful practices in utilization, or of other topics that often are the concern of conservationists. These items may or may not be involved eventually. At this time, they are secondary to the determination of what consequences attend different amounts of fishing and cannot be intelligently considered until these are known. In fact, the method of conserving a commercial fishery involves social, economic, and political considerations and lies in the field of political economy. Biologists need only determine the consequences of certain actions and make them known to the law-makers and administrators.

## Characteristics of Catch and Stock

The objectives are stated in terms of what will be caught at different levels of fishing intensity. With sufficient information, the characteristics of the catch could be defined each season, and over a long time, empirical curves could be made that would show the relationship of intensity of fishing with quantity and quality of catch. Indeed, save for data on fishing intensity, ready collection of which was precluded by certain practices of the fishery, this job of biological accounting has been done by the California State Fisheries Laboratory over a period of 23 years during which the fishing intensity has varied widely.

Had it been possible to include fishing intensity or its complement, relative abundance[1], today's task would be enormously facilitated. Even so, it would be necessaty to relate or transform the characteristics of catch to those of the stock, for replenishment depends on the fish that are left in the sea.

Of course, if the fishery took a random sample of what is in the sea, the characteristics of catch would be the same as those of stock. But if we can be sure of only one thing, it is that the fishery does not take a random sample. In the Pacific Northwest (Oregon, Washington, and British Columbia) the fishery over-samples the older fish; in southern California, the young. In central California, it perhaps over-samples those of intermediate ages. In certain areas between ports, notably off northern California and southern Oregon, there is no fishing. At a single port, the size composition changes significantly from day to day, week to week, and month to month, and there is no assurance that the catch of the various sizes is proportional to their relative abundance in the sea. In fact, it is obvious that the various components of the stock are represented in the catch in proportion to the length of time each is subject to fishing in a particular area and not at all in proportion to its abundance in the sea.

Thus the major problem of research is how to deduce the characteristics of the stock from the available samples in the catch. Once those are known, total mortality can be estimated by computational processes developed by Baranov, Thompson and Bell, Ricker, and others. Also under certain conditions, it will be possible to separate natural from catch mortality; and both being known, to compute the recruitment (the equivalent of the actuary's birth-rate, taken as of the attainment of commercial size).

## Analysis

In the diagram, the central part-analysis is taken up with the processes concerned with adjustments, conversions, and combinations intended to transform data from the catch into attributes of the stock. These processes leading to "vital statistics" are so complex that simple appraisals of their reliability by conventional statistical methods are unavailing. Confirmation must, therefore, be sought in results attained through independent approaches. The only other approach that is currently being followed is tagging. The processes involved in this branch of research are noted in the left-hand portion of the diagram and will be discussed under the heading of "Tagging research." Even after determinations of mortality and recruitment have been made by two methods and one found to verify the other, it is still necessary to investigate recruitment because changes in it are of differing significance, depending on whether they be due to the changes in the stock itself or to fluctuations in the environment. The foreseeable means of dealing with this problem are listed in the right-hand part of the diagram, and will be discussed under the heading, "Recruitment research."

---

[1] At uniform availability and with no competition between units of gear:
Relative abundance = catch-per-unit-of-effort; and

$$\text{Number of units of effort} = \frac{\text{Catch}}{\text{Catch-per-unit-of-effort}}$$

## VITAL STATISTICS

### Source Data

Total catch. - The basic data for this central branch of research are the experiences of the fishermen themselves. Their "Total catch" is needed indirectly to derive "Intensity of fishing." It is used also to compute "Vital statistics," a connection which is not shown in the diagram. These statistics are collected by the several Pacific Coast States and the Province of British Columbia as a matter of administrative routine.

Boat operation. - Records of activity, particularly of the time spent fishing, would be invaluable for computing "Catch-per-unit-of-effort," as it would permit by-passing two adjustments and would avoid an additional difficulty inherent in statistics of "Catch-per-boat-week." Unfortunately, records of boat operation are lacking except for a very small sample resulting from an observer's interviews with fishermen. Whether or not these interview-data may be pressed into service in lieu of more complete operational records remains to be seen.

Boat-catch-records. - For the time being, the records of individual daily landings by fishing boats, are the main reliance in deducing changes in abundance or in availability of the pilchards from time to time and from place to place. These records collected by the State and Provincial Governments, give only the quantity of sardines in each delivery to the processing plants. In California, each delivery represents one night or a fraction of one night of fishing, in the Pacific Northwest, from a fraction of a day to several days of fishing. In neither region is there any record of nights or days spent in fruitless effort.

Length samples. - "Length samples" cover the measurements and designations of sex of a sample, usually 50, of individuals, from a delivery of sardines. In California, prior to the season of 1941-42, semi-weekly samples from 5 deliveries were taken by the California State Fisheries Laboratory. Since then, daily samples up to ten in number were taken by the California State Fisheries Laboratory at San Pedro and Monterey and by the Fish and Wildlife Service at San Francisco. Supplementing these are special series of 100-fish samples collected by the Fish and Wildlife Service at San Francisco and Monterey daily over certain periods during the three seasons prior to 1941-42. In the Pacific Northwest, sampling has been somewhat less systematic. In British Columbia, the Fisheries Research Board of Canada has taken one 100-fish sample as nearly daily as feasible. In Washington, the Fish and Wildlife Service in some seasons and the Washington Fisheries Department in others have collected one to several 50- to 100-fish samples daily. In Oregon, the Oregon Fish Commission has taken one to several 50- to 100-fish samples sometimes daily and sometimes intermittently.

Scale samples. - Beginning in 1941-42, scale samples have been systematically collected from ten fishes in each length sample by all of the agencies engaged in sampling. During three prior seasons similar samples were less regularly obtained by the Fish and Wildlife Service and in these and earlier seasons some scales and otoliths were gathered by the California State Fisheries Laboratory in California and by the Fisheries Research Board in Canada. The utility of these earlier collections is dubious but is now being surveyed by the Fish and Wildlife Service.

## Analysis

Catch-per-boat-week. - The processes described under this heading have been devised for handling the California statistics for the seasons, 1932-33-1940-41. Modifications will be necessary for use with data for the Pacific Northwest and for other periods in California. The accepted manner of computing the catch-per-boat eliminates two sources of variability that are extraneous to fluctuations in abundance or availability, namely: variations in number and in the type or size of boats fishing. This is accomplished by comparing a boat's performance during two separate periods. The resulting pairs of relative catches are combined by averaging to represent fleet performance, and combined by linking to form a time series. Because the opportunity to fish is variable, depending on the duration of the moonless portion of the night, the statistical series have been divided into lunar periods and each lunar period into four lunar weeks. Year-to-year ratios are then computed between pairs of homologous lunar weeks. However, this statistic still contains several extraneous sources of variability. One is the varying amount of idleness of boats, assumed to be fishing, but actually in port on account of repairs to machinery or gear and of miscellaneous causes. It has been assumed that this is random in occurrence, and has no trend effect; and lacking any record, no account of it is taken in the computations. Two other sources of variability are treated below.

Adjust for efficiency. - There may be changes in efficiency connected with the skill of crews and modifications of gear. As yet no means has been devised of dealing with such variations.

Adjust for weather. - By computing regressions of average daily catch per boat according to weather conditions a relation between the two is derived and used as an adjustment factor. The effect of variation of available fishing time each night is also incorporated in the regression systems.

