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THE CESIUM: POTASSIUM RATIO -- A CHEMICAL INDICATOR OF TROPHIC LEVEL DIFFERENCES IN MARINE ORGANISMS

Glen: See pp: 5, 17-18, 20, 22 Dave

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INTRODUCTION

ONE OF THE PRINCIPAL CONCERNS REGARDING DISPOSAL OF MAN'S WASTES IN THE MARINE ECOSYSTEM IS THE POSSIBILITY THAT ASSOCIATED TOXIC SUBSTANCES MAY BE ACCUMULATED BY LOWER ORGANISMS AND SUCCESSIVELY CONCENTRATED AS THEY PASS TO HIGHER TROPHIC LEVELS. ISAACS (1972) APPLIED THE TERM "STRUCTURED FOOD WEB" TO SUCH ECOSYSTEMS. THIS CONCEPT IS SO WELL ESTABLISHED THAT IT IS COMMON TO FIND REFERENCE TO FOOD CHAIN OR FOOD WEB MAGNIFICATION OF POLLUTANTS IN THE LITERATURE. HOWEVER, MARINE FOOD WEBS ARE USUALLY QUITE COMPLEX, AND PRINCIPAL FEEDING RELATIONSHIPS MAY CHANGE SUBSTANTIALLY OVER SPACE AND TIME. THIS LEADS TO UNCERTAINTIES IN THE RELATIVE POSITIONS OF MEMBERS OF A MARINE FOOD WEB, WHICH CONFOUND EVALUATIONS OF THE POTENTIAL FOR POLLUTANT BIOMAGNIFICATION IN A SPECIFIC SYSTEM.

PURPOSE

THE PURPOSE OF THE RESEARCH REPORTED HERE WAS TO DEVELOP A CHEMICAL METHOD OF TESTING HYPOTHESIZED DIFFERENCES IN AVERAGE TROPHIC, OR FEEDING, LEVELS WHICH COULD CAUSE SUCCESSIVE INCREASES IN POLLUTANT CONCENTRATIONS IN MARINE FOOD WEBS. TO THIS END, I UTILIZED AN ENCLOSED QUASI-MARINE ECOSYSTEM, WHOSE RELATIVELY SIMPLE TROPHIC STRUCTURE HAD ALREADY BEEN IDENTIFIED AND WELL-DESCRIBED (WALKER, 1961). THE RESULTS WERE THEN APPLIED TO A CONCEPTUALLY SIMPLE POLLUTANT BIOMAGNIFICATION MODEL DEVELOPED IN CONJUNCTION WITH DR. ALAN MEARNS (SEE PAPER 32D-11, THIS CONFERENCE).

BACKGROUND

CESIUM AND POTASSIUM

PRIOR TO THIS INVESTIGATION, A NUMBER OF STUDIES HAD SHOWN THAT CONCENTRATIONS OF THE TRACE ALKALI METAL CESIUM (CS), AND ITS RATIO TO THE BIOLOGICALLY-ESSENTIAL ALKALI METAL POTASSIUM (K), INCREASE BY FACTORS OF 2-3 OVER DISTINCT FEEDING LINKS OR TROPHIC LEVEL STEPS IN TERRESTRIAL AND FRESHWATER ECOSYSTEMS. ANDERSON ET AL. (1957) POINTED OUT THAT THE LONGER RESIDENCE TIME OF CESIUM IN MAN, COMPARED TO THAT OF POTASSIUM, SHOULD RESULT IN AN INCREASE IN HIS CESIUM/POTASSIUM RATIO OVER THAT OF HIS DIET, CORRESPONDING TO THE RATIO OF WHOLE-BODY BIOLOGICAL HALF-TIMES OF CESIUM AND POTASSIUM. ON THE BASIS OF VALUES OF 140 AND 58 DAYS FOR THE TWO HALF-TIMES, AND ASSUMING EQUAL ASSIMULATION OF CESIUM AND POTASSIUM, THEY PREDICTED THAT RADIOCESIUM RELATIVE TO POTASSIUM SHOULD BE CONCENTRATED BY A FACTOR OF 140/58, OR 2.4. MCNEILL AND TROJAN (1960), STUDYING RADIOCESIUM AND RADIOPOTASSIUM ACTIVITIES IN TORONTO RESIDENTS AND THEIR DIETS, ARRIVED AT A RATIO OF 3.0 FOR THE RATIO OF $^{137}Cs/^{40}K$ IN WHOLE BODIES RELATIVE TO AVERAGE CONCENTRATIONS IN FOOD. PENDLETON ET AL. (1965), IN THEIR COMPREHENSIVE DISCUSSION OF THIS EFFECT, EMPLOYED THE PHRASE "INCREASE RATIO," ONE FORM OF WHICH IS:

$$\text{INCREASE RATIO} = \frac{\text{BODY OR TISSUE Cs/K}}{\text{DIET}}$$

EXPERIMENTING WITH BEAGLES, THEY FOUND A WHOLE-BODY INCREASE RATIO OF ABOUT 2. FOR MUSCLE TISSUE FROM UTAH COUGARS AND MULE DEER ON WHICH THE COUGAR HAD BEEN FEEDING, THE CORRESPONDING INCREASE RATIO FOR THE MUSCLE WAS 3.4. HANSON ET AL. (1964) FOUND THAT FLESH FROM

ALASKAN WOLF AND RED FOX HAD 2 TO 3 TIMES MORE ^{137}Cs THAN DID FLESH OF CARIBOU FROM THE SAME REGIONS. HERE, THE SIMILARITY OF THE POTASSIUM LEVELS IN THESE MUSCLE SAMPLES PERMITS A DIRECT CESIUM COMPARISON IN ESTIMATING THE INCREASE RATIO. HANSON (1967) SUBSEQUENTLY REPORTED AN INCREASE IN FALLOUT CESIUM OF ABOUT A FACTOR OF 2 PER TROPHIC LEVEL STEP IN THE ALASKAN LICHEN-CARIBOU-MAN FOOD CHAIN. IN AN EARLIER STUDY, GREEN ET AL. (1961) FOUND THE $^{137}Cs/K$ RATIOS OF PIGS AND CALVES TO BE ABOUT DOUBLE THOSE OBSERVED IN THEIR FOODS. PENDLETON (1964) POINTED OUT THAT SUCH TROPHIC LEVEL INCREASES WERE CONSISTENT WITH VALUES FOR BIOLOGICAL HALF-TIMES OF CESIUM AND POTASSIUM IN MAMMALS (E.G., 13 VS 4 DAYS IN RATS, 25 VS 8 DAYS IN DOGS, AND 110-154 DAYS VS 58 DAYS IN MAN).

TROPHIC LEVEL INCREASES OF CESIUM ALSO HAVE BEEN REPORTED FOR FRESHWATER FISHES. PENDLETON ET AL. (1965) REPORTED THAT WHOLE BLUEGILL, WHICH HAD BEEN FEEDING ON SUNFISH IN A ^{137}Cs-CONTAMINATED POND, HAD 3.3 TIMES AS MUCH RADIOCESIUM AS DID THE PREY. HASANEN AND MIETTINEN (1963) LISTED $^{137}Cs/K$ VALUES FOR PISCIVOROUS FISH FROM FINNISH LAKES WHICH WERE 2 TO 6 TIMES THOSE IN THE INVERTEBRATE-FEEDERS. GUSTAFSON (1967), WORKING AT RED LAKE, MINNESOTA, FOUND INCREASE RATIOS OF 1.5 AND 3.5 IN THE PERCH--MIXED SMALL FISH AND THE NORTHERN PIKE--PERCH PAIRS, RESPECTIVELY.

STUDY AREA

BECAUSE LITTLE WAS KNOWN REGARDING THE APPLICABILITY OF THIS RELATIONSHIP TO MARINE ORGANISMS, DURING 1967 I CONDUCTED A YEAR-LONG INVESTIGATION OF THE DISTRIBUTION OF THE ALKALI METALS CESIUM, RUBIDIUM, AND POTASSIUM IN THE SIMPLIFIED ECOSYSTEM OF THE SALTON SEA (FIGURE 1).

LYING ABOUT 60 M (200 FEET) BELOW SEA LEVEL IN THE IMPERIAL DESERT OF SOUTHERN CALIFORNIA, THE SALTON SEA SUPPORTS A NUMBER OF INTRODUCED MARINE SPECIES THAT HAVE REPRODUCED THERE FOR GENERATIONS. ALTHOUGH THIS SALINE LAKE IS OF FRESH-WATER ORIGIN, HAVING REPEATEDLY BEEN FLOODED BY THE COLORADO RIVER SYSTEM IN RECENT GEOLOGIC TIME, EVAPORATION FROM THE SINK AND STABILIZATION OF THE WATER LEVEL BY IRRIGATION RUN-OFF HAVE RESULTED IN A SALINITY SIMILAR TO THAT OF THE OCEAN. HOWEVER, THE RATIOS OF CERTAIN MAJOR ANIONS AND CATIONS DIFFER BY SEVERAL FACTORS FROM THOSE IN SEA WATER (TABLE 1). ALSO, THE ENTIRE SALTON SEA COMMUNITY, WHICH INCLUDES A FEW NON-REPRODUCING MIGRANT SPECIES FROM THE FRESH WATERS EMPTYING INTO THE SEA, IS SUBJECT TO A MEAN ANNUAL TEMPERATURE RANGE OF ABOUT 20° CELSIUS (FIGURE 2). AN ECOLOGICAL SURVEY MADE TEN YEARS EARLIER (WALKER, 1961) HAD SHOWN THE FOOD WEB TO BE RELATIVELY SIMPLE (FIGURE 3). I ANTICIPATED THAT IF THIS SITUATION STILL EXISTED, IT WOULD BE OF GREAT VALUE IN INVESTIGATING THE RELATIONSHIP BETWEEN TROPHIC LEVEL AND ALKALI METAL DISTRIBUTION FOR MARINE SPECIES.

METHODS

Sampling Program

To investigate the distribution of cesium, rubidium, and potassium, as well as DDT and its residues in the Salton Sea ecosystem, I collected most of its major components each month during 1967:

1. Orangemouth corvina: *Cynoscion xanthulus*
2. Gulf croaker: *Bairdiella icistia*
3. Sargo: *Anisotremus davidsoni*
4. Threadfin shad: *Dorosoma petenense*
5. Striped mullet: *Mugil cephalus*
6. Pile worm: *Neanthes succinea*
7. Mixed zooplankton
8. Mixed phytoplankton or algae
9. Bottom sediment
10. Salton Sea water

During each quarter, samples of water, the pile worm and most fish species were collected in successive months from stations off North Shore, Bombay Beach, and Desert Shore, respectively. Water and zooplankton also were collected monthly from the Central Station. Mullet were collected from the southern end of the sea beginning in April 1967; thus, water samples also were collected there in May, July, and September. The floating algae mat samples were collected off Benson Landing in October 1969. This ecosystem was resampled for analysis of elemental cesium and potassium, and total DDT, in water and fish muscle tissue collected off North Shore and Bombay Beach in February 1978 (Young and Mearns, 1978). Because mullet were not obtained in this 1978 survey, samples of the herbivorous Sailfin Molly (*Peocilla latipinna*) were collected instead.

Glen- I must obtain this old ref & confirm the facts. Dave

BECAUSE OF THE POSSIBILITY OF SIGNIFICANT SYSTEMATIC ERRORS IN TRACE ELEMENT ANALYSIS, IN THE 1967 SURVEY I ATTEMPTED TO DETERMINE CONCENTRATION FACTORS FOR CESIUM AND POTASSIUM IN THE BIOTA (RELATIVE TO CONCENTRATIONS IN WATER AND LOWER ORGANISMS) BY TWO INDEPENDENT TECHNIQUES. THE FALLOUT RADIOISOTOPE ^{137}Cs AND THE NATURALLY-OCCURRING RADIOISOTOPE ^{40}K WERE MEASURED IN THE SAMPLES WHERE POSSIBLE BY GAMMA-RAY SPECTROMETRY. RESULTANT CONCENTRATION FACTORS WERE COMPARED TO THOSE FOR FISH MUSCLE AND WHOLE INVERTEBRATES OBTAINED BY FLAME PHOTOMETRIC ANALYSIS OF STABLE CESIUM, RUBIDIUM, AND POTASSIUM.

OWING TO THE SPARSE PRECIPITATION IN THE AREA DRAINING INTO THE SALTON SEA, THE FALLOUT ^{137}Cs LEVELS WERE RELATIVELY LOW. THUS, ABOUT 100 LITERS WERE REQUIRED FOR EACH WATER SAMPLE. SEVERAL HUNDRED GRAMS OF WET TISSUE WERE NECESSARY TO OBTAIN SUFFICIENT PRECISION IN THE RAIOASSAY OF ^{137}Cs AND ^{40}K; THEREFORE I COLLECTED KILOGRAM-SIZED SAMPLES OF THE BIOTA WHENEVER POSSIBLE.

