THE 1994 MEXICO–U.S. SPAWNING BIOMASS SURVEY FOR PACIFIC SARDINE (*SARDINOPS SAGAX*) AND THE 1995 CALCOFI SARDINE SYMPOSIUM

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INTRODUCTION

Mexican (Instituto Nacional de la Pesca) and U.S. (California Department of Fish and Game and the National Marine Fisheries Service) scientists carried out a daily egg production method (DEPM) survey during 11 April–14 May 1994 to measure the spawning biomass of Pacific sardine (*Sardinops sagax*). The project was the largest and most comprehensive cooperative survey of a transboundary fishery resource ever undertaken by government agencies in the two countries. Five research vessels from both countries (table 1) surveyed 380,000 km^2 along the west coast of the Californias from near San Francisco in the north to San Ignacio Lagoon (near Punta Abreojos), Baja California, in the south. The DEPM survey is described by Lo et al. and Macewicz et al. (this symposium).

Results of the 1994 DEPM survey were presented and discussed at the special Sardine Symposium held during the annual CalCOFI (California Cooperative Oceanic Fisheries Investigations) Conference in 1995 at Lake Arrowhead, California. The following pages contain seven papers that were originally presented at the Sardine Symposium, and one paper (Cisneros-Mata et al.) prepared afterward.

This introduction to the CalCOFI Sardine Symposium offers a historical perspective and outlines primary results from the DEPM survey. We conclude with our perspectives about uncertainties and directions for future research.

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HISTORY

The Pacific sardine was once the largest fishery in North America, with peak landings of 664,000 MT during 1936 and peak biomass (ages 2+) of 3.6 million MT during 1934 (Murphy 1966; MacCall 1979). Sardine biomass fell to less than 10,000 MT by 1965; the fisheries collapsed; and the stock did not increase noticeably for about fifteen years (Barnes et al. 1992). Meanwhile, the demise of the Pacific sardine fishery became a well-known, textbook example (Hilborn and Walters 1992) of the boom-and-bust cycles characteristic of clupeoid stocks and fisheries.

As sardine biomass declined, fisheries collapsed in a southerly direction, beginning off British Columbia (Radovich 1982). Small fisheries off central and southern Baja California, at the southern end of the sardine's range, developed and continued after the collapse in the north was complete (Lluch-Belda et al. 1989). In addition, a substantial fishery for sardine developed in the Gulf of California (Cisneros-Mata et al. 1995). By state law, the California sardine fishery was significantly restricted in 1969 and virtually eliminated in 1972 (Wolf 1992).

Sardine science and research during and following the collapse of the historical sardine fishery were of exceptionally high quality. The historical work sets a high standard for current research and, more important, provides data and analyses that are a sound basis for comparison. Research during the historical period included large-scale tagging studies (Clark and Janssen 1945), the development of the CalCOFI program for regular and

TABLE 1
Vessels Used in the 1994 Daily Egg Production Method (DEPM) Spawning Biomass Estimate for Pacific Sardine

Vessels	Survey dates From	Survey dates To	Sampling	Region
RV *El Puma* (UNAM/INP)	18 April	11 May	Eggs	San Ignacio Lagoon, Baja California–Ensenada, Baja California
RV *MacArthur* (NMFS/NOAA)	18 April	11 May	Eggs	San Francisco–San Diego
RV *David Starr Jordan* (NMFS/NOAA)	14 April	4 May	Eggs	San Diego–Point Eugenia, Baja California
RV *Mako* (CDFG)	11 April	6 May	Adults	Point Conception, Baja California–San Diego
RV *BIP12* (INP)	18 April	12 May	Adults	San Ignacio Lagoon–Ensenada
Mexican commercial vessels	21 April	14 May	Adults	Vicinity of Ensenada
U.S. commercial vessels	4 April	5 May	Adults	Vicinity of Monterey Bay and San Pedro, Calif.

UNAM means Universidad Nacional Autónoma de México (Autonomous National University of Mexico); INP means Instituto Nacional de la Pesca; NMFS/NOAA means National Marine Fisheries Service/National Oceanographic and Atmospheric Administration; CDFG means California Department of Fish and Game.

intensive ichthyoplankton sampling (Hewitt 1988), and the development of cohort analysis (Murphy 1966), also called virtual population analysis or VPA (Megrey 1989), for estimating trends in stock biomass from fisheries data. Many of these data sets (Roemmich and McGowan 1995; Jacobson and MacCall 1995) and methods (Murphy 1966; Megrey 1989) are used today to address important problems and issues.

RECENT DEVELOPMENTS

In the early 1980s, qualitative information (Wolf 1992) indicated that the Pacific sardine stock along the west coast of California and Baja California had begun to increase. In response to interest in commercial fishing off California, Wolf and Smith (1985) developed an "inverse egg production method" for estimating spawning biomass of sardine based on the area occupied by spawners. The inverse egg production method (Wolf and Smith 1986; Wolf et al. 1987) indicated that spawning biomass of sardine had grown to at least 20,000 MT, and in 1986, as specified in California law, a small quota (908 MT) was allowed for directed fishing in U.S. waters. At about the same time, sardine landings began to increase in Baja California at Ensenada (Jacobson et al. 1995) and as far south as Magdalena Bay (Félix-Uraga et al., this symposium).