Extensive experimental analysis of wind movement as recorded by anemometer at such meteorological stations as were available, has led to the discarding of this source of weather data. Instead, the wind movement is deduced from barometric gradients in a manner which gives a representation of conditions over an extensive sea area adjacent to each fishing port. Direction as well as force is correlated with catch, and both enter into the adjustment. Other elements such as fog and precipitation appear to have no statistically consistent effects on the catch, probably because conditions at the observation points differ too much from those on the fishing grounds.

The weather adjustments already computed have measured the effect on daily catch-per-boat as an 8-season average effect and, while reliable over a long period, are not accurate for short periods of time or for specific days.

Adjust for limits. - Processing plants, at times, have limited the amount of fish receivable from a boat. Under these conditions, compliant boats stop fishing when the limit is approximately attained and the average catch must be less than if there had been no limit.

The adjustment for the effect of limits, however, is based on the assumption that their principal effect is to shorten the period of fishing per night. When a limit catch is attained by a boat early in the night, that boat's fishing effort should be figured as only a fraction of a night. This may be computed as the ratio of the actual, to the total available, fishing time.

Account is taken of boat-capacity, as well as imposed, limits. The time of attaining limits is recorded only for the catches of boats whose skippers are interviewed when a sample of fish is taken. This is only a small fraction of the whole number but it is assumed that the average time applies to the entire fleet. Due to the smallness of the sample, the adjustment is computed as an average for an entire lunar week. It is probably reliable for long, but not for short, periods. Complete operational records for the boats would be better if these were available.

Convert weight to number. - Catch statistics are always in terms of weight, but data must be in numbers of fish for computation by the methods of vital statistics. As the relationship of weight to number fluctuates in accordance with size-composition, the conversion is made on a daily basis. From a predetermined length-weight relationship, the average weight of fish in the day's length-frequency distributions is computed and this average weight divided into the pounds-caught-per-boat-day, converting that statistic into numbers-caught-per-boat-day. For samples taken in 1941-42 and subsequent seasons, the average weight is determined by direct weighing of each sample.

If now, we were to weight each day's frequency by each day's numbers-caught-per-boat-day and sum the frequencies for all ports and all days for each season, the resulting curves might be taken as representing the relative abundance of each size of fish for the series of seasons and the task of converting catch statistics into stock statistics be considered complete.

Indeed, Hodgson (1939) regarded this very process, less some of the adjustments, as giving the relative abundance of each year-class in the East Anglian herring fishery. To use an analagous method for the Pacific sardine would be to assume either that: (1), The average boat's fishing capacity was equal in the fleet of each port, or that an equal proportion of the fish population was drawn upon by each port; and (2), the various sizes of fish were available randomly from each port, or that the length of time a complex of sizes of fish was available at each port was proportional to the population. However, these assumptions are either known or suspected to be erroneous. Various further devices of weighting, selection, and combination need be employed.

Adjust for aggregation habits. - If a series of samples taken at a particular fishing port be compared as to size-composition, it is apparent that among them there are samples that resemble each other sufficiently to have come from the same population but differ enough from certain other samples to indicate that the latter must have come from different populations. Since the various samples come from different schools it appears that certain groups of schools have a uniform pattern of size-composition and, if so, they must have been associated for a significant period of time during which their reaction pattern was the same within, but different between, the groups of schools. This corresponds to views expressed by W. F. Thompson (1926 p. 163): "Catches of a certain type, or 'runs' having certain characteristics, prevail for varying periods of time, and each of these periods is a variable unit itself." Our view differs only in supposing that there may be simultaneous occurrence of different types of "runs," -- a possibility doubtless appreciated by Thompson or one that certainly would have been, if the fishery of a given port had spread over as large an area, then as now. It will be convenient to refer to what we have called "groups of schools" and what Thompson has called "runs" as school-groups.

Obviously the population fished from a given port is not randomly distributed as to size. Unless the period of time each school-group is "available" to the fishery is either: (1) Random or (2) proportional to the abundance of each school-group, our sampling system, even though "stratified" as to time, and even though weighted according to catch-per-boat in the time strata, cannot faithfully represent the population of school groups fished from that port during a fishing season.

The summation of such weighted samples would weight the sizes in accordance with the frequency or length of time the school-groups dominated by those sizes were fished by the fleet. Since the length of time the school-group is present and available on a ground is more likely to be associated with its reaction pattern and the fluctuations in oceanographic conditions than with the relative numbers of fish represented by each school-group, such weighting would represent largely availability rather than abundance of fish.

At the present time (spring of 1942) means of distinguishing school-groups are being developed. Methods of employing the school-group idea in adjusting samples will have to await analysis of the occurrence and persistence of school-groups. It may lead to a method of weighting in school-groups or of combining samples in certain manners or may merely serve as back-ground information for appraising the validity of methods based on other principles. Since methods are still uncertain the rectangle labeled "Adjust for aggregation habits" has been related to the main line of procedure by a broken line.

Compute seasonal weights. - Apart from the departure from random distribution of school-groups within short periods of time, there is an even greater difference between the fall and winter populations in California, especially in the seasons prior to 1938-39. The fall fish are predominantly young adults, 3 to 5 or 6 years of age; the winter fish, old

adults over 5 or 6 years of age. Usually the fall season has been longer than the winter season and direct summation of samples would heavily weight the young adults. Judging from preliminary computations, which indicate greater abundance - more marked a decade or more ago than at present - in the winter when the old adults are dominant, weighting in the opposite direction would be more appropriate. Obviously, these phenomena need be taken into account in combining the samples for the two parts of the fishing season.

Compute regional weights. - The sardine at different ages tends to frequent different places along the Pacific coast (F. N. Clark 1940 pp. 44-46). In general, smaller individuals prevail in the south and larger ones in the north, with many exceptions in detail. Hence, the fishery at any one port does not afford a true cross-section of the entire population. To get that, samples from the different ports must be combined in proper ratios. Logically they should be weighted in proportion to the fraction of the total population available from each port. As these fractions differ from one part of the season to another, and in any case are difficult to determine, the computation of regional weights is no simple task.

In general, the basis for such weighting might reasonably be the estimate of relative abundance provided by the catch-per-boat-week. But the method by which this statistic has been computed uses a different yardstick at each port. That standard must be calibrated by some kind of determination of the relative fishing capacities of the boats in the fleet of each port. This project is under development but has not yet been advanced to the point where its usability is assured.

Another measure for determining the weighting for each port might be derived from the statistical analysis of tagged-fish returns. It would depend on computing the proportional amount that tagged fish are diluted by release in the population of each fishing region. Certain difficulties common to many tagging computations have so far prevented its use; but its desirability is indicated by the broken line running from "Statistical analysis" of the tagging procedural line to "Compute regional weights."

Combine samples. - At present, alternate ways of combining samples are under consideration. The first and simplest plan assumes that the weightings have fully discounted variations in availability so that a simple summation of weighted samples will suffice to give seasonal frequency distributions that will portray relative abundance of each size class and show the relative abundance of all commercial sizes from one season to another. As before stated, however, there is reason to distrust this assumption and unless further considerations dictate otherwise, an alternative will be adopted.

The second plan does not require assumptions as to whether the weighted samples represent relative availability or abundance. It is designed to provide an adjustment converting availability to abundance that will not produce erroneous results even if availability is not a factor to be discounted. In essence, it is a method of selecting among the weighted samples

for all sampling days at all ports the ordinates for each size-category which most nearly represent homologous levels of availability. The method takes its form from the idea that each size-category is present in varying degrees of availability to the fishery from time to time and from place to place throughout the extent of the fishing grounds. If then, the weighted, sample-day frequencies correctly portray the availability of each size-category, then, for each size-category a frequency distribution of ordinate heights will describe the number of times this size-category occurs at various levels of availability.