ANALYSIS OF SAMPLES

IN PRELIMINARY EXPERIMENTS I FOUND THAT THE FALLOUT RADIOISOTOPE ^{137}Cs AND THE NATURAL RADIOISOTOPE ^{40}K WERE MEASURABLE IN SUB-KILOGRAM SAMPLES OF WET MUSCLE TISSUE OF SALTON SEA FISH. THIS SUGGESTED THAT BOTH THE RADIONUCLIDE AND ELEMENTAL CONCENTRATIONS OF CESIUM AND POTASSIUM IN THE BIOTA COULD BE MEASURED, TO OBTAIN INDEPENDENT VALUES FOR CONCENTRATION FACTORS OF THESE TWO ALKALI METALS RELATIVE TO LEVELS IN WATER OR PREY. ALTHOUGH ^{40}K WAS DETECTABLE BY DIRECT RADIOASSAY OF SALTON SEA WATER, THE LEVELS WERE SO LOW THAT I DECIDED TO OBTAIN INDEPENDENT MEASUREMENTS OF ELEMENTAL POTASSIUM IN THE WATER BY OTHER LABORATORIES, AND TO TAKE ADVANTAGE OF THE KNOWN RATIO OF ^{40}K

TO ELEMENTAL POTASSIUM IN ORDER TO ESTABLISH THIS PART OF THE DUAL APPROACH. ^{137}Cs CONCENTRATIONS IN THE WATER ALSO WERE LOW, BUT TECHNIQUES HAD BEEN DEVELOPED IN OUR LABORATORY FOR THE REMOVAL OF THIS ELEMENT FROM SEA WATER (FOLSOM AND SREEKUMARAN, 1968). A BRIEF DESCRIPTION OF THE GENERAL APPROACHES EMPLOYED IN THE MEASUREMENTS IS PRESENTED BELOW; DETAILS OF THE ANALYTICAL PROCEDURES ARE REPORTED ELSEWHERE (YOUNG, 1970).

THE RADIOCESIUM CONTENT OF THE SALTON SEA WATER SAMPLES WAS DETERMINED BY SLOWLY PASSING LARGE UNFILTERED SAMPLES (USUALLY 60 LITERS) THROUGH COLUMNS CONTAINING FERROCYANIDE GRANULES. INITIAL EXPERIMENTS HAD VERIFIED THAT VACUUM FILTRATIONS OF THESE LARGE SAMPLES WAS UNNECESSARY, AND RECOVERY EFFICIENCY APPROXIMATED 100%.

UPON ADDING BLANK-FREE GRANULES TO OPTIMIZE THE SAMPLE SIZE, I TRANSFERRED THE MATERIAL TO A STANDARD POLYETHYLENE CONTAINER AND ASSAYED IT FOR RADIOCESIUM BY GAMMA-RAY SPECTROMETRY. SIMILAR RADIO-ANALYSES OF MY FISH MUSCLE SAMPLES (100-500 G) WERE MADE BY PLACING THE WET MATERIAL IN IDENTICAL CONTAINERS FOR GAMMA COUNTING. I OBTAINED THE FISH SAMPLES BY EXCISING WHITE MUSCLE FROM THE DORSAL SIDE OF THE SPECIMENS.

I MADE ELEMENTAL ANALYSES OF THE CESIUM, RUBIDIUM, AND POTASSIUM CONCENTRATIONS IN FILTERED AND ACIDIFIED WATER FROM THE SALTON SEA BY USING THE METHOD OF STANDARD ADDITIONS, A PROCEDURE THAT GIVES RECOVERY-CORRECTED CONCENTRATIONS. THE POTASSIUM MEASUREMENTS REQUIRED ONLY DILUTION OF THE SAMPLE BEFORE ASPIRATION IN THE HYDROGEN-OXYGEN BURNER OF THE FLAME PHOTOMETER. CHEMICAL CONCENTRATION AND SEPARATION WERE REQUIRED FOR THE DETERMINATION OF STABLE RUBIDIUM AND CESIUM. THESE RARE ALKALI METALS WERE REMOVED FROM ALIQUANTS OF THE WATER SAMPLES BY

ION EXCHANGE ONTO AMMONIUM-12- MOLYBDOPHOSPHATE MICROCRYSTALS. THEN THESE CATIONS WERE EXTRACTED INTO SODIUM TETRAPHENYLBORON SOLUTION, WHICH WAS ASPIRATED. I USED 2-3 LITER ALIQUANTS FOR THE CESIUM SAMPLES, AND 200 ML ALIQUANTS FOR THE RUBIDIUM ANALYSES.

THE FIRST STEP IN MEASUREMENT OF THESE ELEMENTS IN FISH MUSCLE WAS TO BRING ABOUT 50 G OF TISSUE INTO SOLUTION WITH FUMING NITRIC ACID. AFTER MOST OF THE ORGANIC MATERIAL HAD BEEN DESTROYED BY WET-ASHING, I DILUTED THE SOLUTION WITH DEIONIZED WATER AND TOOK ALIQUOTS FOR ANALYSIS. I DID NOT WET-ASH THE INVERTEBRATE SAMPLES (USUALLY 100 G EACH), DUE TO THE POSSIBILITY OF HIGH SEDIMENT LOADS, WHICH CONTAINED RELATIVELY LARGE CONCENTRATIONS OF INORGANICALLY-BOUND ALKALIES, ESPECIALLY CESIUM. INSTEAD I DEVELOPED AND UTILIZED A DEIONIZED WATER LEACHING TECHNIQUE WHICH HAD ADEQUATE EXTRACTION AND RECOVERY EFFICIENCIES FOR CESIUM (42±8%) AND POTASSIUM (68±4%) IN ORGANIC MATTER, BUT VERY LOW EFFICIENCIES (LESS THAN 0.1%)FOR CESIUM FROM THE CONTAMINATING SEDIMENTS.

BOTH THE 1967 AND 1978 TISSUE SAMPLES WERE ANALYZED FOR DDT AND ITS RESIDUES UTILIZING PACKED-COLUMN GAS CHROMOTOGRAPHY WITH ELECTRON CAPTURE DETECTION, FOLLOWING THE PROCEDURES DESCRIBED BY YOUNG ET AL. (1976).

MICROSCOPIC ANALYSES WERE CONDUCTED ON THE STOMACH CONTENTS OF THE FISHES SAMPLED THROUGHOUT 1967. ALTHOUGH TOO FEW SAMPLES WERE OBTAINED IN THE SINGLE 1978 SAMPLING TO PROVIDE SIGNIFICANT RESULTS, INFORMATION ON FEEDING RELATIONSHIPS IN THE SEA FOR THAT YEAR SUBSEQUENTLY WAS OBTAINED FROM THE CALIFORNIA DEPARTMENT OF FISH AND GAME (GLEN BLACK, PERSONAL COMMUNICATION).

RESULTS AND DISCUSSION

Dissolved Solids

Table 1 lists the average concentration (plus or minus one standard error) of major cations and anions in water collected during 1967 from a variety of Salton Sea stations and measured by three independent laboratories. For each ion the mean value obtained by each laboratory was weighted equally. Also shown are corresponding averages for surface seawater from the world ocean. The value for Total Dissolved Solids in the Salton Sea is based on fifteen surface water samples collected throughout the year at my five stations. The average concentrations off Benson Landing, Desert Shores, North Shore, Bombay Beach, and at the Central station were 36,700; 35,800; 36,700; 32,300; and 36,200 mg/liter respectively. Thus, despite the several major inputs of irrigation runoff to the Sea, the values for average salt content of surface waters from the five stations did not vary from the over-all 1967 average by more than about 10%, and the values also agreed, within about 10%, with salinities typically measured in seawater.

Temperature

Frequent measurements of the surface water temperature were made during the various sampling efforts in 1967, and comparison of these values with the extensive 1954-1956 monitoring data for surface and bottom temperatures (Walker, 1961) showed that a very similar thermal regiem existed during the periods. During 1967, the average temperature in the Sea covered a 20° Celcius range, from about 12° C in January and February to about 32° C in July and August.

Plankton

The species of dinoflagellates most frequently observed in the monthly phytoplankton collections made by continuous-flow centrifuge at Benson's Landing were *Exuviella compressa* and *Glenodimium* sp.; of the diatoms identified, *Thalassionema nitzschioides* was the most abundant, followed by *Nitzschia longissima*. The monthly zooplankton tows (mesh size 53 microns) made in the center of the Sea revealed that, between March and May, the planktonic forms of the barnacle *Balanus amphitrite saltonensis* were by far the most abundant animal identified. However, by the end of June the copepod *Cyclops dimorphus* had emerged as the principal zooplankter, and this species was by far the most abundant animal in the samples throughout the remainder of the year.

Food Studies

To establish the major foods of the five species of Salton Sea fishes collected in 1967, I examined gastro-intestinal tract contents from several specimens of each species for nearly every month in which samples were available. Over 400 microscopic examinations were made, and the feeding relationships defined by this analysis were quite distinct and were similar to those described in earlier studies. The result revealed that, in the size classes regularly sampled, the species of Salton Sea fish collected in 1967 belonged to four trophic levels. The major foods of the mullet, shad, sargo and croaker, and corvina in my samples were plant material, zooplankton, pile worm, and croaker respectively. I did not observe any critical changes in distribution of organisms or feeding relationships that would suggest

A CHANGE IN THE MAJOR FOOD CHAIN DESCRIBED BY WALKER (1961): PHYTOPLANKTON- DETRITUS- DETRITUS-EATING WORM- WORM-EATING FISH (SARGO AND CROAKER)- CORVINA.

FIGURE 2 PRESENTS A DIAGRAM OF THE PRINCIPAL FEEDING RELATIONSHIPS IN THE FOOD WEB OF THE SALTON SEA DURING 1967. THE ESTIMATED AVERAGE POSITIONS OF THE MAJOR FOOD WEB COMPONENTS IN THE SIMPLIFIED TROPHIC LEVEL MODEL DISCUSSED ABOVE ARE INDICATED IN PARENTHESES. UTILIZING THE NUMERIC TROPHIC LEVEL ASSIGNMENT (TLA) CONCEPT DESCRIBED BY DR. ALAN MEARNS (1982) AND AT THIS CONFERENCE (PAPER 32D-11), I HAVE GIVEN THE FOLLOWING TLA VALUES TO THE COMPONENTS OF THE SALTON SEA FOOD WEB SAMPLED DURING 1967:

ORGANISM	TLA
CORVINA	4.5
CROAKER	3.5
SARGO	3.5
SHAD	3.0
PILE WORM	2.5
MULLET	2.0
ZOOPLANKTON	2.0
ALGAE	1.0

RADIOANAYSES

THE AVERAGE CONCENTRATION OF ^{137}CS (AND 95% CONFIDENCE INTERVAL BASED ON RADIOCOUNTING STATISTICS) IN THE LARGE WATER SAMPLES COLLECTED THROUGHOUT 1967 FROM THE FIVE SALTON SEA STATIONS IS ILLUSTRATED IN FIGURE 4. THESE DATA INDICATE THAT THERE WERE NO SIGNIFICANT SPATIAL ON TEMPORAL DIFFERENCES IN THE WATER CONCENTRATIONS OF ^{137}CS THAT WOULD PRECLUDE AVERAGING OVER SPACE OR TIME.

Figures 5-8 show the average concentrations (and 95% confidence intervals) of ^{137}Cs and K (obtained from ^{40}K values) in muscle tissue of mullet, sargo, croaker, and corvina, respectively. These values are based on four samples for each month that specimens were collected. Again, there was no evidence of significant spatial or temporal differences, despite the 20°C range in water temperature measured during 1967. Thus, for each sample class, all of the cesium, potassium, and cesium/potassium values obtained from these radioanalyses were averaged for the year (Table 2).

To determine the relation between cesium and potassium concentrations in white muscle tissue and in the whole fish, I radioassayed six samples of whole Salton Sea croaker. I used three fish per sample, and each fish was selected randomly from a different seasonal catch. The average $^{137}Cs/K$ ratio (7.8 pCi/g) was similar to that for croaker muscle tissue (9.1 pCi/g), indicating that the Cs/K ratios obtained for fish muscle are representative of the corresponding whole body ratios.

ELEMENTAL ALKALI METAL ANALYSES

THE CONCENTRATIONS OF ELEMENTAL CESIUM, RUBIDIUM, AND POTASSIUM OBTAINED FOR THE MONTHLY COLLECTIONS OF WATER ARE ILLUSTRATED IN FIGURE 9. ONE-WAY ANALYSES OF VARIANCE (BASED ON THREE SAMPLES FROM EACH OF THE FIVE STATIONS) SHOWED NO SIGNIFICANT DIFFERENCES BETWEEN THE YEARLY STATION AVERAGES FOR ANY OF THE ALKALI METALS. I PROCESSED REPLICATE BLANK SAMPLES WITH NEARLY EVERY SET OF CESIUM AND RUBIDIUM SAMPLES. THE UNCERTAINTIES ASSOCIATED WITH THE RESULTANT BLANK CORRECTIONS WAS ONLY 2-4% OF THE NET CONCENTRATIONS OBSERVED.

THE ALGAE MAT, ZOOPLANKTON, AND PILE WORM SAMPLES WERE CONTAMINATED TO VARYING DEGREES BY BOTTOM SEDIMENTS THAT CONTAINED RELATIVELY HIGH CONCENTRATIONS OF CESIUM. THUS, A DEIONIZED WATER LEACHING TECHNIQUE WAS EMPLOYED WHICH RECOVERED INSIGNIFICANT QUANTITIES OF THE INORGANICALLY BOUND ALKALIES (YOUNG, 1970). COMPARISON OF THE TWO EXTRACTION TECHNIQUES ON FISH MUSCLE SAMPLES UNCONTAMINATED BY SEDIMENTS INDICATED OVERALL EXTRACTION AND RECOVERY VALUES FOR CESIUM AND POTASSIUM IN ORGANIC MATERIAL OF 42 ± 8% AND 68 ± 4%, RESPECTIVELY. ALTHOUGH THE TOTAL CESIUM RECOVERY VALUE FOR THIS LEACHING TECHNIQUE WAS ONLY ABOUT HALF THAT FOR THE WET ASHING TECHNIQUE (88%), THIS METHOD HAD THE DISTINCT ADVANTAGE THAT LESS THAN 0.01 UG OF CESIUM AND 1 MG OF POTASSIUM WERE WASHED FROM A GRAM OF SALTON SEA SEDIMENT. THIS WAS A VERY SIGNIFICANT REDUCTION FROM THE LEVELS OF 2-4 UG CESIUM AND 6-24 MG OF POTASSIUM OBTAINED PER GRAM FROM AVERAGE SEDIMENTARY MATERIAL BY ACID DISSOLUTION (SREEKUMARAN ET AL., 1968). BECAUSE THE ASH-FREE DRY WEIGHT IS A BETTER MEASURE OF ORGANIC MATERIAL THAN IS WET WEIGHT OR DRY WEIGHT IN WHOLE INVERTEBRATE SAMPLES, VALUES FOR THESE SAMPLES WERE CALCULATED ON THE FORMER BASIS.

