SPAWNING BIOMASS AND EARLY LIFE OF NORTHERN ANCHOVY, *ENGRAULIS MORDAX*, IN THE NORTHERN SUBPOPULATION OFF OREGON AND WASHINGTON

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ABSTRACT

A major spawning center for the northern subpopulation of northern anchovy, *Engraulis mordax*, is documented off the Oregon-Washington coast beyond the continental shelf, based on collections of planktonic eggs in July 1975 and July 1976. Biomass estimates of northern anchovy in this spawning concentration ranged from 262,506 to 769,511 metric tons in 1975 and 144,654 to 1,005,263 metric tons in 1976, based on egg and larva surveys. Spawning biomass was estimated to be 800,000 metric tons in 1977, based on an acoustic survey of adults. The most probable biomass may be more than 100,000 but less than 1,000,000 metric tons. Potential yield estimates ranged from 86,792 to 633,316 metric tons, but realizable yields may be considerably lower if management strategies applied to northern anchovy in the central subpopulation are implemented for the northern subpopulation.

Spawning appears to be associated with waters of the Columbia River plume which may provide favorable conditions, in terms of stability and productivity, for survival of first feeding northern anchovy larvae. Evidence of larval transport south away from the spawning center leads to questions about return mechanisms to explain the occurrence of juveniles in Oregon bays and rivers later in the season. Additional spawning centers within the range of the northern subpopulation have not been documented although some evidence from the literature indicates another spawning center may occur in the Strait of Georgia, British Columbia, around the Fraser River plume.

Conditions related to spawning differ between the northern and central subpopulations. Off Oregon, spawning occurs from mid-June to mid-August, when current flow to the south is at a maximum, water temperatures are reaching maximum levels for the year, coastal upwelling is at a maximum, and day length is at or near maximum duration. Off California, peak spawning occurs from January through April when southward current flow is minimal, water temperatures are reaching minimal levels for the year, upwelling is minimal, and day length is at minimum duration. These factors are indicative of some degree of reproductive isolation as well as differing reproductive strategies between the two subpopulations.

The northern anchovy, *Engraulis mordax* Girard, is an abundant pelagic schooling fish that occurs along the west coast of North America from Cape San Lucas, Baja California, to the Queen Charlotte Islands, British Columbia (Miller and Lea 1972; Hart 1973). It is the object of an expanding fishery off central and southern California and Baja California where about 204,000 metric tons (t) were harvested in 1975, mainly for fish meal (Pacific Fishery Management Council[2]). In the northern part of its range it is utilized only to a small degree as bait by local fishermen although its potential as a harvestable resource has been suggested (Pruter 1966, 1972). Reports of dense schools off the Oregon and Washington coasts indicate northern anchovy biomass may be substantial (Pruter 1966, 1972). Estimates of an annual consumption of 28,000 t of northern anchovy by four species of marine birds off the Oregon coast (Wiens and Scott 1975) further indicates sizeable biomass.

In the absence of a fishery, biomass estimates are unavailable for northern anchovy north of California. We know that in the 1940's northern anchovy in ocean waters adjacent to the Columbia River supported a live bait fishery for albacore tuna (Pruter 1966, 1972). Reported commercial landings of northern anchovy in Washington in 1947-49 ranged from 20 to 182 t annually and were 28 and 76 t in Oregon in 1948 and 1953 (Pruter 1966). A small purse seine fishery for canning once existed around southern British Columbia where harvests ranged from 64 to 6,201 t annually between 1939 and 1947 (Roach and Harrison 1948; Pike 1951).

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[2]Pacific Fishery Management Council. 1978. Northern anchovy fishery management plan. U.S. Dep. Commer., NOAA Federal Register 43(141) Book 2:31651-31783.

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Because of the relatively unfished state of northern anchovy off Oregon and Washington, the lack of biomass estimates, and the potential for fishery development, this study was undertaken to define spawning centers and provide the first preliminary estimates of spawning biomass within such defined spawning centers by means of ichthyoplankton survey. Additional information on adult school distributions and another independent estimate of biomass were obtained by acoustic survey (Smith[3]). Ecological data on the early life of these northern occurring fish were also examined. Aspects of adult life history, particularly reproduction, are presented in a separate paper (Laroche and Richardson 1981).

THE NORTHERN SUBPOPULATION

Northern anchovy occurring north of Cape Mendicino, Calif., compose the northern subpopulation of *E. mordax*, one of three subpopulations (Figure 1) distinguished on the basis of meristic counts (McHugh 1951) and electrophoretic separation of blood serum protein (Vrooman and Paloma[4]). The central subpopulation occurs primarily off southern California and northern Baja California and the southern subpopulation is off central and southern Baja California. A separate subspecies, *E. mordax nanus*, has also been described from San Francisco Bay (Hubbs 1925).

Compared with the central and southern subpopulations, relatively little detailed information is available on spawning and early life history of northern anchovy in the northern subpopulation. Off California and Baja California spawning seasons and locations are well defined (e.g., Ahlstrom 1966, 1967; Baxter 1967; Kramer and Ahlstrom 1968), eggs and larvae have been illustrated (Bolin 1936; Ahlstrom 1956, 1965; Kramer and Ahlstrom 1968), and spawning biomass has been estimated on the basis of larva survey (e.g., Pacific Fishery Management Council footnote 2).

For the northern subpopulation, information on spawning and early life history had to be pieced together from a number of sources to provide the background for the present study. Based on monthly plankton collections of larvae off Oregon

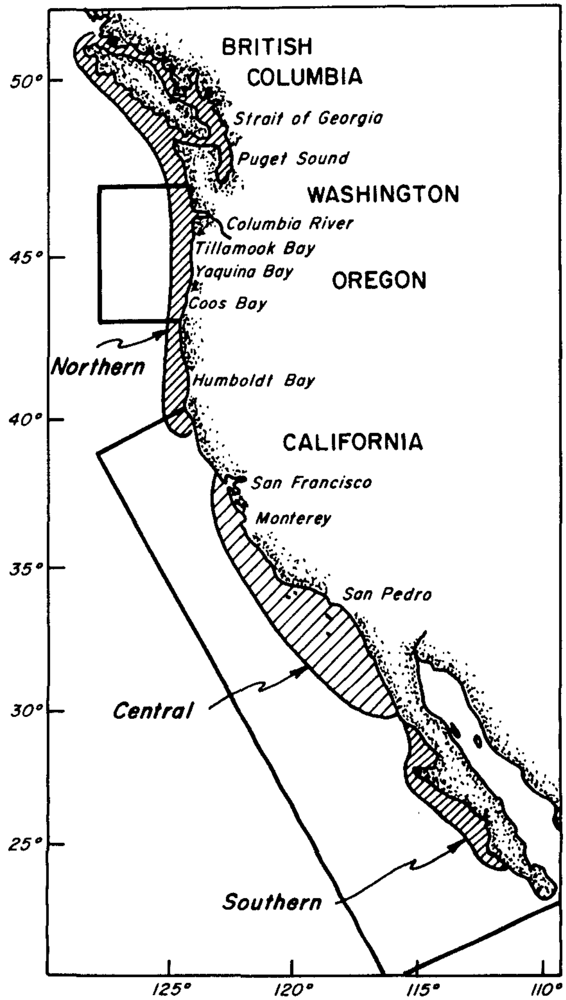

FIGURE 1.—Geographic ranges (hatched) of the three subpopulations (northern, central, southern) of *Engraulis mordax* (modified from Smith and Lasker in press). Rectangular area outlined off Oregon and Washington shows ichthyoplankton survey grid boundaries for this study. Rectangular area outlined off California and Baja California shows approximate boundaries of the principal portion of the CalCOFI survey grid (after Kramer et al. 1972).

(Richardson 1973, see footnote 5; Richardson and Pearcy 1977) and maturity studies involving measurements of ova diameters from ovaries of fish collected off British Columbia (Pike 1951), the spawning season is short, lasting from about mid-June to mid-August. Based on available catch records (Williamson 1929 [in Pike 1951]; Pike 1951;

[3]P. E. Smith, Southwest Fisheries Center La Jolla Laboratory, National Marine Fisheries Service, NOAA, P.O. Box 271, La Jolla, CA 92038, pers. commun. March 1978.

[4]Vrooman, A. M., and P. A. Paloma. 1975. Subpopulations of northern anchovy, *Engraulis mordax* Girard. NOAA NMFS Southwest Fish. Cent., Admin. Rep. No. LJ-75-62, 10 p.

[5]Richardson, S. L. 1977. Larval fishes in ocean waters off Yaquina Bay Oregon: abundance, distribution, and seasonality January 1971 to August 1972. Oreg. State Univ. Sea Grant Coll. Prog. Publ. No. ORESU-T-77-003, 73 p.

Parsons et al. 1970; Eldridge and Bryan 1972; Blackburn 1973; Richardson 1973, footnote 5, unpubl. data; Pearcy and Myers 1974; Laroche 1976; Misitano 1977; Richardson and Pearcy 1977; Waldvogel 1977; Robinson[6]; Cummings and Schwartz[7]; Forsberg et al.[8]) spawning locations have not been well defined and data are somewhat contradictory. Before the present study, running ripe adults had never been collected. Two nearly ripe females were taken in coastal waters around British Columbia; one ripening female was taken in Tillamook Bay in northern Oregon; and large numbers of ripening adults had been found in Humboldt Bay in northern California (Figure 1). Interestingly, the ripening fish in Humboldt Bay leave in June or July and return again in fall in a spent condition. Planktonic northern anchovy eggs had been reported only from certain inlets of Vancouver, British Columbia, in Puget Sound, Wash., off the Columbia River mouth, and in Yaquina Bay, Oreg. Small (<10 mm) planktonic larvae had been rarely taken in areas where ripening adults or planktonic eggs had been found. Small numbers of these larvae had been reported only from Yaquina Bay and Humboldt Bay. Large concentrations of small larvae had been reported only from ocean waters off Oregon. Larvae ≥10 mm had been taken in small numbers in the Strait of Georgia, British Columbia, inside the mouth of the Columbia River, in Yaquina Bay, and in Humboldt Bay. As with small larvae, large concentrations had been found only off the Oregon coast. Juveniles ≥35 mm had been taken in ocean waters off Oregon as well as in the Strait of Georgia, British Columbia; Puget Sound, Wash., inside the Columbia River mouth; in Tillamook Bay, Yaquina Bay, and Coos Bay, Oreg.; and in Humboldt Bay, Calif. Juveniles taken offshore were usually <50 mm while most of those in bays and sounds were >50 mm.