The problem then is one of selecting from these ordinate-height frequencies the ordinate classes representing homologous levels of availability. Theoretically, it would be desirable to have a selection that would represent maximum (or 100 percent) availability of each size-category. This would require selection of the maximum ordinate among the whole collection of ordinates for a given size-category. But the ordinate heights contain two important sources of variability apart from availability: errors introduced by weighting factors and those introduced by the random departures of numbers in each size class from the true number in the population from which drawn. Therefore the maximum ordinate in many instances would, by chance, be above rather than at the maximum level of true availability. To avoid this it has been decided tentatively to take the ordinate class at the ninth decile position. In other words, we would derive a frequency curve which represents the 90 percent level of apparent availability of each size. For the reasons just stated, this level of apparent availability may be very close to the 100 percent level of real availability.

The first plan requires that availability of each size-category have the same pattern from year to year, the second requires merely that at one time or another during the season the levels of availability of the several size classes approach their maxima. It appears that the latter involves a more conservative approach. It is to be expected that knowledge of aggregation habits, leading to the classification of school-groups, will provide important modifications in, or appraisals of, the proposed methods.

Determine length frequencies of year-classes. - Assuming that one plan or another has produced a properly weighted combination of samples to represent the stock in the sea, there remains the problem of converting each season's length-frequency, into an age-frequency, distribution. Its solution, for the years prior to the beginning of routine scale sampling in 1941, involves the use of certain statistical constants derived from scale readings.

By this is meant determination of the parameters of the length-frequencies of single age-groups or year classes that will define the shape of the frequency curves in sufficiently general terms to be applicable to years other than that in which the scales are collected. So far the only parameter we have worked with is the standard deviation, as a function of age, assuming each age group to have a normal distribution of lengths. While apparently reliable results are obtained, there is evidence

that skewness may be introduced by selective availability of the fish or by fisherman selection in favor of largest members of young year-classes, or, in certain localities, converse selection of favored small fish. It may be necessary to include a skew factor to some extent. There also are indications of multimodality in the length-frequencies of individual year classes. Whether this is sufficiently pronounced to require statistical recognition remains to be seen.

Determine growth rate. A growth curve or curves is needed to give another parameter, the mean or modal size, of the frequency distributions of year classes. Having age readings made in any one year it is simple to establish a growth curve, but such a curve would be a true one for only that year. There is evidence that growth differs from year to year, from year-class to year-class, and, more disturbing still, it appears to differ by fishing areas. For instance, a given year-class has a lower modal length in the San Pedro, than in the Monterey area. We are faced by the dilemma of using either a general growth curve fitting no specific situation, or a variety of curves to fit situations that are largely unknown. It remains to be seen whether there is sufficient regularity in geographical or annual variations to permit age determinations of recent years to be applied to the length data of former years.

Convert length-composition to age-composition. - The translation of a length-frequency curve to an age-frequency curve has proved unexpectedly difficult. As may have been anticipated from the previous discussion of parameters, the only method so far found to be applicable is that of discovering what combination of year-class length-frequencies will fit a season's length-frequency. The fixing of two of the parameters, standard deviation and mean, leaves only the third parameter, relative area, to be varied in the curve fitting. Even so, it is a laborious process by the trial and error method, but as yet we know no other. Furthermore, error in either of the two fixed parameters very seriously affects the results. In other words, the problem should be approached with extreme caution.

An expedient that greatly facilitates the process may be employed in certain situations where one is justified in the assumptions: (1) That the year-classes were of uniform initial numerical strength and (2) that they experienced uniform annual mortality since becoming of commercial size. These assumptions are approximately justified in dealing with a length-frequency distribution of fish pooled from a considerable number (enough to "average out" inequalities in initial year-class strength) of contiguous seasons during which the fishing intensity was nearly enough constant to have produced nearly uniform mortality. This severely limits the combinations of frequency-curve areas and a unique fit is soon discovered. The goodness of fit serves as an indication of how nearly the assumptions were fulfilled, except that uniform trends through the series, either upward or downward and in either year-class strength or intensity of fishing, would not be revealed by poorness of fit.

Abundance and age composition of stock. - When the weighted, combined, length-frequency distribution has been converted to age-frequency we have a series of season's curves representing the relative abundance of each age of fish in the stock. These are useful in deducing the relations between abundance and spawning and between abundance and competition effects. This is indicated by broken lines in the diagram and will be discussed later. At the moment we shall pass on to determination of mortalities and recruitments.

Compute "Vital statistics." - By vital statistics we refer to recruitment and mortality, the fisheries counterpart of the actuary's births and deaths. One might also use the term "population dynamics." The computations involved are adaptated from methods previously developed or employed by Baranov, 1918; Thompson and Bell, 1934; and Ricker, 1940.

Total mortality is readily computed in situations where recruitment and mortality can be reasonably assumed to have been uniform during as many years (prior to the year in question) as there are ages present in the stock. Then, it is necessary to have only one season's age distribution, for each age class will be a constant percentage less numerous than the next younger. The constant percentage then is the annual mortality rate.

Such simple situations are rare, but, fortunately, they are not the only ones amenable to analysis for mortality. That statistic may be readily deduced from the age frequencies of two successive seasons, providing that they truly represent the stock in the sea. Here the decline would be measured by the relative numbers of a given year-class in the two frequencies and the percentage reduction of a year-class from the first to the second season would represent the annual mortality rate. If all year classes have been fished with equal intensity, hence have suffered equal catch mortality, and also have experienced equal natural mortality, the indicated total mortality will be sensibly equal for all but the "entering" year classes. Inequalities, therefore, may be ascribed to age-selective, natural mortality or age-selective fishing intensity. Correlation of the absolute quantities of each year-class in the catch with their respective mortalities should distinguish between these two age-selective processes.

Recruitment. - As used herein, recruitment means the number of sardines reaching commercial age each year. Given age-distributions that reliably represent the abundance and age composition of the stock, the recruitment is directly proportional to the numbers of individuals in the year-class that has, for the first time, appeared in the commercial catch. The only complicating feature is that there has been nothing in the previous adjustments to insure that the entering year-class will be fully represented if, in its first season, it is only partially available to the fishery. Hence, in this respect, we cannot consider the weighted curves as reliably representing the stock. However, from a series of age-distributions it should be possible, without great effort, to distinguish the age at which a year-class becomes fully available, deduce

further its percentage availability in previous years, and so arrive at a numerical evaluation of its relative strength at commercial age. Indeed, trial computations have practically proved the feasibility of this calculation.

Natural mortality. - In computations so far undertaken we have assumed the probability that mortality from natural causes is constant. This greatly simplifies the calculation of catch mortality. However, this assumption should be examined critically and perhaps revised if it is discovered that predators (other than man), and therefore predation, has increased or decreased to an important extent in any two periods under consideration.[2]

Also the probability of death from natural causes may vary with age, and the formulations may need appropriate revision. These eventualities cannot be appraised until a series of age-distributions, properly representing the sardine stock, become available.

Catch mortality. - While remaining aware of the possible necessity for revising the assumption of constant natural mortality, it is convenient to employ this assumption to simplify the computation of catch mortality. Given two periods, in one of which the intensity of fishing was greater than in the other, there is a unique combination of differing catch-mortalities in the first and second periods and of constant natural mortality for both periods that will account for the total mortalities and the total catches in the two periods, respectively. The mathematical formulation must take into consideration that the natural and catch causes for death are operating simultaneously and, therefore, compete with each other for the lives of the fish. It also involves consideration of whether an increase in fishing intensity, i.e. the employment of more effort or gear, brings in competition between fishing units. That is difficult of appraisal for the sardine fishery because addition of boats may as easily produce an effect the opposite of competition, i.e. cooperation, through extending the scouting area and communicating information on the location of schools. The effect of cooperation has been neglected in the computations so far contemplated. It should be taken into account, and probably will be, as soon as a method of measuring it can be devised.