THE CONCENTRATIONS OF ELEMENTAL CESIUM, RUBIDIUM, AND POTASSIUM WERE MEASURED IN BI-MONTHLY SAMPLES OF WHITE MUSCLE FROM MULLET, SHAD, SARGO, CROAKER, AND CORVINA. EACH SAMPLE WAS A COMPOSITE OF TISSUE FROM THREE OR MORE SPECIMENS. IN MOST OF THE SAMPLES THE SIGNAL PEAKS BY FLAME PHOTOMETRY WERE COMPARED TO EXTERNAL STANDARDS FOR CESIUM AND RUBIDIUM. YIELD TESTS WITH SPIKES OF CS AND RB STANDARD SOLUTIONS REVEALED THAT THE FOUR SPECIES TESTED HAD SIMILAR EFFICIENCIES OF RECOVERY FOR BOTH ELEMENTS, AVERAGING 88 ± 2.0% AND 77 ± 1.9%, RESPECTIVELY. ALL POTASSIUM VALUES WERE OBTAINED BY THE METHOD OF STANDARD ADDITION. BLANK CORRECTIONS FOR POTASSIUM AND RUBIDIUM CONCENTRATIONS IN THE FISH SAMPLES WERE LESS THAN 1% AND 1%-2% RESPECTIVELY OF THE NET VALUES. THE AVERAGE CESIUM BLANK WAS 0.17 UG/SAMPLE (GENERALLY ABOUT 20 GRAMS OF WET TISSUE PER CESIUM ALIQUANT). THUS, THE AVERAGE CORRECTION FOR CESIUM BLANK RANGED FROM ABOUT 25% OF THE NET MULLET CONCENTRATIONS TO ABOUT 4% OF THE CORVINA VALUES. TABLE 3 LISTS THE AVERAGE NET CONCENTRATIONS OF THE THREE ALKALI METALS, AND CS/K RATIO, IN MUSCLE TISSUE OF THE SALTON SEA FISHES, AND THE CS/K RATIOS OBTAINED FROM THE CONCENTRATIONS MEASURED IN THE WHOLE INVERTEBRATE SAMPLES ON AN ASH-FREE DRY WEIGHT BASIS. (ALL VALUES ARE CORRECTED FOR BLANKS AND FOR RECOVERY EFFICIENCIES). CORRESPONDING PREDITOR/-PREY INCREASE RATIOS FOR THE ELEMENTAL CS/K AVERAGE VALUES ARE SHOWN IN TABLE 4.

Trophic Level Increases

The average cesium and cesium/potassium values for the 1967 Salton Sea organisms obtained independently by radioanalysis (Table 2) and elemental analysis (Table 3) both clearly indicate distinct increases with the TLA value. The specific preditor/prey increase ratios for average Cs/K values (Table 4) have a median of 2.6, and three of the four values fall within the very narrow range of 2.2 to 2.7. These latter data are consistent with reports that cesium or the cesium/potassium ratio typically increases by a factor of 2-3 over one trophic level step, resulting from the fact that the biological half-life of the cesium generally is 2-3 times that of the essential (and, therefore, physiologically regulated) alkali metal potassium. In contrast, the rubidium concentrations did not increase systematically with trophic level, but (with the exception of the mullet values) appeared to follow those of potassium. Thus, the detailed 1967 investigation of cesium and potassium in the well-documented food web of the Salton Sea demonstrated the utility of Cs and Cs/K values in reflecting the existence of distinct trophic levels in marine food webs that could lead to the biomagnification of chemically and biologically persistent pollutants.

Exponential Biomagnification Model

The simplest case of biomagnification occurs when, within the range of trophic levels sampled, the concentration (C_N) of a constituent in an organism at a given trophic level (N) is multiplied by a constant amplification factor (A.F.) to obtain the concentration

AT THE NEXT HIGHEST TROPHIC LEVEL (N+1). AS SHOWN BELOW, A LINEAR RELATIONSHIP OF THE FORM

$$\ln C_N = M\,(TLA)_N + B$$

CORRESPONDS TO THE CASE OF A CONSTANT TISSUE CONCENTRATION AMPLIFICATION FACTOR PER UNIT TROPHIC LEVEL STEP, WHOSE VALUE IS GIVEN BY THE EXPRESSION e^M :

$$A.F. \equiv \frac{C_{N+1}}{C_N}$$

$$= \frac{e^{M\,(TLA)_{N+1}}\ \cancel{e^B}}{e^{M\,(TLA)_N}\ \cancel{e^B}}$$

$$= e^{\left[M\,(TLA)_{N+1} - (TLA)_N\right]}$$

BUT FOR A UNIT TROPHIC LEVEL STEP:

$$(TLA)_{N+1} - (TLA)_N = 1$$

THUS: $$A.F. = e^M$$

TO DETERMINE IF A SET OF CONCENTRATION DATA C_N FIT THIS CONCEPTUALLY- SIMPLEST MODEL, A STATISTICALLY SIGNIFICANT ($P < 0.05$) LINEAR REGRESSION IS SOUGHT BETWEEN

$\ln C_N$ AND $(TLA)_N$:

$$\ln C_N = M\,(TLA)_N + B$$

DISPROVING THE NULL HYPOTHESIS (HO) THAT THERE IS NO REGRESSION (HO: THE REGRESSION COEFFICIENT M EQUALS ZERO) ENABLES THE AVERAGE AMPLIFICATION FACTOR PER UNIT TROPHIC LEVEL STEP (A.F.) TO BE OBTAINED DIRECTLY FROM THE EXPRESSION e^M.

APPLICATION OF THE MODEL

FIGURE 10 ILLUSTRATES THE FITTING OF THE 1967 SALTON SEA CS/K DATA, OBTAINED FROM ELEMENTAL ANALYSIS, TO THE EXPONENTIAL BIOMAGNIFICATION

MODEL. THE LINEAR REGRESSION IS FOUND TO BE SIGNIFICANT ($P < 0.001$) WITH A REGRESSION COEFFICIENT $M = 0.86$, YIELDING AN AVERAGE AMPLIFICATION FACTOR A.F. OF 2.4, IN GOOD AGREEMENT WITH THE MEDIAN PREDITOR/PREY INCREASE RATIO OF 2.6 (TABLE 4). UTILIZATION OF THE ELEMENTAL CS/K DATA FOR FISH MUSCLE ONLY YIELDS A SIGNIFICANT FIT ($0.001 < P < 0.005$), WITH $M = 0.76$ AND AN A.F. VALUE OF 2.1. THE CORRESPONDING RESULT BASED ON THE RADIOANALYSES OF THE FISH MUSCLE SAMPLES (FIGURE 11) ALSO IS SIGNIFICANT ($0.01 < P < 0.025$), WITH $M = 0.63$ AND AN A.F. = 1.9. IN THIS CASE, TO MAKE THE DATA AS COMPARABLE AS POSSIBLE, I SIMPLY USED THE MONTH'S AVERAGE OF THE FOUR INDIVIDUAL $^{137}Cs/K$ VALUES FOR EACH SPECIES COLLECTED DURING THE SEVEN MONTHS (MAY-NOVEMBER) IN WHICH SPECIMENS OF ALL FOUR FISH SPECIES WERE OBTAINED. THUS, THE AMPLIFICATION FACTORS OBTAINED FROM THE ELEMENTAL AND RADIOISOTOPIC ANALYSES OF THE FISH SAMPLES ALONE AGREE WITHIN 10%. THIS CLOSE AGREEMENT BETWEEN THE RESULTS OF THE TWO INDEPENDENT METHODS INCREASES THE CONFIDENCE IN THE CHEMICAL ANALYSES ON WHICH THE CONCLUSIONS OF THIS STUDY ARE BASED.

FIGURE 12 ILLUSTRATES THE RESULTS OF ASSUMING THAT THE FISHES SAMPLED FROM THE SALTON SEA IN 1978 HAD THE SAME TLA VALUES AS THEY DID ELEVEN YEARS EARLIER (AND SUBSTITUTING MOLLIES FOR MULLET). ALTHOUGH THE LINEAR REGRESSION IS SIGNIFICANT ($0.02 < P < 0.05$), CONSIDERABLY LOWER VALUES FOR THE REGRESSION COEFFICINT AND THE CORRESPONDING AMPLIFICATION FACTOR ARE OBTAINED:

$$M = 0.36; \quad A.F. = 1.4$$

THIS SUGGESTS THAT A SUBSTANTIAL REDUCTION IN THE "STRUCTURE" OF THE SALTON SEA FOOD WEB OCCURRED BETWEEN 1967 AND 1978. THE HYPOTHESIS IS SUPPORTED BY RESULTS OF AN ECOLOGICAL SURVEY OF THE SEA CONDUCTED during 1978 by the California Department of Fish and Game (Glen Black, personal communication). Their study revealed that over this time interval two euryhaline fishes, the sailfin molly (*Poecilia latipinna*) and a tilapia (*Tilapia sp.*), had migrated from the adjacent freshwater canals and established large populations in the Sea. These fishes apparently feed mainly on algae, and thus would have TLA values near 2. Further, tilapia had become the principal food of the corvina, which is consistent with the large decrease observed in the average Cs/K ratio for corvina muscle (58 to 33 ug/g). The data of Figure 12 show that the predator/prey ratio for the corvina/molly pair is 33/14 = 2.4, consistent with the findings of the varied studies discussed above.

The concentrations of total DDT, measured on a wet weight basis in specimens collected during the 1967 survey, are plotted against Trophic Level Assignment values in Figure 13. However, the mullet data are an order of magnitude above those for the other fishes and therefore were not included in the regression analysis. The mean square for deviations from regression (Sokal and Rohlf, 1981) still is significant ($0.01 < p < 0.025$), exemplified by the degree to which the sargo and croaker deviate (in opposite directions) from the line showing the values predicted by this model. Nevertheless, the mean square for regression also is significant ($0.01 < p < 0.025$), yielding a regression coefficient $m = 0.92$ and an average amplification factor A.F. = 2.5.

To determine if a better fit to the exponential biomagnification model could be obtained, the total DDT values were normalized to a lipid weight basis and replotted against TLA (Figure 14). Although

THE MULLET DATA STILL ARE ANOMALOUSLS HIGH AND THUS AGAIN WERE EXCLUDED FROM THE REGRESSION, NORMALIZATION OF THE DDT CONCENTRATIONS TO LIPID WEIGHT REDUCES THE DISCREPANCY BETWEEN THE MULLETS' MEAN CONCENTRATION AND THE VALUE PREDICTED USING THE REMAINING DATA, FROM TWO ORDERS OF MAGNITUDE (4.2 VS. 0.035 MG/KG WET WT) TO ONE ORDER OF MAGNITUDE (22 VS. 2.8 MG/KG LIPID WT). LIPID NORMALIZATION ALSO YIELDS A MUCH BETTER FIT OF THE SARGO AND CROAKER DATA TO THE EXPONENTIAL MODEL, AND THERE IS NO LONGER A SIGNIFICANT MEAN SQUARE FOR DEVIATION FROM REGRESSION. NORMALIZATION TO LIPID WEIGHT ($M = 0.60$) RATHER THAN WET WEIGHT ($M = 0.92$) REDUCES THE AVERAGE AMPLIFICATION FACTOR PER UNIT TROPHIC LEVEL STEP FROM 2.5 TO 1.8. THIS SUGGESTS THAT SOME OF THE INCREASE OF THE LIPOPHILIC DDT RESIDUES WITH TROPHIC LEVEL RESULTS SIMPLY FROM TROPHIC LEVEL INCREASES OF LIPID CONCENTRATIONS, AND POSSIBLY DIRECT UPTAKE FROM WATER RATHER THAN FOOD. MACEK ET AL. (1979) HAVE UTILIZED THE TERM "BIOCONCENTRATION" TO APPLY TO SUCH A DIRECT UPTAKE PROCESS, AND DISTINGUISHED IT FROM THE TERM "BIOMAGNIFICATION" WHICH APPLIES ONLY TO UPTAKE FROM (AND CONCENTRATION OVER) DIETARY CONTENT (YOUNG, 1984). HOWEVER, THE FACT THAT THERE IS STILL A SIGNIFICANT REGRESSION OF TOTAL DDT CONCENTRATION, ON A LIPID WEIGHT BASIS, WITH TLA, AND AN AVERAGE AMPLIFICATION FACTOR OF 1.8, INDICATES THAT MOST OF THE TROPHIC LEVEL INCREASE OF THIS POLLUTANT OBSERVED ON A WET WEIGHT BASIS IS DUE TO BIOMAGNIFICATION, I.E., THE FEEDING PROCESS.

