

ISOHALINE POSITION AS A HABITAT INDICATOR FOR ESTUARINE POPULATIONS¹

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Abstract. Populations of native and introduced aquatic organisms in the San Francisco Bay/Sacramento–San Joaquin Delta Estuary (“Bay/Delta”) have undergone significant declines over the past two decades. Decreased river inflow due to drought and increased freshwater diversion have contributed to the decline of at least some populations. Effective management of the estuary’s biological resources requires a sensitive indicator of the response to freshwater inflow that has ecological significance, can be measured accurately and easily, and could be used as a “policy” variable to set standards for managing freshwater inflow. Positioning of the 2‰ (grams of salt per kilogram of seawater) bottom salinity value along the axis of the estuary was examined for this purpose.

The 2‰ bottom salinity position (denoted by X_2) has simple and significant statistical relationships with annual measures of many estuarine resources, including the supply of phytoplankton and phytoplankton-derived detritus from local production and river loading; benthic macroinvertebrates (molluscs); mysids and shrimp; larval fish survival; and the abundance of planktivorous, piscivorous, and bottom-foraging fish. The actual mechanisms are understood for only a few of these populations.

X_2 also satisfies other recognized requirements for a habitat indicator and probably can be measured with greater accuracy and precision than alternative habitat indicators such as net freshwater inflow into the estuary. The 2‰ value may not have special ecological significance for other estuaries (in the Bay/Delta, it marks the locations of an estuarine turbidity maximum and peaks in the abundance of several estuarine organisms), but the concept of using near-bottom isohaline position as a habitat indicator should be widely applicable.

Although X_2 is a sensitive index of the estuarine community’s response to net freshwater inflow, other hydraulic features of the estuary also determine population abundances and resource levels. In particular, diversion of water for export from or consumption within the estuary can have a direct effect on population abundance independent of its effect on X_2 . The need to consider diversion, in addition to X_2 , for managing certain estuarine resources is illustrated using striped bass survival as an example.

The striped bass survival data were also used to illustrate a related important point: incorporating additional explanatory variables may decrease the prediction error for a population or process, but it can increase the uncertainty in parameter estimates and management strategies based on these estimates. Even in cases where the uncertainty is currently too large to guide management decisions, an uncertainty analysis can identify the most practical direction for future data acquisition.

Key words: fish; freshwater flow; habitat indicator; interannual variability; mollusc; phytoplankton; Sacramento–San Joaquin Delta; salinity distribution; San Francisco Bay; statistical models.

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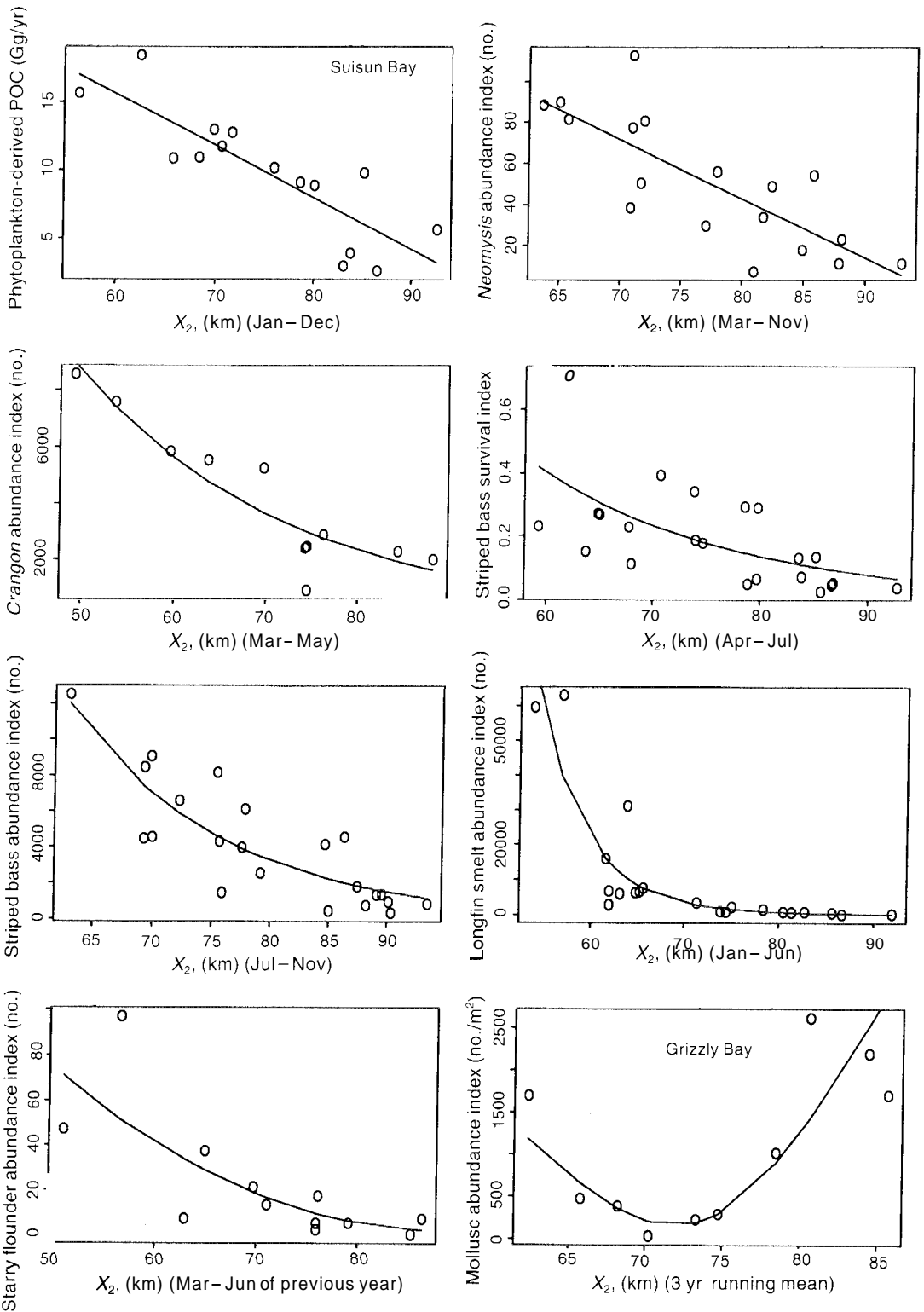