---

[2] It may be possible in such a case to regard the sardine as having a number of predators, including man, and base the formulation on the effects of the simultaneous probabilities of death from the several categories of predation. The mathematics would be complicated and probably require data on more than two seasons, especially if a multiple correlation method were employed, but should be feasible, given an adequate quantity of data of reasonable reliability.

On the other hand, it will probably be safe to regard competition between gear as negligible, a point of view that is tenable if cooperation is the effective result of increasing the number of boats and also if the schools of sardines are so widely distributed that instances are relatively rare wherein a boat is prevented from making a catch by the pre-emption of space by another boat.3/ We do not consider in the category of competition the situation where the probability of catching a school of sardines has been reduced by the number of schools taken out of that locality previously. This is a phenomenon of reduction of the stock by catch mortality. It is taken into account by appreciating the distinction between average abundance and initial abundance in any particular period of time. (See Ricker 1940 p. 45).

## RELIABILITY

Having computed one set of values on natural mortality, catch mortality, and recruitment, one gains a general idea of the magnitude of each, but the result cannot by any means be considered a determination. The various computations and adjustments have contributed errors. Also the original data had variability which perhaps was increased rather than diminished by the subsequent treatment. The mathematical result, therefore, has a probability of differing from the true value by an amount which cannot be known from one set of values alone.

In a series of sets of values, however, from which one might compute a regression, say, of catch mortality on fishing intensity, the spread of values around the regression line would give a measure of variability and one could be said to have really made a determination if that spread is small in relation to the magnitude of the observed change in catch mortality.

While this would appraise the random error, it might not detect even a large amount of error consistently above or below the true value for the entire series. Such an error might easily be introduced by simplifying assumptions or by failure to take into account certain sources of consistent bias or selection. It could be detected only by computing the same statistics by an entirely different method and from a distinct source of data. The tagging technique affords such a method and utilizes a considerably different set of original data, although, to the extent that the same commercial catch is involved, errors in fishermen's sampling may be in the same direction as in the other method.

3/Persons familiar with the fishery might say that such instances are common rather than rare. It is true that there often seems to be a race between two or more boats to set their seines around the same school. This may actually take place at times, but more often a boat, preparing to make a set, betrays its intention by its actions, and so leads other boats to come to the same spot. They do so, not necessarily in the hope of beating the original boat to the school it has sighted, but in the hope, often realized, that other schools are to be found in the same vicinity. All such instances should be classified as cooperational rather than competitive. Under the latter category, there should be included only the cases where two boats independently locate and try to set upon the same school. Such cases of true competition probably are not more numerous than would serve to offset the contrary element of cooperation.

## TAGGING RESEARCH

Tagging has been extensively practiced by the California State Fisheries Laboratory, and the Fisheries Research Board of Canada; also to a lesser extent, by the Oregon Fish Commission and the Department of Fisheries of Washington. Having been an interested spectator rather than a direct participant, my discussion may suffer from lack of familiarity with this technique, which is simple and direct in principle but difficult and complex in its application.

## SOURCE DATA

Tag fish. - The tagging operation itself needs little discussion but various aspects of the process require attention in subsequent adjustments of the data. It may be remarked here, however, that the tags are of metal and inserted into the body of the fish following in general the method first developed by Rounsefell and Dahlgren (1933). They are recovered by electro-magnets installed in the fish-meal line of the reduction plants. The fish to be tagged are obtained, for the most part, from commercial fishermen and are subject to the same selections that influence the raw materials used in the vital statistics method. Since the numbers of "samples" tagged are fewer, the danger of non-random selectivity is greater.

Tag mortality. - It is known that tagged sardines suffer high mortality from the operation itself or from the attendant handling. The only sources of data on the magnitude and variability of tagging mortality are: (1) A limited number of experiments by the California State Fisheries Laboratory in which tagged fish were held in live cars for direct observation, and (2) a correlation establishing the relation between length of time of confinement before tagging and the subsequent returns.

The live-car experiments proved that mortality is high and variable, that small sardines suffer greater mortality than large ones, and that the size of the tag affects the rate of mortality. It is, of course, difficult to perform a sufficient number of such experiments to establish a reliable mean mortality. Moreover, there is uncertainty as to whether the difference in treatment received when the fish are released in the live-car rather than directly into the sea (as in the regular tagging operations) has caused the live-car mortality to differ from that in the sea releases. This uncertainty is especially acute with respect to liberations in the Pacific Northwest, where tags have been applied with a different instrument (tagging-gun) from the scalpel and forceps used in California and where the fish were tagged directly from the fishermen's seine instead of being brailed into a holding net for tagging: and, also, where the roughness of the sea generally imposed more difficult conditions for the handling than in California.

Recover tags. - Since sardines are handled in bulk and mostly by machine, few tags would come to light without a specific recovery system. That now in use consists of magnets installed in the meal-lines at canneries and reduction plants. Difficulties arise in achieving installation

of magnets in all plants, and in connection with their effectiveness when installed in different mechanisms and under different operational methods.

Test magnets. - This requires that each installation be tested to determine its recovery efficiency. Periodic tests of the same installations are made to discover fluctuations in performance and detect any changes that may occur as plant operations are altered. The test consists of mixing a definite number of tagged dead fish with an ordinary lot destined to go through the reduction system and recording the percentage of tags recovered from the magnet. A possibility that the efficiency of recovery of test-tags may differ from that of tags in sea-released fish arises from the fact that the former lie within the body, unattached to the tissues, and not far from the open, insertion incision; whereas the latter are encysted by tissue and the incision healed shut. It is likely, therefore, that the efficiency may be somewhat over-rated by the tests. On the other hand, a few recovery experiments indicate a lessened efficiency of recovery from fish destined for canning than from those destined to go directly to the reduction machinery. This is probably due to the loss of tags from the body cavity in the cutting and eviscerating process. The performance of testing experiments in connection with canning operations has met with obstacles preventing the accumulation of sufficient experience to gauge the reliability of efficiency ratings. Their value for adjustments is also lessened by the custom of mixing whole fish with cutting offal in the ordinary operating procedure. In all, the efficiency of recovery varies widely and while important for our calculations is difficult to determine.

## Analysis

Adjust for tagging mortality. - Two basic adjustments are made to deduce the actual number of viable tagged fish released. The first utilizes the live-car experience in adjusting release records downward by the indicated amount of mortality induced by the tagging process, with due regard to the size of the sardines. The second takes into account the additional mortality brought about by the increased time of holding to which the late-tagged members of a given batch of fish were subjected. It involves establishing a regression of returns on serial order of tagging in blocks of 100 or other suitable number of individuals for each batch or group of batches of fish tagged. These regression values adjust not only for the time-connected differential mortality within a batch but also for the differences in mortality between small batches tagged in a short time and large batches requiring more time for tagging.

These adjustments have been employed in the analysis of returns from California-tagged fish, but no comparable methods are available for those tagged in the Pacific Northwest, though it would appear that the second adjustment at least would be feasible for releases in that area.

Adjust for recovery efficiency. - This adjustment applies the magnet efficiency records and also incorporates a calculation taking into account any amounts of fish run through plants when or where magnets were not in operation. To some extent a differential adjustment for recoveries from reduction of whole fish and reduction of canning offal is feasible from a comparison of returns from the two categories wherever plant records permit segregation. Since canning is not practiced in Washington and Oregon, this feature is not a problem there, but it exists in British Columbia as well as in California.

