Ichthyoplankton and Fish Recruitment Studies in Large Marine Ecosystems

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Introduction

Resource assessment studies of the National Marine Fisheries Service (NMFS) were expanded significantly during the middle 1970's to support the conservation and management of marine fishery resources within the U.S. Fishery Management Zone (FMZ) established by Congress in 1976 (Fig. 1). This law extended U.S. jurisdiction to a 322 km (200-mile) wide strip of ocean off all the U.S. coasts (over 3.5 million km²).

ABSTRACT—Within the Fishery Management Zone of the United States, seven Large Marine Ecosystems (LME's)—Insular Pacific, Eastern Bering Sea, Gulf of Alaska, California Current, Gulf of Mexico, Southeast Atlantic Shelf, and Northeast Atlantic Shelf—support multi-billion-dollar fisheries, operating at different trophic levels. The LME's are characterized by unique bathymetry, hydrography, productivity, and population structure. To improve abundance forecasts of recruitment success of incoming year classes, two assessment strategies are used by NMFS in the LME's: 1) Fisheries independent surveys of fish eggs and larvae on mesoscale grids of 20-100 km at frequencies of two to twelve times a year to obtain estimates of the size of the spawning adult stocks, and 2) other studies within the mesoscale survey matrix aimed at discovering the processes controlling the annual recruitment success of new year classes. Processes under investigation include growth and mortality of eggs and larvae under variable density-dependent predator-prey interactions and density-independent influences of changes in circulation, water-column structure, biological production, and pollution. The sampling designs of the multispecies ichthyoplankton surveys in the LME's provide measures of spatial and temporal variability within acceptable confidence limits for estimating changes in abundance levels of spawning stock sizes off the northeast coast and in the California Current areas.

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In this paper we provide an overview of the research strategies and new studies implemented by NMFS to overcome resource assessment problems posed by the large-scale temporal and spatial biological and environmental changes influencing the abundance levels of U.S. fishery resources within the FMZ. The new studies are part of an NMFS-NOAA initiative known as the Marine Resources Monitoring Assessment and Prediction (MARMAP) program.

The MARMAP program was built around a matrix of existing NMFS fishery resource assessment activities

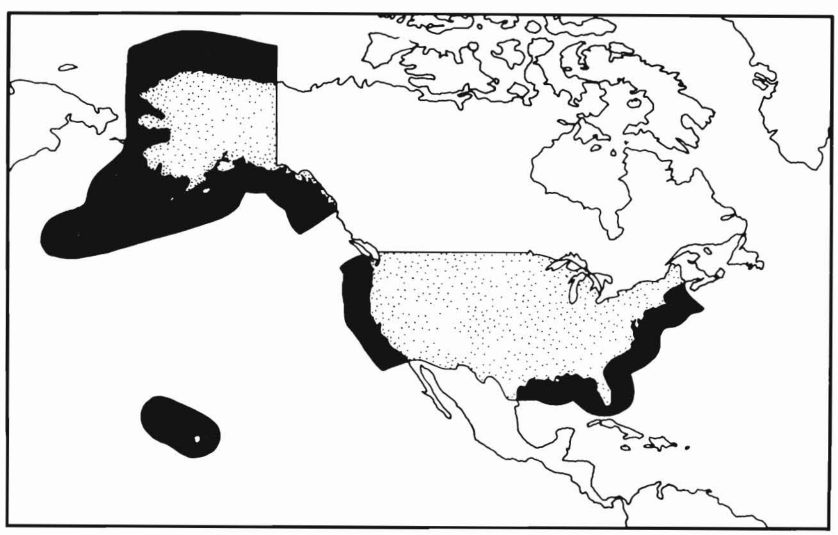


Figure 1. — The 3.5 million km² area of the U.S. Fishery Management Zone.

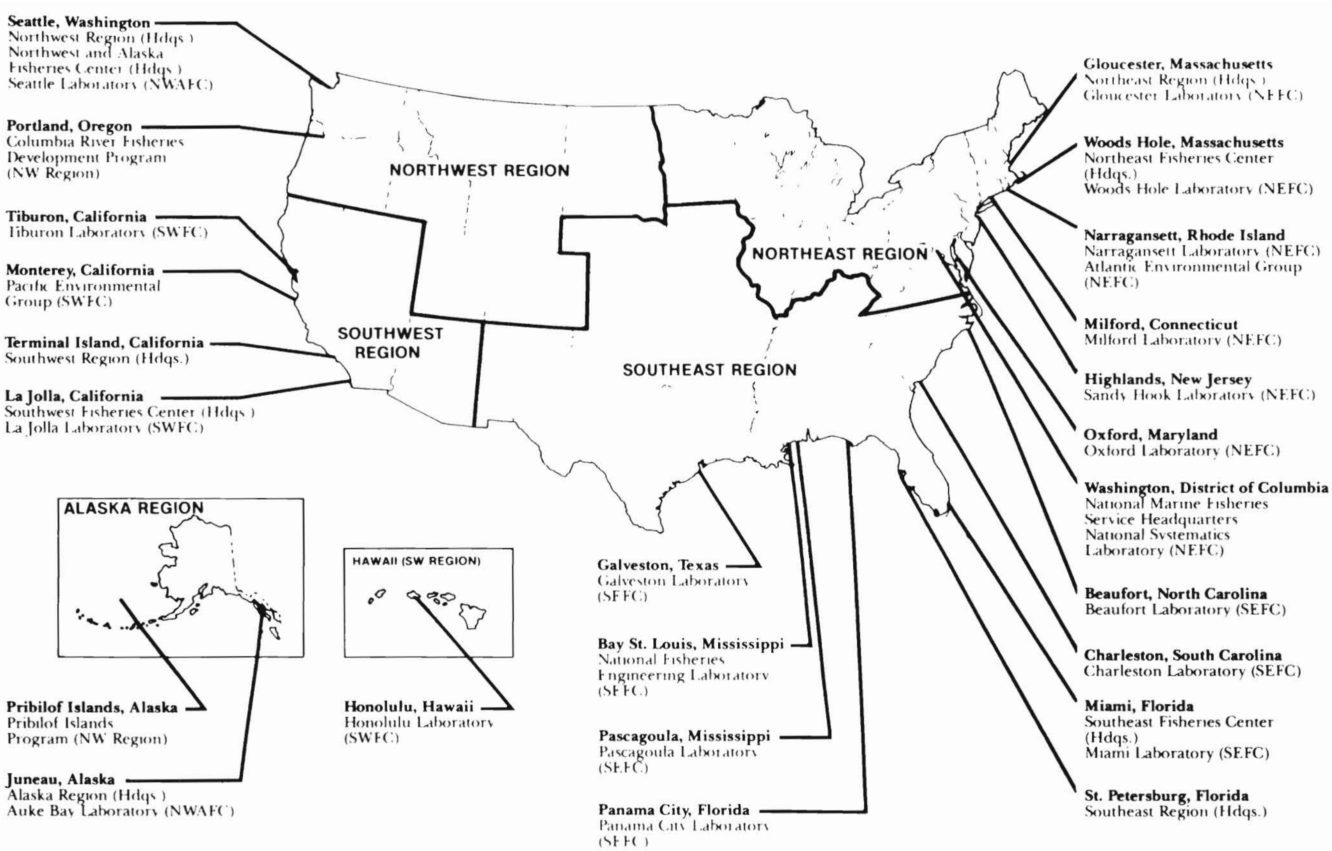


Figure 2.—The four fisheries centers and associated laboratories of the National Marine Fisheries Service, and the five regional headquarters and related offices.

including studies dealing with the analyses of catch statistics, the results of fishery surveys (pelagic, demersal, ichthyoplankton), fisheries oceanography, and fisheries engineering. A description of the early development of MARMAP program elements is given in a series of planning documents prepared by NMFS with the assistance of the Ocean Systems Division of TRW Company[1] (TRW Systems Group, 1973a,b, 1974.)

The coordination and integration of investigational components of MARMAP are major research activities of the four NMFS fisheries centers (Fig. 2). The Northwest and Alaska Fisheries Center, Seattle, Wash., is responsible for studying resources in the Gulf of Alaska, eastern Bering Sea, and off the coasts of Washington and Oregon. The Southwest Fisheries Center, La Jolla, Calif., has responsibility for the studies of the living resources of the California Current, Hawaii, and the Pacific Trust Territories. The Southeast Fisheries Center, Miami, Fla., assesses the resources from North Carolina to the Florida Keys, and in the Gulf of Mexico and Caribbean. The Northeast Fisheries Center, Woods Hole, Mass., studies the resources on the continental shelf from the Gulf of Maine to Cape Hatteras. The energetically related biological communities, bathymetry, hydrography, circulation, and productivity within each of these regions comprise coherent ecological systems encompassing broad geographic areas designated as Large Marine Ecosystems (LME's).

The fishery resources within the LME's are subject to management by Regional Fishery Management Councils, and management plans must ensure optimal sustained yields based on ecological, economic, and social considerations. The ecological decisions are based on the best scientific information available. Each fisheries center conducts ichthyoplankton studies as an important part of the overall MARMAP assessment to support the councils in developing management and conservation plans for regional fishery resources.

[1]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Fisheries Studies in Large Marine Ecosystems

From the turn of the century through the middle 1970's, fisheries studies were mainly focused on the yields of single species. This was not due to any lack of awareness of the interaction and interdependence of species, but rather to budget constraints on fisheries research institutions. However, from a fisheries management point of view, the best and most sought data follow an accurate prediction of future stock sizes and of the effect of different levels of fishing or environmental perturbation on the continued production of economically viable resource populations.

At present, NMFS under MARMAP has a more holistic approach to fishery assessment studies, with a focus on whole ecosystems and the multispecies interactions at different trophic levels that influence the annual production of fish populations. There are no shortcuts to obtain the comprehensive population and environmental information required to improve forecasts of fish abundance within the FMZ. A balanced approach is being implemented by NMFS that allows for:

1) A time-series of measurements in the form of standardized multispecies resource assessment and hydrographic surveys,

2) a systematic collection of fish-catch data, and

3) process-oriented studies dealing with biological and environmental linkages among key ecosystem components important to fish production in the sea.

Studies of single species alone do not provide sufficient data for effective management of multispecies fisheries operating at different trophic levels. While it is important for management purposes to continue these studies, they are now being pursued by NMFS within a broader matrix that measures interactions leading to changing abundance levels among the key species in the ecosystem. Single-species yield models have been augmented with multispecies models that are ecologically sensitive (Regier and Henderson, 1973; Parrish, 1975; Andersen and Ursin, 1977; Sheldon et al., 1977; Beddington et al., 1979; Grosslein et al., 1980; Laevastu and Favorite, 1981; Laevastu and Larkins, 1981; Mann, 1982; Sissenwine et al., In press; Jones[2]; Laevastu and Favorite[3]; Sherman et al.[4]).

These models deal with multispecies fishery interactions at different trophic levels. They are important approximations of the consequences of predator-prey dynamics, based on fishery-imposed selective mortality, and hold promise for providing a basis for the management of marine ecosystems. For example, possible species replacements of heavily fished mackerel and herring stocks with smaller, fast-growing, economically less desirable species have been reported for the North Sea based on a multispecies predator-prey model simulation supported by yield data (Andersen and Ursin, 1978) (Fig. 3). A review of the fish-stock replacement concept can be found in Daan (1980). However, if ecosystem models are to assume an appropriate role in the management of fishery resources, it will be necessary to overcome present deficiencies in:

1) Identifying the linkages between primary, secondary, and fish production;

2) quantifying predator-prey dynamics; and

3) understanding the relationship between stock size and recruitment.

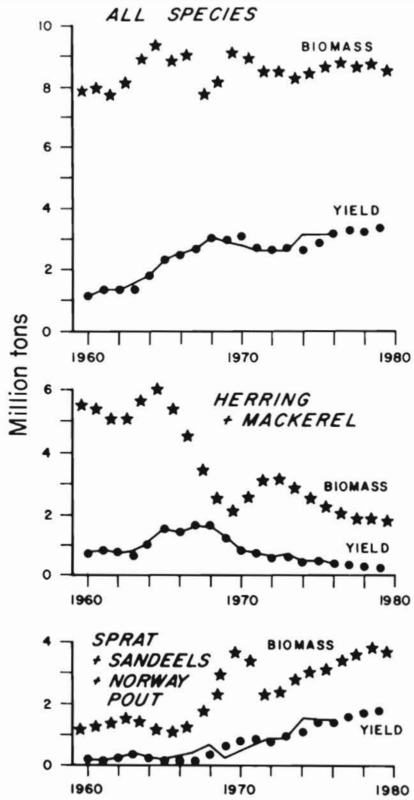


Figure 3. — Estimated changes in the biomass of fishes in the North Sea, 1960-76, with simulated yield and biomass projections to 1980. The 1.0 million metric ton decline in mackerel and herring stocks from 1968-76 from excessive fishing mortality is thought to be compensated for in the North Sea Ecosystem by replacement with small, fast-growing, opportunistic species (i.e., sprat, sand lance, Norway pout). Source: Andersen and Ursin (1977).

Ichthyoplankton Studies in LME's

The role played by ichthyoplankton in the transfer of energy in the food web is critical to an understanding of the density-independent (environmental) and density-dependent (competitor, predator) controls over the recruitment of new year classes in LME's. The six LME's for which significant NMFS resources have been dedicated to ichthyoplankton investigations include the Eastern Bering Sea, Gulf of Alaska, Washington-Oregon Coast, California Current, Gulf of Mexico, and the Northeast Continental Shelf (Fig. 4). Each is characterized by unique bathymetry, hydrography, productivity,

[2] Jones, R. 1976. An energy budget for North Sea fish species and its application for fish management. ICES C.M.1976/F:36.

[3] Laevastu, T., and F. Favorite. 1978. Numerical evaluation of marine ecosystems. Part I. Deterministic bulk biomass model (BBM). NMFS Northwest and Alaska Fisheries Center, Seattle, Wash. Processed Rep., 22 p.

[4] Sherman, K., E. Cohen, M. Sissenwine, M. Grosslein, R. Langton, and J. Green. 1978. Food requirements of fish stocks of the Gulf of Maine, Georges Bank, and adjacent waters. ICES C.M.1978/Gen:8 (Symp.).

