CORRELATION OF UPWELLING INDEX AND DUNGENESS CRAB CATCH

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ABSTRACT

The statistical relationship between upwelling intensity and the annual *Cancer magister* catch is examined using techniques of time series analysis. The statistical relationships between upwelling in different years and crab catch in different years are examined. The statistic used is the correlation coefficient for varying time lag. The results correlating upwelling and crab catch indicate that time lag is short enough to demonstrate that adults are affected, and that the time lag is shorter in California than in Oregon or Washington. The crab catches appear to be cyclic with a period of 9 yr in California and 12 yr in Washington and Oregon. Possible causal mechanisms for the statistical relationships are presented. Results suggest that variations in crab catches may be due primarily to biological rather than abiotic influences.

Large fluctuations in yearly catch in the Pacific Coast Dungeness crab fishery have been observed over the years for which records were kept. The catch in some years is as low as 20% of the catch in good years. Furthermore, the fluctuations seem to be of a cyclic nature: 3 or 4 yr of low catch are often followed by 3 or 4 yr of high catch after which the same pattern occurs. Based on the fact that the variation in catch was similar along the entire west coast, the Pacific Marine Fisheries Commission (1965:38) concluded that a large-scale abiotic influence was responsible.

Many other explanations of the fluctuation in crab catch have rested on Cleaver's (1949) contention that abundance of adult crabs fluctuates widely in accordance with conditions affecting the early stages, e.g., the Pacific Marine Fisheries Commission (1965:38) suggested that seasonal currents possibly sweep the larvae to unfavorable settling areas. However, although the larvae may be more sensitive than juveniles to environmental changes and the percentage of them surviving is certainly less, there has been no experimental proof that fluctuation in abundance depends primarily on larval survival.

Peterson (1973) was the first to examine the statistical relationship between the Dungeness crab fishery and upwelling. (His paper serves as a good introduction to our work; much valuable information is not repeated here.) He compared the upwelling index developed by Bakun (1973) to the crab catch records for the years 1949 to 1972. The comparison was made for three different locations: Washington (lat. 48°N, long. 125°W), Oregon (lat. 45°N, long. 125°W), and northern California (lat. 42°N, long. 125°W).

Peterson used graphical comparison and two statistical techniques—the corner test and the contingency table—to evaluate the relationship between upwelling index (summed over the summer months) and the annual crab catch for several different lag times at each location. The conclusion was that good crab catch followed a good upwelling summer by 1½ yr in California and Oregon and ½ yr in Washington. Two aspects of these results are unexpected: 1) the short lag times and 2) shorter lag time in Washington than in California and Oregon. The short lag times seem to preclude the effect of upwelling on larval or early stages being the dominant cause of the large catch. The shorter lag time in Washington is unexpected because of the shorter generation times of most species in the marine food chain at the higher temperatures of more southerly waters.

Peterson explained the lag differences by proposing that the final molt from sublegal to legal size was the determining factor. Dungeness crabs molt later in more northerly waters (late fall in Washington, late summer in Oregon, and early summer in California). It was hypothesized that the Washington animals were molting after the summer upwelling and benefited from the increased food supply, whereas animals in more southerly waters molted prior to the increased food supply and did not benefit until the following summer molt.

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In this paper we have used a different statistical technique than Peterson's and have reached a different result regarding lag differences. We have computed the correlation coefficient for varying lag times. This technique uses higher resolution in the data than the techniques used by Peterson and results in a graphical presentation of the magnitude of correlation at each lag. The results show that significant correlation extends for longer lag times than ½ or 1½ yr and reverse the order of the difference in lag times along the coast. Also, we have used the same technique to describe the relationship between catches in different years. These results show that the primary cause of the cyclic nature of the variations may not be upwelling.

MATERIALS AND METHODS

The data used were the same as those used by Peterson (1973). The catch data are based primarily on the annual reports of the Pacific Marine Fisheries Commission and the California Department of Fish and Game (see Peterson 1973 for detailed discussion of sources). The total catch for each year (Figure 1) is believed to represent almost all that year's legal-size male crabs (Pacific Marine Fisheries Commission 1965:38). The completeness of this yearly sample makes the Dungeness crab an attractive species for analysis of population dynamics.