Borrowing techniques developed for northern anchovy (*Engraulis mordax*), the California Department of Fish and Game (CDFG) carried out a DEPM survey (Lasker 1985) in 1986 that resulted in a sardine spawning biomass estimate of about 8,000 MT with a coefficient of variation (CV) of about 51% (Scannell et al. 1996). Additional DEPM surveys (Lo et al., this symposium) were attempted in 1987 (1,600 MT, CV 91%) and 1988 (14,000 MT, CV 160%). Imprecision and severe undersampling of adult sardines was a persistent problem in these first attempts to apply the DEPM to Pacific sardine. In addition, the estimates appeared suspiciously low. Difficulties in sampling adult sardine led to development of the high-speed trawl described by Dotson and Griffith (this symposium) for sampling pelagic fish.

Information from the early DEPM surveys (e.g., size of spawning area and estimates of adult reproductive parameters) was an important part of data used to manage the stock (Wolf 1992). As sardine biomass continued to increase, more sophisticated stock assessment models (Barnes et al. 1992; Deriso 1993) based on a wide range of fishery and fishery-independent data were developed. Results from the models verified that sardine biomass was increasing rapidly, but the current biomass was uncertain.

One of the key difficulties in early modeling studies was lack of information about adult reproductive parameters and age-specific net fecundity for sardine. These biological parameters are used to convert CalCOFI and other ichthyoplankton-based survey data to units of spawning biomass, and to convert estimates of spawning biomass to units of total biomass (Barnes et al. 1992; Deriso 1993). Another problem was that abundance data from CalCOFI, fish spotters (Lo et al. 1992), and other sources did not cover the entire range of the sardine, particularly as the stock's geographic range and abundance continued to expand.

Sardine fisheries are managed by the Instituto Nacional de la Pesca (INP) in Mexico, and by CDFG (with technical assistance from the National Marine Fisheries Service, NMFS) in the United States. Parties on both sides of the U.S.–Mexico border became concerned that increased harvest rates in the United States and Mexico would quash the long-awaited recovery of the sardine stock. Consequently, a workshop was convened in Rosarito, Baja California, during 1993 to bring together key persons from both nations to discuss the status of the sardine population and fisheries.[1] The Rosarito meeting included industry representatives, scientists, and government officials. After reviewing all available evidence, the participants concluded that sardine abundance was increasing, but that the size of the population and future trends were uncertain. The meeting was very productive because communication was enhanced, plans for future research were discussed, and the seeds of a shared scientific understanding were sown.

In May of 1993, following up on a proposal made at the Rosarito meeting, NMFS, INP, and CDFG resolved to carry out a cooperative DEPM survey to estimate spawning biomass of the recovering sardine population over as much of the spawning area as possible. Resources and ship time were limited in both countries, so cooperation and efficiency were critical. After many planning and coordination meetings in the United States and Mexico, and after countless phone calls, faxes, and e-mail messages, the joint survey was launched in April 1994.

RESULTS

All eight papers in the Sardine Symposium section of this volume contribute to the understanding of Pacific sardine. Dotson and Griffith's new, high-speed research trawl can be used to obtain better, more representative samples of sardine (and other pelagic fish) than are obtained from commercial purse seine catches. Butler et al. document the rapid individual growth rates and early sexual maturity that have contributed to rapid growth

[1]Baumgartner, T., G. Hammann, and M. M. Mullin. 1993. A binational workshop for the scientific evaluation of the recovery of the Pacific sardine in the California Current—Final narrative report for the project of UC MEXUS Program on Environmental Issues and the U.S.–Mexican border. Unpubl. Rep. 24 pp.

of the sardine stock in recent years. Macewicz et al. give new estimates of batch fecundity and spawning frequency for sardine and suggest that reproductive data might be used to infer movements of sardine. Bentley et al. estimate that about 50,000 MT of sardine were spawning in the Columbia River plume off the Pacific Northwest during 1994, an area where sardine have been absent for decades. Bentley et al. and Lo et al. report that sardine spawning habitat occurs at temperatures of 14°–15°C along thermal fronts and coastal upwelling areas. Lo et al. hypothesize, based on this information, that sardine use suitable spawning habitat opportunistically. In addition to estimating spawning biomass in the DEPM survey area (111,000 MT, CV 33%), Lo et al. estimate the time of peak spawning for sardine and develop a temperature-dependent egg-development model. Bentley et al. give criteria for distinguishing between sardine eggs and eggs of similar size spawned by other fishes in northern areas. Using DEPM and other data, Deriso et al. estimate that Pacific sardine biomass (age 1+) during July 1995 was about 344,000 MT (CV = 33%) and that sardine biomass, despite fishing, increased by 28% year^{-1}, on average, during 1983–95.