These data, and particularly the earlier study by Richardson (1973), indicated the possible existence of a spawning concentration of northern anchovy within the northern subpopulation located off the Oregon-Washington coast. Richardson suggested spawning might be associated with the Columbia River plume. The present study was designed to test that hypothesis and to estimate the biomass of spawning adults located therein.

METHODS

Field Procedures

Standard ichthyoplankton surveys (Smith and Richardson 1977) were conducted off the Oregon-Washington coast in the region outlined in Figure 1. This survey area was designed to border at least the inner bounds of the Columbia River plume. Cruises were conducted at the presumed time of peak spawning in mid-July: 10-18 July 1975 and 7-15 July 1976.

A grid of 70 stations along seven east-west transects (Figure 2) was sampled. Stations ex-

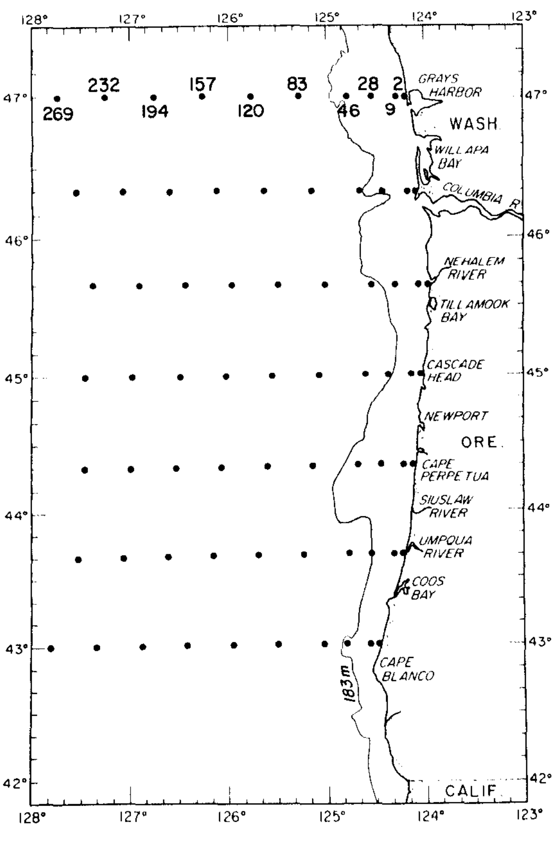

FIGURE 2.—Ichthyoplankton survey grid with 70 cm bongo net sampling stations occupied in July 1975 and July 1976 off Oregon and Washington. Numbers on upper transect represent kilometers from the coast and apply to all seven transects.

[6]Robinson, D. G. 1969. Data record. Number, size composition, weight and food of larval and juvenile fish caught with a two-boat surface trawl in the Strait of Georgia July 4-6, 1967. Fish. Res. Board Can., Manuscr. Rep. Ser. No. 1012, 71 p.

[7]Cummings, E., and E. Schwartz. 1971. Fish in Coos Bay, Oregon, with comments on distribution, temperature, and salinity of the estuary. Oreg. Fish. Comm., Res. Div., Coastal Rivers Invest. Inf. Rep. 70-11, 22 p.

[8]Forsberg, B. O., J. A. Johnson, and S. M. Klug. 1976. The identification, distribution, and notes on food habits of fish and shellfish in Tillamook Bay, Oregon. Oreg. Dep. Fish Wildl., Res. Sect., Fed. Aid Prog. Rep.: Fish., Feb. 1974-June 1976, 117 p.

tended from 2 to 269 km offshore and covered a north-south distance of 450 km. Transects were 74 km apart and stations on a transect were 46 km apart except the most inshore stations which were closer together. The grid covered an area of 120,150 km^2.

Oblique 70 cm bongo net tows were made at each station from 150 m (or just above the bottom) to the surface. Vessel speed was 2-3 knots and retrieval speed was 20 m/min. The bongos were fitted with 0.333 and 0.571 mm mesh Nitex[9] nets, TSK flowmeters and a time-depth recorder. Stations were occupied when the ship arrived, day or night. Samples were preserved in 10% buffered Formalin.

Temperature, salinity, and chlorophyll were monitored at 3 m depth every 9 km along each transect using a flow-through fluorimeter system (AMINCO Fluro-colorimeter). At each bongo station a bathythermograph cast was made to 140 m depth (or 5 m above the bottom) and a surface bucket temperature was recorded. During the July 1976 cruise, surface drifters, consisting of a labelled plastic tag made buoyant with Styrofoam, were released to provide information on surface water movement. Fourteen drifters were dropped at each bongo station except on the southernmost transect (lat. 43°00′ N) where only 10 were released at the 120 km station and none at the 157, 194, 232, and 269 km stations.

Between 18 and 25 July 1977 an acoustic survey was conducted cooperatively by the National Marine Fisheries Service (NMFS) in the same area as the previous ichthyoplankton surveys (Smith[10]). The same seven transects plus an eighth transect to the south along lat. 42°20′ N were surveyed acoustically during daylight using the methods of Smith (1970). Distance covered on each line extended from the 91 m depth contour westward 167 km. In addition to the acoustic work, temperature and salinity at 3 m depth were monitored every 9 km using a flow-through salinograph, and expendable bathythermographs were cast every 9 km on every other transect. Following a day's sonar run, nighttime surface trawls were made with a 40 m modified Cobb pelagic trawl (Smith footnote 10) on the latter half of the sonar track in areas of biological aggregations identified and measured by sonar. Standard oblique 60 cm bongo tows (Smith and Richardson 1977) were made at each trawl station from 70 m to the surface. Samples were processed at sea using CalCOFI (California Cooperative Oceanic Fisheries Investigations) techniques (Kramer et al. 1972) except that the 0.333 mm mesh samples were preserved in ethyl alcohol for special studies (Methot[11]).

Laboratory Procedures

Plankton volumes for each 0.333 mm mesh bongo sample from the 1975 and 1976 cruises were determined by displacement (Kramer et al. 1972), and northern anchovy eggs and all fish larvae were sorted. Northern anchovy eggs were enumerated. Measurements of long and short axes of eggs were made on selected samples using an ocular micrometer in a stereomicroscope. Northern anchovy larvae were identified, enumerated, and measured in 0.5 mm size classes using a plastic rule beneath a glass slide. The 0.333 mm mesh bongo samples only from the 1977 cruise were processed by personnel from Scripps Institution of Oceanography and the NMFS Southwest Fisheries Center according to techniques described by Kramer et al. (1972). Numbers of eggs and larvae in each sample were standardized to the number under 10 m^2 sea surface (Smith and Richardson 1977):

$$C_i = 10\,(a_i^{-1} b_i^{-1} c_i d_i) \tag{1}$$

where C_i = number of eggs or larvae beneath 10 m^2 sea surface at station i

a = mouth area of the bongo net used at station i in square meters

b = length of tow path in meters estimated from a calibrated flowmeter at station i

c = number of eggs or larvae in the ith sample

d = maximum depth of tow in meters.

Egg and Larva Census Estimates

Census estimates (i.e., estimates of the total number of northern anchovy eggs and larvae in

[9]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

[10]Smith, P. E. 1977. Cruise report, R/V *David Starr Jordan*, 7705(111), Mordax North, Leg A, 13-27 July 1977. Rep. dated 5 December 1977. On file at National Marine Fisheries Service Southwest Fisheries Center, P.O. Box 271, La Jolla, CA 92038.

[11]R. D. Methot, Scripps Institution of Oceanography, Graduate Department, La Jolla, CA 92093, pers. commun. July 1977.

the area represented by the survey grid during each cruise in 1975 and 1976) were determined by two methods, the Sette and Ahlstrom Census and the Smith Census. The Sette and Ahlstrom Census was the polygon method of Sette and Ahlstrom (1948) in which the number of individuals under 10 m^2 sea surface at each station was weighted by the area represented by the station. These areas are polygons formed "by constructing perpendicular bisectors of lines drawn from the station to each of all surrounding stations" (Sette and Ahlstrom 1948). The census estimate is then:

$$C_k = 10 \sum_{i=1}^{n} A_s \, (a_i^{-1} b_i^{-1} c_i d_i) \qquad (2)$$

where C_k = estimate of abundance of eggs or larvae during cruise k

A_s = area of a polygon constructed of perpendicular bisectors of lines between station i and all adjacent stations

n = number of stations.

Polygon areas, determined by planimeter, ranged from 0.38 to 2.89×10^9 m^2 but were $>2.00 \times 10^9$ m^2 for all stations 46 km or more from the coast.

The Smith Census was the "regional census estimate" of Smith (1972):

$$C_{kr} = 10 \; A_r n^{-1} \sum_{i=1}^{n} (a_i^{-1} b_i^{-1} c_i d_i) \qquad (3)$$

where C_{kr} = estimate of abundance of eggs or larvae in region r during cruise k

A_r = area of region r in numbers of 10 m^2 areas (in my study,

$$10 \; A_r \;=\; \sum_{i=1}^{n} A_s = 148.81 \times 10^9 \text{ m}^2).$$

The Smith Census method can be less tedious than the Sette and Ahlstrom Census method if the area represented by the survey can be determined in a gross manner, i.e., without planimetry. Values of the Smith Census in my study were always lower than those of the Sette and Ahlstrom Census. The Smith Census was computed here primarily to allow for comparison with CalCOFI data (Smith 1972; Pacific Fisheries Management Council footnote 2).

Spawning Biomass Estimates

Four methods were used to estimate spawning biomass, three based on egg census estimates (Sette and Ahlstrom Egg Method, Simpson Egg Method, Saville Egg Method) and one based on larva census estimates (Smith Larva Method). The use of three egg methods generally follows the approach of Houde (1977) in estimating spawning biomass of round herring, *Etrumeus teres*. Because the shape of the egg production curve throughout the spawning season is unknown for northern anchovy, the use of these three egg methods takes into account the range of possibilities (discussed below) for comparative purposes.

All three egg methods ultimately use the same formula (Saville 1964) to estimate spawning biomass:

$$B = \frac{E_s}{KF} \qquad (4)$$

where B = biomass of spawning adults

E_s = total number of eggs spawned during a season, i.e., seasonal egg production. (This estimate varies according to the egg method used as described below.)