FIGURE 15 PRESENTS THE RESULTS OF THE TOTAL DDT ANALYSES (ON A LIPID WEIGHT BASIS) IN THE FISHES COLLECTED FROM THE SALTON SEA IN FEBRUARY 1978. IN THIS CASE THERE IS ONLY A TREND TOWARDS A FIT TO THE MODEL ($0.10 < P < 0.05$); WERE THE REGRESSION TO BE SIGNIFICANT,

THE CORRESPONDING A.F. VALUE ON A LIPID WEIGHT BASIS WOULD BE 2.6 (SHOWN ONLY IN PARANTHESIS). THIS FAILURE TO SIGNIFICANTLY FIT THE EXPONENTIAL BIOMAGNIFICATION MODEL CORRELATES WITH THE REDUCED "STRUCTURE" OF THE 1978 SALTON SEA FOOD WEB AS INDICATED BY THE Cs/K DATA AND THE RESULTS OF THE CALIFORNIA DEPARTMENT OF FISH AND GAME ECOLOGICAL INVESTIGATION. ALTERNATE EXPLANATIONS ARE THAT THE LACK OF STATISTICAL SIGNIFICANCE RESULTS FROM LOWER PRECISION OF THE DATA OWING TO THE FEWER SAMPLES TAKEN, AND/OR LOWER DDT CONCENTRATIONS MEASURED IN THE 1978 SURVEY.

SUMMARY AND CONCLUSIONS

1. A YEAR-LONG STUDY OF THE SIMPLE AND WELL-DOCUMENTED FOOD WEB IN THE SALTON SEA DEMONSTRATED THAT THE Cs/K RATIO IS A RELIABLE INDICATOR OF TROPHIC LEVEL DIFFERENCES IN MARINE ORGANISMS. UTILIZING INDEPENDENT RADIOISOTOPIC AND ELEMENTAL ANALYSIS TECHNIQUES IN THIS HIGHLY-STRUCTURED FOOD WEB, THE CONCENTRATION OF CESIUM AND THE Cs/K RATIO WERE SHOWN TO INCREASE 2-3 FOLD PER UNIT TROPHIC LEVEL STEP, AS PREDICTED BY THE RELATIVE BIOLOGICAL HALF-LIVES FOR THESE ALKALI METALS AND NUMEROUS PREVIOUS OBSERVATIONS IN TERRESTRIAL AND FRESH-WATER FOOD CHAINS.

2. IN CONTRAST, NO TROPHIC LEVEL INCREASES OCCURRED FOR RUBIDIUM CONCENTRATIONS, WHICH GENERALLY FOLLOWED THOSE OF POTASSIUM.

3. THERE WAS NO DETECTABLE EFFECT OF A 20°C ANNUAL VARIATION IN WATER TEMPERATURE ON FISH MUSCLE TISSUE CONCENTRATIONS OF POTASSIUM, RUBIDIUM, OR CESIUM.

4. A CONCEPTUALLY SIMPLE BIOMAGNIFICATION MODEL, BASED ON THE ASSUMPTION OF A CONSTANT TISSUE CONCENTRATION AMPLIFICATION FACTOR PER UNIT TROPHIC LEVEL STEP, ADEQUATELY EXPLAINS THE Cs/K DATA. THE TEST FOR A FIT OF A DATA SET TO THIS MODEL IS A SIGNIFICANT LINEAR REGRESSION OF THE FORM:

$$\text{LN (CONCENTRATION)} = M\,(\text{TLA}) + B$$

WHERE THE TROPHIC LEVEL ASSESSMENT (TLA) IS A NUMERIC ESTIMATE OF FOOD WEB POSITION.

5. APPLICATION OF THIS CHEMICAL PROCEDURE IN A SINGLE RE-SURVEY OF THE SALTON SEA ECOSYSTEM ELEVEN YEARS LATER INDICATED SIGNIFICANT BUT SUBSTANTIALLY REDUCED STRUCTURE IN THE FOOD WEB THERE. THIS SUBSEQUENTLY WAS CONFIRMED BY A CALIFORNIA DEPARTMENT OF FISH AND GAME ECOLOGICAL INVESTIGATION.

6. THE EXISTENCE OF SIGNIFICANT STRUCTURE, OR BIOMAGNIFICATION POTENTIAL, IN THE 1967 SALTON SEA FOOD WEB DEMONSTRATED BY THIS STUDY WAS EXEMPLIFIED BY THE RESULTS FOR TOTAL DDT. WITH THE EXCEPTION OF ONE ORGANISM (MULLET), TISSUE CONCENTRATIONS ON A WET WEIGHT BASIS FIT THE EXPONENTIAL BIOMAGNIFICATION MODEL, WITH AN AVERAGE AMPLIFICATION FACTOR PER UNIT TROPHIC LEVEL STEP OF 2.5. NORMALIZATION TO LIPID WEIGHT SUBSTANTIALLY IMPROVED THE FIT, AND THE CORRESPONDING AMPLIFICATION FACTS WAS 1.8. THIS SHOWED THAT THE MAJORITY OF THE INCREASE IN DDT CONCENTRATION WITH TROPHIC LEVEL WAS CONSISTENT WITH THE HYPOTHESIS OF DDT BIOMAGNIFICATION, AND WAS NOT DUE MERELY TO CORRESPONDING INCREASES IN LIPID CONCENTRATIONS.

7. ALTHOUGH BIOMAGNIFICATION MAY RESULT IN SUBSTANTIAL INCREASES IN TISSUE CONCENTRATIONS OF DDT RESIDUES, THE 1967 RESULTS FOR THE MULLET SPECIMENS, EVEN ON A LIPID WEIGHT BASIS, INDICATE THAT FACTORS OTHER THAN TROPHIC LEVEL CAN BE MUCH MORE IMPORTANT IN CAUSING HIGH MUSCLE TISSUE CONCENTRATIONS OF THIS POLLUTANT.

8. THE 1978 RESURVEY OF THE SALTON SEA FOOD WEB FAILED TO YIELD A SIGNIFICANT FIT OF THE TOTAL DDT CONCENTRATIONS TO THE EXPONENTIAL BIOMAGNIFICATION MODEL. THIS MAY BE A RESULT, AT LEAST IN PART, OF THE REDUCED STRUCTURE OF THIS FOOD WEB IN 1978, DEMONSTRATED BOTH BY THE INDEPENDENT ECOLOGICAL SURVEY AND BY THE CS/K DATA REPORTED HERE.

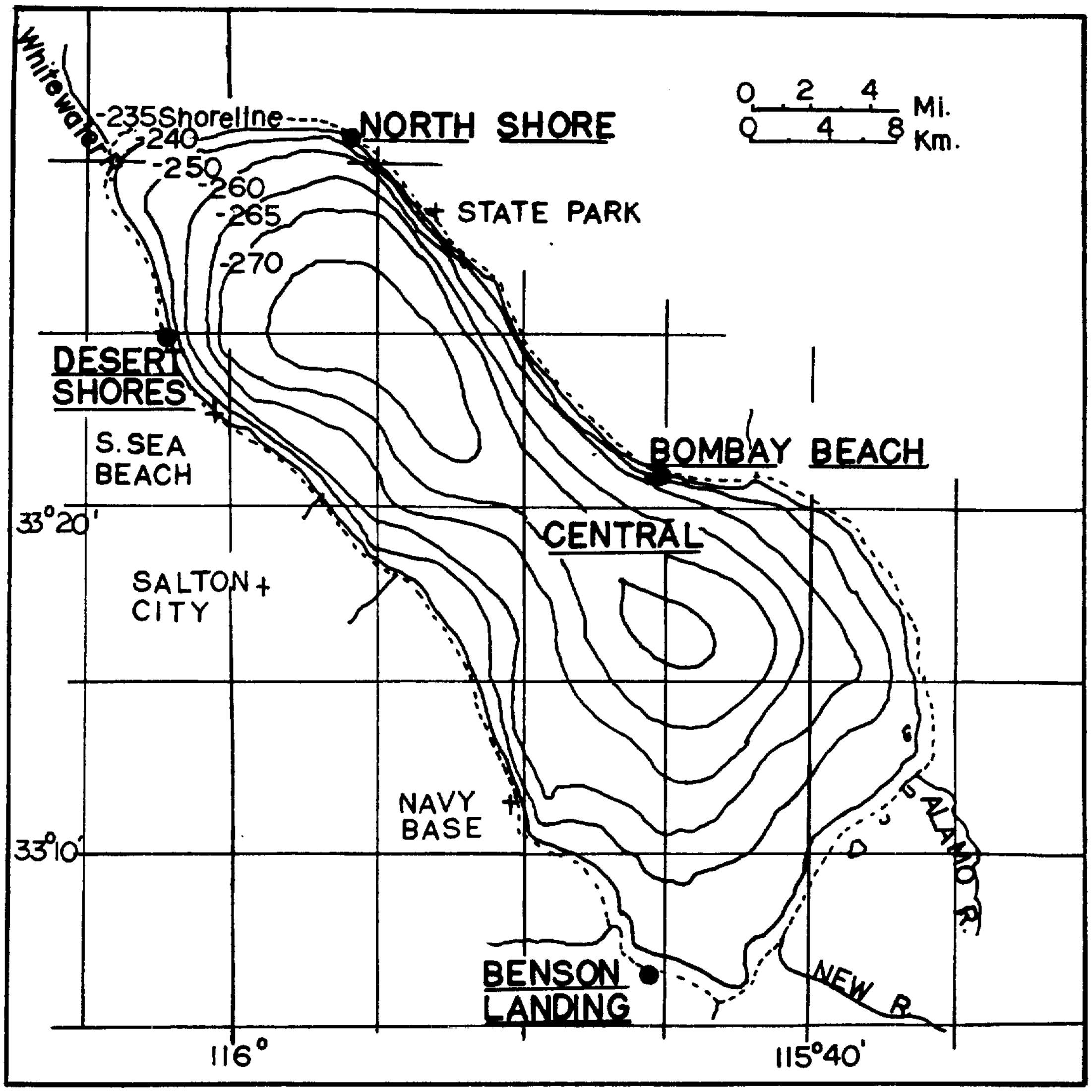

FIG. 1. SALTON SEA, CALIFORNIA, STUDY AREA.

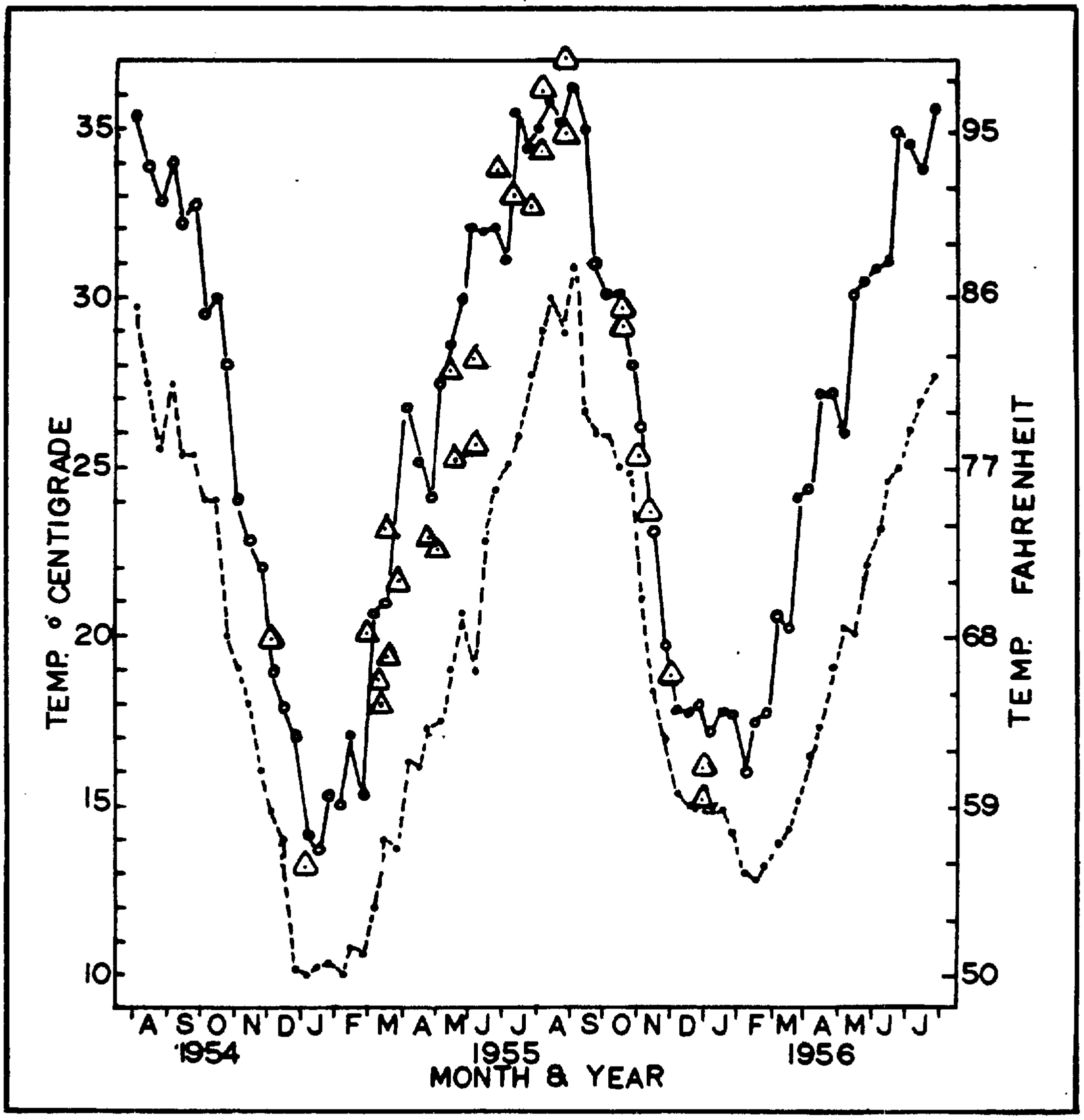

FIG. 2. SALTON SEA SURFACE AND BOTTOM (3 METERS) WATER TEMPERATURES. LINES INDICATE 1954-1956 DATA. TRIANGLES INDICATE 1967 DATA.