Adjust for intensity of fishing. - One essential statistic sought through the tagging technique is the catch-mortality. If it were possible to release all the tagged fish immediately prior to the fishing season and if they were immediately distributed at random through the commercially-fished population, this statistic would be the ratio of first-season returns to the number tagged. Another essential statistic, total stock, could then be computed simply by the proportionality:

$$\frac{\text{number of fish tagged}}{\text{total stock}} = \frac{\text{number of returns}}{\text{total catch}}$$

But tagging can be done only at intervals during the fishing season and the tagged fish probably diffuse only gradually through the general stock. Hence, first season's returns are almost useless and it is necessary to deduce from subsequent years' returns what the first year's returns would have been under the simple conditions described above. That deduction is made by extrapolating back to the first year a line representing the annual rate of decline of tag returns. Since the annual returns depend in part on the amount of fishing done, some adjustment must be made when the amount of fishing changes during the series of years included in the tagging experiment.

The adjustment used for the California statistics has been to compute for each season the number of returns per unit number of fish caught. An identical adjustment would be feasible also for the Pacific Northwest tagging returns. While this adjustment may suffice for useful approximations, it obviously gives identical treatment to a fluctuation in catch whether due to a change in the amount of fishing or in abundance of the sardines. Yet these two phenomena have different effects on the returns. Furthermore, the fishing in a current year, by removing a certain number of tagged fish, influences the returns of subsequent years. Except, therefore, in situations where it may be safely assumed that the fluctuations in catch have arisen only from moderate and random changes either in intensity of fishing or in abundance, this adjustment may require revision. Where a trend exists in fishing intensity or in abundance there would be particular likelihood of erroneous results. Such cases would require additional adjustments appropriate to the particular circumstances, and possibly materials from the vital statistics methods could be drawn upon for such analyses. This has not been indicated in the diagram.

Statistical analysis. - As explained in the previous section, the statistical analysis of tagging experiments depends mainly on a line "or curve) representing the trend in annual adjusted returns. The intercept of the line at year one (an extrapolation) is used to compute catch mortality. By another computation, it also results in estimate of total commercial stock. The rate of decrease in annual returns is taken as the total annual mortality. The remaining statistic, natural mortality, is derived algebraicly from catch mortality and total mortality.

Since the trend curve is based on returns during a series of years, the statistics resulting therefrom, represent the conditions, not in any one year, but are an average (not necessarily an arithmetic mean) for the series of years.

It has already been pointed out that the adjustments, particularly that involving the size of the catch, may have affected the data in a way that calls for modification of the above-described computations. Instead of that, determination for a number of periods of overlapping years might point the way to an interpretation or correction of the statistics for individual periods or even individual years. Thus far, however, records are available for only two periods and these possibilities cannot yet be examined.

A further aspect of the computations so far made is that when Pacific Northwest catch and Pacific Northwest returns of fish released in California are excluded different rates are indicated than when they are included. This points either to the non-availability to the California fishery of at least a portion of the stock that migrates seasonally to northern waters or to some discrepancy of experiment or analysis so far unrecognized.

Fortunately, there is reason to believe that many of the difficulties of interpreting tagging results may disappear or be resolvable as more data accumulate.

The value of the tagging method as a largely independent method of determining mortalities cannot be over-emphasized and it is particularly encouraging that the computations have led to determinations practically identical with those resulting from a preliminary application of the method of vital statistics.

At the same time it should be emphasized that both the tagging, and the vital statistics, methods depend, in the last analysis, on the representative nature of the sample dealt with. At its present stage of development, the method of vital statistics includes a much larger sample, better distributed in time and space and more thoroughly adjusted to exclude the effects of extrinsic influences than does the tagging method.

## RECRUITMENT RESEARCH

Determination of the amount of recruitment would be an outstanding achievement, but would be, of itself, of only limited usefulness so long

as nothing is known as to which of two major influences determine its value. These influences are those: (1) Not connected (let us say, extrinsic influences); and (2) connected (i.e., intrinsic influences) with the size of the sardine population itself. The first category would include hydrographic and oceanographic conditions that may influence the amount of spawning and the survival of young. It would also embrace competition with, or predation by, other marine animals. The second category would include the direct influence of population numbers on the amount of spawn produced and the competitive effects of population numbers on the number surviving. The amount of spawn would be directly, and the amount of survival inversely, proportional to population numbers. The survival rates might be different for the various stages of young.

So far as intrinsic influences are concerned, one would expect recruitment to be small even at low levels of fishing intensity where there is a very large spawning population and also a very crowded condition which could impose a high mortality. At intermediate levels of fishing intensity there would be maximal recruitment resulting from a still large spawning population and the low mortality associated with an uncrowded condition. At extremely high levels of fishing intensity there should again be low recruitment due to a very small population producing insufficient spawn for maximal recruitment even in a very much thinned-out condition where competition within the population would result in negligible mortality.

If the intrinsic influences were operating alone, it would be a simple matter to construct a curve of recruitment according to levels of fishing intensity by merely observing what happens to recruitment over a range of fishing intensities. But the extrinsic influences, operating simultaneously also affect the recruitment. For instance, preliminary analysis of vital statistics for two periods of the sardine fishery showed that quadrupling of fishing intensity was accompanied by doubling of recruitment. The earlier period with the low intensity of fishing covered 8 seasons, and the later one of high intensity, 4. Both periods were thus of sufficient duration to have had a variety of extrinsic influences and their effects on mean recruitment should to some extent "average out." Yet one would be bold to conclude that they had indeed averaged out and that the increase in recruitment was in fact due to the increased intensity of fishing. On the contrary, one could almost as easily argue that through the later period, there had been 4 years of favorable extrinsic conditions that were responsible for the increase.

Yet a choice must be made between the alternatives. If the increased recruitment were in fact due to the thinning out of the population by intensive fishing, then this high rate of utilization, with the attendant large annual catches could go on with no ill consequences other than a not intolerable reduction in average size of fish. But if it were due to a lucky run of good survival years, the present rate of fishing could

not go on without serious diminution of the population, resulting in both markedly lower annual catches and a marked and perhaps intolerable decrease in average size of fish.

At the moment there is no basis for making the choice, but the program charted in the right-hand portion of the diagram, facing page 1 which is now to be discussed, is designed to distinguish between the effects of the extrinsic and intrinsic influences.

Source Data

Egg and larvae samples. - By a plankton-collecting program designed to sample the egg and larval pilchard population in waters of the spawning region, it is planned to obtain material for two sets of data on each season: 1) The numbers of eggs spawned and 2) the survival of the larvae to the post-planktonic stage.

To serve these purposes, quantitative collections of eggs and larvae must be made. Features of quantitative technique so far employed in this branch of the program are use of: The oblique method of towing to sample all egg-and-larva-bearing strata; current meters in the nets to measure the quantity of water strained in each haul; regular pattern of stations; and regular periodicity in making collections. Additionally, there have been special collections or special methods employed in the regular collections to test the reliability of the tow-net method for sampling eggs and larvae. These special inquiries have convinced us that quantitative work is feasible, if also difficult. Some of the techniques still have to be improved.