K = the proportion of spawning adults that are females. [In this paper the overall sex ratio of *E. mordax* is assumed to be 1:1 following Smith (1972) and Klingbiel (1978).]

F = mean fecundity, i.e., the number of eggs produced per gram of female per spawning season. [The mean fecundity of *E. mordax* in the northern subpopulation off Oregon is estimated to be 720 ova/g total weight female (Laroche and Richardson 1981).]

The number of eggs spawned in a season (E_s) was estimated by three methods, each using the two egg census estimates described above.

The Sette and Ahlstrom Egg Method of estimating seasonal egg production (E_s) follows the approach of Sette and Ahlstrom (1948).

$$E_s = \sum_{i=1}^{N} \frac{C_k D_i}{t_i} \quad \text{or} \quad \sum_{i=1}^{N} \frac{C_{kr} D_i}{t_i} \qquad (5)$$

where N = number of cruises in a season

D_i = number of days represented by cruise i. [Sette and Ahlstrom (1948) defined this to be the days included in the cruise plus one-half the days since the previous cruise and one-half the days to the next cruise; in this study only one cruise was made during the spawning season and the number of days represented by the cruise was taken to be the entire spawning season. Duration of the spawning season for *E. mordax* off the Oregon-Washington coast was estimated from monthly or bimonthly collections of larvae taken off Oregon in 1969, 1971, and 1972 (Richardson 1973, footnote 5, unpubl. data; Richardson and Pearcy 1977). The earliest that northern anchovy larvae were taken in those years was 19 June and the latest that small larvae (<10 mm) were collected was 10 August. Peak abundance, >100/10 m² or >1,000/1,000 m³ at a station, occurred only between 21 July and 6 August. The spawning season was estimated to last approximately from 15 June to 15 August, or 62 days.]

t_i = the time in days from spawning to hatching of the egg determined from the equation given by Zweifel and Lasker (1976) for incubation times for northern anchovy:

$$I_T = I_0 \exp\left[m(1 - \exp(-\beta T))\right] \qquad (6)$$

where $I_0 = 1861$

$m = -5.4572$

$\beta = 0.0626$

T = the mean temperature at 3 m depth at stations where northern anchovy eggs were taken, 15.18° C in 1975 and 16.09° C in 1976.

The Sette and Ahlstrom Egg Method assumes a constant egg production throughout the spawning season.

The Simpson Egg Method of estimating the number of eggs spawned in a season (E_s) was that given by Simpson (1959) as modified by Houde (1977). The cruise census estimate, C_k or C_{kr}, was used to determine the number of eggs produced per day during the spawning season

$$E_d = \frac{C_k}{t_i} \text{ or } \frac{C_{kr}}{t_i} \qquad (7)$$

where E_d = daily egg production

t_i is defined under Equation (5).

The seasonal estimate of egg production (E_s) was then determined by plotting the daily egg production against the middate of the cruise representative of the spawning season. The area under the resulting polygon (triangle in this case), determined by planimetry, was then equated with egg production for the entire spawning season. This method assumes a high egg production midseason tapering off to low production at the beginning and end of the spawning season. It approaches a normal distribution of egg production. For species with a short spawning season as in northern anchovy off Oregon and Washington, estimates obtained by this method are about one-half as large as those obtained by the Sette and Ahlstrom Egg Method.

The Saville Egg Method of estimating seasonal egg production (E_s) is based on Saville's (1956, 1964) approach. It assumes that egg production follows a normal distribution throughout the spawning season. A census estimate (C_k or C_{kr}) of eggs obtained from a cruise made during the spawning season represents a proportion of the area under a normal curve. If the duration and peak of the spawning season are known, seasonal egg production (E_s) can be estimated (Houde 1977) as:

$$E_s = \frac{C_k y_i}{x_i t_i} \text{ or } \frac{C_{kr} y_i}{x_i t_i} \qquad (8)$$

where y_i = the number of days in cruise i

x_i = the proportion of the area under the normal curve represented by cruise i

t_i is defined under Equation (5).

Duration of the spawning season is assumed to be 62 days, lasting from 15 June to 15 August (see D_i under Equation (5)). The spawning peak is assumed to be the middate, 15 July.

The Smith Larva Method of estimating spawning biomass (B) is modified from the method used in the CalCOFI program (Smith 1972; Pacific Fishery Management Council footnote 2). It relates the census estimate (C_k or C_{kr}) of northern anchovy larvae to spawning biomass by means of a regression. Smith (1972) demonstrated that in the CalCOFI survey area the annual regional census estimate (sum of four quarterly estimates) of larvae is related to northern anchovy spawner biomass in the following way:

$$B_a = 0.098 L_a \tag{9}$$

where B_a = anchovy spawner biomass in short tons
L_a = annual regional census estimate of larvae × 10^9 which is the sum of the four quarterly census estimates.

This equation was based on yearly data from 1951 to 1966 and 1969, with the zero intercept forced, giving 18 data points. Data, upon which Smith's (1972) equation was based, can be used to obtain a modification of this relationship, applicable to this study, if certain assumptions are met, or can be accounted for: 1) the same relationship between census estimates of the number of northern anchovy larvae and northern anchovy spawning biomass exists in the northern subpopulation as in the central and southern subpopulations; 2) the larva census estimate obtained from one cruise at the time of peak spawning during the shortened spawning season in the northern subpopulation is equivalent to a quarterly census estimate made during the peak spawning period, i.e., winter or spring quarter (Ahlstrom 1967) in the central subpopulation; 3) conditions, primarily temperature, which influence development time and therefore length of planktonic life, are similar in the northern and central subpopulations for the time periods considered; 4) sampling in the two survey regions is similar; 5) spawning frequency during the time period considered, i.e., during one quarter in the central subpopulation and during the 2-mo spawning season in the northern subpopulation, is the same in both areas.

Data from the Pacific Fishery Management Council (footnote 2) on quarterly larva census estimates for the central subpopulation for winter and spring quarters (Table 1) were regressed on spawner biomass estimates for the years 1951 through 1966 and 1969, 1972, and 1975, with the zero intercept forced, giving 20 data points each.

$$\text{Winter quarter: } B_a = 614 + 0.152 L_w \tag{10}$$
$$r^2 = 0.70$$

$$\text{Spring quarter: } B_a = 645 + 0.151 L_s \tag{11}$$
$$r^2 = 0.72$$

where L_w = the winter quarterly regional census estimate of northern anchovy larvae
L_s = the spring quarterly regional census estimate of northern anchovy larvae.

Because Smith's (1972) equation yielded a spawning biomass estimate in short tons, the values obtained in Equations (10) and (11) are also in short tons and may be converted to metric tons (t) by multiplying by 0.9078. Larvae in my study were collected with a 0.333 mm mesh net instead of the 0.55 mm mesh silk net upon which CalCOFI larva census estimates are based (Lenarz 1972; Pacific Fishery Management Council footnote 2). To correct for the increased retention by the smaller mesh net, larva census estimates were divided by the factor given by Lenarz (1972):

$$C_k \text{ corrected} = \frac{C_k}{1.7} \text{ or } C_{kr} \text{ corrected} = \frac{C_{kr}}{1.7}. \tag{12}$$

Thus, in my study I assumed that

$$L_w = L_s = C_k \text{ (or } C_{kr}\text{) corrected.} \tag{13}$$

TABLE 1.—Census estimates (units × 10^9) of *Engraulis mordax* larvae in the central stock for winter and spring quarters and spawner biomass estimates (in 10^3 short tons) of the central stock [from Pacific Fishery Management Council (text footnote 2) A.14 and A.15] from which Equations (10) and (11) were derived (see Methods section).

Year	Winter census	Spring census	Spawner biomass
1951	298	690	180
1952	407	457	156
1953	1,210	373	510
1954	4,469	988	768
1955	5,588	1,709	846
1956	1,911	1,206	485
1957	5,954	4,308	1,172
1958	8,114	5,236	1,479
1959	6,341	8,155	1,514
1960	7,552	7,547	1,540
1961	992	6,714	1,159
1962	4,814	23,567	2,986
1963	17,377	24,818	4,254
1964	8,941	14,383	2,901
1965	19,155	22,690	4,659
1966	15,103	15,865	3,572
1969	19,756	6,538	2,999
1972	8,213	14,335	2,784
1975	29,754	4,071	3,603

Yield Estimates

Because the northern anchovy stock under consideration is in a nearly virgin state, an estimate of potential yield can be obtained using Gulland's (1971) formula

$$Y_{pot} = XMB_0 \quad (14)$$

where Y_{pot} = maximum potential yield
X = a constant coefficient [0.6 for northern anchovy based on MacCall et al. (1976)]
M = instantaneous natural mortality rate [1.00-1.05 for northern anchovy based on MacCall et al. (1976) and Pacific Fishery Management Council (footnote 2)]
B_0 = mean virgin biomass, in this case spawning biomass.

SURVEY RESULTS

Hydrography and Plankton Volume

In all 3 yr, upwelling activity was observed along the coast, evidenced by the colder, <14° C water nearshore (Figures 3-5). This is a typical summer condition when winds blow mainly from the north, currents tend generally to the south, upwelling takes place in a narrow band along the coast with resultant offshore transport of surface waters (Wyatt et al. 1972; Smith 1974; Huyer et al. 1975; Ingraham and Hastings 1976; and others). Offshore, especially beyond the continental shelf, water temperatures were >14° C, well within the range for successful northern anchovy spawning and early development (Brewer 1976).

Salinity contours showed that all three surveys covered the inner bounds of the Columbia River plume, delineated by the 31‰ isohaline (Figures 3-5). The outer bounds of the plume, defined by the 32.5‰ isohaline (Barnes et al. 1972), were not encompassed. This plume is a persistent hydrographic feature off the Oregon coast in summer (Barnes et al. 1972). The Columbia River reaches maximum outflow in June and flows southerly, under the influence of prevailing winds and currents, as a plume of shallow (20-40 m deep), low salinity, warm water on top of the more saline and colder ocean water. It can extend as far as 800 km offshore and as far south as northern California. In 1976 the plume extended farther south and was closer to the coast than in 1975. In 1977 the central core of the plume was much reduced reflecting the extreme drought conditions of that year. High salinities, >33‰, along the coast were indicative of upwelling.