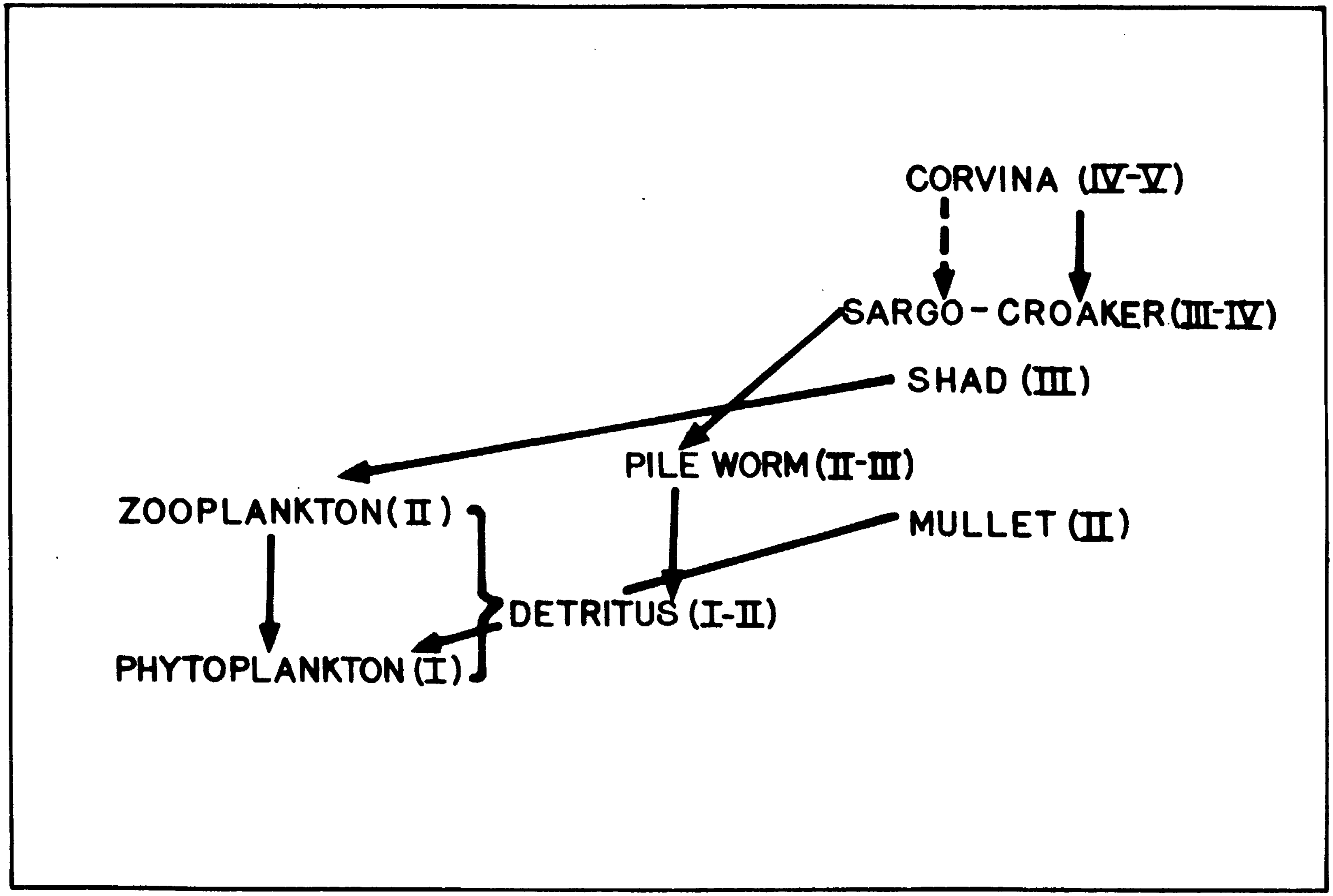

FIG. 3. PRINCIPAL FEEDING RELATIONSHIPS (AND AVERAGE TROPHIC LEVELS) OF MAJOR COMPONENTS IN SALTON SEA FOOD WEB, 1967.

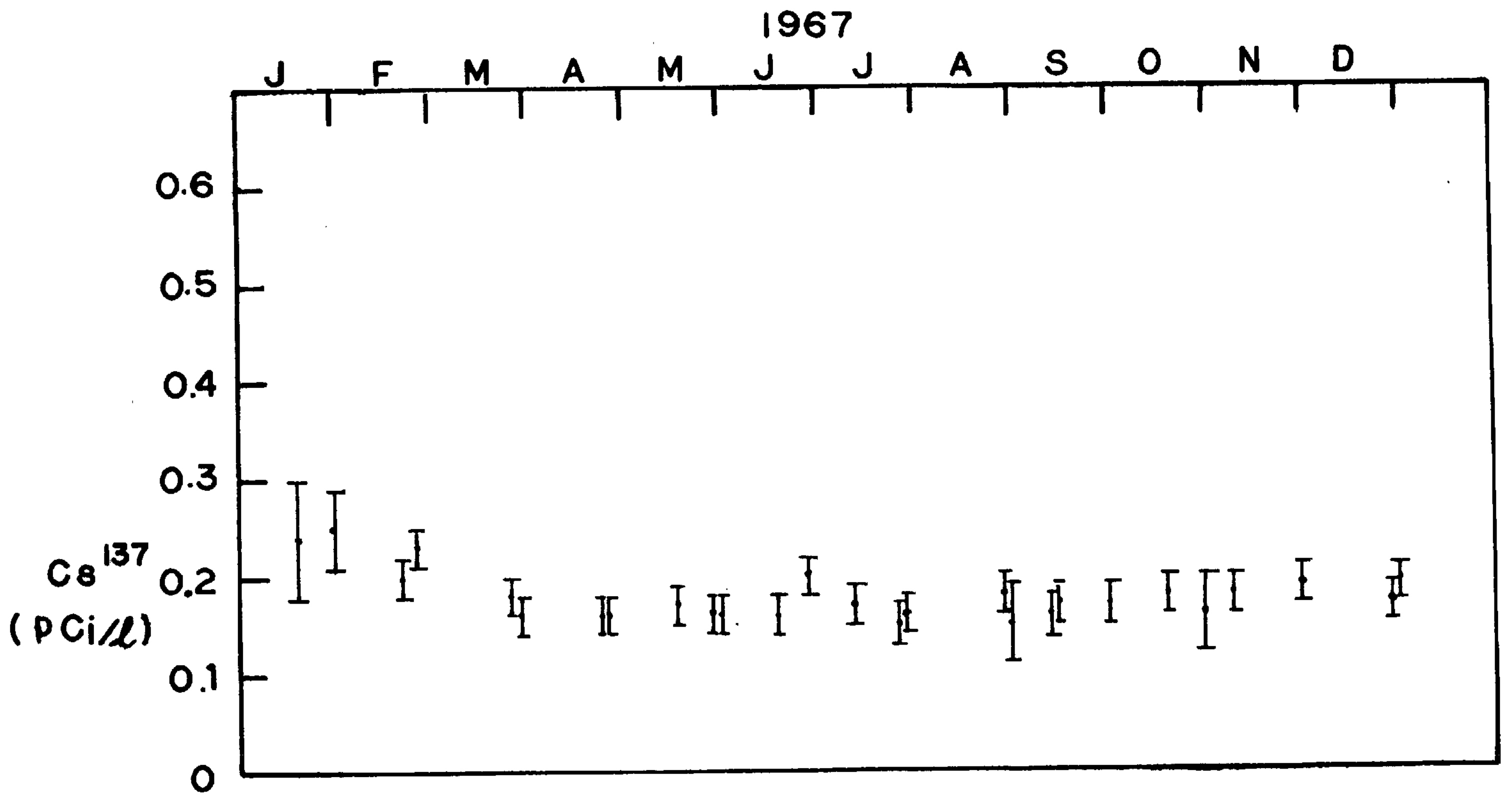

FIG. 4. SALTON SEA SURFACE WATER CONCENTRATIONS OF ^{137}Cs (pCi/LITER ± 2S), 1967.

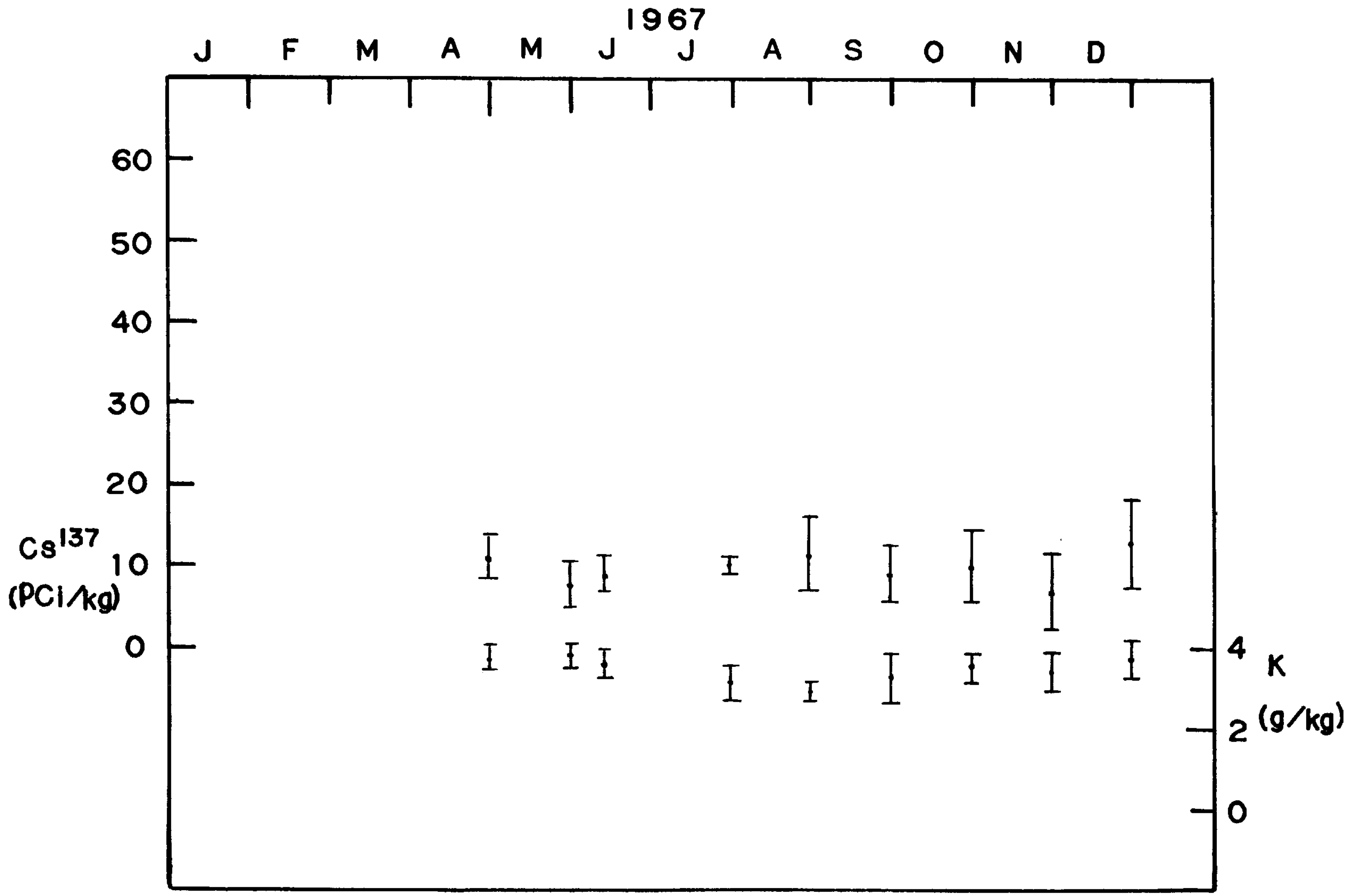

FIG. 5. MONTHLY AVERAGE CONCENTRATIONS (AND 95% C.I.; N = 4), OF ^{137}CS (PCI/KG) AND K (G/KG) IN WET MUSCLE TISSUE OF SALTON SEA MULLET, 1967.