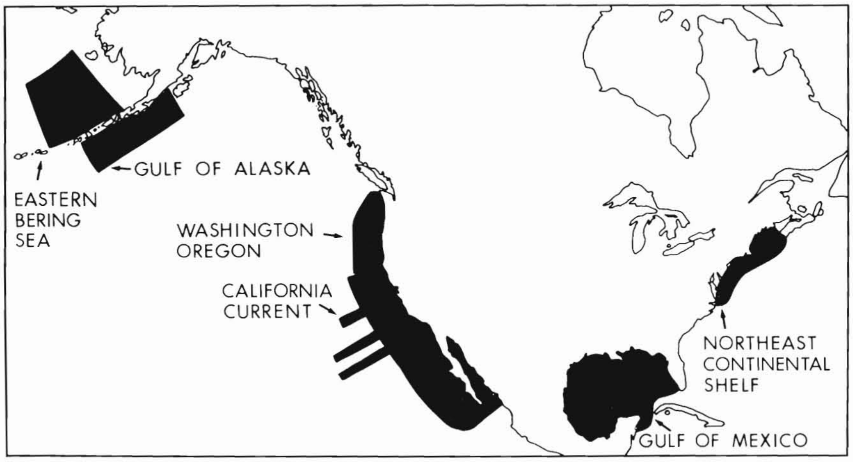


Figure 4. — The six Large Marine Ecosystems where NMFS ichthyoplankton assessment studies are underway.

and population structure. Collectively, they yield approximately 5 percent of the global fish catch, and support a multibillion-dollar annual fish catching, processing, and marketing industry.

In the LME's, two assessment strategies — ichthyoplankton surveys and trawl surveys — are used by NMFS to improve abundance forecasts of recruitment success of incoming year classes. Fisheries-independent surveys of fish eggs and larvae are conducted on mesoscale grids of 20-100 km at frequencies of two to twelve times a year to estimate the size of the spawning adult stocks. Ichthyoplankton surveys represent the most effective sampling strategy available for measuring abundance levels of all fish species inhabiting the LME's. The CalCOFI (California Cooperative Oceanic Fisheries Investigations) studies pioneered by Ahlstrom (1954) attest to the tractability of measuring population-level changes in the ichthyoplankton of the California Current system. The CalCOFI prototype ichthyoplankton survey was used as the standard approach in MARMAP and adapted for use in the LME's under investigation by NMFS. Ichthyoplankton surveys have only recently been implemented in the Gulf of Mexico, eastern Bering Sea, Gulf of Alaska, and off the Washington-Oregon coast by NMFS. Assessments of spawning biomass are an integral part of fish stock assessments in the California Current region and off the northeast coast.

The eggs and larvae of nearly all marine species in an LME can be quantitatively sampled with a single device — the plankton net. The early developmental stages are all vulnerable to the paired 60 cm bongo nets used on NMFS surveys (Posgay and Marak, 1981). Trawl surveys employing net systems, and in some areas acoustic signals and net systems, (e.g., for juveniles and adults of demersal and pelagic species) are more selective samplers. The sampling designs of the multispecies ichthyoplankton surveys within the LME's provide measures of spatial and temporal variability that are within acceptable confidence limits for estimating changes in abundance levels of parental spawning biomass in the California Current and off the northeast coast (Stauffer and Charter, 1982; Pennington and Berrien[5]). To obtain samples of ichthyoplankton used in spawning biomass estimates, the sampling is designed to encompass the temporal and spatial extent of spawning using a systematic grid of stations. A detailed description of the methods used by NMFS for multispecies ichthyoplankton sampling is given in Smith and Richardson (1977).

Within the mesoscale (20-100 km) multispecies ichthyoplankton time-series surveys (bimonthly to semi-annual), studies of the recruitment process are nested for target species on a finer horizontal and vertical scale (Lasker, 1981a; Lough and Laurence[6]) aimed at discovering the processes controlling annual recruitment success of new year classes. Processes under investigation include growth and mortality of eggs and larvae under variable density-dependent predator-prey interactions and density-independent influences of changes in circulation, water-column structure, biological production, and pollution. Among the target species of recruitment studies are walleye pollock, *Theragra chalcogramma*; Pacific king crab, *Paralithodes* spp.; Pacific sardine, *Sardinops sagax*; Pacific anchovy, *Engraulis mordax*; Atlantic mackerel, *Scomber scombrus*; Pacific salmon, *Oncorhynchus* spp.; striped bass, *Morone saxatilis*; Pacific hake, *Merluccius productus*; silver hake, *Merluccius bilinearis*; Atlantic menhaden, *Brevoortia tyrannus*; Gulf shrimp, *Penaeus* spp.; bluefin tuna, *Thunnus thynnus*; spot, *Leiostomus xanthurus*; Atlantic croaker, *Micropogonias undulatus*; Atlantic cod, *Gadus morhua*; and haddock, *Melanogrammus aeglefinus*.

Southeast Fisheries Center

Initiation of Gulf of Mexico Ichthyoplankton Surveys

The ichthyoplankton programs of the Southeast Fisheries Center, under the direction of William Richards, have included pioneering surveys of the ichthyoplankton populations of the

[5] Pennington, M., and P. Berrien. 1982. Measuring the effect of the variability of egg densities over space and time on egg abundance estimates. *In* Report of the Working Group on Larval Fish Ecology, Lowestoft, England 3-6 July 1981, p. 127-141. ICES C.M.1982/L:3

[6] Lough, R. G., and G. C. Laurence. 1982. Larval haddock and cod survival studies on Georges Bank. *In* Report of the Working Group on Larval Fish Ecology, Lowestoft, England 3-6 July 1981, p. 103-119. ICES C.M.1982/L:3.

Gulf of Mexico. From 1977 through 1982, the first comprehensive surveys were conducted over the entire region, including a total of 500 stations and 1,500 MARMAP-type bongo and neuston samples. Station locations are shown in Figure 5. Preliminary results are given in a report by Richards et al.[7] In addition to ichthyoplankton tows, the 1978-81 time-series included water-column measurements of temperature, salinity, nutrients, chlorophyll, and light penetration.

Preliminary analysis of species-abundance relationships demonstrated significant differences in rank order of abundance of the 20 most numerous families among the northeast, southeast, northwest, and southwest quadrants of the Gulf of Mexico (Table 1). A total of 137 genera and species in 91 families were identified from the samples. Mesopelagic families including the Myctophidae and Gonostomatidae were the predominate ichthyoplankton groups in the collections followed by the third- and fourth-ranking Bregmacerotidae, and the Scombridae (Potthoff et al., 1981). These analyses were performed on the 1978 time-series. Other samples are presently being sorted and the larvae identified to the family level by the Plankton Sorting and Identification Center in Szczecin, Poland (Sherman and Ejsymont, 1976).

Ichthyoplankton Identification Studies

The waters studied by the SEFC contain a basically tropical fauna, characterized by a large number of species (estimated at 1,500). Ichthyoplankton samples from tropical waters are generally characterized by few specimens but a great many species in each sample. Consequently, a large amount of effort has gone into studies to develop methods of identification of larval fish and eggs. In the late 1960's and early 1970's, over 60 species were reared in the laboratory from which identification series were developed. Interestingly, the first laboratory rearing of tuna was accomplished by Edward Houde and William Richards (Houde and Richards, 1969). Identification of larval series of tropical fish includes studies on tuna (Potthoff and Richards, 1970; Richards and Dove, 1971; Potthoff, 1974, 1975; Richards and Potthoff, 1974a,b; and Potthoff et al., 1980), on billfish (Richards, 1974; Potthoff and Kelley, 1982), on clupeoids (Houde et al., 1974; Richards et

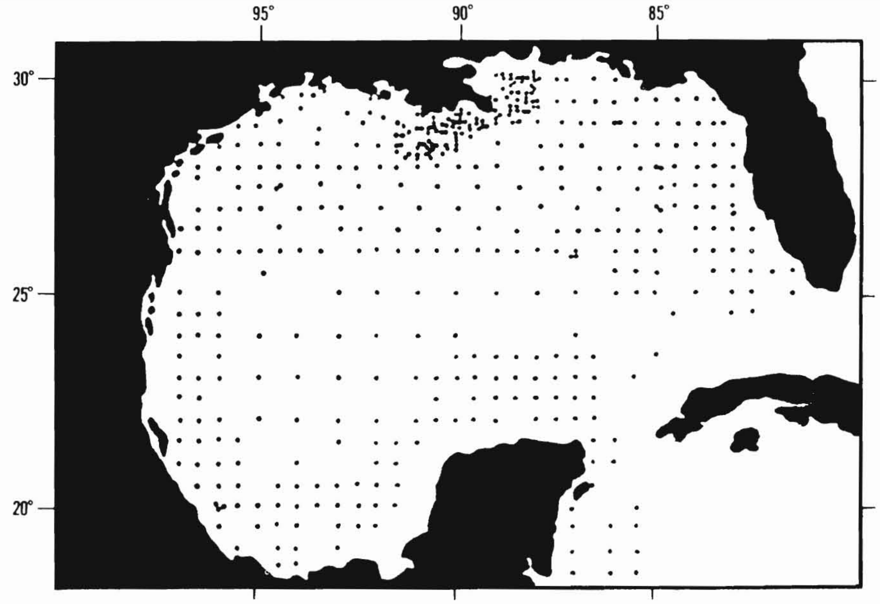


Figure 5. — Station pattern of the Gulf of Mexico ichthyoplankton surveys, 1982.

Table 1. — Rank order of the 21 most abundant families, *Oregon II* Cruise 87, 1978 overall and by quadrant in the Gulf of Mexico.

	Rank by quadrant			
Overall rank	Northeast	Southeast	Northwest	Southwest
1 Myctophidae	Myctophidae	Myctophidae	Myctophidae	Myctophidae
2. Gonostomatidae	Gonostomatidae	Gonostomatidae	Gonostomatidae	Gonostomatidae
3. Bregmacerotidae	Scombridae	Bregmacerotidae	Bregmacerotidae	Apogonidae
4. Scombridae	Bregmacerotidae	Scaridae	Gobiidae	Bothidae
5. Paralepididae	Stromateidae	Bothidae	Clupeidae	Bregmacerotidae
6. Stromateidae	Paralepididae	Scrombridae	Stromateidae	Stromateidae
7. Gobiidae	Carangidae	Labridae	Paralepididae	Paralepididae
8. Bothidae	Bothidae	Gobiidae	Serranidae	Scombridae
9. Serranidae	Synodontidae	Tetraodontidae	Synodontidae	Gobiidae
10. Synodontidae	Scaridae	Gempylidae	Scombridae	Serranidae
11 Scaridae	Serranidae	Carangidae	Bothidae	Gempylidae
12. Clupeidae	Gempylidae	Ophidiidae	Engraulidae	Engraulidae
13. Apogonidae	Apogonidae	Scorpaenidae	Carangidae	Anguilliformes
14. Carangidae	Labridae	Synodontidae	Anguilliformes	Carangidae
15. Labridae	Gobiidae	Serranidae	Gempylidae	Labridae
16. Engraulidae	Anguilliformes	Stromateidae	Apogonidae	Scaridae
17. Gempylidae	Engraulidae	Apogonidae	Labridae	Scorpaenidae
18. Tetraodontidae	Scorpaenidae	Paralepididae	Scaridae	Synodontidae
19. Anguilliformes	Tetraodontidae	Anguilliformes	Ophidiidae	Tetraodontidae
20. Ophidiidae	Ophidiidae	Engraulidae	Tetraodontidae	Ophidiidae
21 Scorpaenidae	Clupeidae	Clupeidae	Scorpaenidae	Clupeidae

[7] Richards, W. J., M. F. McGowan, and J. A. Ortner. 1982. Summary of Gulf of Mexico ichthyoplankton research 1977-1982 with bluefin tuna population estimates and preliminary analyses of larval bluefin distribution and ichthyoplankton assemblages. NMFS Southeast Fisheries Center, Miami Laboratory, Ref. Doc.

al., 1974), and on reef fishes (Saksena and Richards, 1975; Richards and Saksena, 1980; Houde and Potthoff, 1976). In addition to these publications, taxonomic studies are continuing on reef fish and oceanic pelagic larvae.

Bluefin Tuna Assessments

One of the priority species targeted for fisheries-independent estimates of parent stock biomass is the bluefin tuna, *Thunnus thynnus*. Estimates of spawning stock sizes were derived from larval abundances in 1977, 1978, and 1981 (Table 2). These estimates were of the same order of magnitude as fishery-dependent estimates derived from virtual population analyses. Distributions of bluefin tuna larvae in the Gulf of Mexico are shown in Figure 6. Correlations between bluefin tuna larval abundance and surface temperature, latitude, and zooplankton displacement volumes provide evidence of nonrandom distribution of bluefin tuna larvae in the Gulf of Mexico. Further analyses of the relationship between bluefin tuna larvae and environmental parameters will provide additional information on the species' life history. The spatial and temporal distributions will be used as a basis for stratification of the ichthyoplankton sampling design to reduce the variance of the population size estimates.

Table 2. — Estimates of bluefin tuna larvae and spawning stock with 95 percent confidence limits from Gulf of Mexico ichthyoplankton surveys.

Item	1977	1978	1981
Total larvae times 10^{10}	256± 826	594± 461	338± 635
Spawning stock	302,206 ± 1,007,555	699,951 ± 622,959	398,892 ± 791,402
Stations	48	135	76
Stations with bluefin larvae	15	49	13
Actual catch of bluefin larvae	34	292	51
Maximum catch per tow	7	33	19
Stations with >10 larvae	0	7	1

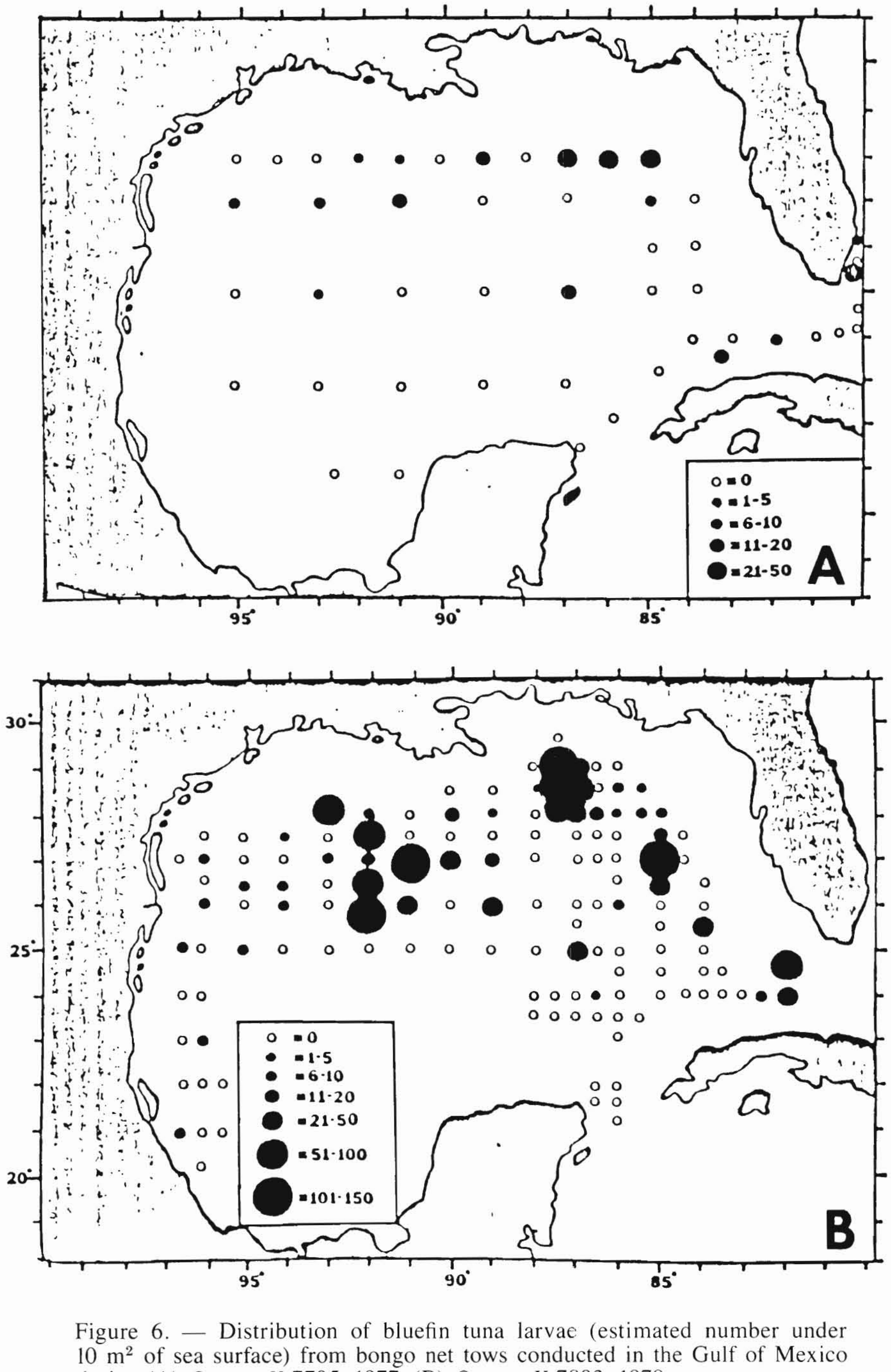


Figure 6. — Distribution of bluefin tuna larvae (estimated number under 10 m² of sea surface) from bongo net tows conducted in the Gulf of Mexico during (A) *Oregon II* 7705, 1977; (B) *Oregon II* 7803, 1978.