Chlorophyll concentrations at 3 m in 1975 and 1976 were greatest near the coast in regions of upwelling and generally decreased with distance from shore (Figures 3, 4). In 1975, relatively moderate concentrations extended beyond the continental shelf in the region of the lowest salinity plume water. This may be indicative of higher productivity associated with nutrient rich plume waters near the Columbia River mouth (Anderson 1972).

Of the 920 surface drifters released in July 1976, 24 or 2.6% were returned by 21 August 1976 (Figure 6). No additional returns were reported as of February 1977. All but seven of the returns were from the 2 km stations. All returns that had been released off Oregon indicated southward transport. Two returns from the 2 km station near the Columbia River indicated some transport into the river and one return showed northward movement. Three drifters released 46 km off Grays Harbor, Wash., were transported toward the coast while three drifters from the 2 and 9 km stations were transported moderate distances northward. The low number of returns (2.6%) probably reflects the offshore component of surface drift which is generally observed during the summer upwelling season (Wyatt et al. 1972; Huyer 1974).

Plankton volumes, which ranged from 30 to 4,726 ml/1,000 m^3 in 1975 and 8 to 3,670 ml/1,000 m^3 in 1976, were greatest on the continental shelf with the highest volumes (>2,000/1,000 m^3) occurring at stations 2, 9, and 28 km from shore (Figures 3, 4). In these areas the plankton consisted largely of phytoplankton and ctenophores although at 9 and 28 km off Cape Perpetua, Oreg., in 1975 it consisted mainly of copepods and euphausiids. Nearshore low plankton volumes <100 ml/1,000 m^3 were observed at the 2 km stations off Grays Harbor in both 1975 and 1976 and off the Columbia River in 1975. High plankton volumes appeared to be mainly associated with coastal upwelling with no obvious relationship to the Columbia River plume. However, plume waters are a near surface phenomenon while the plankton was sampled from 150 m to the surface possibly obscuring any relationship.

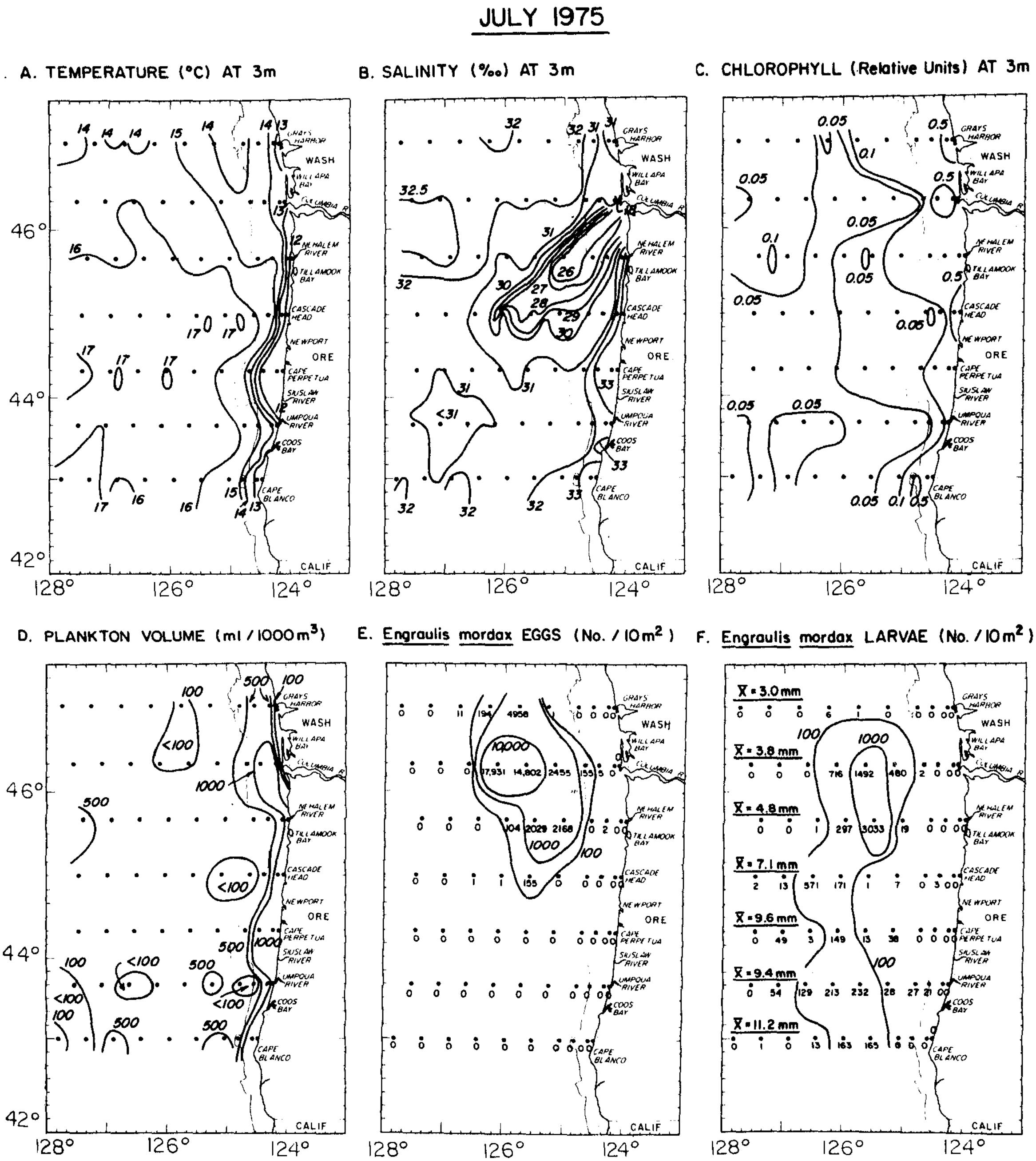

FIGURE 3.—Results from the July 1975 ichthyoplankton survey off Oregon and Washington: hydrography, plankton volume, *Engraulis mordax* eggs and larvae. One chlorophyll unit is equivalent to 46.3 μg coproporphyrin standard/l or 6.14 μg chlorophyll a/l. Mean standard length of northern anchovy larvae on each transect is listed along the left margin of F.

Eggs and Larvae

Northern anchovy eggs were taken at 17 and 23 of the 70 stations sampled in 1975 and 1976 (Figures 3, 4; Table 2). In 1975 the center of egg abundance was north of the Columbia River plume. Largest concentrations, up to 17,931 under 10 m² sea surface, occurred 120-157 km off the mouth of the Columbia River. In 1976, the center of abundance was located 83 km off the Oregon coast

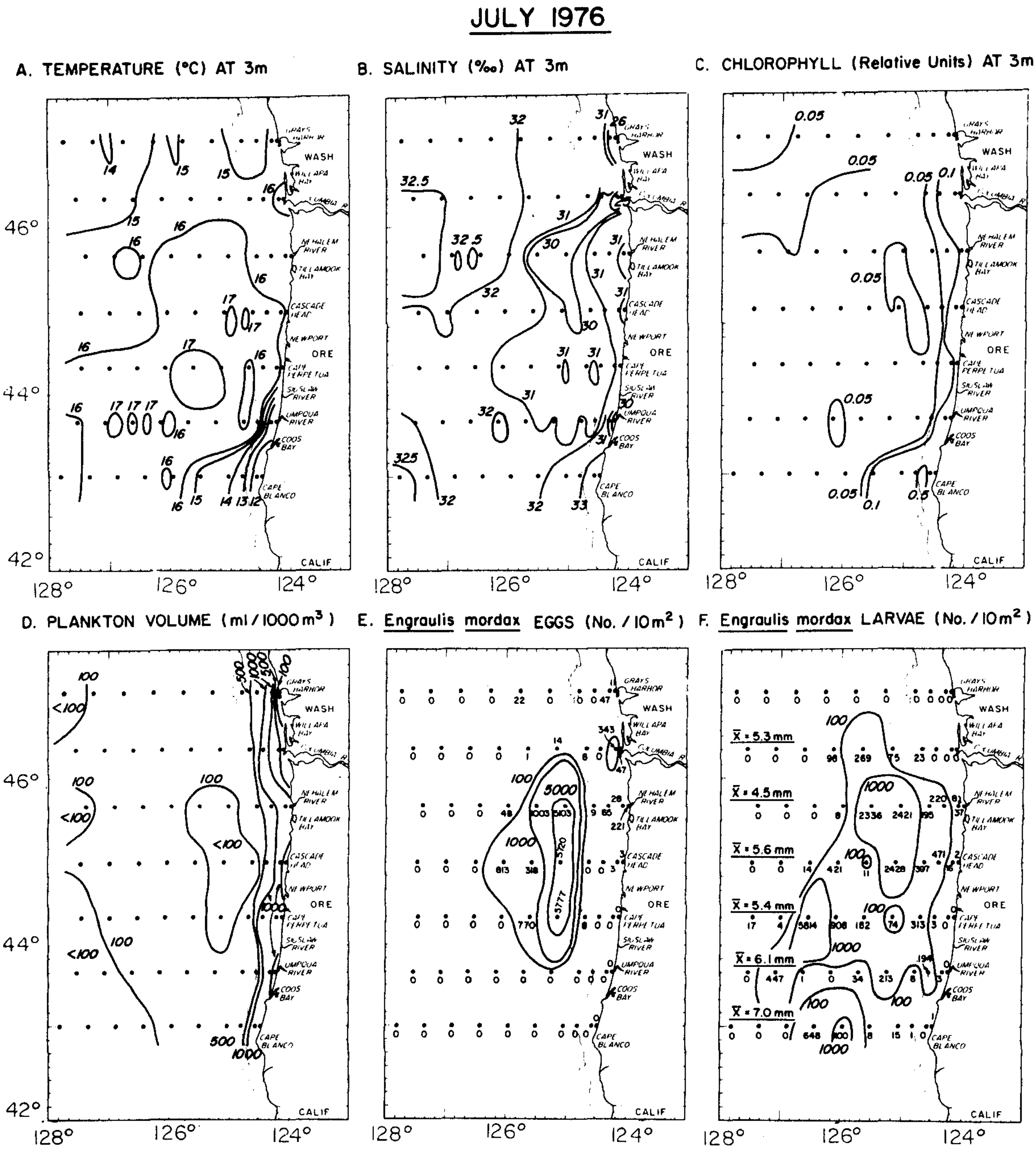

FIGURE 4.—Results from the July 1976 ichthyoplankton survey off Oregon and Washington: hydrography, plankton volume, *Engraulis mordax* eggs and larvae. One chlorophyll unit is equivalent to 46.3 μg coproporphyrin standard/l or 6.14 μg chlorophyll *a*/l. Mean standard length of northern anchovy larvae on each transect is listed along the left margin of F.