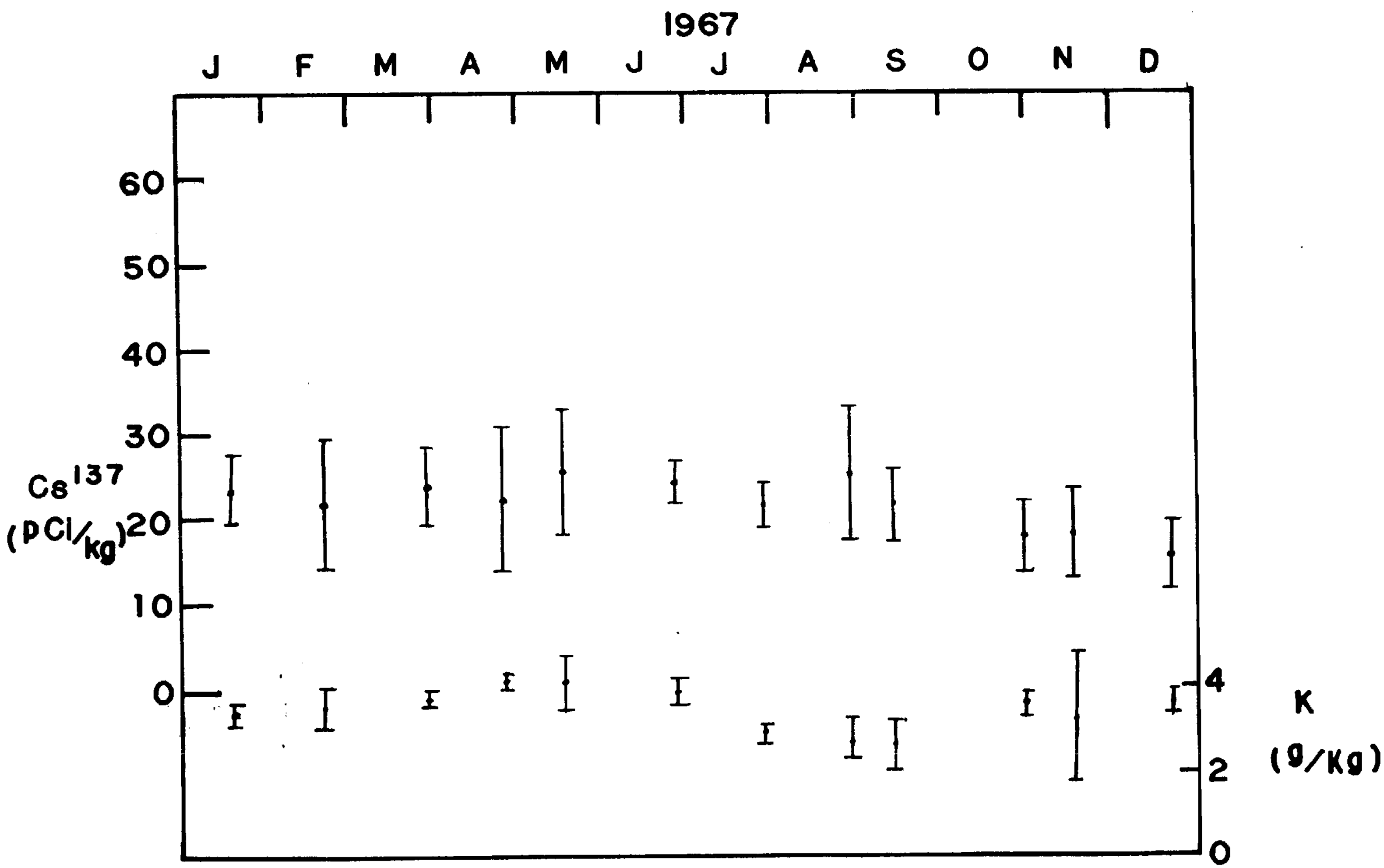

FIG. 6. MONTHLY AVERAGE CONCENTRATIONS (AND 95% C.I.; N = 4), OF ^{137}Cs (pCi/kg) AND K (g/kg) IN WET MUSCLE TISSUE OF SALTON SEA SARGO, 1967.

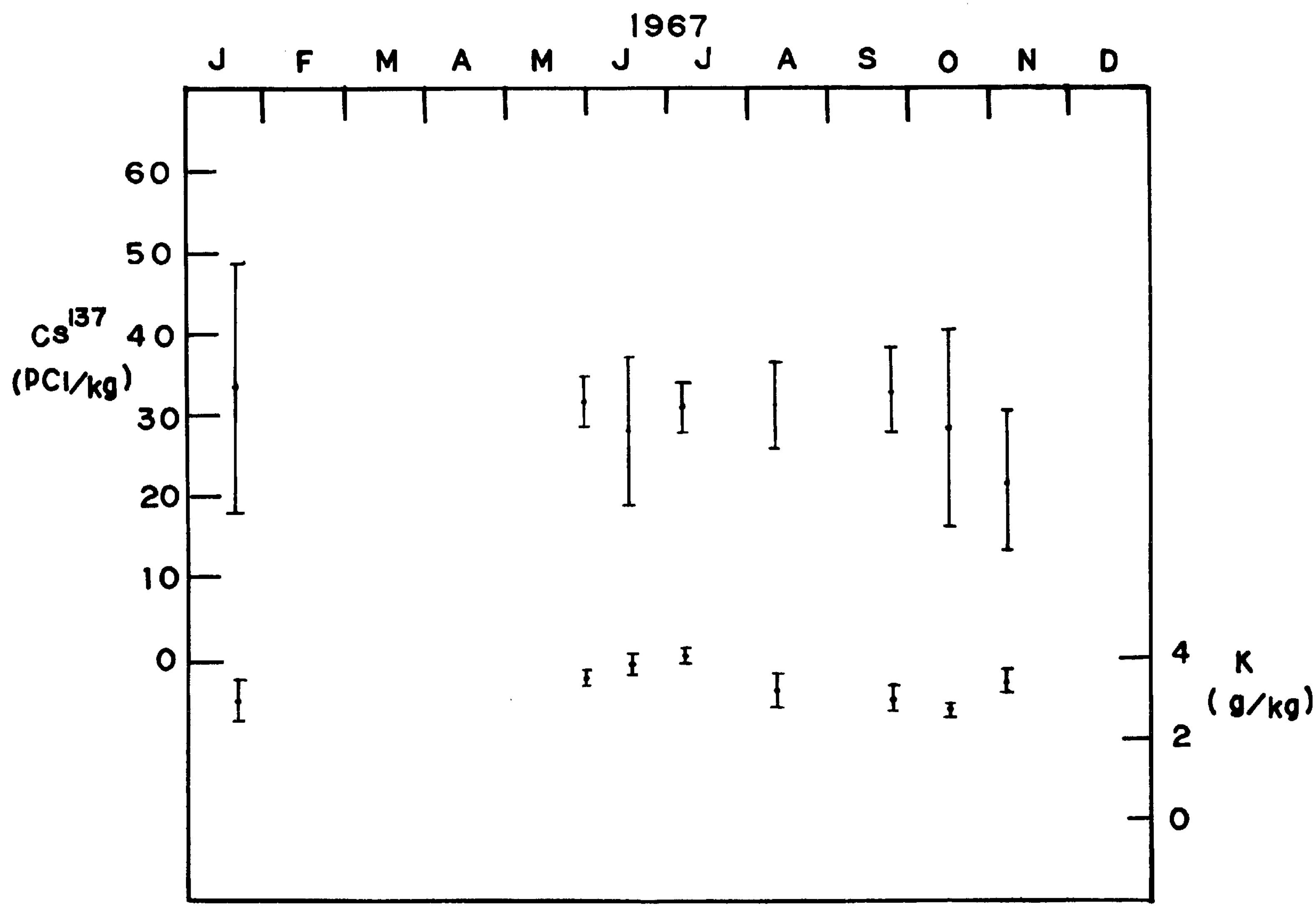

FIG. 7. MONTHLY AVERAGE CONCENTRATIONS (AND 95% C.I.; N = 4), OF ^{137}CS (PCI/KG) AND K (G/KG) IN WET MUSCLE TISSUE OF SALTON SEA CROAKER, 1967.

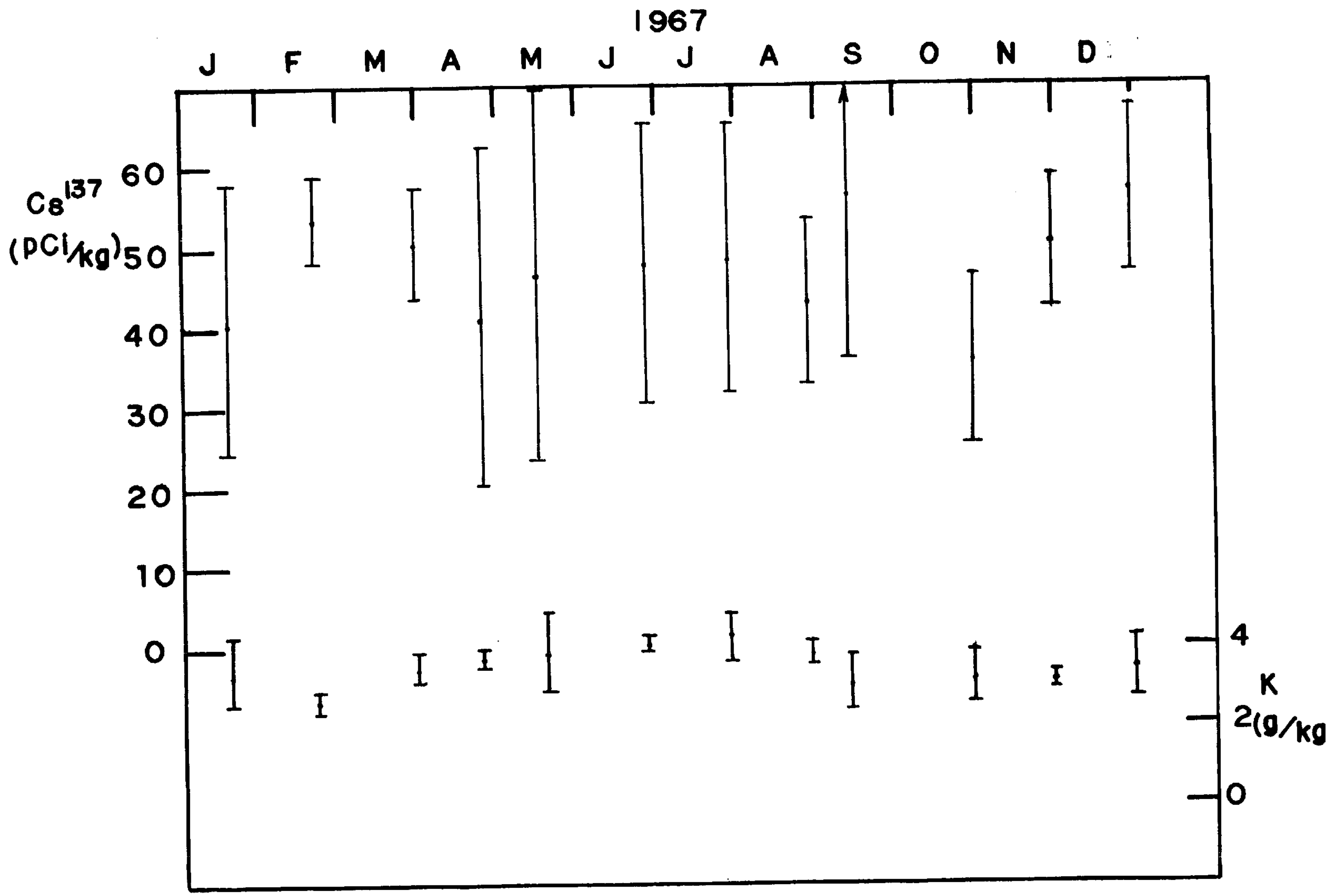

FIG. 8. MONTHLY AVERAGE CONCENTRATIONS (AND 95% C.I.; N = 4), OF ^{137}Cs (PCI/KG) AND K (G/KG) IN WET MUSCLE TISSUE OF SALTON SEA CORVINA, 1967.

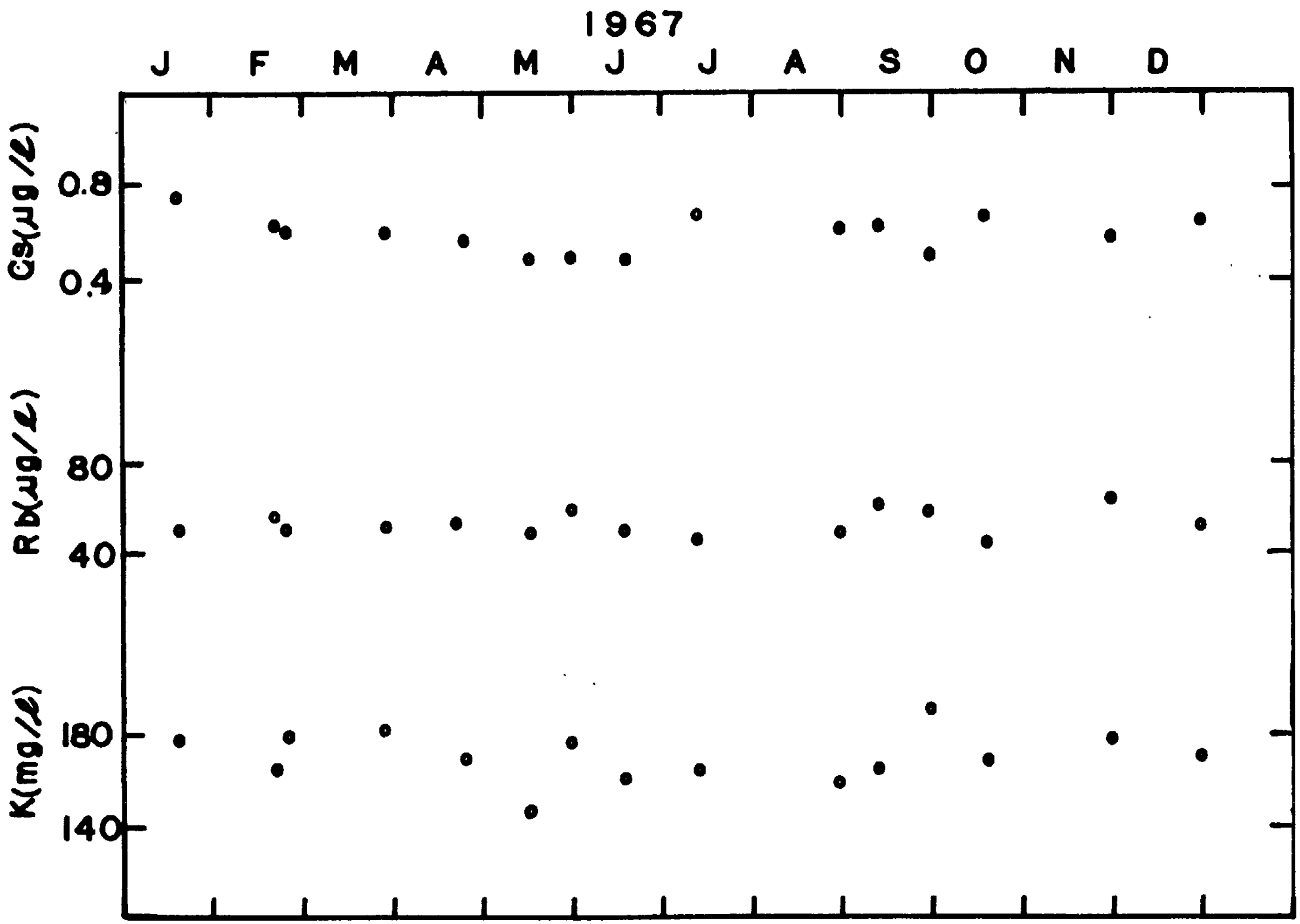

Fig. 9. Salton Sea surface water concentrations of cesium (ug/liter), rubidium (ug/liter), and potassium (mg/liter), 1967.