FIG. 5. Relationships between various biological variables and X_2 , the position of the 2‰ isohaline. —; fitted values using the generalized linear models summarized in Table 2 (POC: particulate organic carbon). Months refer to averaging intervals.

TABLE 2. Summary of relationships between response variable Y and predictor variable X_2 ; n , number of observations (years); g , link function; V , variance function; df , degrees of freedom for X_2 in model (1 = linear, 2 = natural spline with one interior knot); r , correlation between Y and the fitted values; s/\bar{Y} , square root of mean squared residual as proportion of mean response.

Y	n	g	V	Spline		r	s/\bar{Y}
				df			
POC supply	15	I	I	1		0.85	0.26
<i>Neomysis</i>	18	I	I	1		0.79	0.39
<i>Crangon</i>	11	log	μ	1		0.93	0.23
Longfin smelt	21	log	μ	2		0.89	0.85
Striped bass survival	22	log	μ	1		0.59	0.66
Striped bass	22	log	μ	1		0.85	0.45
Molluscs	10	I	μ	2		0.80	0.65
Starry flounder	12	log	μ	2		0.76	0.94

nificant relations show a decline as X , increases. Molluscs exhibit an increase at extreme values of X , whether high or low. Two of the variables—POC supply and *Neomysis*—were linear in X . The others required some form of nonlinearity, either by transforming the response variable (*Crangon* and striped bass), the predictor variable (molluscs), or both (longfin smelt and starry flounder). Interannual variability in *Eurytemora* and delta smelt could not be described with a generalized linear model in X_2 , at least for the averaging periods used here.

The correlation r between the response variable and fitted values (Table 2) is simply the multiple correlation coefficient in the case of classical linear models; its square is therefore a guide to the proportion of variability attributable to the model. Similarly, s is the standard error of estimate for classical linear models and is a guide to the precision of predictions.

Multiple predictors for striped bass survival

Generalized additive modelling was used to explore the simultaneous effects of X_2 and the monthly series for freshwater diversion (DIV) on striped bass survival. The link function was taken to be $g = \log$, and the variance function $V = \mu$. Survival appeared to have a nonlinear dependency on X_2 , but a more or less linear dependency on DIV (Fig. 7). The X effect was unimodal with a peak between 70 and 80 km, while DIV had a monotonic negative effect. The correlation between response and fitted values increased substantially to 0.74 (cf. Table 2). The dependence of the variance on the mean was consistent with assumptions, and the residuals exhibited no autocorrelation. Only 1 yr, 1982, was not fit well by the model.

