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Ancient Blue Oaks Reveal Human Impact on San Francisco Bay Salinity

San Francisco Bay is one of the most important estuaries on the west coast of the Americas. Its water quality is controlled primarily by streamflow from the Sacramento and San Joaquin rivers. In fact, freshwater inflow from the Sacramento-San Joaquin Delta explains 86% of the salinity variability at the mouth of the San Francisco Bay estuary [*Peterson* et al., 1989]. The massive diversion of streamflow by the California State Water Project and the Central Valley Project, part of the largest man-made water control system on Earth [*Reisner*, 1988], has raised salinity in the estuary on daily seasonal, and annual timescales [*Nichols* et al., 1986; *Peterson* et al., 1989].

Reduced freshwater inflow and increased salinity are part of a larger syndrome of anthropogenic impacts that imperil water quality and ecosystem function in this important estuary Regional drought conditions not only lead to high salinity, but also to increased concentrations of contaminants and nutrients in San Francisco Bay Biologically available metal concentrations and dissolved nutrients reached record levels during the 1976–1977 drought and had serious consequences on the pelagic food web and fisheries in the Bay [Nichols et al., 1986].

Salinity variations are also strongly linked to total biological productivity in the estuary especially in response to changes in the geographic position of the null zone, the region of convergence between fresh surface and saline bottom currents in the northern reach of the Bay [Nichols et al., 1986; *Jassby* et al., 1995]. A near-bottom salinity threshold has been used since 1995 as a sensitive indicator of the ecological response to changing freshwater inflow into the estuary (U.S. Environmental Protection Agency standards listed in the *Federal Register* Part II:4463–4709, 1995). During the post-World War II era of rising salinity, many populations of aquatic organisms in the Bay have declined, due in part to decreased freshwater inflow higher salinity, and changes in the geography and geometry of the null zone. Because salinity and freshwater inflow are so tightly coupled, high salinity conditions are also synonymous with low inflow, lower freshwater flushing, higher concentrations of pollutants in the Bay, and salt water intrusion into the agricultural complex of the Sacramento-San Joaquin Delta.

The degree to which freshwater diversion has altered the natural variability of San Francisco Bay salinity has been difficult to quantify given the short period of salinity measurement and the large natural variation in streamflow and estuarine salinity A new tree ring reconstruction of surface salinity for Fort Point on the south shore of the Golden Gate, using extreme moisture-stressed blue oak trees (*Quercus douglasii*; Figure 1), indicates that the appropriation of freshwater by state and federal water projects has led to unnatural salinity extremes and long-term trends that are unprecedented in the Bay for over 400 years.

Precipitation-Sensitive Blue Oak and Fort Point Salinity

Blue oak tree ring chronologies can provide an accurate, long-term perspective on the natural variability of San Francisco Bay's salinity because blue oak growth and estuarine salinity both tend to integrate precipitation and temperature conditions over the winter-spring season. Winter-spring precipitation and temperature then translate into river discharge conditions that actually control flushing and salinity changes in the Bay Blue oak tree ring chronologies are highly and positively correlated with winter-spring precipitation and Sacramento-San Joaquin streamflow and are negatively correlated with spring temperature and monthly, seasonal, and annual salinity throughout the estuary.

Blue oak trees often form the lower forest border on the foothills of the Coast Range and Sierra Nevada, a forest environment where blue oak radial growth critically depends on precipitation during the winter/spring/early-summer season. We have developed 12 new blue oak chronologies throughout the native range of this species in California, and these chronologies record one of the strongest precipitation signals ever detected in tree ring data. All 12 blue oak chronologies are significantly correlated with winter-spring salinity in San Francisco Bay but the highest correlations are recorded by the five chronologies closest to the Bay in central California (Figure 2). This contrasts somewhat with the spatial pattern of precipitation influence on salinity, because most of the freshwater inflow that controls salinity comes from more remote sectors of the drainage basin in the Sierra Nevada and Northern Coastal Range [e.g., *Dettinger and Cayan*, 2001].

Fig. 1. A wind-sculpted 340-year-old blue oak (Quercus douglasii) *at Pacheco State Park, California (view is toward the south). These moisture-stressed trees provide a superb ring-width proxy for regional precipitation, streamflow, and salinity in San Francisco Bay.*

However, the five moisture-stressed blue oak chronologies nearest the Bay are simply more sensitive to precipitation than the available blue oak chronologies from northern California. In addition, some 10% of the freshwater inflow to San Francisco Bay does come from local tributaries [*Conomos*, 1979], so the strong salinity correlation of the Mt. Diablo chronology nearest the Bay may, in part, reflect the precipitation and runoff from the immediate drainage basin ($r = 0.90$; Figure 2). Precipitation over the central coast region where the five chronologies are located is also very well correlated with precipitation over the entire Sacramento ($r = 0.92$) and San Joaquin ($r = 0.89$) river basins for the January-July season.