between the Nehalem River and Cape Perpetua within the Columbia River plume. The largest egg concentration, 5,777 under 10 m² sea surface, was one-third the highest concentration found in 1975. Overall mean egg abundance was 642 and 291 under 10 m² sea surface in 1975 and 1976, and at positive stations it was 2,645 and 886 under 10 m². In both years the egg distribution was bounded to the south and offshore but not to the north, although relatively few eggs were taken on the

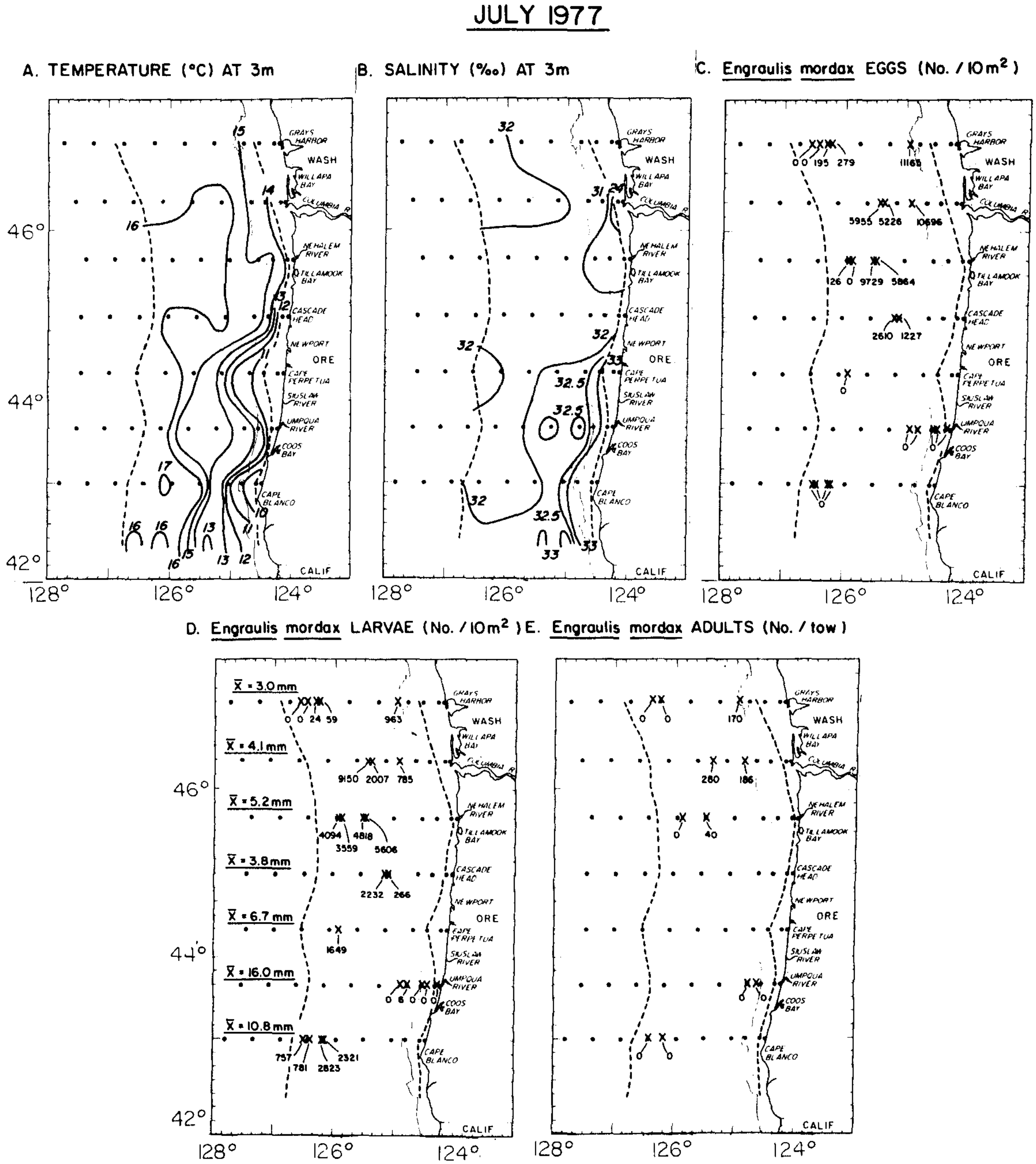

FIGURE 5.—Results from the July 1977 acoustic survey off Oregon and Washington: hydrography, *Engraulis mordax* eggs, larvae, adults. Values for adult catches are based on a 30 min surface tow of a pelagic trawl. Dotted lines delimit east and west cruise track boundary. On C and D, "X" indicates location of the only bongo samples taken during this cruise. On E, "X" indicates location of pelagic trawl stations. Mean standard length of anchovy larvae on each transect is listed along the left margin of D. Data in C and D courtesy of Methot (text footnote 11). Data in E from Smith (text footnote 10).

northernmost transect in 1976. No eggs were taken in regions of active upwelling and few were taken nearshore over the continental shelf except at the 9 km station just north of the Columbia River mouth in 1976 where a patch of warm, <16° C, surface water occurred. The farthest offshore

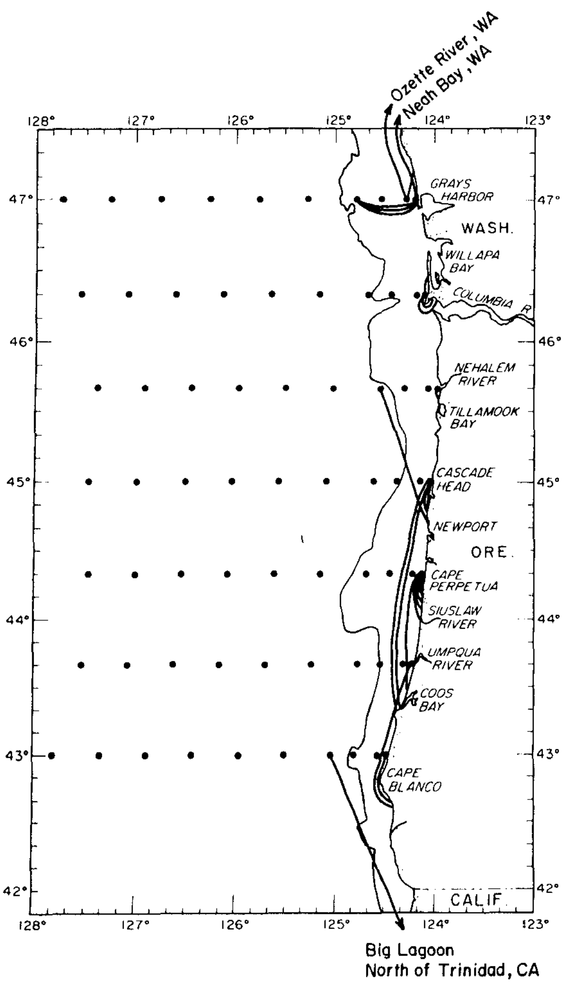

FIGURE 6.—Returns of surface drifters released at the sampling stations off Oregon and Washington during the July 1976 ichthyoplankton survey and returned by 21 August of that year. Lines represent drift paths from release point (sampling station) to return location. Depth contour is 183 m.

TABLE 2.—Summary of collection data on *Engraulis mordax* eggs and larvae off the Oregon-Washington coast from ichthyoplankton surveys conducted in 1975 and 1976. Seventy stations were occupied on each survey.

Item	10-18 July 1975	7-15 July 1976
No. positive stations		
Eggs	17	23
Larvae	33	40
Eggs or larvae	38	45
Eggs and larvae	12	18
Mean no. eggs/10 m²		
All stations	642.49	291.15
Positive stations	2,645.54	886.10
Mean no. larvae/10 m²		
All stations	115.89	278.73
Positive stations	245.82	487.78

that eggs were taken was 194 km and few were found beyond 157 km. All eggs were taken at stations where surface temperatures were >14° C. Mean temperature at 3 m depth at positive stations was 15.18° and 16.09° C and mean salinity was 30.69 and 30.07‰ in 1975 and 1976. Egg concentrations did not correlate with high surface chlorophyll levels and greatest concentrations were in regions of low plankton volumes. Although bongo samples were taken only at trawl stations during the acoustic survey in 1977 (Figure 5) catch trends of eggs were similar to the previous two surveys (Methot[12]). Northern anchovy eggs were taken only on the four northern transects in concentrations up to 11,165 under 10 m² sea surface.

Northern anchovy larvae were more widely dispersed than northern anchovy eggs with 33 and 40 positive stations in 1975 and 1976 (Figures 3, 4; Table 2). Thirty-eight and 45 stations had either eggs or larvae in 1975 and 1976 and 12 and 18 stations had both, respectively. In 1975, highest numbers of larvae, >1,000 under 10 m² sea surface, were found 120 km offshore, near and south of the highest egg concentrations. In 1976, greatest larva concentrations occurred 83 and 120 km offshore between the Nehalem River and Cascade Head, Oreg.; 194 km off Cape Perpetua; and 120 km off Cape Blanco, Oreg. Overall mean abundance was 115 and 278 under 10 m² sea surface in 1975 and 1976, and 487 and 245 under 10 m² at positive stations. In 1975 larvae occurred mainly in a corridor paralleling the coast beyond the continental shelf while in 1976 they were more widely distributed and also occurred closer to the coast. The sampling grid apparently bordered their center of abundance to the north and offshore but not to the south. As with the eggs, larvae were generally not found in regions of active upwelling. Mean length of larvae on each transect in 1975 increased progressively from 3.0 mm in the north to 11.2 mm in the south, evidence of drift south from the spawning center based on egg distributions and seasonal flow patterns. In 1976 mean length of larvae per transect increased from 4.5 mm off the Nehalem River to 7.0 mm off Cape Blanco but the trend was not as pronounced as in July 1975. This reduced trend may be partly a result of decreased northerly winds, evidenced by reduced upwelling, and reduced southward transport compared to 1975.

[12]R. D. Methot, Scripps Institution of Oceanography, Graduate Department, La Jolla, CA 92093, unpubl. data.