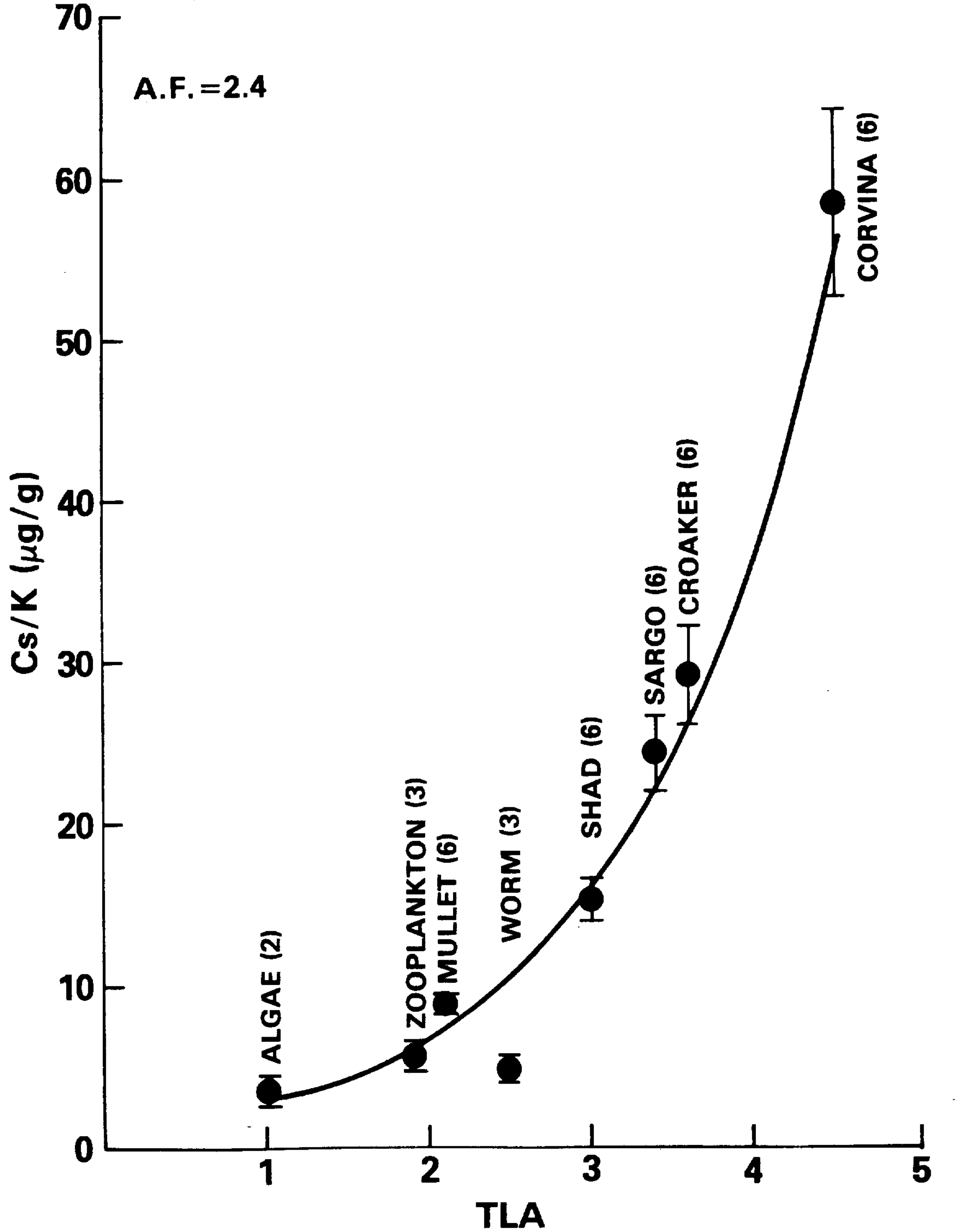

FIG. 10. AVERAGE Cs/K RATIO (±1 STD. ERROR; N SHOWN) IN 1967 SALTON SEA FOOD WEB COMPONENTS VS. TROPHIC LEVEL ASSIGNMENT, FROM ELEMENTAL ANALYSIS. LINE IS FROM LINEAR REGRESSION: LN (Cs/K) = 0.86 (TLA) + 0.17 ($P < 0.001$), YIELDING AVERAGE AMPLIFICATION FACTOR = 2.4.

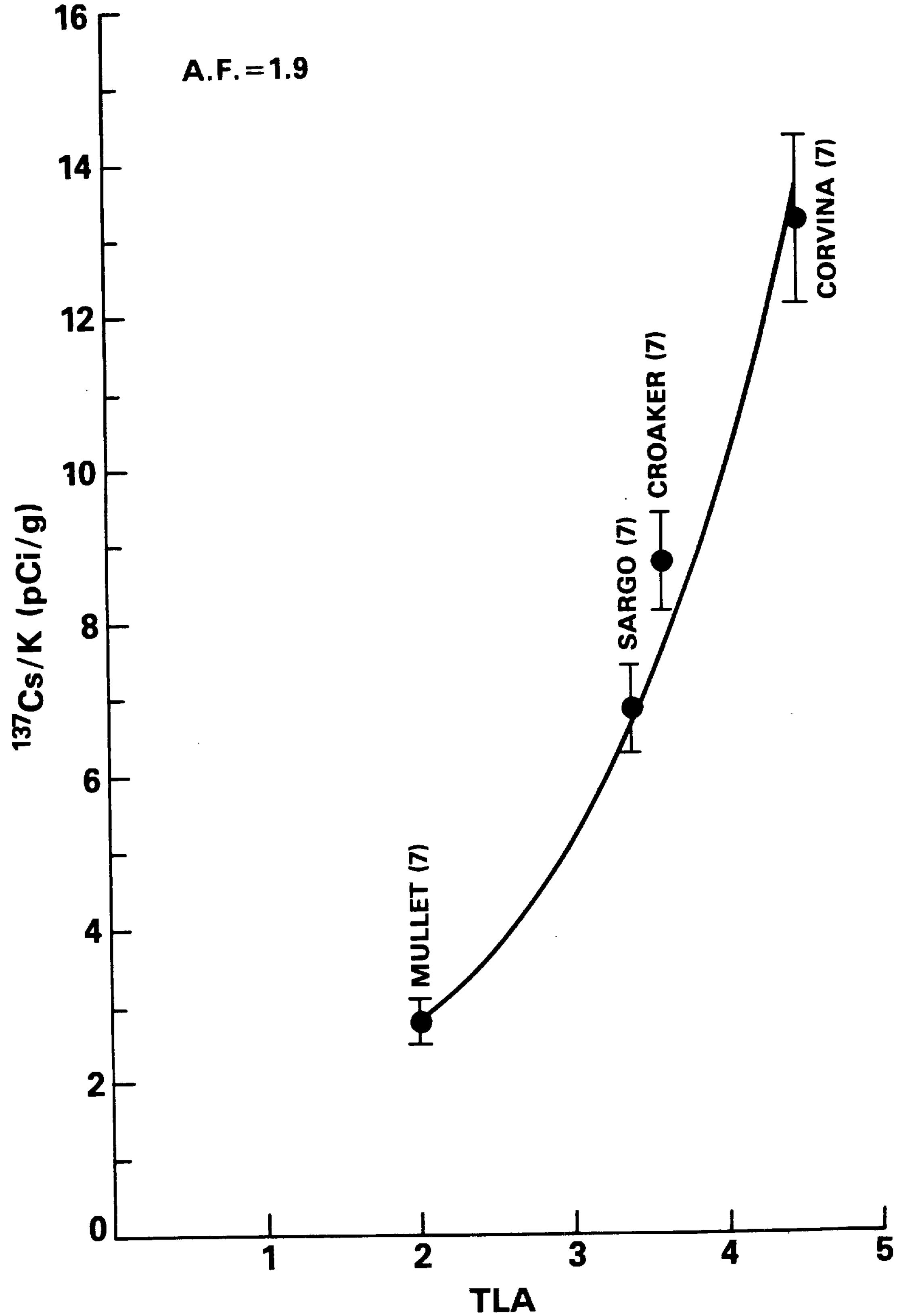

FIG. 11. AVERAGE ^{137}Cs/K RATIO (±1 STD. ERROR; N SHOWN) IN 1967 SALTON SEA FISH MUSCLE VS. TROPHIC LEVEL ASSIGNMENT, FROM RADIOANALYSIS. BASED ON MONTHLY MEANS FOR 7 MONTHS (MAY-NOV.). LINE IS FROM LINEAR REGRESSION:
LN (^{137}Cs/K) = 0.63 (TLA) - 0.24 ($0.01 < p < 0.025$), YIELDING AVERAGE AMPLIFICATION FACTOR = 1.9.

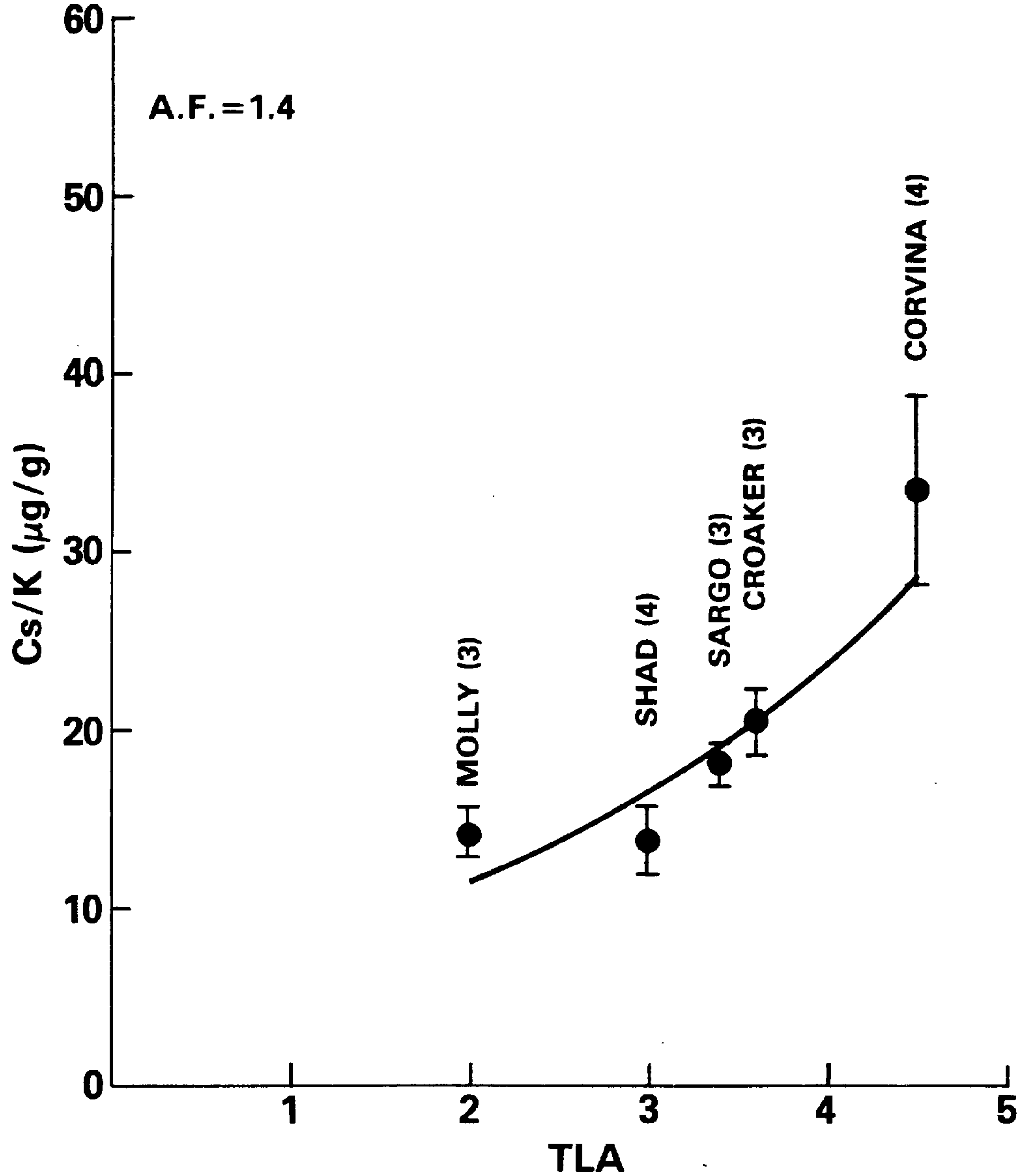

FIG. 12. AVERAGE Cs/K RATIO (±1 STD. ERROR; N SHOWN) IN 1978 SALTON SEA FISH MUSCLE VS. TROPHIC LEVEL ASSIGNMENT, FROM ELEMENTAL ANALYSIS. LINE IS FROM LINEAR REGRESSION: LN (Cs/K) = 0.36 (TLA) + 1.71 ($0.025 < p < 0.05$), YIELDING AVERAGE AMPLIFICATION FACTOR = 1.4.