Shifting to the southern end of the California sardine's range, Félix-Uraga et al. give new information about stocks and fisheries off central and southern Baja California (south of the DEPM survey area), an area that may serve as a refuge when sardine are rare in the north (Lluch-Belda et al. 1989). Finally, Cisneros-Mata et al. analyze deterministic effects of fishing, climate change, and other factors on abundance of Pacific sardine in the Gulf of California by using a simulation model and data that have only recently become available.

DISCUSSION

The 1994 DEPM survey demonstrated the ability of agencies in Mexico and the United States to work cooperatively and efficiently on large and complex field studies. Moreover, the survey and subsequent analyses resulted in significant scientific progress.

The 1994 DEPM survey provided answers to many questions, but uncertainties remain, and there are exciting new questions to be addressed. Deriso et al. (this symposium) estimate that DEPM spawning biomass estimates for Pacific sardine during 1994 and earlier years may have measured only 34%, on average, of the actual spawning biomass. We hypothesize that the DEPM survey areas (380,000 km^2 in 1994 and smaller in earlier years) were not large enough to encompass the entire spawning habitat. This hypothesis is supported by the historical geographic range of the sardine population (Mexico to British Columbia, Radovich 1982); spawning sardine in the Columbia River plume off Oregon during 1994 (Bentley et al., this symposium); observations of sardine off British Columbia during 1992–95 (Hargreaves et al. 1994); and the impending development of a small sardine fishery in Canadian waters (D. Ware, Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, BC, V9R 5K6, Canada, pers. comm.).

New techniques of fisheries science are needed for surveying sardine when abundance is high and the geographic range of the stock is large (e.g., from Baja California to British Columbia during 1994) because it may be impossible to survey the entire stock with conventional techniques like the DEPM (Deriso et al., this symposium). Complicated models that measure the degree of undersampling (Butterworth et al. 1993; Deriso et al., this symposium) may be required to interpret DEPM and other data for large stocks. New survey technologies such as aerial lidar (light detection and ranging),[2] continuous underway egg sampling (Checkley[3]), adaptive sampling (Thomson 1992), and remote sensing (Simpson 1994) may provide information for larger areas in less time and at lower cost. New analytical approaches such as Bayesian statistics (Walters and Ludwig 1994) and geostatistics (Pelletier and Parma 1994) may make better use of the data that are collected.

Environmentally driven predictors for habitat size, in addition to new survey methods, may be required to effectively and efficiently survey sardine. It would be easier to devise cost-effective surveys if the boundaries of spawning (Bentley et al., this symposium) and feeding habitats could be predicted on the basis of satellite or other real-time environmental measurements. Despite difficulties in conducting and interpreting survey data, the experience of Deriso et al. (this symposium) indicates that survey-derived information is necessary to assess and manage the sardine fishery.

Sardine fisheries exist once again along the entire coast from Baja California to British Columbia. It is an opportune time for managers and scientists to reevaluate the assumptions about stock structure used to assess and manage the fisheries (Radovich 1982; Hedgecock et al. 1989). Is spawning habitat in northern areas important in terms of recruitment? Bentley et al. (this symposium) found that sardine egg production per unit area in spawning habitat off the Columbia River was as great as in the Southern California Bight, but that oil droplets in eggs were sometimes smaller and dispersed and that the size of eggs was more variable off Oregon. Do differences in eggs from northern areas imply reduced fitness? Peak catches in Magdalena Bay, at the southern

[2]Lidar surveys use a laser at a frequency that penetrates water to locate fish schools (Hunter and Churnside 1995).

[3]Checkley, D. M., Jr. A continuous, underway fish egg sampler. MS.

end of the sardine's range, occur at much warmer temperatures than in northern areas. Are sardine in the south genetically adapted to their subtropical environments, or are these differences due to phenotypic plasticity? Are growth rates (Butler et al., this symposium) and maturity rates (Deriso et al., this symposium) of sardine in northern areas due to size-specific migration patterns or to localized adaptation? Did Deriso et al.'s (this symposium) estimate of sardine biomass implicitly include the sardine biomass discovered off Oregon by Bentley (this symposium)? Should fishery managers in California consider abundance of sardine off Oregon, Mexico, and elsewhere when regulating the California fishery? Can stocks along the west coast be assumed to mix because of dispersion or because of feeding and spawning migrations (Macewicz et al. and Félix-Uraga et al., this symposium)? Over what time scales does mixing occur? Should managers and scientists regard sardine along the west coast as a metapopulation comprising groups with restricted interchange or as a single, homogenous population? Are complicated, geographically stratified models required for management purposes?

CONCLUSION

Many of our questions and uncertainties about sardine were raised by scientists and managers decades ago. Clark and Marr (1955) proposed, for example, the existence of regional, partially intermixing, groups of sardine that migrate north and south along the coast of North America. It is likely that many questions will be answered as recent data augment historical information and as new statistical techniques are applied (e.g., Jacobson and MacCall 1995). Molecular and other genetic approaches to studying the distribution of fish (Hedgecock 1994), together with historical tagging studies (Clark and Janssen 1945) may, for example, answer questions about mixing of sardine and about localized adaptations. It is clear that the distribution and relationships among sardine along the west coast of North America, from Mexico in the south to Canada in the north, will remain an interesting topic of research in the coming years.

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