Also, based on egg distribution the spawning aggregation appeared more widely distributed in a north-south distance. Mean temperature and salinity at 3 m depth at positive stations in 1975 and 1976 were 15.66° and 15.96° C and 31.07 and 31.28‰, respectively. Distribution of larvae did not correlate with high surface chlorophyll levels and abundance was generally highest in regions of low plankton volume. During the acoustic survey in 1977, northern anchovy larvae were collected (Methot footnote 12) on each transect in concentrations up to 5,606 under 10 m² sea surface (Figure 5). No larvae were found in samples taken within 46 km of the coast. Mean length of larvae on each transect again showed an increasing trend toward the south.

Adults

During the acoustic survey in 1977, running ripe adult northern anchovy were collected on the three northern transects (lat. 47°02′ N, long. 124°56′ W; lat. 46°60′ N, long. 126°33′ W; lat. 46°19′ N, long. 124°54′ W; lat. 45°40′ N, long. 125°30′ W) between 56 and 130 km offshore (Figure 5). No adult northern anchovy were collected at trawl stations on the southern two transects. No trawls were made on the transects off Cascade Head or Cape Perpetua.

School concentrations, recorded by sonar, were presented by Smith (footnotes 10, 3). Based on sonar traces and results of the pelagic trawl catches, he concluded schools of spawning adult northern anchovy were centered 83 km offshore in the surveyed area and 37 km south of the Columbia River mouth with the inner edge about 37 km offshore and the western edge between 102 km and 130 km offshore. The northern edge was not defined above lat. 47° N and the southern edge was at lat. 44° N.

EGG AND LARVA CENSUS ESTIMATES

The total area represented by the survey in 1975 and 1976, was 148.81×10^9 m². Census estimates of the total number of northern anchovy eggs and larvae in that area for each cruise are in Table 3.

TABLE 3.—Egg and larva census estimates (C_k and C_{kr}) and spawning biomass estimates (B) of *Engraulis mordax* in the survey area off Oregon and Washington in 1975 and 1976. Values of parameters used in the biomass estimating procedures are presented except those for K (proportion females) and F (mean fecundity) which are constants, 0.5 and 720. See Methods section for description of procedures and equations.

Spawning biomass estimating method	Year and season	Sette and Ahlstrom Census [1]C_k (units $\times 10^{11}$)	Sette and Ahlstrom Census corrected L_W or [2]L_S (units $\times 10^9$)	Days represented by cruise D_i	Days included in cruise Y_i	Proportion of area under normal curve X_i	Time to hatch in days [3]t_i
Sette and Ahlstrom Egg Method	1975	121.98		62			2.73
[Equations (4) and (5)]	1976	54.89		62			2.43
Simpson Egg Method	1975	121.98					2.73
[Equations (4) and (7)]	1976	54.89					2.43
Saville Egg Method	1975	121.98			9	0.3335	2.73
[Equations (4) and (8)]	1976	54.89			9	0.3081	2.43
Smith Larva Method	1975 winter	22.22	1,307				
[Equations (10) and (11)]	1975 spring	22.22	1,307				
	1976 winter	52.06	3,062				
	1976 spring	52.06	3,062				

Spawning biomass estimating method	Year and season	Daily egg production [4]E_d ($\times 10^{11}$)	Seasonal egg production E_S ($\times 10^{11}$)	Spawning Biomass Estimate [5]B_a (tons)	Spawning Biomass Estimate [5]B (t)	Smith Census [6]C_{kr} ($\times 10^{11}$)	Spawning Biomass Estimate [7]B (t)
Sette and Ahlstrom Egg Method	1975		2,770.24		769,511	95.60	603,094
[Equations (4) and (5)]	1976		1,400.49		389,025	43.32	307,022
Simpson Egg Method	1975	44.68	1,316.27		365,631	95.60	294,933
[Equations (4) and (7)]	1976	22.59	708.87		196,909	43.32	170,694
Saville Egg Method	1975		1,205.82		334,951	95.60	262,506
[Equations (4) and (8)]	1976		659.84		183,289	43.32	144,654
Smith Larva Method	1975 winter			812,664	737,736	17.14	696,479
[Equations (10) and (11)]	1975 spring			842,357	764,692	17.14	723,705
	1976 winter			1,079,424	979,901	41.48	894,074
	1976 spring			1,107,362	1,005,263	41.48	920,001

[1]Equation (2).
[2]Equations (12), (13).
[3]Equation (6).
[4]Equation (7).
[5]Based on Sette and Ahlstrom Census.
[6]Equation (3).
[7]Based on Smith Census.

The Smith Census estimate was always lower than the Sette and Ahlstrom Census estimate. Both estimates were used to calculate spawning biomass of adults.

Larva abundance was not corrected for day-night catch differences. A correction factor could not be derived from the data. No consistent pattern of daytime avoidance was apparent based on cruise plots of night to day catch ratios for each millimeter length class as Houde (1977) demonstrated for clupeid larvae. If daytime avoidance did occur, larva census estimates would be low and in turn biomass estimates would be low. Net avoidance of larvae increases with age and since 94% of the larvae captured in 1975 and 98% in 1976 were ≤10 mm SL (standard length), errors due to avoidance should be small. Also, Smith (1972) made no day-night corrections for the CalCOFI program. Thus data from my study are comparable.

SPAWNING BIOMASS ESTIMATES

These biomass estimates apply only to that portion of the spawning population within the northern subpopulation off Oregon and Washington that was sampled in my survey area. In 1975, the egg concentration (Figure 3) was bounded inshore, offshore, and to the south, but the northern boundary was not encompassed. If major egg concentrations occurred north of the sampling area, the biomass estimates would be low. In 1976, essentially the entire egg concentration was bounded. In both 1975 and 1976, larva concentrations were bounded to the north and offshore, but not to the south. The estimates do not account for any additional spawning concentrations within the northern subpopulation should they exist.

The three methods of estimating spawning biomass based on egg abundance (Sette and Ahlstrom, Simpson, and Saville Egg Methods) include the assumption that northern anchovy spawn only one batch of eggs, those in the most advanced mode and upon which fecundity estimates are based, during the time sampled by the survey. This is particularly critical since the recent work by Hunter and Goldberg (1980) has indicated that a ripe adult northern anchovy can mature a batch of eggs and spawn once every 6 or 7 d in the central subpopulation. In this study the area in which northern anchovy eggs were collected was sampled in 5 d in 1975 and 6 d in 1976. It is assumed that the eggs collected represented no more than a single spawning, because batch 1 would hatch before batch 2 was spawned.

The three egg methods of estimating biomass do not take into account egg mortality. Rates of egg mortality in the ocean are unknown for northern anchovy and could not be determined in this study. Eggs could not be staged due to poor condition resulting from collection techniques. If mortality of spawned eggs were high and disintegration rapid (i.e., dead eggs not occurring in plankton samples), the estimates of total number of eggs spawned would be low and the resulting biomass estimates would also be low. However, Sette and Ahlstrom (1948) obtained similar biomass estimates for *Sardinops caerulea* using two techniques, one that involved aging of eggs and another, the Sette and Ahlstrom Egg Method used in my paper, that did not. Presumably egg mortality was not a major factor influencing their estimates. A similar situation may exist for northern anchovy which also has a relatively short-lived (2 or 3 d) egg stage.

Sette and Ahlstrom Egg Method

The egg census estimate (Table 3) for each cruise was divided by the duration of the egg stage, estimated to be 2.73 d in 1975 and 2.43 d in 1976, Equation (6), to obtain estimates of daily egg production. This value was then expanded to the number of days (62) represented by the cruise, Equation (5). Biomass estimates for each cruise were then obtained, Equation (4).

Estimated spawning biomass using the Sette and Ahlstrom Census was 769,511 t in 1975 and 389,025 t in 1976 (Table 3). Somewhat smaller values were obtained with the Smith Census 603,094 and 307,022 t. Since the method used to derive the Smith Census is merely a simplified version of the method used for the Sette and Ahlstrom Census, biomass estimates based on the latter may be better, at least for the egg data. Confidence limits (95%) based on variance estimates of egg abundance, using methods of Houde (1977), gave a range around the point biomass estimates of ±11-15% for all egg methods. However, the variance estimates were low and statistically not very precise because of the low number of data points and are thus not included here. The Sette and Ahlstrom Egg Method assumes a constant egg production throughout the 62-d spawning season. If egg production tapers off at the beginning or end of the season, the biomass estimates would be high.

Differences in biomass estimates between the 2 yr based on eggs reflects the fact that more than twice as many eggs were collected in 1975 than in 1976. This could be the result of a decrease in spawning biomass between the years although small sample size is probably just as important. Biomass estimates based on eggs are likely to be more variable than those based on larvae. Northern anchovy is a schooling fish; therefore eggs released from spawning schools are clumped, resulting in a sample of high variance (Pacific Marine Fishery Management Council footnote 2).

Simpson Egg Method

Estimates of daily egg production, Equation (7), 44.68×10^{11} in 1975 and 22.59×10^{11} in 1976 using the Sette and Ahlstrom Census (Table 3) and 35.02×10^{11} and 17.83×10^{11} using the Smith Census, were plotted against the cruise middate. The area under the resulting triangle was then equated with egg production for the entire spawning season, $1{,}316.27 \times 10^{11}$ in 1975 and 708.87×10^{11} in 1976 with the Sette and Ahlstrom Census and $1{,}061.76 \times 10^{11}$ and 614.50×10^{11} with the Smith Census. Biomass estimates were then obtained with Equation (4).

Spawning biomass estimates were 365,631 t in 1975 and 196,909 t in 1976 using the Sette and Ahlstrom Census and slightly smaller with the Smith Census (Table 3). These biomass values are nearly one-half those obtained by the Sette and Ahlstrom Egg Method. This reflects the different assumption of this method regarding egg production where it is high in mid season and low at both ends.

Saville Egg Method

Egg production is assumed to follow a normal curve throughout the 62-d spawning season from 15 June to 15 August. Each cruise within that period represents a proportion of the area under that normal curve. In this study, each cruise was of 9 d duration and was made near the peak of the spawning period. In 1975 the cruise represented 33.35% of the curve and in 1976, 30.81%. Seasonal egg production was then estimated by Equation (8) and biomass by Equation (4).

Estimates of biomass using this method were smaller, 334,951 t in 1975 and 183,289 t in 1976 using the Sette and Ahlstrom Census, than in the two previous methods (Table 3). If egg production is skewed from a normal distribution, large errors could be introduced into the biomass estimate.