SEAMAP

The MARMAP studies of ichthyoplankton in the Gulf of Mexico have been designated as the SEAMAP (Southeast Area Monitoring Assessment and Prediction) program which is a joint Federal-State program coordinated through the Southeast Fisheries Center. During 1982, the first year of SEAMAP operations, ichthyoplankton sampling was expanded in the Gulf of Mexico in cooperation with scientists and ships from Mexico, Texas, Florida, Louisiana, and Mississippi. A listing of survey dates and sampling

Table 3. — Summary of ichthyoplankton cruises and types of samples collected in the Gulf of Mexico 1977-82.

Year	Cruise	Date	No. of completed stations	Environmental parameters										
				Bongo	Neuston	XBT	Surface temp.	Chloro-phyll	Salinity	Secchi disk	Irra-diance	Nutri-ents	^{14}C uptake	Gelb-stoff
1977	*Oregon II*-77	29 Apr. - 24 May	48	X	X		X							
1978	*Oregon II*-87	2 May - 30 May	134	X	X	X	X	X						
1980	*Oregon II*-105	25 Feb. - 27 Mar.	80	X	X	X	X	X			X	X	X	X
1981	*Oregon II*-117	1 May - 26 May	102	X	X	X	X							
	Oregon II-120	15 Aug. - 28 Aug.	45	X	X	X	X							
1982	*Oregon II*-126	15 Apr. - 23 May	120	X	X	X	X	X	X	X				
	SEAMAP	June - July	491	X	X	X	X	X	X					

operations is given in Table 3. The Instituto Nacional de Pesca of Mexico employed three Mexican vessels to provide complete coverage of Mexican waters. Ichthyoplankton stations in the Gulf of Mexico were occupied by six research vessels. All the cruises were conducted in May, June, and July, the peak spawning time for many Gulf species. The ichthyoplankton samples from the surveys will be processed by the Polish Sorting Center. In 1983, the cooperative SEAMAP survey for ichthyoplankton has been repeated. In addition, a survey was conducted in the fall to obtain data on fall-spawning species.

The continued SEAMAP cooperation will allow for fisheries-independent estimates of stock size for all Gulf of Mexico species with pelagic eggs and larvae. The information will provide needed data on fishery resources, the nature of the early life history of these resources, and the mechanisms which affect growth and survival of early life history stages. Among the multispecies target resources to be investigated are tunas, mackerels, clupeoids, and reef fishes.

Ichthyoplankton and Pollution Stress

Under the direction of Ford Cross, the SEFC Beaufort Laboratory is conducting studies of the impact of pollutants in the Mississippi River plume on larval menhaden, croaker, and spot. Ichthyoplankton sampling is conducted from Cape San Blas, Fla., to Galveston, Tex., with a principal transect off the Mississippi River Delta. Collections are made with the standard bongo sampler and the multiple opening-closing net system (MOCNESS). Larvae are examined to determine age composition and prey composition and preference. Analyses of stable carbon ratios are conducted on components of the planktonic food web in the northern Gulf in conjunction with larval fish feeding studies to evaluate the importance of terrestrial organic matter as a source of carbon in their prey. In the transfer of carbon up the food chain, dinoflagellates and tintinnids have been established as the principal food source for first-feeding Gulf menhaden, *Brevoortia patronus*, larvae, whereas zooplankton is utilized as food by larval croaker and spot. Shipboard feeding experiments, using laboratory-reared larval menhaden and spot, are conducted to evaluate the effects of net collection procedures on the fate of soft-bodied prey, including tintinnids. In addition, laboratory studies are conducted on spot and Gulf menhaden to describe morphological indicators of starvation at different temperatures and growth rates.

Southwest Fisheries Center

Pioneering Studies

The NMFS Southwest Fisheries Center (SWFC) has an extensive larval fish program in its Coastal Fisheries Resources Division, led by Reuben Lasker. Studies on larval fish at the SWFC were begun by the late Elbert H. Ahlstrom who is acknowledged as a pioneer in larval fish identification and as the originator of egg and larvae surveys to determine the distribution and number of fish in the sea (Ahlstrom, 1954, 1959, 1965). The areal extent of the CalCOFI ichthyoplankton studies in the California Current ecosystem is shown in Figure 7. The ichthyoplankton abundance information obtained by Ahlstrom was instructive in documenting the failure of sardine recruitment in the California Current ecosystem and the increase in anchovy biomass, particularly in the absence of commercial fishery and associated catch statistics for the anchovy stocks during the 1950's and 1960's (Ahlstrom, 1966; Kramer and Smith, 1971) (Fig. 8). H. Geoffrey Moser continues ichthyoplankton work at the SWFC today and emphasizes the ecological interrelationships of all species of larval fish with their surrounding biota (Ahlstrom and Moser, 1981; Stephens and Moser, 1982; Butler et al., 1982).

Considerable effort has been expended over the past two years in organizing a symposium to honor Ahlstrom. The symposium, held 15-18 August 1983, was an attempt to summarize what is known of the systematics of early life histories of fishes and produce a compendium of egg and larval stages on a global scale. The published proceedings will extend the utility of ichthyoplankton studies in fishery assessments by providing a ready source for the identification of egg and larval stages for stock assessment purposes.

Physiological Ecology Studies

Physiological studies on larvae in the laboratory began with Reuben Lasker's work in the late 1950's. These investigations have now shifted to the field where laboratory data on larval fish are applied to ecological situations. This work attempts to provide insights into the relationship between the size of a fish stock and recruitment. Laboratory

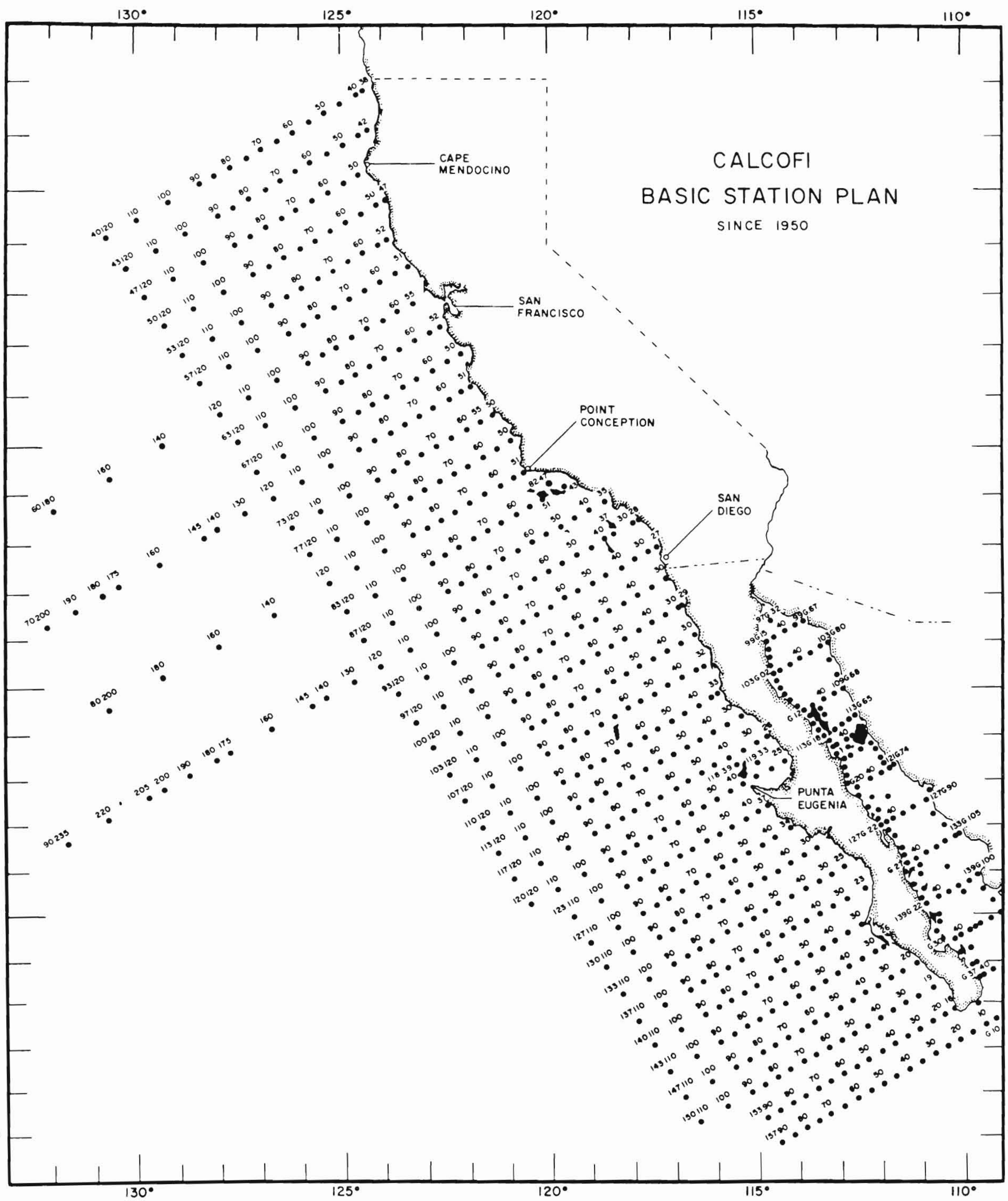


Figure 7. — CalCOFI area and ichthyoplankton station pattern since 1950.