The upwelling index developed by Bakun (1973) is based upon measurements of atmospheric pressure. Upwelling and downwelling are the result of Ekman transport which is, in turn, due to surface winds. Bakun developed a method of estimating the intensity and direction of Ekman transport by relating the wind speed and direction to atmospheric pressure measurements. Using this method, he computed monthly averages of the component of Ekman transport perpendicular to and away from the shoreline. This upwelling index is assumed to indicate the average monthly upwelling. Peterson (1973) summed the monthly Bakun upwelling index over the summer upwelling season to compute a seasonal upwelling index (Figure 2). The upwelling indices were summed over the time periods from May through September for California.

These data were analyzed using a technique commonly employed in analysis of random processes to determine the degree to which two processes (or separated points of one process) covary. The formula used was:

$$R_{xy}(i) = \frac{1}{(n-i)} \sum_{j=1}^{n-i} x(j)\, y(j+i)/S_x S_y$$

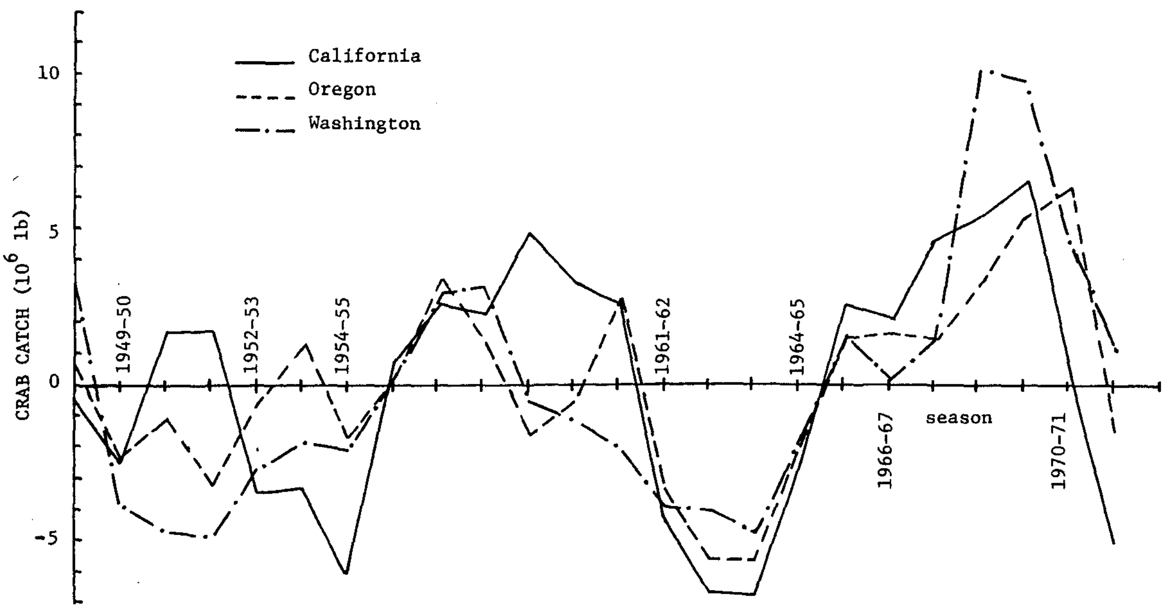

FIGURE 1.–Crab catch data for Washington, Oregon, and California (mean removed).