In order to quantify the relationship in more familiar terms, a classical linear model was constructed using the generalized additive model results as a guide. The response was log-transformed and the nonlinearity in X_2 was represented with a quadratic term:

$$\ln B = \alpha + \beta_1 X_2 + \beta_2 X_2^2 + \beta_3 \text{DIV}. \quad (3)$$

where B = striped bass survival index; $\alpha = -38 \pm$

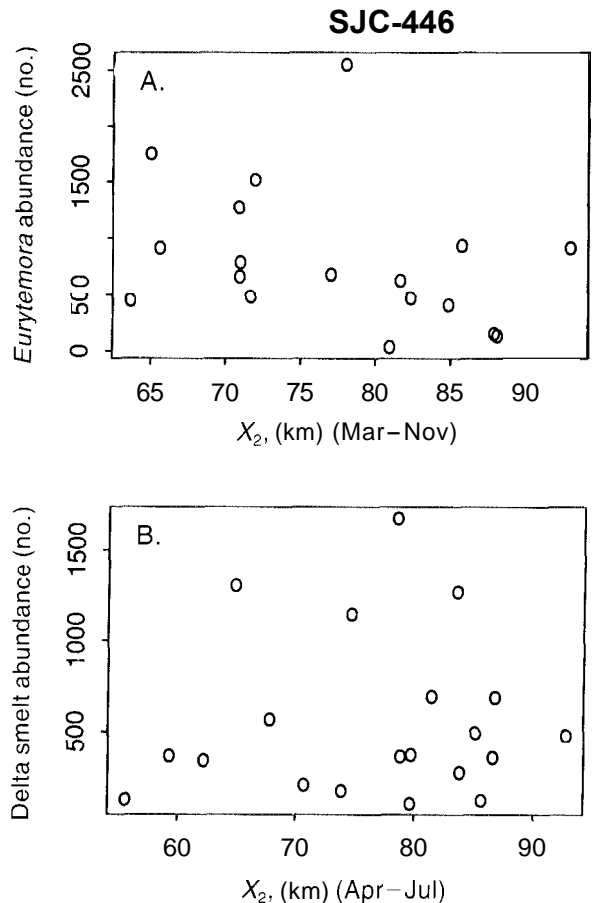


FIG. 6. (A), *Eurytemora affinis* abundance index vs. X_2 ; (B), delta smelt (*Hypomesus transpacificus*) abundance index vs. X_2 . Months refer to averaging intervals.

15; $\beta_1 = 1.0 \pm 0.4$; $\beta_2 = -0.0064 \pm 0.0024$; and $\beta_3 = -7.3 \pm 3.3$ (mean ± 1 SE). The diagnostic plots were essentially unchanged, once again showing consistency with the underlying assumptions. The multiple correlation coefficient between the untransformed survival index and the predictors was $r = 0.71$ ($P < 0.001$), almost as high as the generalized additive model that used an additional degree of freedom for the DIV effect.

Further linear models were constructed with subsets of predictor variables and their PSE values compared (Table 3). On the basis of PSE, as well as traditional statistics such as the adjusted coefficient of determination and standard error of estimate, the full model appeared superior. Also on the basis of PSE, the predictive capabilities of all remaining models were similar, except for one inferior to the others that used a linear term only for both X_2 and DIV.

DISCUSSION

Why estuarine resources are associated with X_2

This study demonstrates that X , has extensive relationships with estuarine resources in the Bay/Delta es-