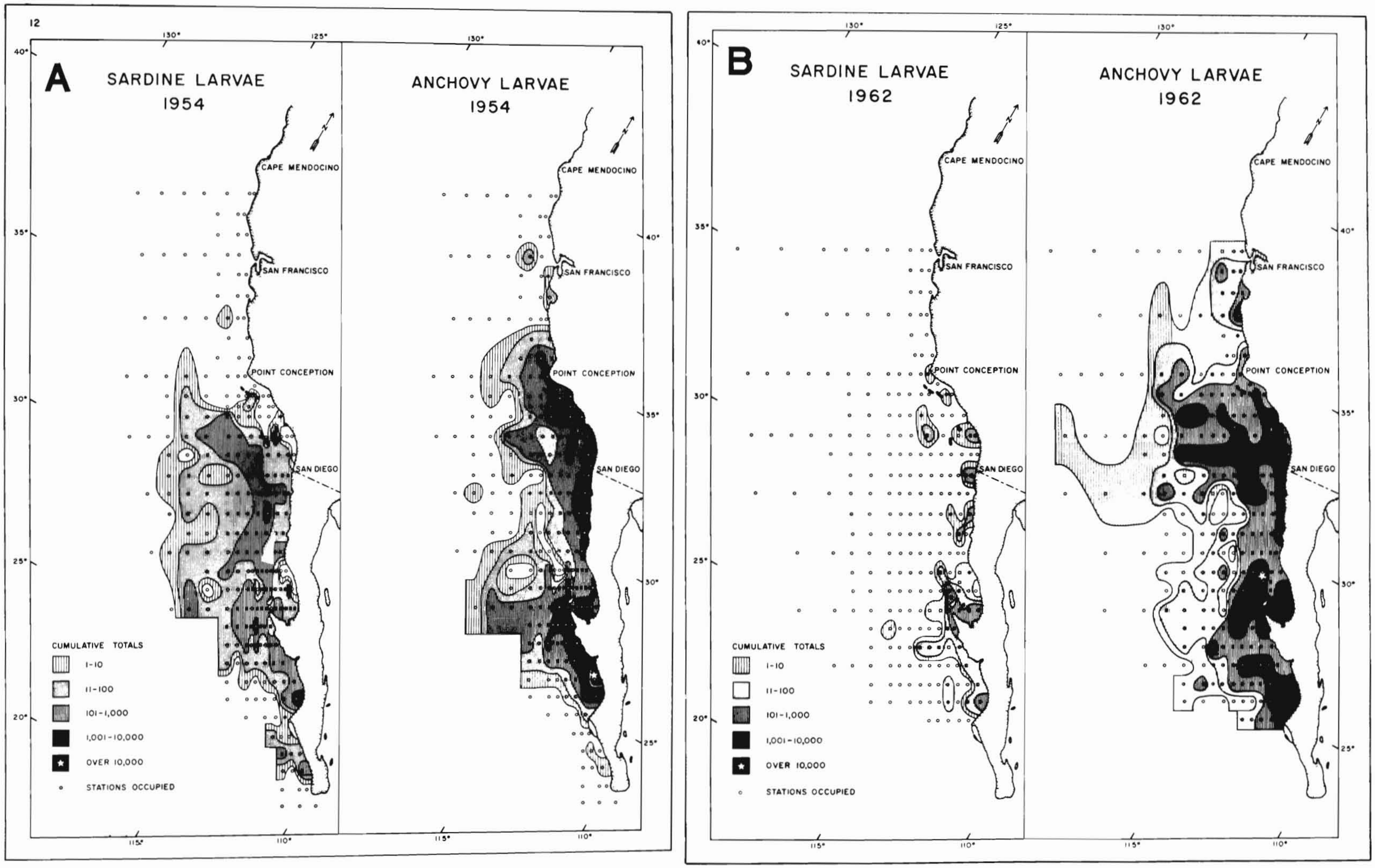
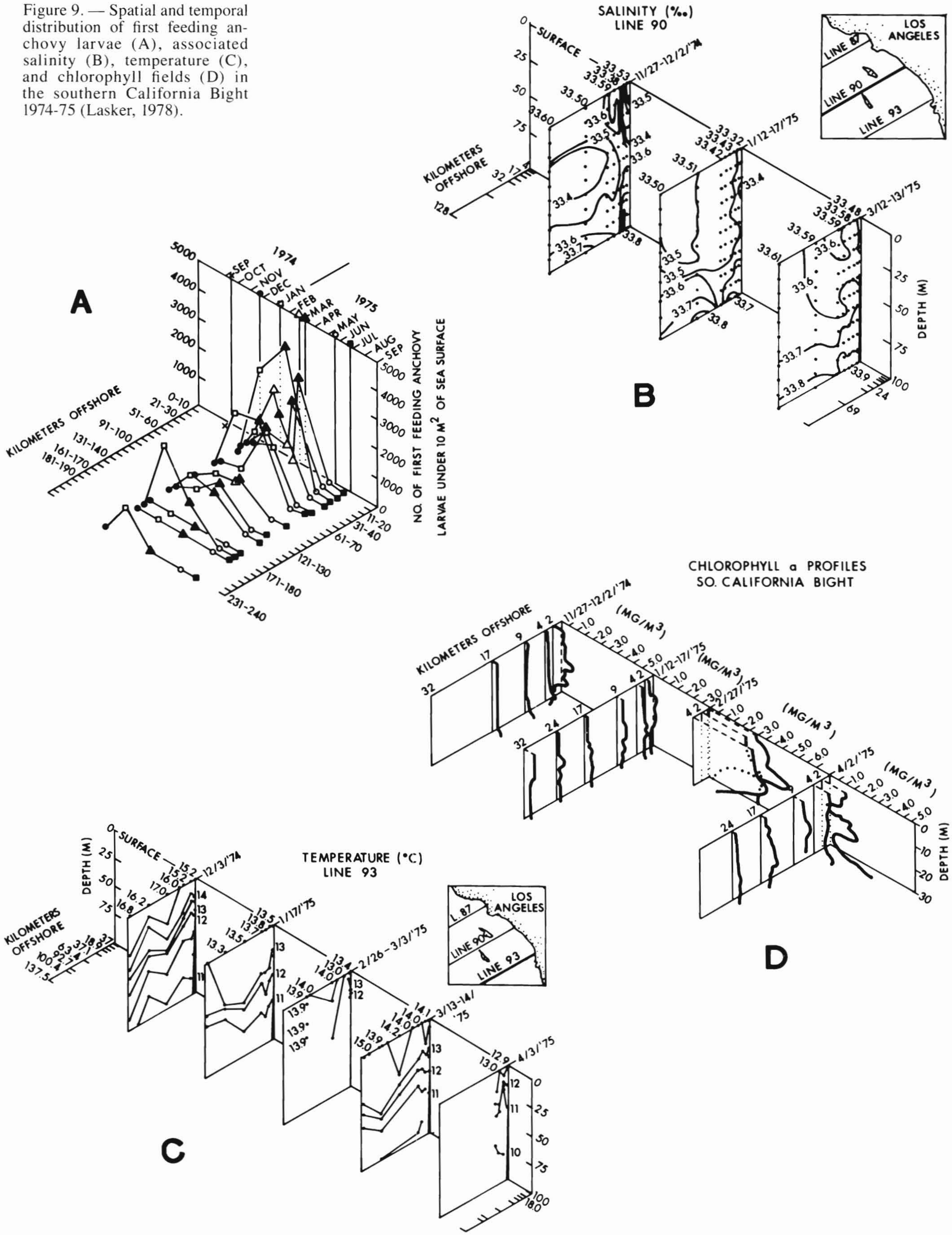


Figure 8. — Changes in the abundance of sardines and anchovies have been documented through the CalCOFI ichthyoplankton survey method. A = Relative abundance of sardine and anchovy larvae in 1954. B = The decline in sardines and population increase in anchovy based on CalCOFI surveys in 1962 (Ahlstrom, 1966).

Figure 9. — Spatial and temporal distribution of first feeding anchovy larvae (A), associated salinity (B), temperature (C), and chlorophyll fields (D) in the southern California Bight 1974-75 (Lasker, 1978).



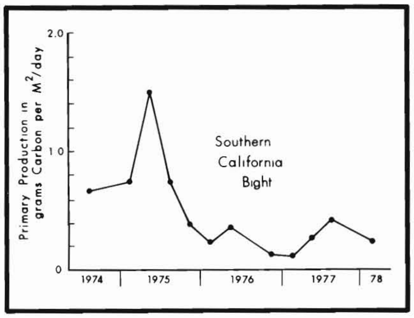


Figure 10. — Cumulative carbon production of the southern California Bight, 1974 through 1978 (Lasker, 1981).

and field data have been documented which support the hypothesis that stability of the ocean is an important factor in survival of anchovy year classes. The holistic ecosystem approach for investigating the oceanographic factors controlling year-class recruitment in relation to the growth and survival of anchovy larvae in the sea has been most productive. The CalCOFI sampling area encompasses the temporal and spatial extent of spawning, thereby allowing for a series of successful large-scale, at-sea experiments within the CalCOFI sampling grid on predator-prey relationships between anchovies and their prey field. Temperature, salinity, and chlorophyll profiles are used to identify oceanographic features that concentrate phytoplankton cells of the appropriate size and food quality for anchovy (Fig. 9). It is interesting to note that during the 5 years from 1974 through 1978, the greatest abundance of phytoplankton measured as the average production of mg C/m^2 d^{-1} was highest in 1975, the year of the poorest anchovy recruitment during the 5-year time-series of observation (Fig. 10).

Recruitment studies on the anchovy conducted by Lasker and his group have demonstrated the importance of moderate levels of stability in the California Current upwelling system to support the growth of the appropriate dinoflagellate prey, *Gymnodinium splendens*. Lasker (1975), with laboratory-spawned larvae of the northern anchovy, *Engraulis mordax*, in the sea at 13°-14°C, showed that they needed 30 40-50 μm (diameter) particles ml^{-1} to stimulate feeding and gut filling. This result was verified with laboratory experiments. Hunter (1977) has shown that the anchovy larvae need as many as 230 40 μm particles d^{-1}. Chlorophyll layers were discovered not far off the southern California coast which contained enough particles of *Gymnodinium splendens* to support the anchovy larvae (34-300 ml^{-1}, 40-50 μm in diameter). One such layer formed a patch about 100 km in length (Lasker, 1975).

Lasker (1981a) ranked anchovy year classes between 1962 and 1977. The 1975 year class was the lowest in rank in a calm year with high productivity, but *Gonyaulax polyedra* predominated. Scura and Jerde (1977) had shown that *G. polyedra* is not very nutritious and that anchovy larvae do not eat diatoms. The 1976 year class was the highest in rank in a calm year with low productivity, but *Gymnodinium splendens* predominated. From these studies it was concluded that larval anchovies probably use particles the size of *G. splendens* in the chlorophyll layers. Year-class strength of anchovies may depend upon the presence of *G. splendens* (as opposed to *Gonyaulax polyedra*) and upon the maintenance of the layers. Poor year classes may be the result of layer breakdown due to wind mixing or to the presence of *G. polyedra*.

Working closely with the Coastal Division, Richard Parrish, Andrew Bakun, Craig Nelson, and David Husby have applied newly devised oceanographic indexes to the study of this hypothesis and the concomitant larval drift theory of larval mortality (Bakun, 1973; Parrish, 1976; Bakun and Nelson, 1977; Parrish and MacCall, 1978; Bakun and Parrish, 1980, 1982; Parrish et al., 1981; Husby and Nelson, 1982; Brewer and Smith, 1982).

John R. Hunter began his larval fish studies by describing the behavior of anchovy larvae. While this work has continued on a number of species, he has in recent years shifted his emphasis to a study of the effect of alterations in the reproductive physiology of fishes on egg and larval survival (Hunter, 1972, 1981; Hunter and Kimbrell, 1980a,b; Hunter and Coyne, 1982).

In Hunter's Physiological Ecology group, Gail Theilacker and Charles O'Connell have established criteria for determining whether larvae in the sea are starving (Theilacker, 1978; O'Connell, 1980). Angeles Alvariño provides information on the distribution and abundance of invertebrate predators of larval fish (Alvariño, 1980, 1981). Robert Owen studies small-scale distribution of larvae and their food (Owen, 1980, 1981); and Richard Methot and Roger Hewitt have been making a careful analysis of the mortality of northern anchovy eggs and larvae in relation to the environment (Hewitt, 1981; Methot, 1981; Hewitt and Methot, 1982).

Paul E. Smith is responsible for studies of biomass estimation using egg and larval abundance as indicators of adult fish abundance (Smith, 1972). He provides the SWFC Coastal Division with the development and evaluation of survey systems, particularly the design and testing of new plankton nets, and is responsible for designing the surveys themselves.

CalCOFI Population Assessments

The Coastal Division also has responsibilities to the Pacific Fishery Management Council for biomass estimation of the northern anchovy and for monitoring the populations of a variety of other commercially valuable pelagic fish in the California Current ecosystem. Using the extensive background information on anchovy larvae and adults obtained over more than 20 years, a new "egg production method" for biomass estimation was devised by a Coastal Division team (Parker, 1980).

The egg production method produced by the SWFC for estimating the biomass of anchovy is used by the Pacific Fishery Management Council to manage the anchovy fishery. Besides its use off California, the method is being tried off Peru and South Africa. A number of other important techniques have been developed at the SWFC, e.g., spawning and rearing of many species of fishes with pelagic eggs and larvae (Lasker et al., 1970), precise ageing of larvae by counting daily increments on larval otoliths (Brothers et al., 1976; Methot, 1981; Methot and Kramer, 1979), the resonance frequency acoustic technique for counting larvae and juveniles in the sea (Smith, 1972, 1978), histological and morphological measurements of larvae to indicate starvation (O'Connell, 1976, 1980, 1981), the use of ovarian follicle histology to determine frequency of spawning (Hunter and Macewicz, 1980), and others.

In the study of fish recruitment, the SWFC Coastal Division maintains over 25 years of egg, larva, and oceanographic data collected by CalCOFI. Many of the results appear in an annual peer-reviewed journal, the *CalCOFI Reports*. Processed data for the large area of the California Current ecosystem are published in the occasional publication, the *CalCOFI Atlas*, now in its thirtieth volume (Lynn et al., 1982). A short review and bibliography of the division's recent work are available in a book entitled "Marine Fish Larvae" and edited by R. Lasker (1981b).

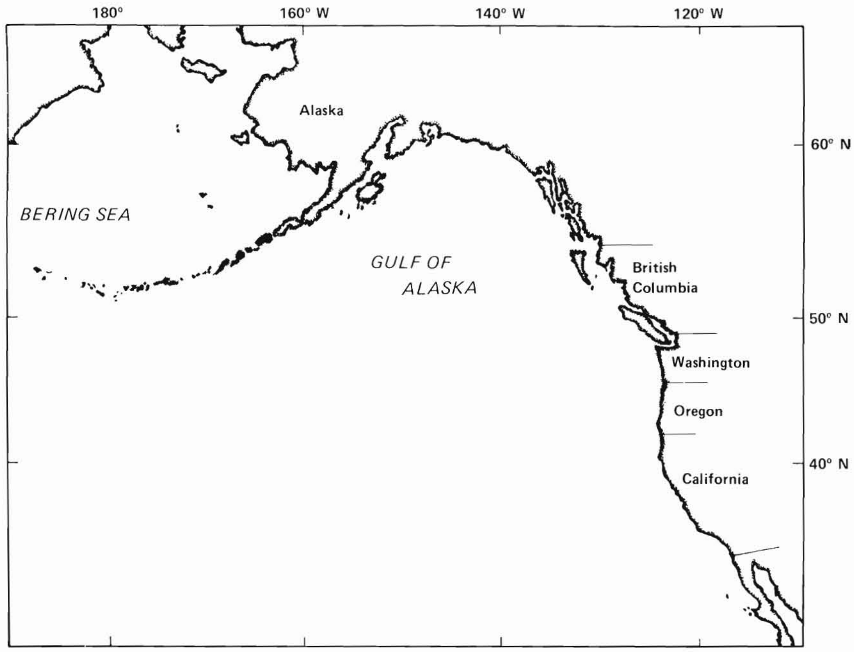


Figure 11. — Extent of ichthyoplankton studies of the Northwest and Alaska Fisheries Center in three LME's — Eastern Bering Sea, Gulf of Alaska, and off the Washington-Oregon Coast.

Ichthyoplankton and Pollution Stress

Studies of the impacts of pollution on the early life stages of marine fish are conducted at the SWFC Tiburon Laboratory under the direction of Janet Whipple. The target species in the study is the striped bass, *Morone saxatilis*. The abundance of striped bass in the San Francisco Bay and Delta region has decreased in recent years. Concerned with the future of this popular sport fish, a joint study team of scientists from the Center's Tiburon Laboratory, the University of California at Davis and Santa Cruz, and the California Department of Fish and Game have been studying likely causes of the decline. Preliminary results of the team's effort indicate that chronic toxic chemical exposures affect every stage of the striped bass life cycle, including significant depression in viable egg production and concentration of petrogenic hydrocarbons at levels sufficient to cause mortalities of larvae and juveniles (Whipple et al., 1981; SWFC Monthly Report[8]).

Studies are underway at the Honolulu Laboratory of SWFC to develop methods for breeding and rearing tuna in captivity for eventual assessment of environmental impacts on larvae and juveniles.

Northwest and Alaska Fisheries Center

Areas of Interest

The Northwest and Alaska Fisheries Center is responsible for recruitment processes studies for fishery resources in three LME's: Eastern Bering Sea, Gulf of Alaska, and off the Washington-Oregon Coast (Fig. 11). Studies are carried out under the direction of Arthur Kendall. In each of these areas the level of background information on the fish stocks varies, as do the fisheries-related problems. Within the framework of understanding causes of variation in year-class strength of fishes, tractable problems are being resolved by building on a growing information base that is developing step-by-step (Kendall et al.[9]).