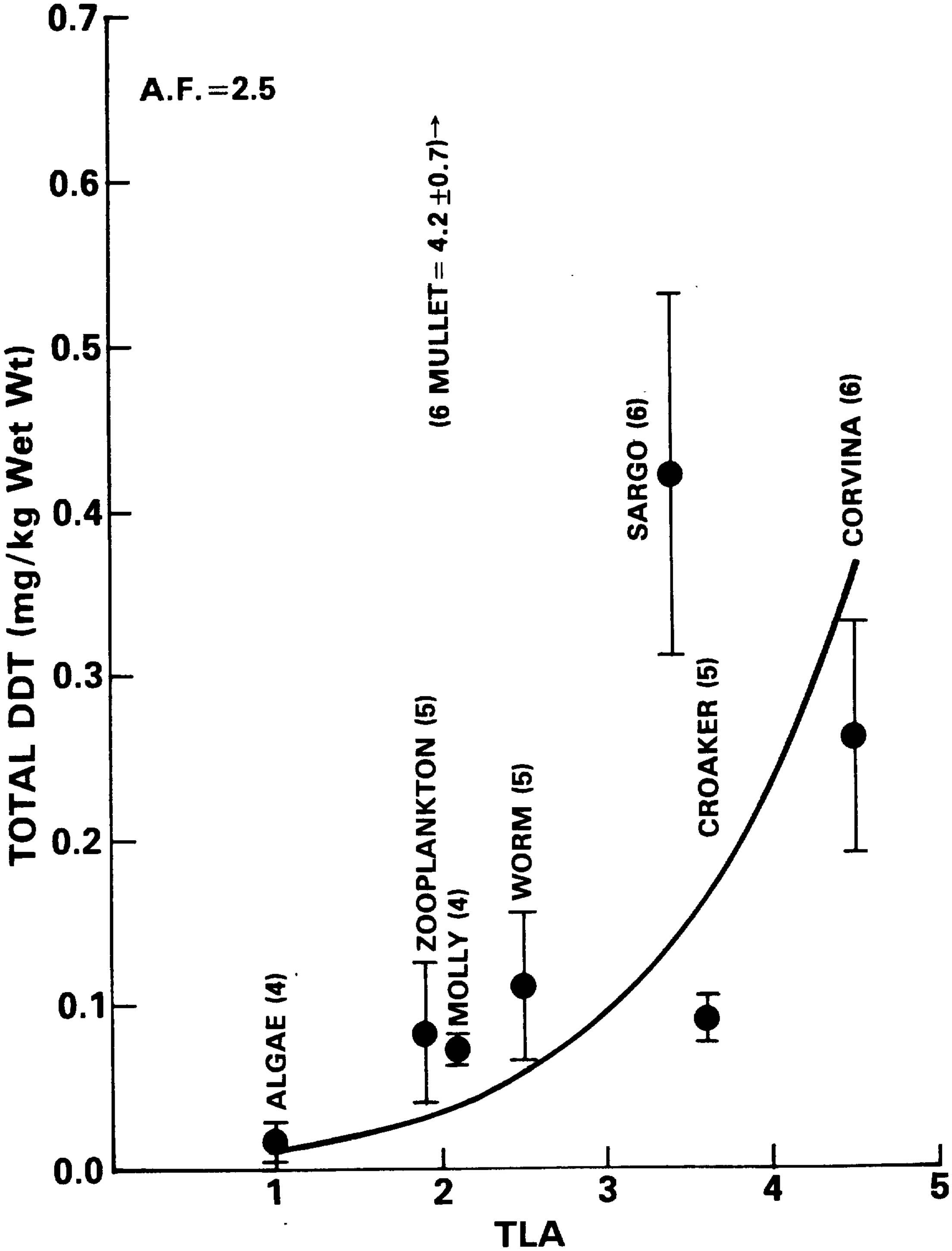

FIG. 13. AVERAGE TOTAL DDT CONCENTRATIONS (±1 STD. ERROR; N SHOWN) IN 1967 SALTON SEA FOOD WEB COMPONENTS VS. TROPHIC LEVEL ASSIGNMENT, WET WEIGHT BASIS. LINE IS FROM LINEAR REGRESSION (WITHOUT MULLET): LN (TOTAL DDT) = 0.92 (TLA) - 5.12 ($0.01 < P < 0.025$), YIELDING AVERAGE AMPLIFICATION FACTOR = 2.5.

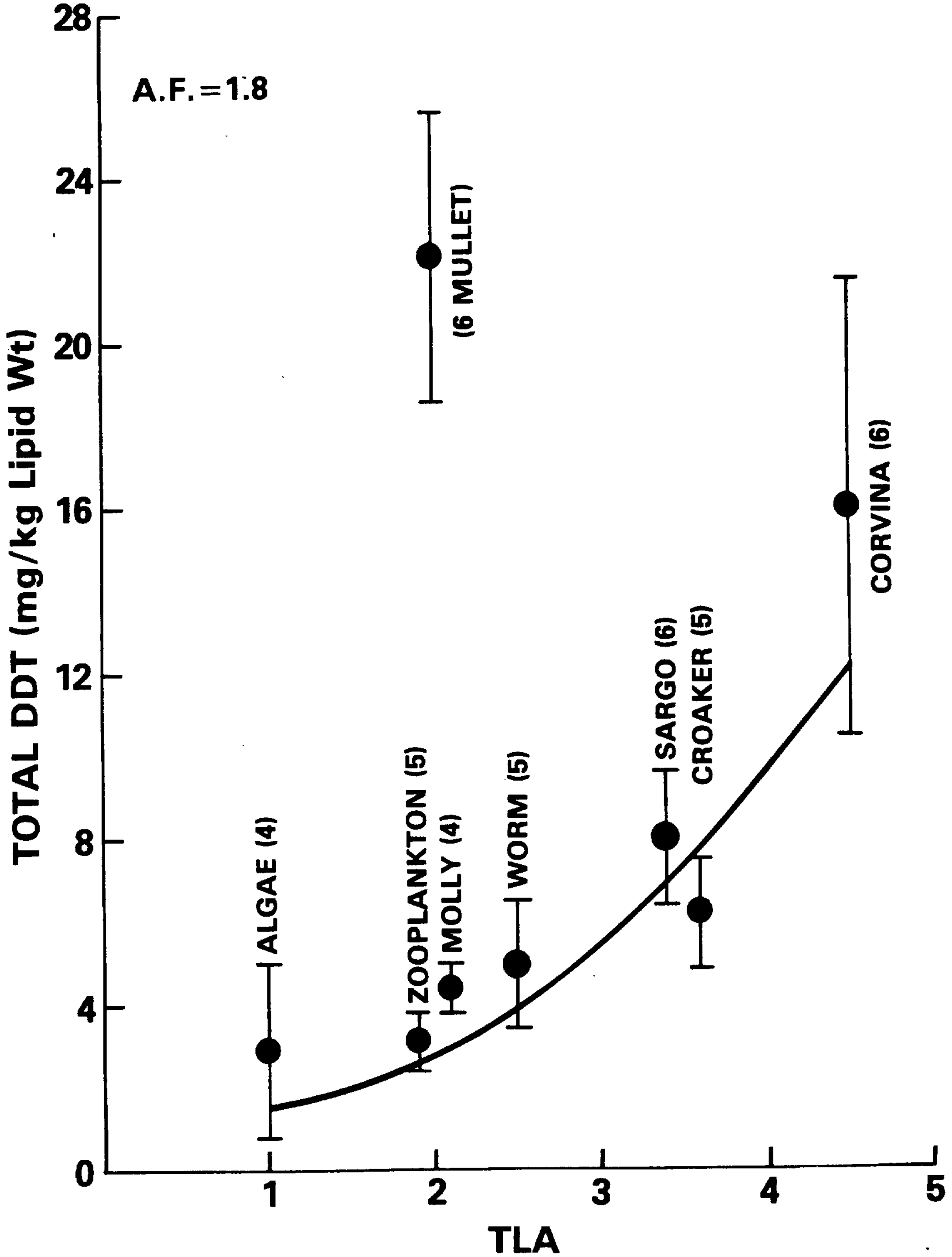

FIG. 14. AVERAGE TOTAL DDT CONCENTRATIONS (±1 STD. ERROR; N SHOWN) IN 1967 SALTON SEA FOOD WEB COMPONENTS VS. TROPHIC LEVEL ASSIGNMENT, LIPID WEIGHT BASIS. LINE IS FROM LINEAR REGRESSION (WITHOUT MULLET): LN (TOTAL DDT) = 0.61 (TLA) - 0.18 ($p < 0.001$), YIELDING AVERAGE AMPLIFICATION FACTOR = 1.8.

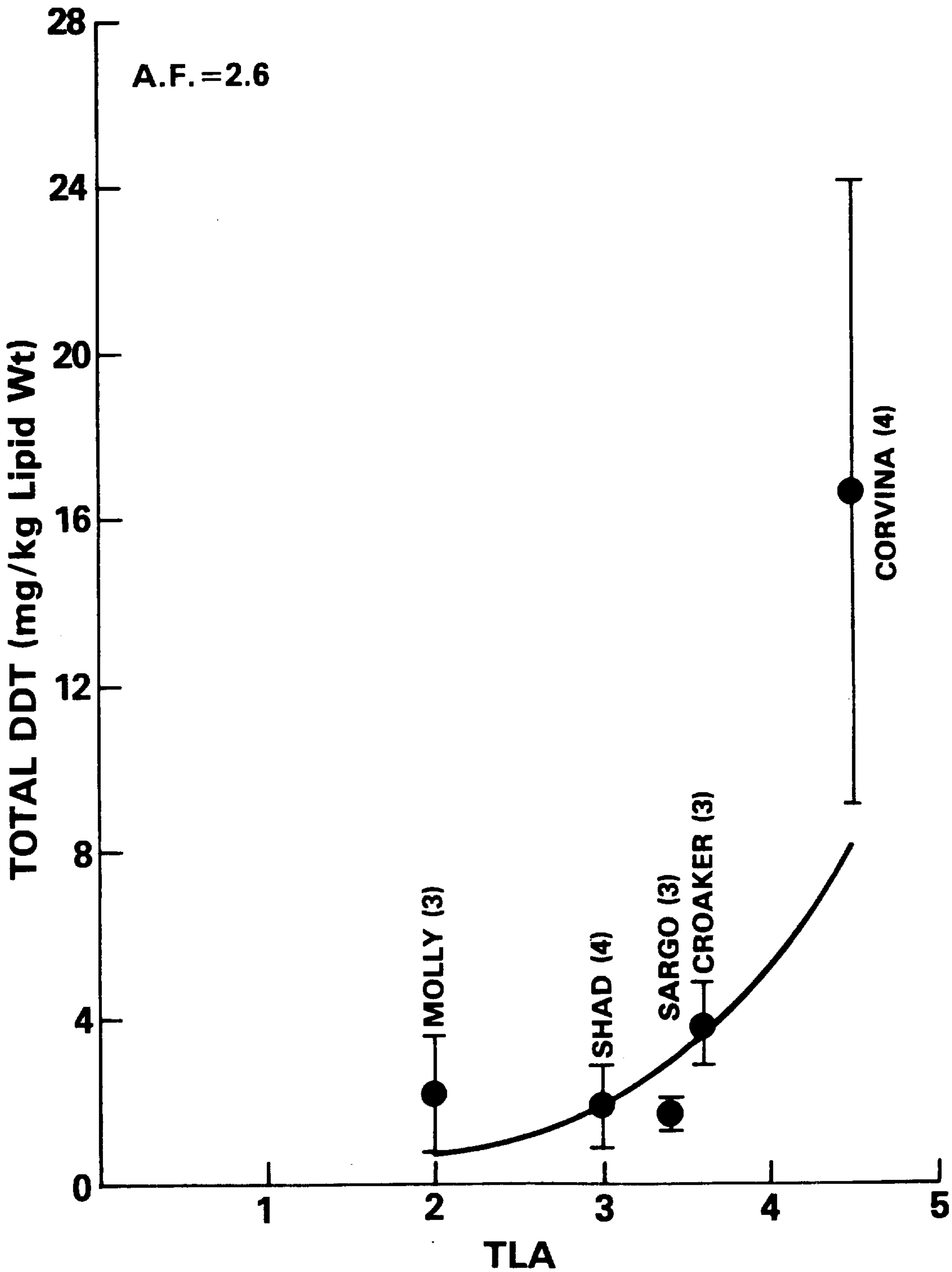

FIG. 15. AVERAGE TOTAL DDT CONCENTRATIONS (±1 STD. ERROR; N SHOWN) IN 1978 SALTON SEA FISH MUSCLE VS. TROPHIC LEVEL ASSIGNMENT, LIPID WEIGHT BASIS. LINE IS FROM LINEAR REGRESSION: LN (TOTAL DDT) = 0.95 (TLA) - 2.16 ($0.05 < p < 0.10$), WHICH DOES NOT YIELD A SIGNIFICANT FIT OF THESE DATA TO THE EXPONENTIAL BIOMAGNIFICATION MODEL.