Smith Larva Method

This method of estimating spawning biomass assumes that a similar linear relationship exists between numbers of larvae and adult spawning biomass in both the central and northern subpopulations. Although this assumption seems reasonable, the recent fecundity estimate for northern anchovy off California, 340 eggs/g total female weight (Hunter and Goldberg 1980), is considerably less than the fecundity estimate obtained for northern anchovy off Oregon, 720 eggs/g total female weight (Laroche and Richardson 1981). These data indicate it would take more planktonic eggs to represent 1 g of fish in the northern than in the central subpopulation. It follows then that it would also take more pelagic larvae to represent 1 g of fish in the northern subpopulation given that spawning frequency and larval growth and mortality conditions are similar. Thus, biomass estimates obtained by this method may be too high.

Other assumptions of the method seem reasonable (see Methods section). The census estimate obtained from one cruise during the shortened spawning season in the north should be equivalent to a quarterly census estimate obtained during a peak spawning period in the south. Sometimes a quarterly estimate for CalCOFI is based on only one cruise, other times a mean of several cruises. However, my cruise dates were purposefully selected at the time of peak spawning. Sometimes CalCOFI quarterly cruises may be conducted near the beginning or end of a quarter and not necessarily at the peak of spawning. Thus larger numbers of smaller larvae may have been collected in our study, and the relationship between numbers of larvae and biomass may be biased to give a higher biomass estimate in the north.

In general, water temperatures at the time of peak spawning appear to be similar off Oregon and California (Ahlstrom 1959; Baxter 1967) so that growth rates and length of time in the water column are assumed to be similar. Methot (in press) demonstrated that growth rates of larvae in the two subpopulations are similar at similar temperatures.

Sampling techniques used in this study were similar to those of the CalCOFI program (Kramer et al. 1972) except we used 0.333 mm mesh net on 70 cm bongos vs. 0.55 mm mesh on a CalCOFI net. The difference in mesh sizes can be corrected, Equation (12), but because of the reduced avoidance associated with bongo nets, larva catches may be relatively greater resulting in high census estimates and accordingly high biomass estimates.

Spawning frequency during the 2-mo spawning period in the northern subpopulation is unknown. Hunter and Goldberg (1980) indicated that northern anchovy in the central subpopulation may spawn a batch of eggs every 6 or 7 d during peak spawning. If northern anchovy off Oregon respond differently, additional error would be introduced into the biomass estimate. The higher fecundity of fish in the north may be balanced by less frequent spawning.

Spawning biomass estimates derived from the Smith Larva Method are based on larva abundance. Using the larva census estimates corrected for mesh size differences, Equation (12), biomass estimates were obtained by Equations (10) and (11). These estimates were 737,736 and 764,692 t in 1975 and 979,901 and 1,005,263 t in 1976 with the Sette and Ahlstrom Census and slightly less with the Smith Census, 696,479 and 723,705 in 1975 and 894,074 and 920,001 in 1976. In this case, since the Smith Census is based on procedures and data (Smith 1972) from which Equations (10) and (11) are derived, biomass estimates based upon it are probably better than those based on the Sette and Ahlstrom Census.

Because of diffusion and dispersion and length of the larval period (about 30 d compared with 2-4 d for eggs), larvae are more evenly distributed over a given geographic area than eggs and in turn yield a less variable biomass estimate than eggs (Pacific Fishery Management Council footnote 2). This may, in part, account for the smaller year to year difference in biomass estimates based on larvae compared with those based on eggs. Interestingly biomass estimates based on eggs decreased greatly from 1975 to 1976 while those based on larvae increased.

Most Probable Biomass

Spawning biomass estimates (Table 3) ranged from 262,506 to 769,511 t in 1975 and 144,654 to 1,005,263 t in 1976 (Table 3). The biomass estimate based on acoustic survey of adults in July 1977 was about 800,000 t (Smith footnote 3), using methods given by Smith (1970). A reasonable conclusion is that the actual spawning biomass of northern anchovy in the survey area laid or fluctuated between the extreme values in 1975 and 1976 (Houde 1977) and is probably <1 million t but >100,000 t. This line of reasoning is supported by the fact that the estimates from 1975 and 1976 (for a given method) are within twofold of each other and less than tenfold (for any method) from the acoustic survey.

These estimates only include mature spawning adult fish. Laroche and Richardson (1981) reported that northern anchovy in the northern subpopulation attain first sexual maturity at the end of the second year, i.e., in the third summer. Thus northern anchovy <2 yr old are not included in the estimates and may represent additional sizeable biomass. These immature fish are segregated geographically from spawning adults during the spawning season with the young fish occurring in nearshore coastal areas (Laroche and Richardson 1981).

Based on these estimates, spawning biomass of northern anchovy off the Oregon-Washington coast is less than that in the central subpopulation which had a mean estimate of around 3,631,200 t for 1965-72 (MacCall et al. 1976), although a recent population decline has been recorded in 1978 (1,183,771 t) and 1979 (1,564,139 t) (Stauffer 1980). My spawning biomass estimates are more comparable to that for the southern subpopulation of 544,680 t (mean for 1965-69) (MacCall et al. 1976).

YIELD ESTIMATES

Using Gulland's (1971) formula for potential yield to a fishery, Equation (14), with the range of instantaneous natural mortality rates of 1.0-1.05, estimates for a biomass of 144,654 t are 86,792-91,132 t. For a biomass of 1,005,263 t they are 603,158-633,316 t. These potential yield estimates are about 60% of the spawning biomass, which may be dangerously high values for a species known to undergo large year-to-year fluctuations in abundance.

Recommendations for harvest quotas by the northern anchovy management plan for the central subpopulation called for a more conservative yield estimate of 70% of one-third, or about 23%, of the spawning biomass in excess of 907,800 t (Pacific Fishery Management Council footnote 2).

At an estimated spawning biomass of 3,631,200 t (MacCall et al. 1976) the harvest quota would be 635,400 t or approximately 17% of the total spawning biomass. At the recent reduced biomass level of 1,564,100 in 1979, the optimum yield established for the 1979-80 season in the U.S. Fishery Conservation Zone was 153,100 t (Stauffer 1980), equivalent to only 10% of the total spawning biomass.

Thus the actual realizable yield and in turn the feasibility of establishing a fishery on this northern stock of northern anchovy is difficult to assess. Northern anchovy are considered to be important forage items for fishes such as salmon and albacore off Oregon and Washington but northern anchovy biomass actually consumed by these species has not been adequately estimated. Northern anchovy are also important items in the diet of marine birds. Weins and Scott (1975) estimated that four species of marine birds consume 28,000 t of northern anchovy annually off Oregon.

If the northern anchovy stock off Oregon and Washington could support a harvest of 10% of the total biomass, as in the recent quotas on the reduced biomass for the central subpopulation, a yield of about 14,465-100,526 t might result. If this is reasonable, the feasibility of establishing such a fishery still remains to be determined. Feasibility partly depends on distribution patterns and habits of the stock and on economic considerations, the latter of which is beyond the scope of this paper. Seasonal patterns of distribution were discussed by Laroche and Richardson (1981). The most compact aggregations appear to occur during the spawning season in the offshore spawning center. However, school sizes appear to be small. Smith (footnote 3) estimated that half of the northern anchovy schools counted during the acoustic survey in July 1977 were <4 t and only 1.1% were over 64 t. Small school size could be a deterrent to fishery development.

COMPARISON OF NORTHERN AND CENTRAL SUBPOPULATIONS

Important ecological differences exist between the northern and central subpopulations of *E. mordax* with respect to spawning times and locations and associated environmental parameters. Off California, spawning takes place throughout the year (Figure 7) with a peak occurring between January and April (Smith and Richardson 1977). Off Oregon, spawning takes place over a 2-mo period (Figure 7) with a peak in July, based on the collection of small larvae (Richardson 1973, footnote 5). These differences in peak spawning times certainly contribute to reproductive isolation.

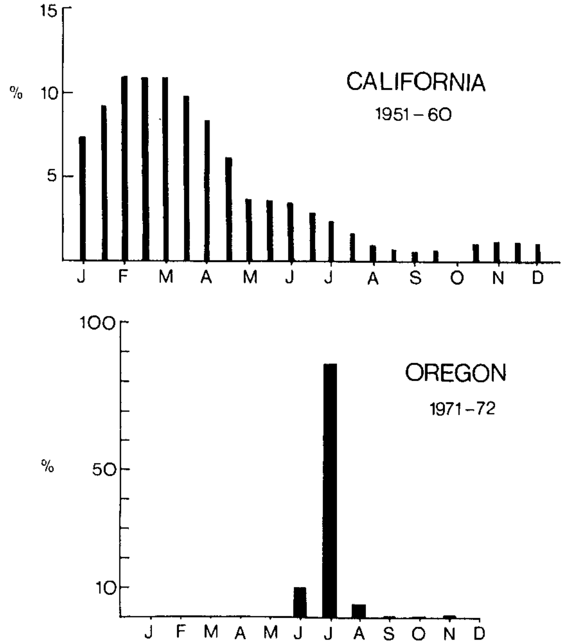

FIGURE 7.—Spawning cycle of *Engraulis mordax* off California and Oregon. Upper graph is after Smith and Richardson (1977). Lower graph is based on catches of northern anchovy larvae given by Richardson (text footnote 5).

Off California (Figure 8), at the initiation of peak spawning southward flow of the California Current is minimal (Saur 1972) with resulting minimal larval transport south away from the spawning area; temperature at 10 m depth (Lasker and Smith 1977) is reaching minimum values in the annual cycle; upwelling is minimal but increasing (Bakun 1973); day length is beginning to increase after the shortest day in December. In contrast, off Oregon (Figure 9), at the time of peak spawning, current flow to the south is at a maximum (Huyer 1977); surface temperatures (Johnson 1961) are reaching maximum values in the yearly cycle (excluding the colder waters of the nearshore upwelling zone); upwelling activity is at a maximum (Bakun 1973); day length is beginning to decrease after the longest day in June.

Off California (Figure 10), spawning takes place closer to the coast (Smith and Duke[13]) than off

[13]Smith, P. E., and S. Duke. 1975. Nearshore distribution of northern anchovy eggs and larvae (*Engraulis mordax*). NOAA NMFS, Southwest Fish. Cent., Admin. Rep. No. LJ-75-58, 15 p.