Identification Guide

Early life history studies are focused on providing sufficient taxonomic expertise to identify the eggs and larvae of the most important species. Descriptions have been prepared of the diagnostic characteristics used for identification of Pacific tomcod, *Microgadus proximus*; walleye pollock, *Theragra chalcogramma*; and Pacific cod, *Gadus macrocephalus* (Fig. 12). At present only about half the larvae collected can be identified to species. A major effort now underway is the preparation of a laboratory guide for identification of

[8] SWFC Monthly Report. 1982. Tiburon Laboratory. NMFS Southwest Fisheries Center, La Jolla, Calif., August 1982:22.

[9] Kendall, A. W., Jr., J. R. Dunn, and A. C. Matarese. 1980. Early life history of fishes studied to help explain variations in abundance. Resource Ecology and Fisheries Management Division of Northwest and Alaska Fisheries Center, Seattle, Wash. Monthly Rep. July 1980.

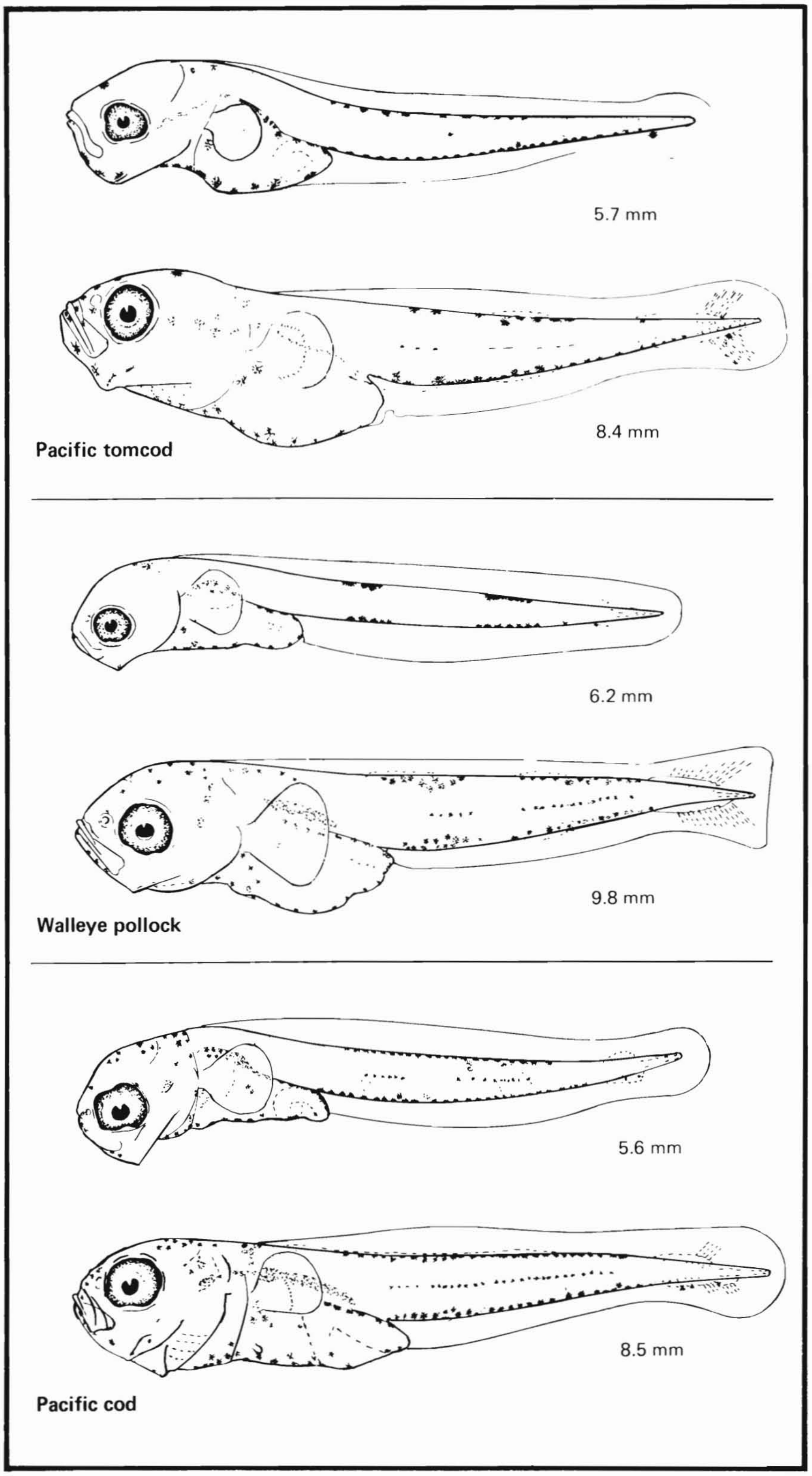


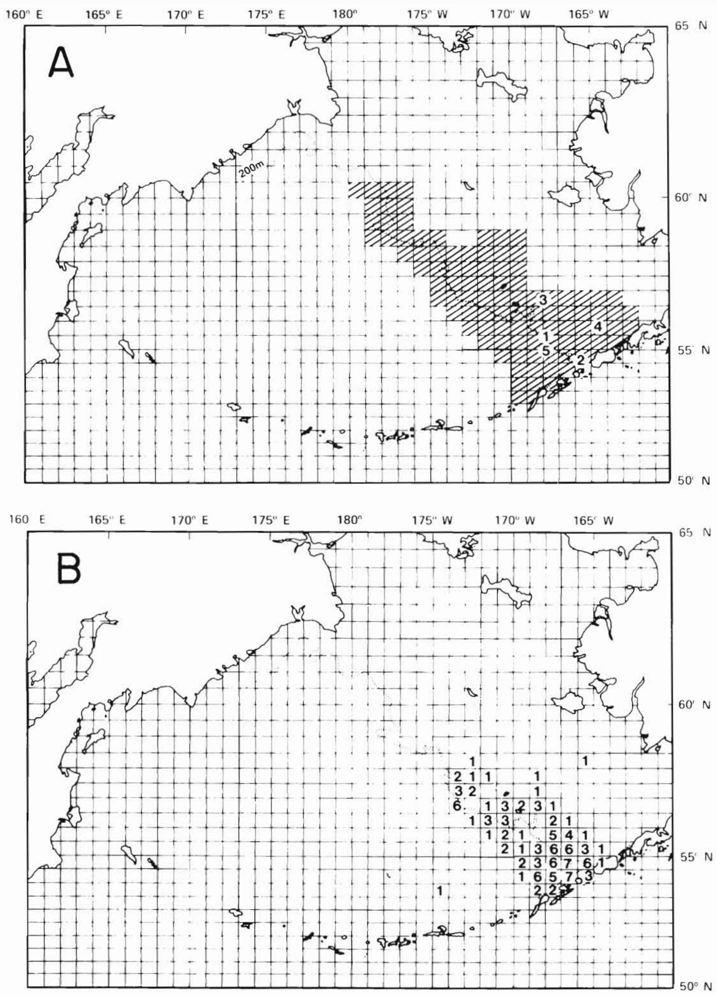
Figure 12. — Larval stages of three species of northeast Pacific gadids from a new taxonomic key in preparation by the staff of the NWAFC.

early life history stages of northeast Pacific fishes. Along with this effort is the initiation of a cooperative program on the identification of rockfish, *Sebastes* spp., larvae. Larvae of this commercially important genus are among the most abundant in the surveys in spring and summer, but cannot be identified to species. It will be necessary to conduct rearing experiments from identified adults to resolve the *Sebastes* taxonomic problem.

Eastern Bering Sea Ecosystem

In recent years ichthyoplankton studies in the Eastern Bering Sea ecosystem have been targeted on the eggs and larvae of walleye pollock. From these studies, information has been obtained on spawning times and places, vertical distribution, and growth patterns (Fig. 13). The National Science Foundation-sponsored Processes and Resources of the Bering Sea (PROBES) shelf program has augmented our knowledge of the ecology of developing walleye pollock eggs and larvae with results from plankton and physical oceanographic studies aimed at describing the processes involved in the initiation and maintenance of the spring phytoplankton-zooplankton bloom which provides the food base for larval and juvenile pollock. Future studies in the Eastern Bering Sea ecosystem will focus on two problems: 1) Acquiring sufficient information on the spatial and temporal distributions of newly-spawned pollock eggs and larvae and 2) the need to measure interannual variability of the key ecosystem components (e.g., light, advection, prey field, predation field) that influence the growth and survival of pollock.

Initial estimates of the size of the spawning biomass of pollock were made in spring 1977. These surveys, and others conducted by scientists of Japan and the U.S.S.R., indicated that walleye pollock spawning begins as early as mid-February and continues through June, and that their planktonic eggs in the eastern Bering Sea are found primarily south and east of the Pribilof Islands and north of Unimak Pass. Estimates of the total number of eggs in the water column were made for five



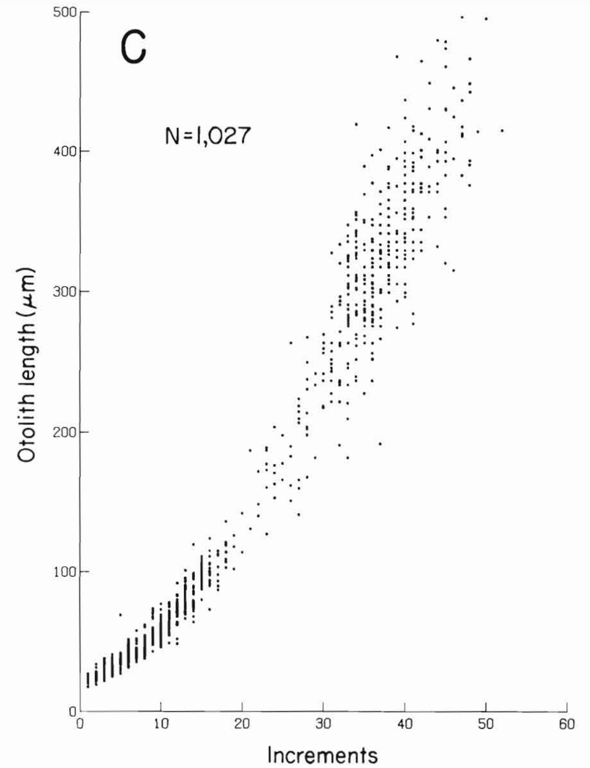


Figure 13. — Areas where walleye pollock eggs and larvae have been caught in plankton tows in the eastern Bering Sea. Shaded area of A is where pollock eggs have been caught; superimposed numbers are areas of maximum abundance in five different years. B shows numbers of stations in each area at which larvae have been caught in spring, and C is otolith length in micrometers plotted against the number of daily growth increments observed. Each point represents one larva.

time-periods from 16 April to 10 May 1977; the maximum estimate was 7.8 × 10^{12} eggs in the period 19-27 April.

In 1977 walleye pollock larvae appeared to be distributed to the west of the area where peak spawning occurred. This observed distribution, however, cannot be explained by circulation of water masses as presently understood. It may be caused by different survival rates in different areas. Modal lengths of walleye pollock larvae increased from 5.5 mm in mid-April to 8.3 mm in mid-May. Estimates were also made of abundance of larvae by time periods. The maximum estimated numbers of larvae (7.5 × 10^{12}) occurred during the same time-period as the highest egg abundance.

Comparisons of estimates of abundance of walleye pollock eggs and larvae during similar time-periods in 1976 and 1977 indicated that eggs were more abundant in 1976 than in 1977, but more larvae were present in 1977 — possibly indicating a change in spawning time. Comparisons of the spatial distribution of eggs and larvae in 1976 and 1977 suggested that the centers of abundance were also different in both years.

To investigate further these apparent temporal and spatial shifts in the distribution of walleye pollock eggs, additional sampling was conducted in the eastern Bering Sea in February and March 1978; June and July 1979; and mid-January to mid-February 1980. Although samples from the latter cruise have not been analyzed, the earlier surveys confirmed the presence of walleye pollock eggs as early as mid-February and as late as mid-June. Future research plans, directed toward early life history of the walleye pollock, include additional work to determine the time and area of spawning and the annual variation of larval abundance in the eastern Bering Sea.

King crab, *Paralithodes* spp., populations have varied in the eastern Bering Sea from about 5 million exploitable males in 1971 and 1981-82 to about 50 million in 1978-79 (and, perhaps, in 1964-65). While fishing may well have affected these fluctuations, independent estimates of portions of the stock not affected by fishing (females and juveniles not harvested) have shown similar fluctuations. Also, other crabs and shrimps with similar life histories have shown major variations in abundance independent of fishing. After hatching, larval crabs remain in the water column for about 6 weeks where they feed and molt into successive forms that eventually settle to the substrate to begin benthic life. During this period, they are subject to variations in transport, turbulence, temperature, food, predation, etc. As benthic animals, the juvenile crabs occupy nearshore shallow habitats and concentrate in large shoals or "pods" that may, at times, be vulnerable to mass mortality caused by predation, or by small-scale spatial-temporal anomalies in environmental conditions. At about 3-4 years of age, the crabs recruit to the offshore populations where they become closely associated with the adult life history categories.

Our approach to recruitment studies of king crab will be to build on the historic data base, and especially the results of the large recent efforts by OCSEAP (Outer Continental Shelf Environmental Assessment Program, BLM and NOAA) and by PROBES. The program will incorporate the talents of the NMFS, National Ocean Survey, Pacific Marine Environmental Laboratory of NOAA, and Northwest and Alaska Sea Grant institutions, and will include review of existing data sets, identification of critical factors, design of experiments in the laboratory and field, and development of analytic and prediction models. Recruitment studies will include surveys to establish an interannual time-series to follow survival of the successive life stages of individual year classes. These hypotheses will be tested: That larval survival is associated with the biological bloom that follows retreat of the ice front and/or that larval survival depends upon the thickness and stability of the mixed layer depth in April in the mid-shelf region. An experiment will be conducted in 1986 to follow the ice meltback of the eastern Bering Sea. The experiment will examine the role of the ice and its meltwater in establishing a "nursery layer" and its impact on crab survival.

Gulf of Alaska Ecosystem

In the Gulf of Alaska, the importance of Shelikof Strait is being evaluated as a principal spawning ground for walleye pollock stocks. Through time-series surveys of pollock eggs and larvae, estimates of pollock spawning biomass have been made. Their populations have shown fluctuations of within-year-class strength of from two to five times the mean number. Research to date indicates that the spawning and subsequent egg and larval drift follows a remarkably consistent pattern from year to year. For example, a single spawning concentration in Shelikof Strait near Kodiak Island contained 2.5 to 2.7 million metric tons of pollock in March 1983. The spawning is restricted in time (late March-early April) and localized geographically (in lower Shelikof Strait in an area 20×70 km). The eggs, and later the larvae, form a large patch that drifts with the prevailing current to the southwest along the Alaska Peninsula, mainly at depths between 20 and 50 m. Development time for the eggs is about 2 weeks; the larva start to feed in the first week after hatching and remain planktonic for about 6-8 weeks. The dominant transport feature of Shelikof Strait is the Kenai Current, which flows westward along the Alaskan coast from the vicinity of the Copper River to Unimak Pass. The two dominant mechanisms of current variability are freshwater runoff and wind stress. There are strong annual and interannual signals in the freshwater discharge, and these are correlated with fluctuations in transport.