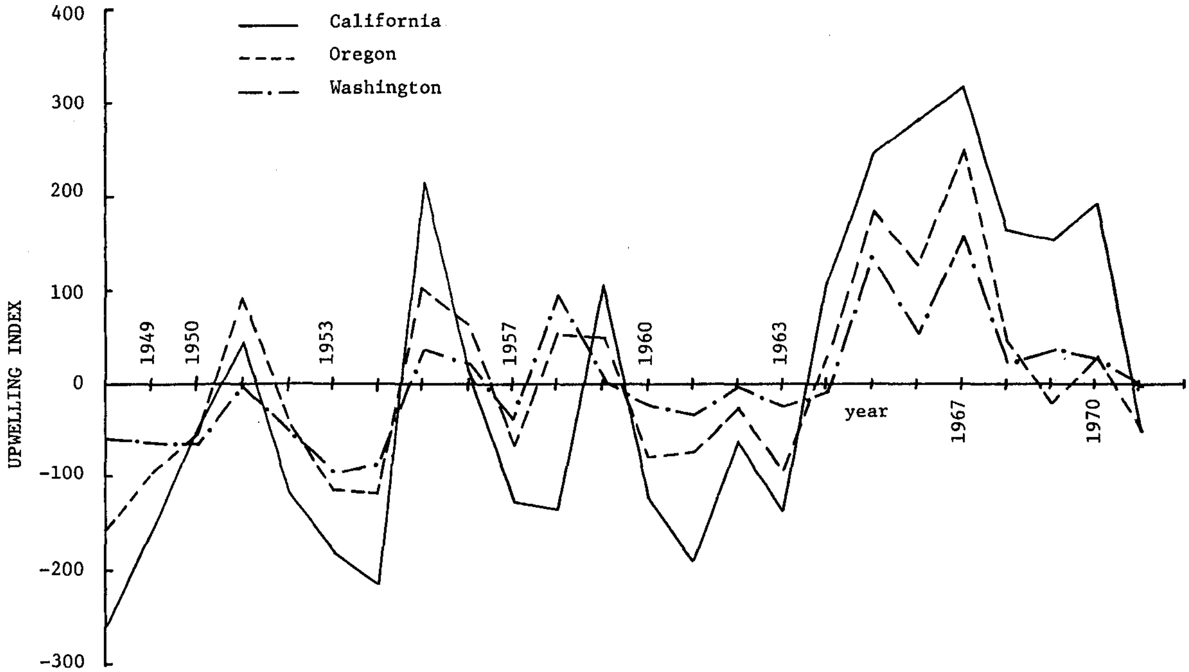

FIGURE 2.—Bakun's upwelling index for Washington, Oregon, and California (mean removed). Units are cubic meters of water upwelled per second per 100 m of coastline.

where $x(j)$ = the value of process x at time j (mean removed)
$y(j)$ = the value of process y at time j (mean removed)
S_x = the sample standard deviation of process x
S_y = the sample standard deviation of process y
n = the total number of samples.

The result of this formula is the product-moment correlation coefficient for each value of lag i. A graph of $R_{xy}(i)$ along the ordinate and i along the abscissa is termed the correlogram (Kendall and Stuart 1968). Assuming that the processes are stationary and ergodic, R_{xy} is an estimate of the expected value of the product of the two variables at each lag time. If x and y are different processes, it is termed the cross-correlation coefficient. If x and y are the same process, it is termed the auto-correlation coefficient.

Because R_{xy} is a sample statistic, the significance of its value must be considered. Although the technique is commonly used in time series analyses, the sampling theory of serial correlations has been developed only for restricted types of data (e.g., normally distributed data). Because the significance decreases as n increases, the serial correlation coefficient is usually only calculated for lags up to 30% of the total length of the data. The interpretation of our results depends only on lags of this length. However, the results are presented for lags beyond this length because they are of interest.

Another consideration in the computation of serial correlations is that of trend removal (Kendall and Stuart 1968; Ontes and Enochson 1972). Trends in the data (linear or higher order) which are not pertinent to the analysis are subtracted from the data before the correlation coefficients are computed. The trend is usually a deterministic artifact of known origin which is not present in the actual data of interest. Although upwelling, and to some extent catch data, seemed to increase over the 24 yr considered, this effect was not irrelevant to the purpose of the analysis. The results presented, therefore, include no trend removal. However, computation of the correlation coefficients was performed after trend removal and the results were similar.

RESULTS

The cross-correlation coefficients for upwelling and crab catch are plotted in Figure 3 as a function of lag time. The general shape of the function is similar for the three different locations. The coefficient for California at 0.5 yr lag is greater than for the other two. The value of the correlation coefficient for California decreases while the value increases for 1 yr at the other locations. This may indicate that high correlation exists at a shorter time lag in California than in ther other locations.

The auto-correlation coefficients for upwelling are plotted in Figure 4. Significant correlation