Hydrographic and meteorological data. - Observations on hydrographic conditions taken simultaneously with the collection of eggs and larvae, are intended to provide a record of conditions to be correlated with the time, place, and volume of spawning and with the survival of larvae. It is already known that the dominant features of oceanic circulation along the west coast, and particularly the maintenance of fertility of the waters through the upwelling process, are connected with the winds. With the establishment of the relationships of the oceanographic features to the meteorological influences, on the one hand, and to the amount of spawning or to the survival of larvae, on the other, it may be possible to establish directly the relationship of amount of spawning or survival of larvae, or both, to the meteorological conditions. Hence simultaneous observations on hydrography, meteorology, and the young stages of sardines promise to elucidate the influences on recruitment.

The particular oceanographic observations so far programmed, include: Those on temperature and salinity down to 500 meters regularly, and pilot observations to greater depths; determination of oxygen and phosphate content for the same strata; and counts of the diatom population for each ten-meter level to 60 meters in depth. All of these observations and

their subsequent analysis are being undertaken by the Scripps Oceanographic Institution in cooperation with the Fish and Wildlife Service. Accessory experimental work on rates of biological processes in the survey area is also under way at that Institution.

## Analysis

Compute total numbers of each stage. - With reliable quantitative collections of eggs and larvae at each station, it is further necessary to integrate the total numbers over both time and space. The time element involves proper weighting to account for the time interval between successive observations over the station pattern. This in turn involves certain assumptions, or preferably a determination of a curve of the volume of spawning as a time function. The integration over space depends upon a curve of distribution of the organisms in the sea area sampled. Both phases of integration are still in the developmental stages. An additional element in the computation is an adjustment necessitated by the smaller catches of larvae by day than by night.

For the time being, work will be directed toward determining total numbers of each stage in the particular area included within the egg and larval survey. This covers only a part of the spawning region. Extension to other areas must await either better boat facilities or a fortunate discovery of relationships with meteorological conditions which may provide a certain reliability in extrapolation.

In any event, the integration must be proceeded or followed by certain adjustments.

Adjust for drift. - Since the survey area is of limited extent and contiguous to other possible areas of spawning, some allowance must be made for gains in numbers by organisms drifting into the area and losses from their drifting out. This aspect is not serious with respect to eggs, which hatch in three days and, therefore, cannot drift far; but it is important in the case of larvae which may spend weeks or even months in the drifting phase. With the pattern of circulation determined from hydrographic observations, an allowance should be feasible. The principal difficulty now foreseen is the amount or rate of lateral diffusion, which would not be apparent from the circulation pattern alone. This adjustment is therefore still in the problem stage.

Adjust for rate of development - The numbers of eggs or larvae found in each stage will vary inversely with the time occupied in passing through the stage. One occupying a short interval of time will afford a smaller accumulation of individuals than one occupying a longer period. Adjusting numbers to allow for the "accumulation effect" involves knowledge of the rate of development or of growth. This has already been worked out for the eggs, but the rate of growth of larvae has yet to be determined.

Infant survival. - Having fully adjusted the data on numbers at each stage of infant survival, its rate should be quite simply described by a frequency distribution of the successive stages. The simplest result to be expected would be a J-shaped curve transformable into a straight line by suitable mathematical procedure. Differences from one season to another in the slope of this line should register the changes in survival rate. If, however, there are variations in that rate during the larval existance, a more complex curve would result and its interpretation would be more difficult.

Amount of spawning. - There are two approaches to the measurement of amount of spawning through 1) Computations from data produced by the vital-statistics method that would effictively enumerate the spawning stock; and 2) sampling the sea water for eggs. Both have serious obstacles. The approach through spawning stock involves the appraisal of fecundity of females by sizes or ages, an appraisal rendered difficult for lack of samples of spawners which resort largely to grounds farther offshore than the area in which commercial fishing takes place.4/ Therefore, this approach has been indicated by a broken line in the diagram facing page 1. The approach through sampling for eggs is far simpler in principle, and in terms of the diagram would be directly from the previous computation of total numbers. However, it involves surveying larger areas than has so far been feasible with the single vessel available for this research. Satisfactory enumeration by either method depends on substantial augmentation of the sea work.

Correlations with hydrographic and meteorological conditions. - So far as recruitment is determined by the amount of spawning and modified only by the rate of larval survival, determination of the former and correlation of the latter with hydrographic and meteorological conditions would give the relationships necessary to the interpretation and prediction of changes in recruitment rate. This correlation must relate to the conditions in the one area of survey, but if it were found very exact and involved hydrographic or meteorological features of wide-spread nature, the results would possibly apply to the entire range of the species. It is more likely, however, that the more complex and extended procedure discussed in the following paragraphs will be necessary.

Multiple correlation to distinguish effects of population density from oceanographic influences. - Thus far a rather simplified view has been taken - one that stresses the larval stages as the only factor critically modifying the relationship between amount of spawning and recruitment. A more comprehensive viewpoint would recognize that there are other influences and that they may be exerted at any stage of life. To illustrate this, the recruitment diagram facing page 25 is given. Instead of a procedural diagram as in the one facing page 1, this is one of mathematical equivalents and correlations.

4/Frances N. Clark, 1934, has studied fecundity in material taken from the commercial catch. Her work proved the paucity of spawning-ripe individuals in the catch and also the difficulties in determining the numbers of eggs spawned per female per season.

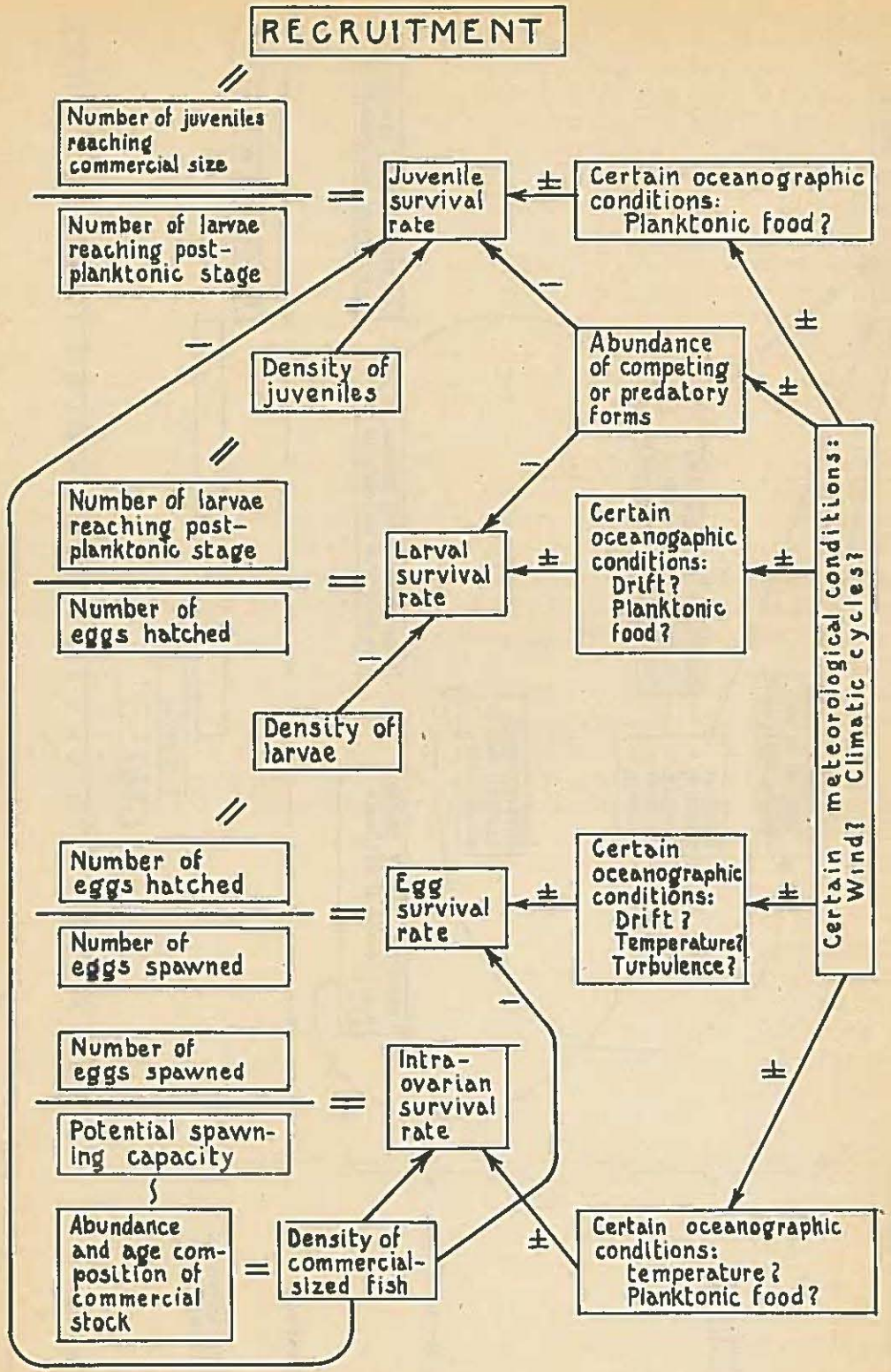
Structure of the recruitment diagram. - The diagram reads from bottom to top, beginning with the production of eggs within the female and leading through successive stages to net recruitment at the top. At the left are variables pertaining to population densities (intrinsic influences), at the right are those pertaining to oceanography (extrinsic influences), and in the middle are the survival rates (dependent variables) upon which the two categories of influences (independent variables) operate to affect the recruitment. Algebraic notations relate equivalents. Thus the fraction "number of eggs hatched" over "number of eggs spawned" equals the "egg survival rate", and the "number of eggs hatched" also equals the "density of larvae", at least initially. Correlation notations are given as arrows pointing from the independent to the dependent variable with a sign to indicate whether the correlation should be negative or positive; and where indeterminate, i.e., depending on the way the independent variable is expressed, the plus-minus sign (±) is used.