Hydrographic data and satellite infrared (IR) observations show warm waters entering Shelikof Strait during March. The juxtaposition of these warm waters with cold, less saline water from Cook Inlet that flows over a rough topography and is influenced by strong local winds, can lead to intense mixing and upwelling. These intense mixings can be sustained by storms, and advected by the currents on time scales of weeks. These transport variations affect the distribution of the pollock eggs and larvae and probably alter their survival rates. The intense, localized nature of this early life-history pattern, in a relatively confined oceanographic setting, lends itself ideally to tractable recruitment experiments, with a high likelihood for prediction of year-class strength and understanding causes of its variability. To gain insight into mechanisms causing variation in recruitment and year-class strength, studies will be conducted on linkages among circulation, spawning, egg and larval growth, survival, and advection in the Gulf of Alaska ecosystem.

Samples from surveys conducted before 1981 have been used to describe the ichthyoplankton community in the vicinity of Kodiak Island (Kendall and Dunn, In prep.). These and later collections will also be used to map the distribution and abundance of walleye pollock in the Shelikof Strait region (Fig. 14). Surveys in this region have been conducted jointly with scientists and vessels of the Soviet Union and South Korea. Future studies will include: 1) Investigation of the factors influencing survival of planktonic early life history stages of fish in relation to recruitment of incoming year classes, and 2) evaluation of the use of early life stages for measuring sizes of parental spawning biomass.

Species of primary interest include: Walleye pollock, rockfishes, flatfishes, Pleuronectidae; greenlings, Hexagrammidae; and sculpins, Cottidae. The areas of primary interest include Shelikof Strait and the continental shelf off Kodiak Island. Specific projects on Gulf of Alaska early life history stages will include studies on: 1) Distribution and abundance of eggs and larvae of walleye pollock, 2) description of the ichthyoplankton community of the Kodiak area, 3) identification of species of *Sebastes* larvae, 4) annual changes in relative abundance of various species in relation to environment, and 5) laboratory guide for identification of eggs and larvae of fishes of the northeast Pacific Ocean.

Washington-Oregon Coastal Ecosystem

In 1980, a cooperative program was initiated with scientists from the TINRO Laboratory in the U.S.S.R. to determine the annual cycle of ichthyoplankton occurrence off the Washington-Oregon coast (Fig. 15). Two surveys per year are conducted on Soviet vessels, sampling about 125 stations per survey. The surveys are conducted at different times of the year, so that after several years the complete cycle of fish egg and larval occurrence can be documented.

Standard MARMAP bongo samplers are deployed on each survey. These surveys will be the first large-scale ichthyoplankton surveys of the area to sample in all seasons. Following completion of the definition of peak spawning periods for the dominant species and/or species groups, specific unresolved problems concerning recruitment can be addressed. Species targeted for recruitment studies are: Sablefish, *Anoplopoma fimbria*; rockfish, *Sebastes* spp.; and flatfishes (*Limanda* sp., *Platichthys* sp., *Eopsetta* sp.). Results from these surveys will be compared with those of CalCOFI to the south, thereby linking the ichthyoplankton data base from off Baja California to Cape Flattery. A description of survey operations and preliminary results from the first two surveys are given by Kendall and Clark[10,11].

Using the CalCOFI data base, it has been possible to relate the seasonal patterns of distribution of larvae, juveniles, and adults of the Pacific hake, *Merluccius productus*, to spawning, feeding, and schooling areas in the California Current and Washington-Oregon coastal ecosystems (Bailey et al., 1982) (Fig. 16). In cooperation with Polish scientists, preliminary information has been obtained on Pacific hake predator-prey relationships (Table 4).

Table 4. — The percent by weight and region of food types in the diet of Pacific hake determined by Polish scientists[1] in summer 1979.

Food type	Percent by region: Eureka	Columbia	Vancouver
Euphausiids	94.2	94.0	85.6
Juvenile rockfish	1.0	1.6	
Pacific herring			
Adult			5.9
Juvenile			6.6
Osmerids		0.4	
Pacific hake	0.5		
Sablefish		2.0	0.1
Flatfish		0.4	
Squid		1.6	
Shrimp		1.6	
Other fish	3.2		1.7
Other invertebrates	0.4		0.1

[1]Jackowski, E. 1980. Biological characteristics of Pacific whiting from Polish surveys of the west coast of the U.S.A. and Canada in 1979. Unpubl. manuscr. presented at the U.S.-Poland bilateral meetings, 1980.

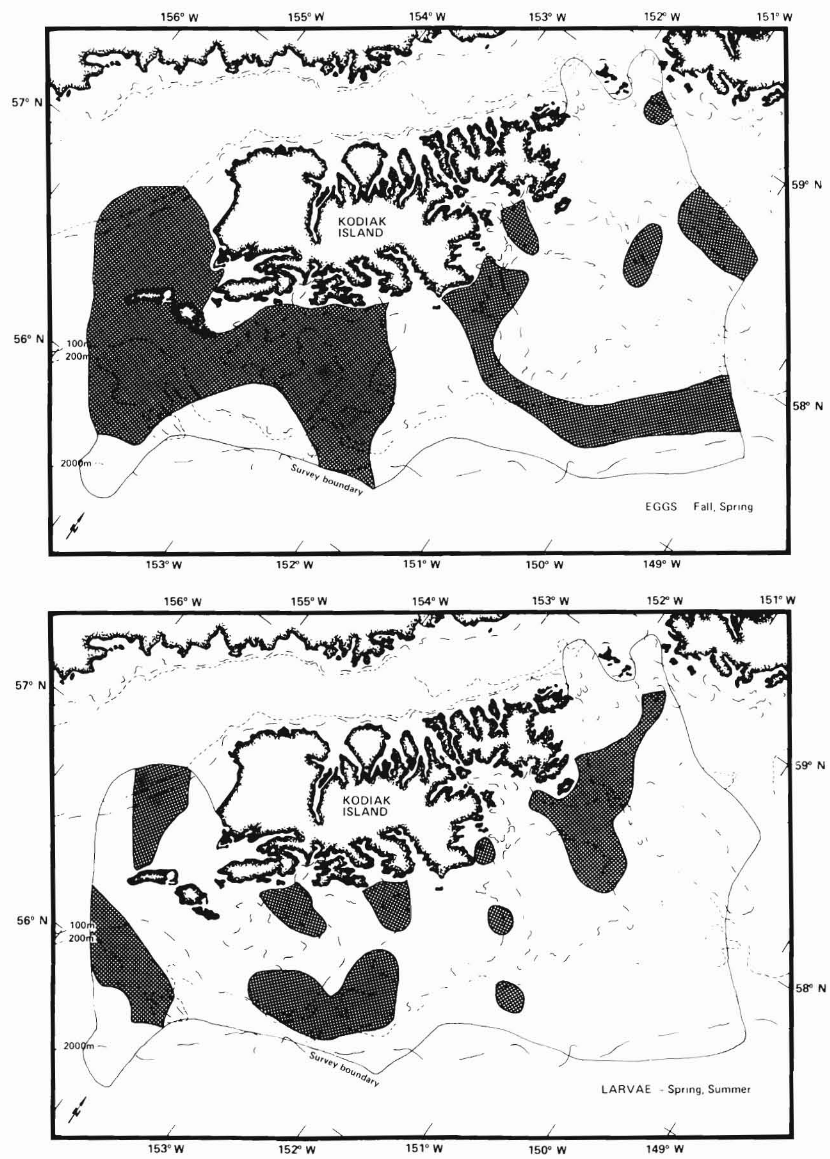


Figure 14. — Areas where walleye pollock eggs and larvae were caught in neuston and plankton tows off Kodiak Island, 1977-78. Eggs were caught in fall and spring; larvae were caught in spring and summer.

Pacific Salmon

The Pacific salmon group is usually second only to shrimp in ex-vessel value to U.S. fishermen ($438 million in 1981). This species group provided

[10]Kendall, A. W., Jr., and J. Clark. 1982. Ichthyoplankton off Washington, Oregon, and Northern California, April-May 1980. NMFS Northwest and Alaska Fisheries Center, Seattle, Wash. Proc. Rep. 82-11, 44 p.

[11]Kendall, A. W., Jr., and J. Clark. 1982. Ichthyoplankton off Washington, Oregon, and Northern California, August 1980. NMFS Northwest and Alaska Fisheries Center, Seattle, Wash. Proc. Rep. 82-12, 43 p.

43 percent of U.S. exports of edible fishery products ($462 million in 1981). Salmon are anadromous and return to coastal rivers and streams to spawn, but are subject to interceptions by foreign nations during their far-ranging migrations in the ocean.

Recruitment research will focus on chinook, *Oncorhynchus tshawytscha*, and coho, *O. kisutch*, salmon in the Columbia River estuary, in ocean plume and coastal waters off Washington and Oregon, and during their ocean migration off southeastern Alaska. These species and stocks were selected for study because they contain large proportions of tagged fish. A recruitment problem exists in that increased releases of coho salmon from hatcheries since the mid-1970's have accompanied declining returns.

Recruitment studies are aimed at reducing uncertainty in predictions of salmon returns through better understanding of the factors that affect early ocean survival of salmon. This will be acquired experimentally through: 1) Studies on salmon physiology and ecology during the period of transition from fresh to salt water; 2) studies on environmental conditions limiting early ocean survival — particularly food availability and predation; 3) modelling studies to optimize the regimen for release of salmon from hatcheries; and 4) development of predictive models to forecast year-class strength. The environmental factors to be examined include conditions abetting food production, such as upwelling (caused by meteorological events and southward flowing currents) or the formation of temperature fronts (caused by eddy dynamics or current shears).

Ichthyoplankton and Pollution Stress

Under the direction of George Snyder, studies are being conducted at the NWAFC Auke Bay Laboratory on the effects of petrogenic hydrocarbons on the viability of early life stages of coho salmon. Short-term exposures of coho salmon eggs, alevins, and fry to aromatic hydrocarbons common to crude oils demonstrated that sensitivity to the aromatics increased from egg to fry,

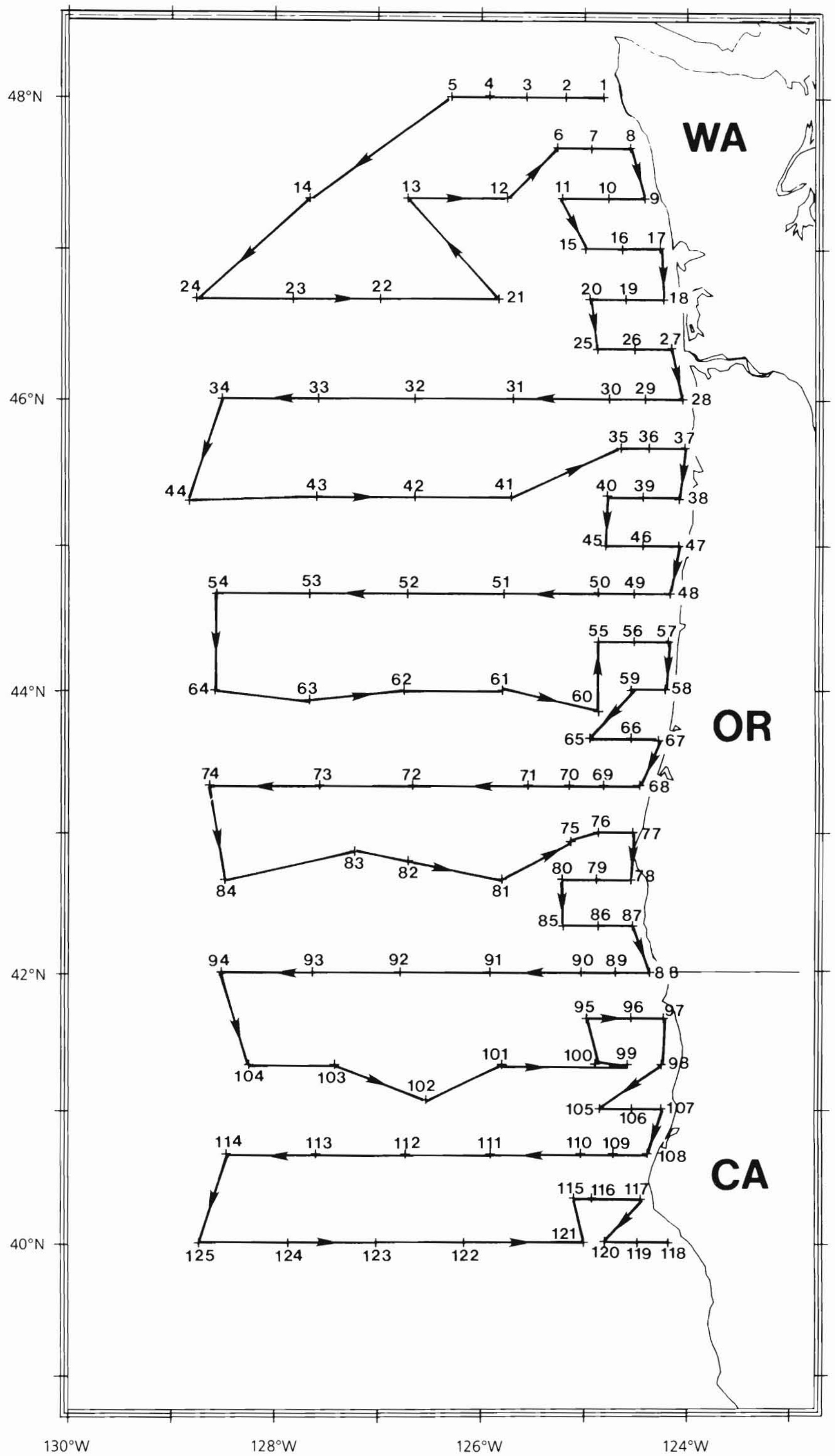
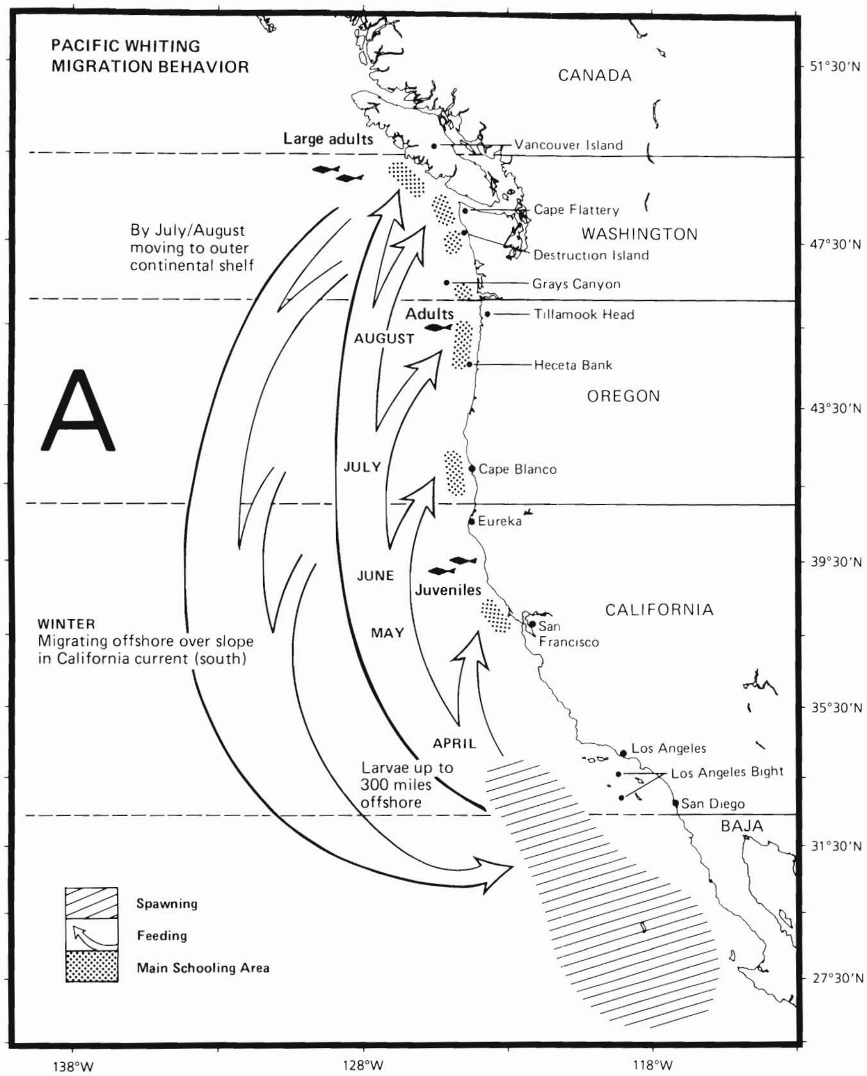