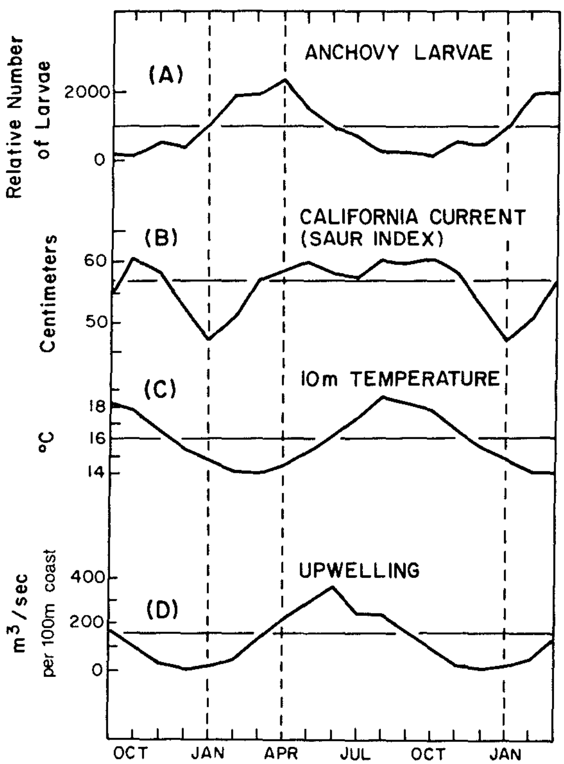

FIGURE 8.—Yearly cycle of *Engraulis mordax* larva abundance and selected environmental parameters [mean annual cycles (1953-60)] off California (reproduced from Lasker and Smith 1976). A) Larva abundance. B) California Current strength indicated by sea level difference approximations (Saur 1972). C) Temperature at 10 m depth. D) Upwelling (Bakun 1973). Dashed lines indicate period of peak spawning between January and April. Horizontal lines are for reference only.

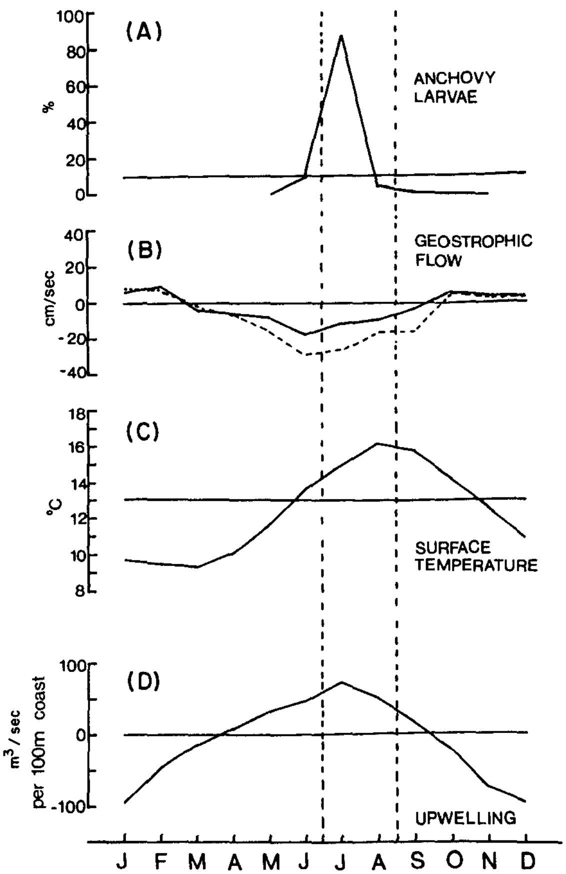

FIGURE 9.—Yearly cycle of *Engraulis mordax* abundance and selected environmental parameters off Oregon. A) Larva abundance in 1971-72 off Newport, Oreg. (Richardson text footnote 5). B) Estimates of alongshore geostrophic flow between 28 and 46 km off Newport at the surface (solid line) and 50 m (dotted line) after Huyer (1977). C) Monthly mean of surface temperatures recorded in six 2° squares off Oregon and Washington (lat. 42°-48° N; long. 124°-128° W) from 1947 to 1958 from Johnson (1961). D) Mean monthly values of upwelling indices for the 20 yr period 1948-67 at lat. 45° N, long. 125° W from Bakun (1973). Dashed lines indicate period of peak spawning. Horizontal lines are for reference only.

Oregon. Relatively little nearshore spawning takes place in the coastal upwelling zone off Oregon which is probably related to the low water temperatures there during the spawning season. Lasker (in press) demonstrated that upwelling may disperse proper-sized food particles, mostly dinoflagellates, and thereby reduce survival of first feeding northern anchovy larvae. These dinoflagellates are replaced by smaller diatoms which are nutritionally inadequate for survival of northern anchovy larvae.

RELATIONSHIP WITH COLUMBIA RIVER PLUME

Data from this study and that by Richardson (1973) provide evidence that a northern anchovy spawning center within the northern subpopulation is closely associated with the Columbia River plume. Reasons for such an association may be related to conditions necessary to induce or trigger spawning in adults or conditions necessary for the survival of the eggs and larvae. Increased river flow and plume size, associated with snow melt and day length, may provide a cue for the offshore spawning migration of adults. Temperature may not be a major factor in the association as both oceanic and plume waters warm to temperatures >13° C (Johnson 1961) needed for spawning, although plume waters warm earlier (Owen 1968).

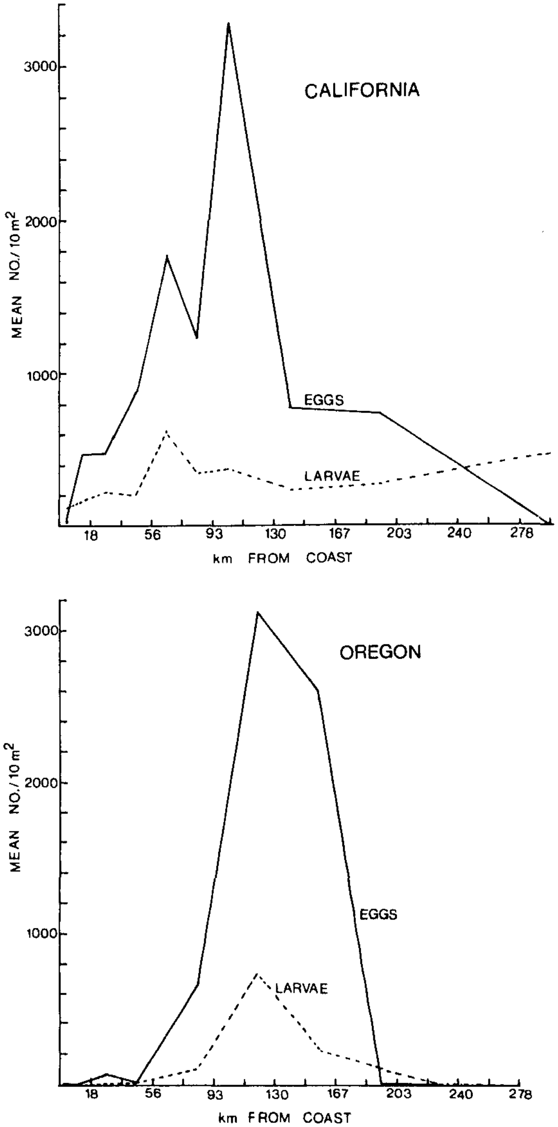

FIGURE 10.—Abundance of *Engraulis mordax* eggs and larvae with distance from the coast off California and Oregon. Upper panel based on data collected off Point Arguello, Calif., in January, April, and July 1964 (Smith and Duke text footnote 13). Lower panel data collected off Oregon and Washington in July 1975.

The plume may provide an optimal environment, in terms of stability and productivity particularly within 100 km or so from the river mouth (Anderson 1972; Barnes et al. 1972), to insure good feeding conditions and enhance survival of first feeding larvae. Such an environment may not exist in the less productive ambient oceanic water or the highly productive but too cold and dynamic coastal upwelling zone. Unfortunately data on type and availability of potential food items in the plume, which would help validate or refute this hypothesis, are not available.

LARVAL TRANSPORT AND JUVENILE NURSERIES

Because of the obvious southward transport of larvae away from the spawning center off Oregon and Washington and the later occurrence of juveniles in Oregon bays and rivers where spawning is apparently rare or unsuccessful, questions arise about return mechanisms. The deep (bottom third of water column) northward flowing countercurrent that develops in late summer beneath southward flowing surface waters (Huyer et al. 1975) could provide a mechanism for reduction of southward transport if larvae utilize it by migrating vertically. Unfortunately we have no depth distribution data on the larvae related to the depth of the shear layer between currents off Oregon to demonstrate this. However, if northern anchovy larvae come to the surface at night to gulp air and conserve energy, as off California (Hunter and Sanchez 1977), then southward and offshore transport would be enhanced, at least at night. Changing wind patterns in the fall from northerly to southwesterly (Wyatt et al. 1972) result in a shift in surface currents from southward to northward, cessation of upwelling, and an onshore drift of surface waters which may contribute to a northerly onshore movement of juveniles. Also, northern anchovy spawned later in the season may not be transported as far south as those spawned earlier and thus would not have to travel as far to return to northern bays and rivers.

An additional offshore spawning center to the north would help explain recruitment of juveniles to the Oregon rivers but there is no evidence for the existence of one, as discussed earlier.

The southward transport of larvae may provide an avenue of gene flow from the northern to central subpopulation.

OTHER SPAWNING CENTERS

Whether the area off the Columbia River is the primary or only spawning center for northern anchovy in the northern subpopulation is unknown. No evidence of spawning to the north exists at least in offshore waters. Also, no evidence is available for a major spawning center to the south off northern California although that area has not been sampled intensively. It is not known where ripening northern anchovy go after they leave Humboldt Bay in June (Waldvogel 1977), i.e., whether they go north to spawn near the Columbia River plume or whether they spawn off northern California.

Some evidence indicates that another spawning center may occur in the Strait of Georgia. Ripening adults (Pike 1951) and larvae as small as 11 mm (Robinson footnote 6) have been collected there. The environment created by the Fraser River may share similarities with that of the Columbia River plume in terms of stability and productivity (Waldichuk 1957). Thus the region may provide another suitable spawning environment. Additional sampling would be needed for adequate documentation. If a second major spawning center were defined in this region, it would be interesting to investigate the degree of mixing between Columbia River-spawned and Fraser River-spawned northern anchovy.

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