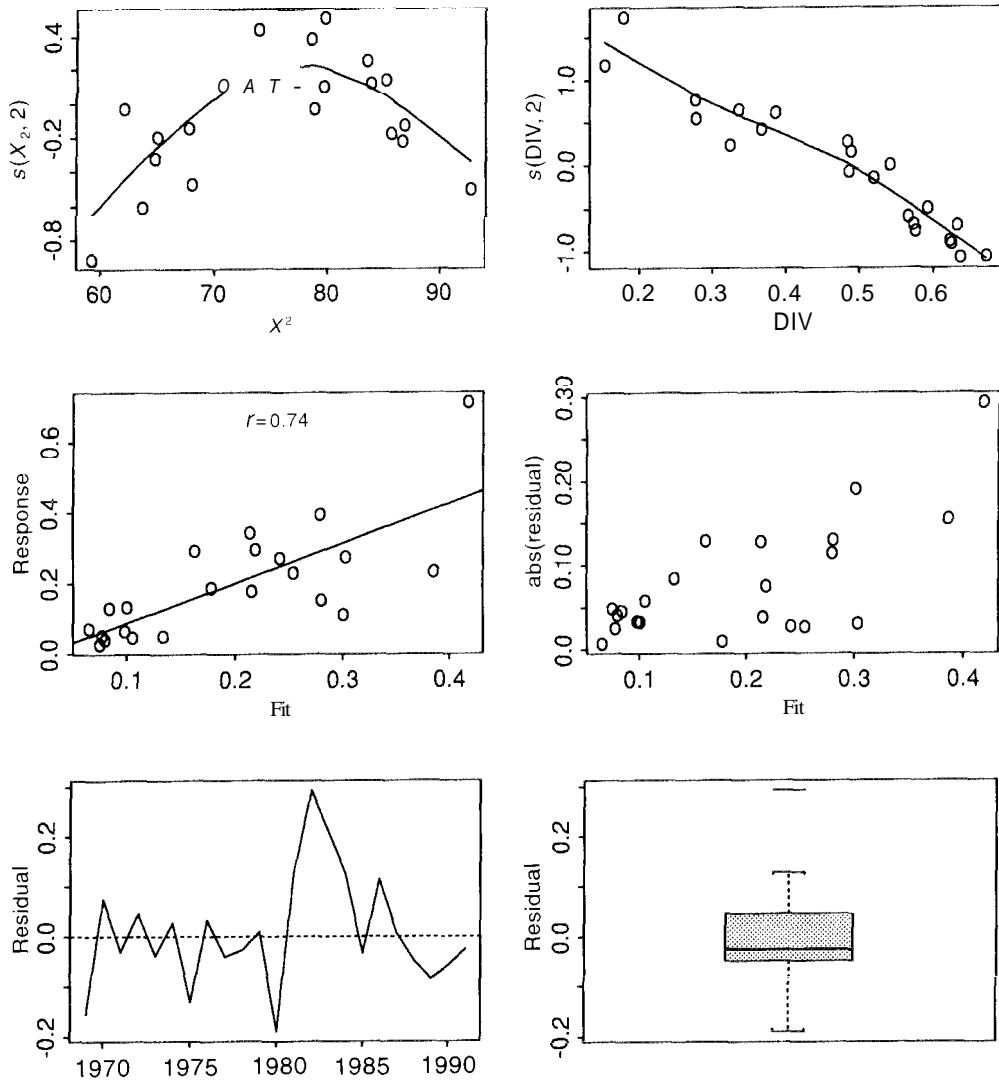


FIG. 7. Diagnostics for generalized additive model of striped bass survival index with link function $g = \log$ and variance function $V = I$: *top panels*, partial residual plots for X_2 and DIV (Freshwater diversion). [$s(X_2, 2)$ and $s(DIV, 2)$ refer to smoothing splines with two degrees of freedom]; *middle panels*, response and absolute value (abs) of residuals vs. fitted values from the survival model; *bottom panels*, time and box plots of residuals (see Fig. 8 caption for a description of box plot).

tuary. The associations exist for benthic and pelagic organisms, planktivorous and piscivorous organisms, and a range of taxa from algae through molluscs and crustaceans to fishes. What are the causal mechanisms underlying these relationships? A variety of potential mechanisms deserves a detailed consideration that is beyond the scope of this study, but a summary is in order here.

In the case of phytoplankton POC, several flow- and salinity-related effects are at work. First, phytoplankton tend to concentrate in the vicinity of the ETM, the upstream boundary of which is marked approximately by X_2 (Kimmerer 1992). If the ETM is positioned in the channels upstream of Suisun Bay, phytoplankton receive insufficient light for the development of blooms; a necessary condition appears to be the po-

sitioning of the ETM downstream near the broad, shallow expanses of Suisun Bay where phytoplankton growth rates are higher (Arthur and Ball 1979, Ball and Arthur 1979, Cloern et al. 1983). Second, persistent low flows of ≥ 2 yr create equable salinity conditions and result in colonization of Suisun Bay by marine suspension-feeding bivalves, increasing losses of phytoplankton (Nichols 1985, Alpine and Cloern 1992). Finally, under low flow conditions, the input of fluvial phytoplankton from upstream areas into Suisun Bay is diminished (Jassby et al. 1993). At high flows, the ETM may be positioned in channels downstream of Suisun Bay (Carquinez Strait), once again leading to severe light-limitation (Cloern et al. 1983). High flows also increase washout of chlorophyll from the ETM (Peterson and Festa 1984). Furthermore, if these high flows