Figure 15. — Station locations and cruise track for the ichthyoplankton surveys within the coastal Washington-Oregon LME — April-May 1980.



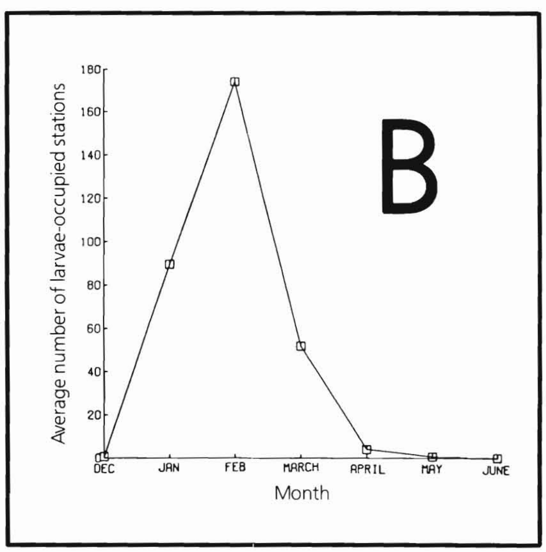


Figure 16. — A = Migratory patterns of Pacific hake. B = seasonal patterns of distribution of larvae, juveniles, and adults of the Pacific hake with relation to spawning, feeding, and schooling areas in the California Current and Washington-Oregon Coast ecosystems. Adapted from Bailey et al. (1982).

with the greatest impact between egg and the early alevin stage (Korn and Rice, 1981).

Northeast Fisheries Center

Stressed Northeast Shelf Ecosystem

The continental shelf ecosystem off the U.S. northeast coast supports a fisheries industry that contributes $1 billion annually to the economies of the coastal states from Maine to North Carolina. However, the fish stocks of the region have been heavily exploited. From 1968 through 1975 the total catchable finfish biomass declined by approximately 50 percent (Fig. 17). This decline was correlated with high fishing mortality (Clark and Brown, 1977). Since 1975, a small recovery trend has been observed among the demersal species (i.e., Atlantic cod, *Gadus morhua*; pollock, *Pollachius virens*; flounders, *Paralichthys* sp., *Hippoglossoides* sp., *Limanda* sp., and *Pseudopleuronectes* sp.). Atlantic herring, *Clupea harengus*; and Atlantic mackerel, *Scomber scombrus*, stocks remain depressed.

The dramatic decline raised several important questions. Would the reduction of predation pressure by the loss of pelagic zooplanktivorous fish result in elevated levels of zooplankton? Would small, fast-growing, opportunistic zooplanktivorous species replace the herring and mackerel populations? Would the depressed stock return to former

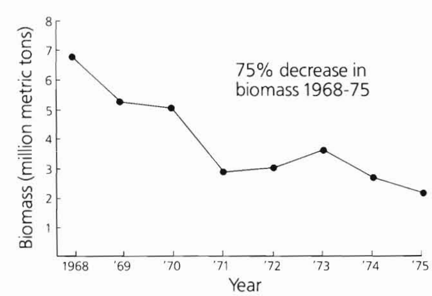


Figure 17. — Decline in the fishable biomass of Georges Bank, Gulf of Maine, and southern New England 1968-75. Adapted from Clark and Brown (1977).

abundance levels with the control of fishing mortality imposed by the establishment of the FMZ and the significant reduction of large-scale factory-trawler operations? In an effort to address these questions, ichthyoplankton sampling was expanded in 1977 to cover the northeast shelf ecosystem and provide fisheries-independent information on the total ichthyoplankton community of the system.

Sampling Strategy

Following the CalCOFI model, a systematic network of sampling for ichthyoplankton was established on a grid network with stations spaced 25-30 km apart over the entire 260,000 km^2 of the northeast shelf (Fig. 18). At each station, collections were made with paired bongo nets fitted with 0.333 mm and 0.505 mm mesh nets. From two to twelve surveys were made each year from 1974 through 1981. All ichthyoplankton and zooplankton collections were sent to the Polish Sorting Center in Szczecin, Poland, for processing. In addition, from 1977 through 1982, water column sampling was conducted for temperature, salinity, nutrients, oxygen, chlorophyll, and primary production (^{14}C) (Evans and O'Reilly, In press; O'Reilly and Thomas, In press).

Sand Lance Explosion

From our analyses of ichthyoplankton species composition and abundance data, we observed a population explosion of sand lance, *Ammodytes* spp., from 1974 through 1981, coincident with a decline in Atlantic herring and Atlantic mackerel (Fig. 19). A similar coincident shift in abundance occurred in the North Sea where the declining Atlantic herring and Atlantic mackerel stocks appeared to be replaced by increases in the populations of small, fast-growing sprat, *Clupea sprattus*; sand lance, and Norway pout, *Trisopterus esmarkii* (Sherman et al., 1981). NEFC studies under the direction of Wallace Smith and his team at the Sandy Hook Laboratory focus on measuring the impact of the perturbation of sand lance abundance on the production of other fish stocks on the shelf, particularly with respect to any recovery in

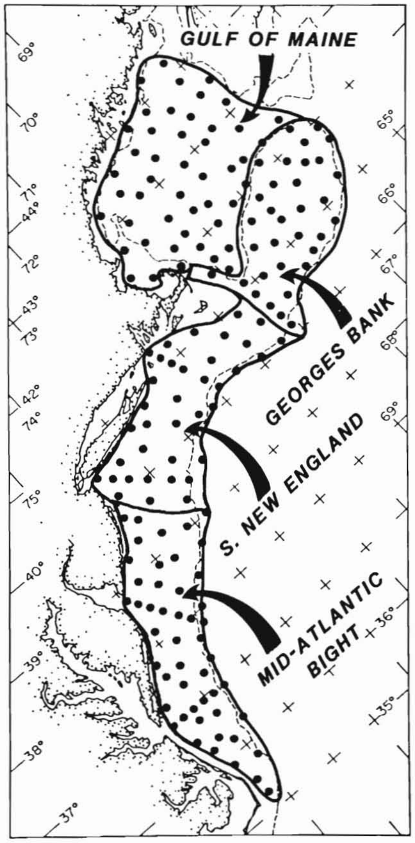


Figure 18. — Station locations for sampling ichthyoplankton on the northeast continental shelf ecosystem.

Atlantic herring and Atlantic mackerel abundance.

Ecosystem Linkages

The 1977-81 MARMAP surveys provided new information on the productivity of the shelf ecosystem. With the exception of the shelf-slope front, the shelf ecosystem is highly productive. Mean annual values of carbon production ranged from 260 g C/m^2 in the mid-shelf off Cape Hatteras to 450 g C/m^2 on Georges Bank (O'Reilly and Busch, In press) (Fig. 20). The shelf ecosystem was divided into subareas based on areal differences in bathymetry, hydrography, circulation, and population structure. Recurrent annual cycles of zooplankton abundance were observed from 1977 through 1981 in each of four

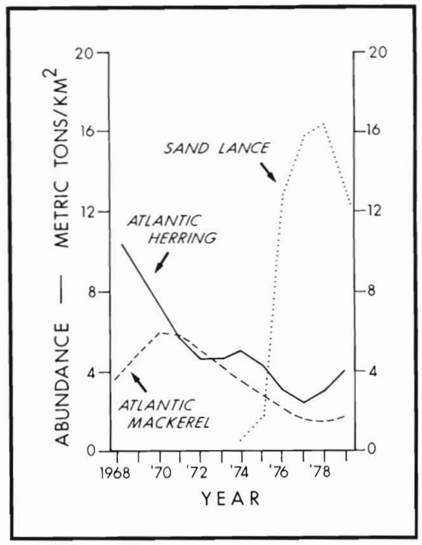


Figure 19. — Decline of Atlantic herring and mackerel and apparent replacement by the small, fast-growing sand lance in the northeast continental shelf ecosystem.

subareas — Gulf of Maine, Georges Bank, Southern New England, and the Mid-Atlantic Bight (Sherman et al., In press).

Wallace Smith and his team at the Sandy Hook Laboratory have observed distribution patterns of larvae that are related to circulation, bathymetry, and plankton production. The "Shelf Gyre" species include redfish, *Sebastes* sp., in the Gulf of Maine, and Atlantic cod and haddock on Georges Bank. Further south the "Shelf Plain" species include bluefish, *Pomatomus saltatrix*, in the Mid-Atlantic Bight and Southern New England, and searobin, *Prionotus* spp., in the same regions. "Shelf Estuarine" species include the northern anchovy, Engraulidae; and croaker, *Micropogonias undulatus*, in the Mid-Atlantic Bight area. Two "Shelf Migrants" were identified: 1) The Atlantic mackerel migrates from the Mid-Atlantic Bight northward in spring in synchrony with the northern spring increase in zooplankton, and 2) the Atlantic menhaden, *Brevoortia tyrannus*, an autumn spawner, was observed to migrate southward from Southern New England

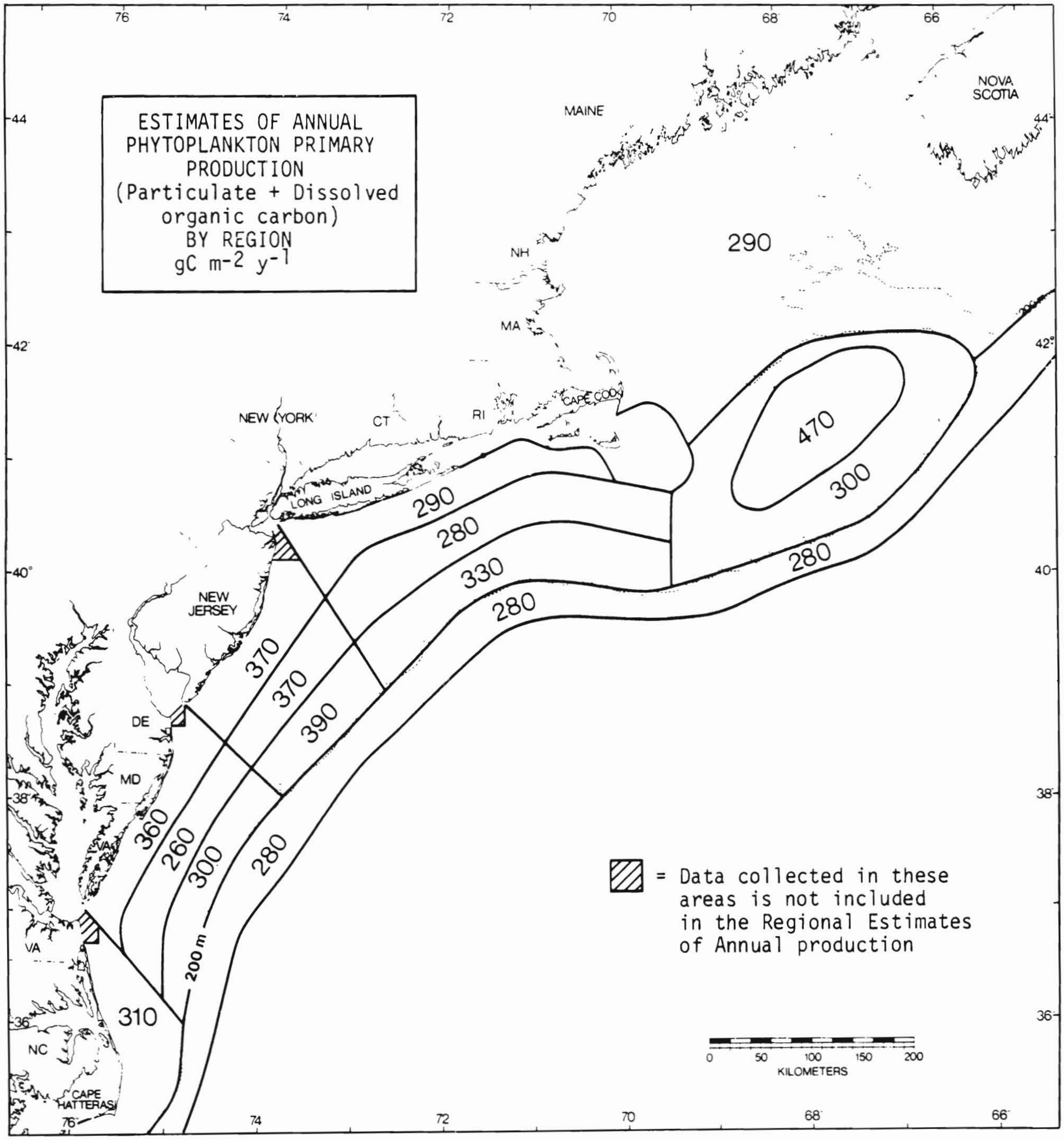


Figure 20. — Average annual primary production (g C/m²) per year based on the MARMAP ¹⁴C method (O'Reilly and Busch, In press).

to the Mid-Atlantic Bight in autumn from an area of moderate zooplankton abundance to the highest concentrations of zooplankton on the shelf in this season off Delaware and Chesapeake Bays. Silver hake, *Merluccius bilinearis*; other hakes, *Urophycis* spp. (predominantly red hake, *Urophycis chuss*); and sand lance, *Ammodytes* sp., are found in each of the four subareas and are classified as "Ubiquitous Shelf" species.