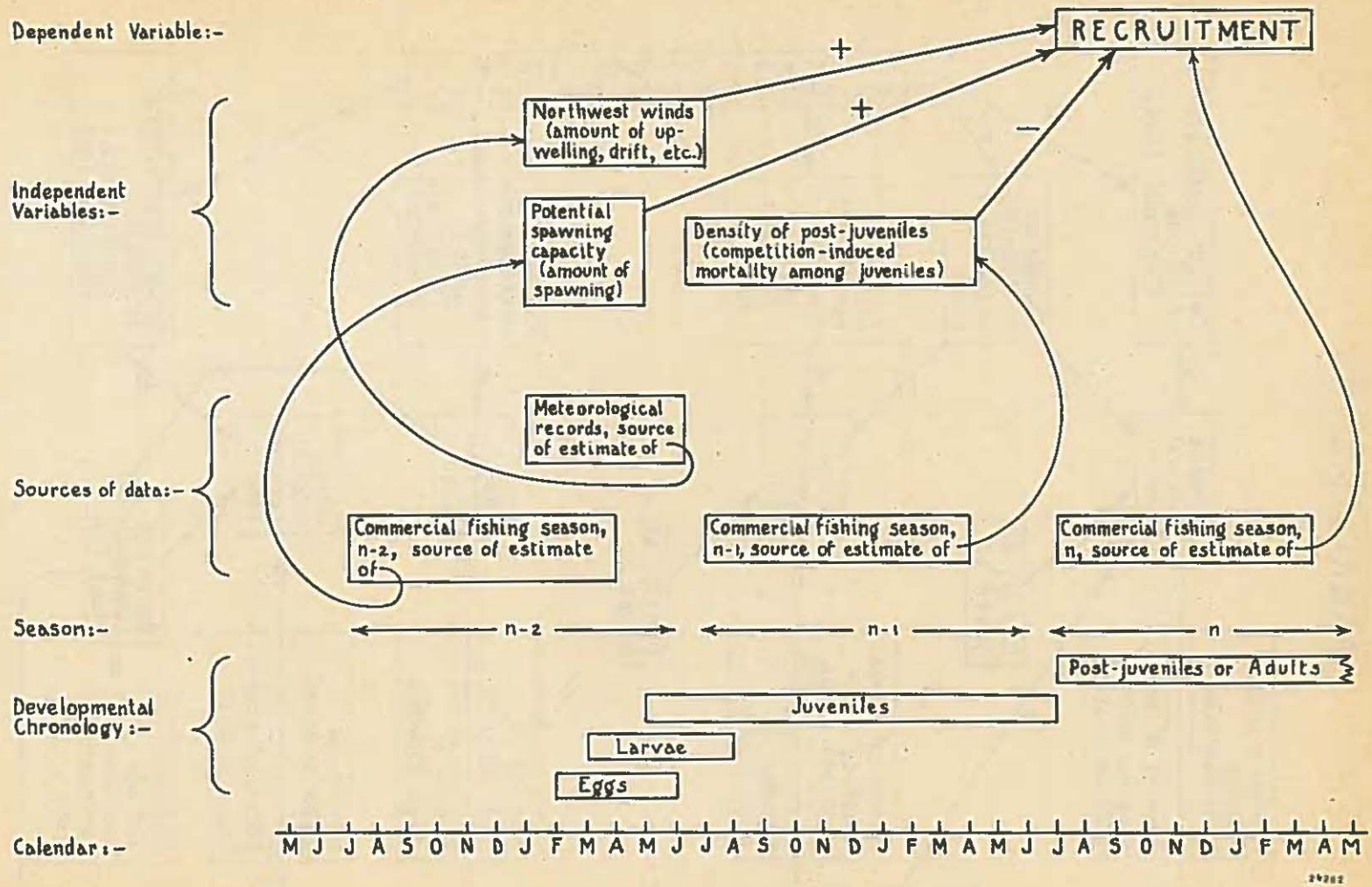
Discussion of the recruitment diagram. - It is not intended that the recruitment diagram should be an outline of procedure. Rather it indicates a complex of relationships too extensive and inclusive of too many subjects upon which data are, for the most part, non-existent at present and difficult to obtain in the future. It illustrates the manifold phases of the recruitment problem and should serve as a reminder of the fragmentary nature of less comprehensive treatments.

This comment, however, should not discourage effort to solve the problem of recruitment by some less comprehensive or abbreviated process. If the survival rate in certain stages of life is relatively constant from year to year these stages can, without risk, be ignored. If this be done and high correlation is found, much time will have been saved. If, on the other hand, the results turn out to be indeterminate, it would merely mean that the stages that were ignored did, in fact, have variability and should have been considered. Since that requires data for which there are now no collection facilities, we will merely have to decide between surveying the significance of available data or neglecting them. It is clear, however, that a program for determining additional aspects of certain reproductive attributes of the pilchard population and also of oceanographic conditions, including study of that portion of the marine fauna which may exert predation on any stage of the pilchard, should be started at the earliest opportunity.

Discussion of an abbreviated recruitment analysis. - It is interesting to speculate on how limited a view would have to be taken if one were confined to data already available or in process of becoming available. The diagram opposite gives a scheme of correlation analysis on what appears to be fairly reasonable grounds. It ignores intra-ovarian, and egg, mortality. Such sampling of eggs on the spawning grounds as has been made is impressive in the relative constancy of the numbers found and fails to suggest important variability in survival.