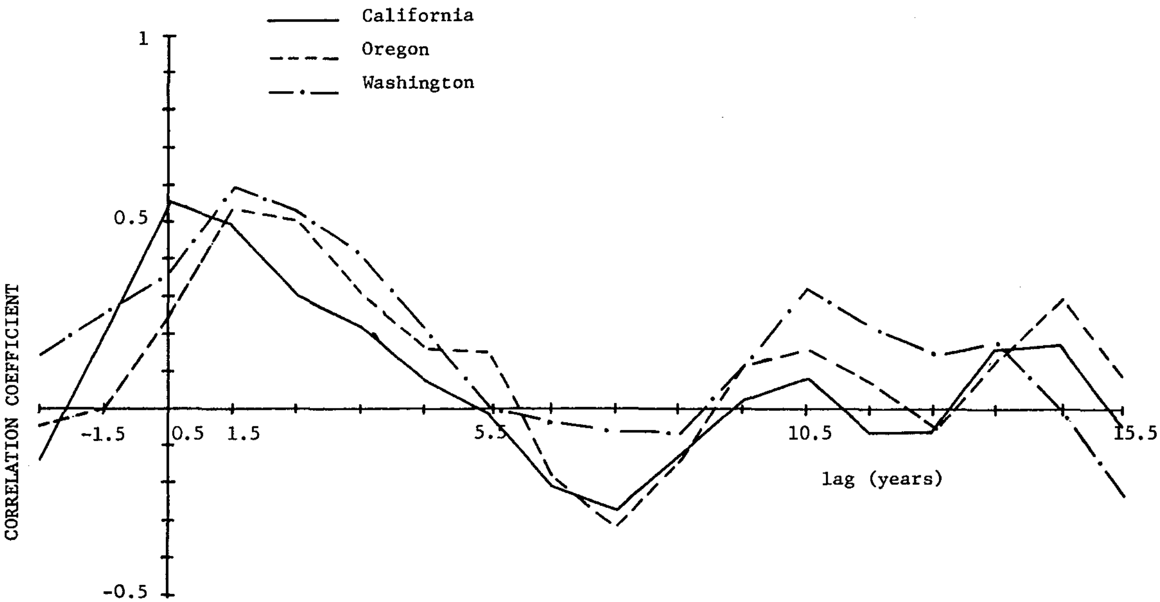

FIGURE 3.—Cross-correlation of upwelling and crab catch for Washington, Oregon, and California.

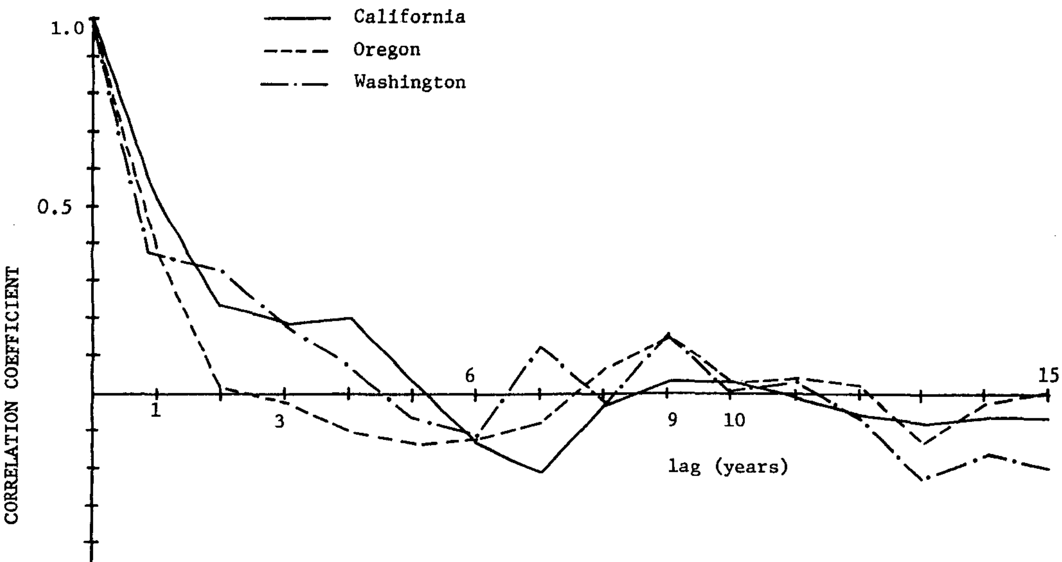

FIGURE 4.—Auto-correlation of upwelling for Washington, Oregon, and California.

exists for all three locations at a lag of 1 yr. For greater time lags no significant characteristics appear.

The auto-correlation of crab catch is plotted in Figure 5. The correlation function for each location decreases to a point of significant negative correlation. This is a characteristic of a cyclic process with a period of twice the lag value at that point. For California the period of the cycle would be 9 yr, and for Washington and Oregon it would be 12 to 13 yr. A subsequent increase to a positive correlation at a lag of twice that of the negative peak is further indication of a cyclic process. However a lag of that length is greater than 30% of the total length of the data.