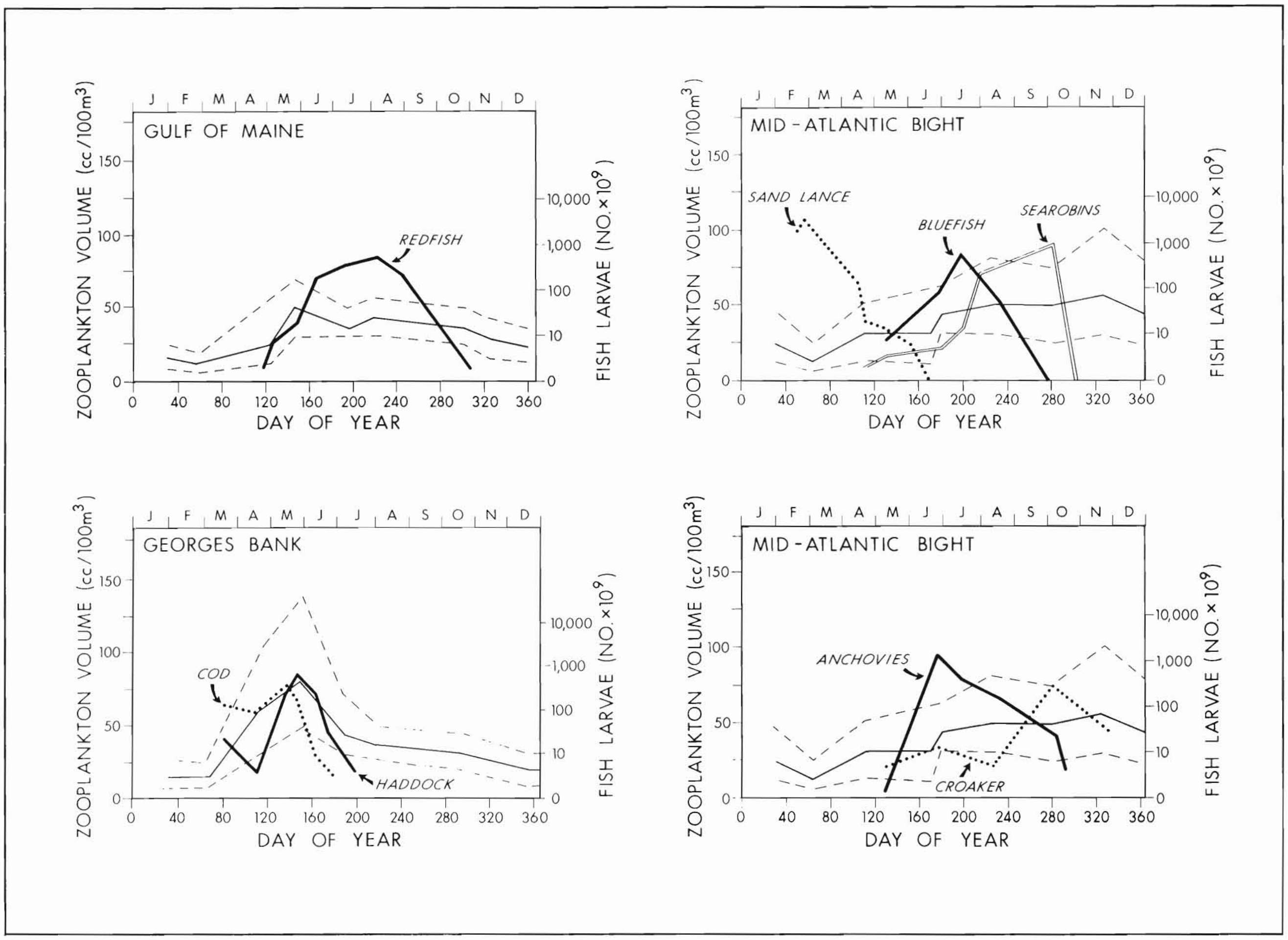


Figure 21. — Synchrony of peak larval production plotted with median zooplankton abundance in four subareas of the northeast shelf ecosystem — Gulf of Maine, Georges Bank, Southern New England, and the Mid-Atlantic Bight. The single light line represents the 5-year (1977-81) mean values of zooplankton volumes (cc/100 m^3) bounded by two standard errors (dashed lines). Mean ichthyoplankton species abundance (1977-80) (N $\times$ 10^9) is shown for: Gulf of Maine redfish (bold line); Georges Bank cod (dotted line), haddock (bold line); Mid-Atlantic Bight sand lance (dotted line, upper right), bluefish (bold line), and searobins (double line); anchovies (bold line, lower right), and croaker (dotted line, lower right).

Spawning strategies are adaptations of the spawning biomass to topographic and circulation features of the northeast shelf and the annual plankton production cycle in each of the four subareas — Gulf of Maine, Georges Bank, Southern New England, and the Mid-Atlantic Bight. Under average conditions, the gyre, shelf-plain, and shelf-migratory spawners reach peak abundance in synchrony with the seasonal pulses in their zooplankton prey (Fig. 21). The ubiquitous spawners appear to maintain relatively high densities of eggs over a wide temporal and spatial range within the shelf ecosystem, thereby enabling them to respond rapidly to favorable environmental conditions (Sherman et al.[12]). Studies off the northeast coast have demonstrated that sand lance is an opportunistic species that can be considered a temporary replacement for the overfished mackerel and herring populations (Sherman et al., 1981).

[12] Sherman, K., W. Smith, W. Morse, M. Berman, J. Green, and L. Ejsymont. 1983. Spawning strategies of fishes in relation to circulation patterns, phytoplankton production, and pulses in zooplankton abundance off the northeastern United States. ICES C.M.1983/L:28.

Spawning Stock Estimates

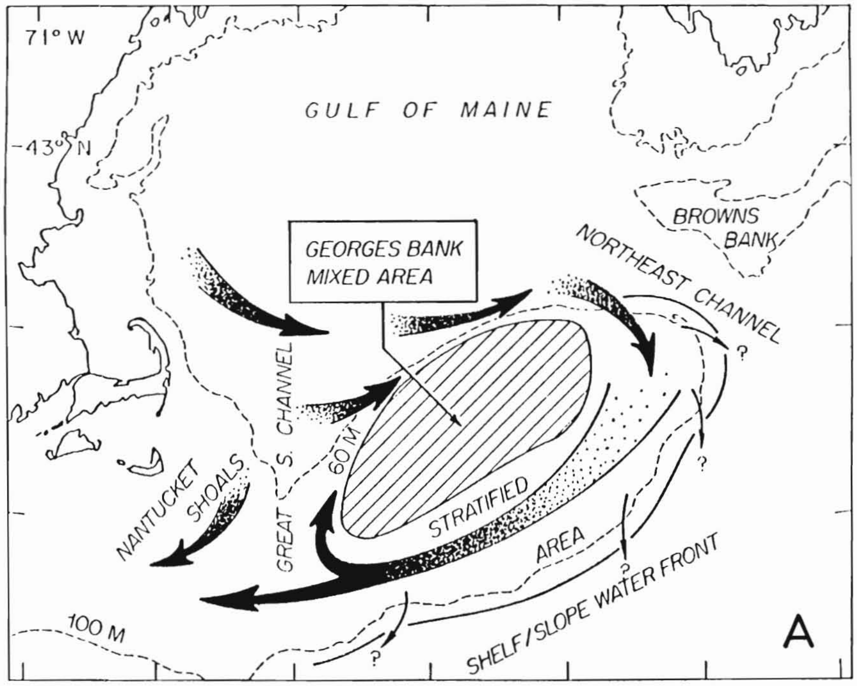
Among the species for which spawning biomass estimates were made from the MARMAP ichthyoplankton collections are silver hake, mackerel, sand lance, bluefish, and yellowtail flounder, *Limanda ferruginea*. Other species targeted for biomass estimates are haddock, Atlantic cod, redfish, and searobin.

Density-Dependent Recruitment Studies

To improve forecasts of abundance it is necessary to obtain a better understanding of the relationship between the abundance of early developmental stages and new recruits to the fisheries. Within the sampling network of the MARMAP multispecies ichthyoplankton surveys, studies are conducted of the factors controlling growth and survival of the target species Atlantic cod and haddock. Age and growth and predator-prey studies of larvae are directed by Gregory Lough and his team at the NEFC Woods Hole Laboratory. Under the direction of Geoffrey Laurence of the NEFC Narragansett Laboratory, studies are now underway to confirm laboratory determinations of optimal prey densities with at-sea experiments on Georges Bank on the availability and abundance of suitable densities of zooplankton prey of cod and haddock (Fig. 22). Plans are also being prepared to conduct predation experiments on eggs and larvae in large enclosures. Preliminary observations made by Geoffrey Laurence and his team indicate that larval growth and survival are very high in large, predator-free, flow-through net mesh enclosures placed in a highly productive estuarine environment (Laurence et al., 1979).

Density-Independent Recruitment Studies

Warm-core rings have been observed entraining large volumes of shelf water across the shelf slope front into a nutrient-poor environment. It has been hypothesized that eggs and larvae of shelf species advected off the highly productive shelf in an entrainment feature would not survive in the prey-poor environment. Collections made in an entrainment experiment conducted by Geoffrey Laurence and his team on the survival of ichthyoplankton in an entrainment feature revealed that no shelf species were in the entrainment. The only ichthyoplankton observed in the collections were larvae of bathypelagic shelf-slope species, suggesting that warm-core rings are not responsible for advective mortality of shelf larvae.



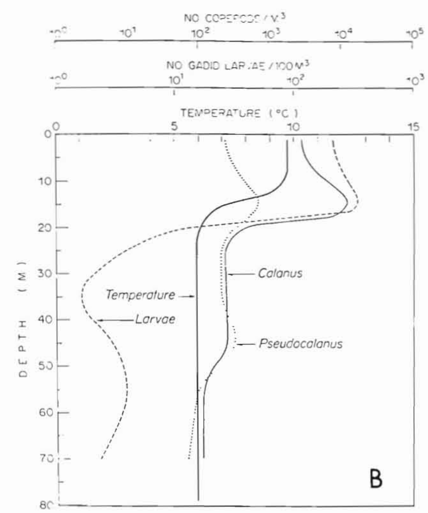


Figure 22. — A = Schematic representation of the well-mixed and stratified waters on Georges Bank and mean circulation flow (arrows) during spring and summer. B = Vertical distribution of gadid (haddock and cod) larvae and dominant copepods (*Calanus finmarchicus*, *Pseudocalanus* sp.) in relation to thermocline on the southeast part of Georges Bank before storm. (MOCNESS-1 m, 0.333-mm mesh, 21 May 1981, 2303-2358 D.S.T., 40°55′N, 67°16′W. Bottom depth: 78-80 m.) Note different log-scales used for copepods and gadid larvae.

Replicate experiments are planned to confirm these preliminary results (Laurence and Burns, 1982).

Pollution Studies

In cooperation with the U.S. Fish and Wildlife Service, studies were made under the direction of Lawrence Buckley (Narragansett Laboratory) of the viability of striped bass larvae from parent stock exposed to heavy metals and other toxins. Initial results indicate significant impact of the exposure to larvae hatched from the Hudson River parent stock.

Other Narragansett Laboratory pollution-related studies underway in cooperation with the Environmental Protection Agency are focused on the impacts of exposures of larvae to urban sludge compounds identical to those now being disposed of on the continental shelf by the State of New York. One of the encouraging advances by Lawrence Buckley and his group is the application of an RNA/DNA analysis for determining the growth potential of larvae collected routinely during the MARMAP surveys. High ratios indicate a "healthy" physiological condition for the larvae, whereas low values indicate that the growth potential of the larvae is impaired (Buckley, 1980, 1982). The RNA/DNA analysis will be conducted on batch samples of larvae collected on MARMAP surveys in an effort to classify, temporally and spatially, larvae in "poor condition."

Management of Large Marine Ecosystems

A growing awareness by marine resource managers of the interrelationships among species and their environments has led to legislated mandates for the conservation and management of total ecosystems. This concern is expressed in the language used in the Magnuson Fishery Conservation and Management Act of 1976 which requires that:

"... Conservation and management measures shall be based on the best scientific advice available.... To the extent practicable, an individual stock of fish shall be managed as a unit throughout its range, and interrelated stocks of fish shall be managed as a unit or in close coordination."[13]

A good deal of the precedent can be attributed to the two-tiered management practice enacted by the International Commission for North Atlantic Fisheries (ICNAF). In 1972 ICNAF established total biomass quotas of finfish for the northwest Atlantic and assigned total allowable catch levels to all target species of the fisheries to be followed on an annual basis (ICNAF, 1973; Grosslein et al., 1979).

The most recent example of the movement toward total ecosystem management is found in the language of the Commission for the Conservation of Antarctic Marine Living Resources. Article II of the Convention calls for holistic management wherein: "... The regime should provide for the effective conservation of the living marine resources of the Antarctic ecosystem as a whole...." Considerable progress has been made by the international scientific community in the coordination and integration of studies in the Antarctic leading to population assessments of the principal ecosystem populations, including krill, *Euphausia* spp., and its predators and prey under the aegis of the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) program (Beddington and May, 1982). The approach in dealing with the world's largest marine ecosystem has been a combination of international krill biomass assessment surveys, an analysis of catch data, and surveys of marine birds, mammals, and fish (Laws, 1980; Everson, 1981; Pommeranz et al., 1981; Hureau, 1982; BIOMASS Working Party on Fish Biology, 1982; BIOMASS Working Party on Bird Ecology, 1982a,b,c). Initial results of this effort have been most effective in refining estimates of krill biomass in the region (BIOMASS Report Series, 1980, 1982).

For effective management of any LME, it is necessary to survey the populations and their environments. Unfortunately, surveys can become dull, routine affairs, but they are critical components of a total ecosystem resources assessment program. Technical advances in hydroacoustics, satellite remote sensing of ocean features (Lasker et al., 1981; Peláez and Guan, 1982), and electronic particle sampling and data processing at sea (Lough and Potter, In press) and in the laboratory (Jeffries et al., 1980), when applied to the MARMAP type multispecies ichthyoplankton time-series surveys and target-species recruitment studies, will contribute to increased sampling efficiencies and reduced costs of the assessment surveys of large marine ecosystems.

[13] Fishery Conservation and Management Act of 1976, USA (FCMA). Public Law 94-265, 94th Congress, H.R. 200, 13 April 1976.

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