The scheme includes only the oceanographic extrinsic variable affecting larval survival because it hardly seems that competition between


RECRUITMENT
Number of juveniles reaching commercial size
Number of larvae reaching post-planktonic stage
Juvenile survival rate
Certain oceanographic conditions: Planktonic food?
Density of juveniles
Abundance of competing or predatory forms
Number of larvae reaching post-planktonic stage
Number of eggs hatched
Larval survival rate
Certain oceanogaphic conditions: Drift? Planktonic food?
Density of larvae
Certain meteorological conditions: Wind? Climatic cycles?
Number of eggs hatched
Number of eggs spawned
Egg survival rate
Certain oceanographic conditions: Drift? Temperature? Turbulence?
Number of eggs spawned
Potential spawning capacity
Intra-ovarian survival rate
Abundance and age composition of commercial stock
Density of commercial-sized fish
Certain oceanographic conditions: temperature? Planktonic food?


Dependent Variable:-
RECRUITMENT
+
+
−
Independent Variables:-
Northwest winds (amount of upwelling, drift, etc.)
Potential spawning capacity (amount of spawning)
Density of post-juveniles (competition-induced mortality among juveniles)
Sources of data:-
Meteorological records, source of estimate of
Commercial fishing season, n-2, source of estimate of
Commercial fishing season, n-1, source of estimate of
Commercial fishing season, n, source of estimate of
Season:-
n-2
n-1
n
Post-juveniles or Adults
Developmental Chronology:-
Juveniles
Larvae
Eggs
Calendar:-
M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M

larvae can be important as they form such a very small fraction of the plankton community. Owing to the lack of data, it ignores competition from other forms. This is perhaps the greatest weakness.

It includes only the intrinsic influence on juvenile survival and considers that the competition takes place between juveniles and post-juveniles rather than within the juvenile category itself. (This particular selection has a back-ground of observation too extensive to describe here. It was suggested by the virtual disappearance of dominance of year classes since intensification of sardine fishing took place.). With juveniles, also, the competition from other forms is ignored for the same reason that it was among larvae. However, utilization of data on predator species of commercial fishes invites attention.

The diagram opposite places the elements on a time-scale horizontally, showing the approximate season and year from which the source data are drawn and the approximate season and year in which the independent would be expected to influence the dependent, variable, recruitment. Thus recruitment of the current season (n) would be estimated from the (fully adjusted) sample of the current commercial fishing season. The numerical value of this recruitment would be correlated with: (1) The density of the post-juvenile population during the previous season (n-1) as estimated from the (fully adjusted) sample of the previous commercial fishing season; (2) the strength (or persistence) of northwesterly winds during the spawning and developmental portion of the second previous season (n-2) as estimated from weather records of that portion of the second previous season; and (3) the amount of spawning during the second previous season (n-2) as estimated from the (fully adjusted) sample of the commercial fishing season with, of course, due allowance for the percentage of fish that are mature and the proportionality between size of spawner and number of eggs spawned.5/ The curved arrows connect source data with the equivalent derived from it. The straight arrows with plus and minus signs point from dependent variables to the independent one. It is assumed that correlation between northwest winds and recruitment is positive through its influence on upwelling and the attendant "fertilizing" of the sea water. It could be negative (or curvilinear, i.e. positive in some parts of its strength or persistence range and negative in others) through its effect on drifting larvae away from the more favorable nursery grounds. Which of these actually occurs would be revealed by the correlation analysis.

The multiple correlation process indicates in the diagram opposite, three independent variables. If the correlations or regressions are rectilinear, 6 degrees of freedom would be absorbed by the multiple correlation process. It appears that data on the two intrinsic independent variables will be derivable for eight seasons when the portion of the program now in progress is completed. By that time, however, two more seasons will have elapsed and if they can be added, a series of ten seasons will be available. The meteorological data, if regular Weather Bureau

---

5/ Using approximate determinations published by Frances N. Clark, 1934.

observation will suffice, would, of course, be available for the same years. With ten seasons and the loss of six degrees of freedom there would be left four degrees of freedom on which to base judgment as to significance of results. This number is perhaps too low to do more than indicate whether the general hypothesis is on the right track. Certainly it will not be enough to conclude that the hypothesis is disproved. (Of course, correlation analysis can only disprove; it can never prove a hypothesis.)

## SUMMARY

As the pilchard program now stands, two lines of evidence when the work on them is completed, will give the rates of catch and natural mortality, and the rates of recruitment over an 8-season period, 1932-3 to 1939-40, with the prospect of adding two subsequent seasons. By appropriate computation, estimates of the total size of the population and its size-composition will be available on an annual basis from the "vital statistics" approach, and also available as a mean for a group of seasons through tagging studies. This will afford estimates of the effects of fishing at different levels of intensity on the quantity and quality of the catch. The estimates will be true only for the seasons covered by the analysis. To extrapolate them so as to predict what consequences will follow any particular level of fishing intensity, a third line of evidence is needed for determining whether the recruitment has been conditioned by the size of the stock itself (and hence predictable from the "vital statistics" evidence) or whether it was affected to an important degree by oceanographic conditions (and therefore unpredictable except in terms of range of variations about a certain mean condition). This matter is being investigated. Great difficulties have been met and still others may be anticipated, but in spite of these possibilities of solution exist.

An important phase of the entire problem is whether the range of intensities of fishing, which happened to have been included in the 8 or 10 seasons under study, is sufficient to cover reasonably well the range to be anticipated in the future. The range could be extended to lower intensities by going back to the records of still earlier periods of fishing. To extend it to higher ranges would depend on developments in the fishery. To permit development to higher ranges of intensity could involve the risk of reducing the stock so far below a desirable level that recovery might be slow. Appraisal of the degree of risk involved and of the desirability of undergoing that risk will depend on the nature of the results that flow from the current program, and may well be deferred until they become known.

## LITERATURE CITED

Baranov, F. I. 1918. Nauchnyi issledovatelskii iktiologisheskii institut. On the question of the biological basis of fisheries. Izvestia I (1), pp. 81-128, 12 figs.

Clark, Frances N. 1934. Maturity of the California sardine (Sardina caerulea), determined by ova diameter measurements. California Division of Fish and Game. Fish Bulletin No. 42, 49 pages, 19 figs.

1940. The application of sardine life-history to the industry. California Fish and Game, Vol. 26, No. 1, pp. 39 - 48; 1 table, 2 figs.

Hodgson, W. C. 1939. An improved method of sampling herring shoals. Cons. Perm. Int. pour l'Expl. de la Mer, Rapports et Procos - Verbaux des Reunions. Vol. CX, pp. 31-38, 5 figs., 4 tables.

Ricker, W. E. 1940. Relation of "Catch per unit effort" to abundance and rate of exploitation. Jour. Fish. Res. Bd. of Canada, Vol. 5, No. 1, pp. 43 - 70, 4 tables, 3 figs.

Rounsefell, George A., and Edwin H. Dahlgren.
1933. Tagging experiments on the Pacific Herring, Jour. du Cons., Cons. Perm. Int. pour L'Expl. de la Mer, Vol. VIII, No. 3, pp. 371 - 384, 6 figs. Copenhague.

Thompson, W. F. 1926. Errors in the method of sampling used in the study of the California Sardine, in The California sardine. California Div. of Fish and Game. Fish Bull. No. 11, pp. 159 - 189, 13 figs.

Thompson, W. F., and F. H. Bell.
1934. Biological statistics of the Pacific halibut fishery. Int. Fish. Comm., Report No. 8, 49 pp., 18 figs., 15 tables.