DISCUSSION

These results must be interpreted in light of the general implications and limitations of statistical correlation. The correlation coefficient is used to measure the intensity of association between two variables and determine whether or not it is greater than that expected by chance alone. A high correlation coefficient serves only as an indication that a causal relationship may exist. The nature of the causal mechanism may take several forms. A high value of the correlation coefficient between two variables may be caused by one variable directly influencing the other. It may also be caused by a third variable influencing them both. Other possible alternative forms are more complicated combinations of these two. The causal mechanism may be very complex and indirect. Conclusions from the results obtained must, therefore, serve only as indications of areas of possibly fruitful investigation.

The results in Figure 3 indicate a possible relationship between upwelling and catch. The positive correlation at 0.5 yr lag which continues for several years could result from increased crab growth or survival due to increased food which may be due to nutrients provided by upwelling. The correlation at low lag time indicates agreement with Peterson's (1973) contention that adults are affected. The maximum correlation, however, appears at a shorter lag time in California than in Washington or Oregon. The fact that a significant correlation continues for an additional year may also be due to the same cause with the longer lag being the sum of the time required for the effect of nutrients to be felt at a point in the food chain in which the crab feeds plus the time required for that crab to reach a catchable size.

The cause of the apparent periodic nature of catch data indicated by Figure 5 is of primary

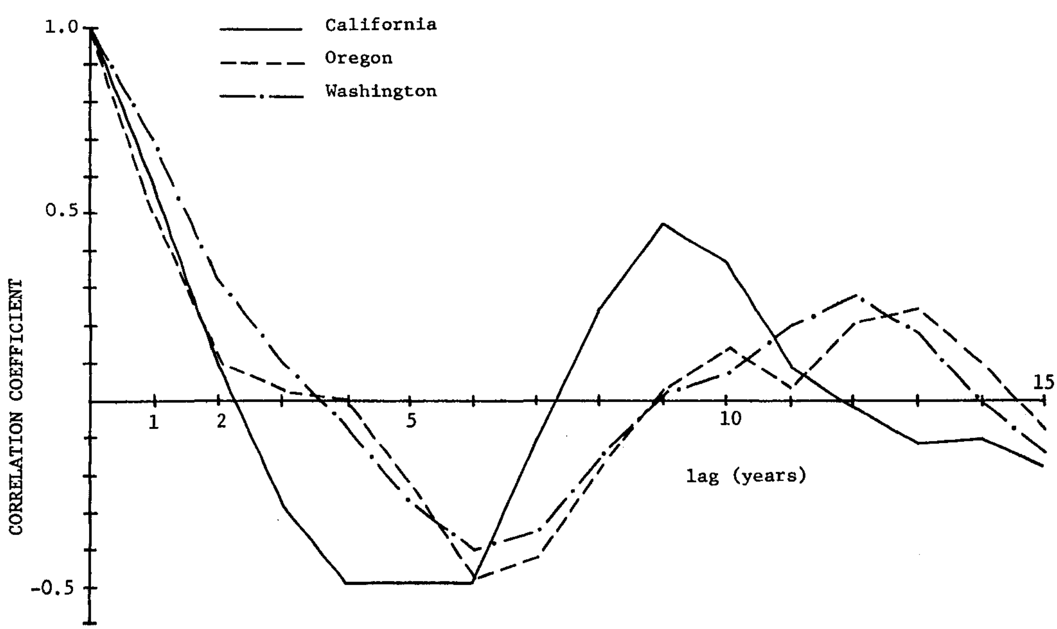

FIGURE 5.—Auto-correlation of crab catch for Washington, Oregon, and California.

concern to fisheries biologists. A possible explanation is that crab catch is merely following the cyclic upwelling. However, the auto-correlation of upwelling (Figure 4) does not indicate significant periodicity and the weak cycles suggested have different periods from those for the catches. This result may be due to the fact that the data used by Bakun (1973) were taken from four different sources covering the time periods January 1946-March 1955, April 1955-December 1959, January 1960-June 1962, and July 1962-December 1971. The data within each time period may differ by a multiplicative factor from the others but are consistent within the time period. This would affect the auto-correlation function more for longer than for shorter lags. The total effect of possible inconsistencies in the data upon the auto-correlation function is difficult to assess since the magnitudes of the multiplicative factors are not known.

A second possible explanation is that years of good catch indicate that a higher than normal percentage of the population is being caught thus depleting the adult reproductive stock. This explanation, however, is not commensurate with the widely held belief that almost all legal males are caught every year.

A third possible cause of the cyclic variations in abundance is predation. The observed cycles may be the result of interaction of crabs with a predator species. However, there is no a priori reason to expect that the period of the cycles would be slightly greater than twice the generation time. Also, the large number of predator species suggests that predation would maintain a fairly constant level unless all predator species were cycling in abundance.

A fourth possible explanation involves interactions between members of the population rather than external causes as dominant factors. Density-dependent factors which limit reproduction or growth and survival of the younger members of a population as the numbers of adults increase may cause cycles in abundance of adults. Ricker (1954) provides a discussion of density-dependent recruitment in fisheries and a simulation of time variation of abundance based on several different density-dependent recruitment relationships. One of the forms of compensatory mortality which could cause density dependent recruitment is cannibalism (Ricker 1954). Butler (1954) reported finding small Dungeness crabs (about 1 cm) among the stomach contents of older Dungeness crabs. For certain stock-reproduction curves the simulated populations oscillated in numbers. The requirements for permanent oscillation were a rapid decrease in reproduction (or survival of the young) beyond the peak of the stock-recruitment curve and mixing of generations in the breeding populations. The period of the oscillations was twice the mean length of time from parental to filial eggs.

Our results show a period of approximately 9 yr in California and 12 yr in Washington and Oregon. This would indicate a generation time of 4.5 yr in California and 6 yr in Washington and Oregon. Poole and Gotshall (1965) stated that mating occurs in California after 2.5 yr and males enter the fishery at 3.5 or 4.5 yr. Cleaver (1949) reported that in Washington maturity occurs at 3 yr and legal size occurs at the end of the fourth year. McKay and Weymouth (1935) reported that female crabs in southern British Columbia probably reach sexual maturity during the fourth or fifth year. The longer generation times in the northerly waters are commensurate with our results, although the period of the cycles indicated by our results is greater than would be expected based on Ricker's simulation and estimates of age at maturity. This disparity may be due to inaccuracies in the estimates or in our results. One possibility is an inaccurate estimate of when, in the life cycle, a major portion of reproduction occurs. If upwelling increases growth rate, the determination may have been made in good years, thereby yielding shorter time periods. A second possible explanation is inaccurate determination of the period of the cycle in our analysis. The length of the data (two or three cycles) is not adequate for accurate determination of the period of the cycle, especially when external influences appear to have caused large variations. Examination of the raw data reveals a reasonable explanation and also demonstrates correlations implied in this paper. In Figure 1, catch for northern California goes from a peak at 1950-51 or 1951-52 through a low point to a peak in 1958-59, a 7- or 8-yr cycle. It then passes through a low point and 7 yr later is again at a high point. However, instead of beginning to decrease, it rises even higher for the next several years before dropping. Figure 2 indicates that this is also the time when upwelling index is at a very high value. That the crab population reached a high density in 1965, but did not suffer the expected decline because the upwelling had provided enough food resources to sustain a larger population is a plausible explanation.

SUMMARY AND CONCLUSIONS

The correlation analysis at different lag times indicates a significant correlation of crab catch with upwelling for several years following upwelling. Auto-correlation of crab catch indicates that catch is of a cyclic nature. The same analysis of upwelling does not show a significant cyclic nature (although this may possibly be due to inconsistencies in Bakun's data). These analyses are not rigorous proofs of the indicated characteristics but rather provide impetus and direction for further research. They suggest that the cyclic variation of crab catch may be primarily due to density-dependent biotic factors rather than upwelling, although upwelling does influence catch. Further conclusions regarding the biological basis for the cyclic nature of catch data require research in the natural history and ecology of the Dungeness crab. A specific question to be answered is over what age groups are the niches similar enough for significant competition to occur. Further conclusions regarding the relationship between upwelling and catch require additional research in the nature of energy transfer from the pelagic to the benthic environment. Research in these directions may provide basis for a more dynamic fishery management policy. For instance, the importance of deciding whether the variations in crab catch are due primarily to density-dependent factors is illustrated by the implication that if competition is occurring between adults and juveniles, limited fishing of females (removing them as competitors) during years of great abundance may provide greater catches in the following years.

The statistical relationships presented also provide a basis for predicting crab catch. The values of upwelling index and crab catch over several years may be used to predict catch for the ensuing years (Rauch et al. 1975). Additional variables may be added to the basis for prediction such as temperature and results of plankton tows. This type of prediction is based on statistical relationships and does not necessarily require causal explanations of the various effects.

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