Monthly salinity measurements are available for Fort Point from 1922 to 1994, though values are missing for 1946 and 1948. The Fort Point record is highly correlated with other salinity stations in the Bay. particularly when the data are seasonalized or annualized.

For example, January-July salinity at Fort Point and Alameda near the center of the Bay are correlated at $r = 0.86$ ($P < 0.0001$) for 1939–1985. Blue oak growth and monthly salinity at Fort Point are most highly correlated during and just after the wet season (January-July) when much (50%) of the precipitation that supports growth and river discharge occurs. and when most (82%) of the Sacramento-San Joaquin streamflow that flushes the Bay also occurs. The significant correlation between growth and salinity in June and July, following the wet season, partly reflects variability in the timing and magnitude of spring snowmelt seasons.

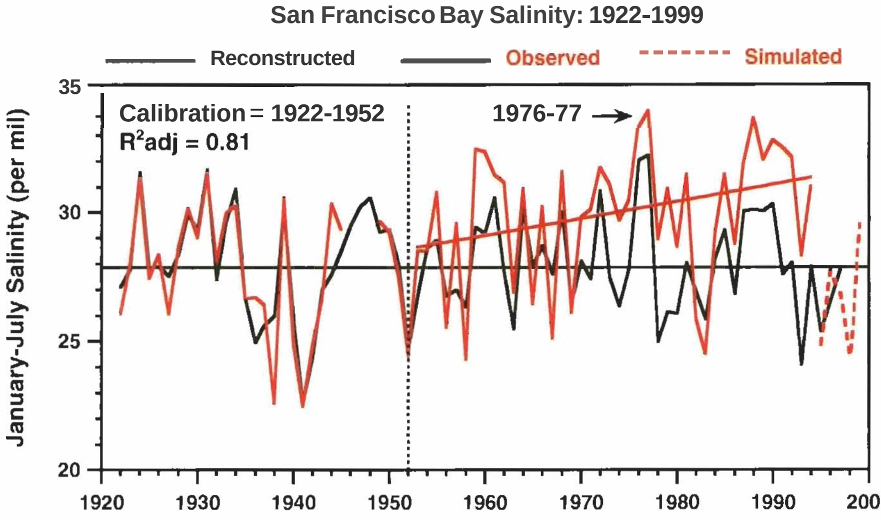

Fig. 3. Observed and tree ring reconstructed January-July surface salinity at Fort Point, 1922–1997. The reconstruction was calibrated with the salinity data from 1922–1952 (1946 and 1.948 are missing, and 1947 is hidden). The horizontal line is 171? mean of the observed salinity for 1922–1952 (27.87‰). The rising trend line was fit to the instrumental salinity data for 1953–1994. Simulated January-July salinity lor the 10 km^2 San Francisco Bay segment 49 is plotted from 1995 to 1999. This simulation estimates the freshening that occurred in the high runoff regime of the late 1990s, but this freshening still did not achieve the low salinity values expected for such high streamflow under pre-diversion conditions.

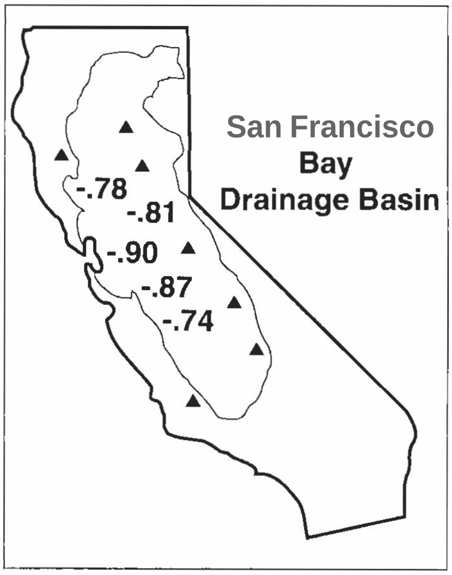

fig. 2. The five blue oak chronologies used to reconstruct salinity are located by their correlation coefficients with Fort Point salinity (January-July for 1922–1952). The five sites (north-south) are Clear Lake State Park, American Rive,; Mt. Diablo State Park, Pacheco State Park, and Pinnacles National Monument. The seven other blue oak chronologies now available are indicated by triangles. The Fort Point salinity station is located at the mouth of San Francisco Bay, on the south shore of the Golden Gate.

A Tree Growth Proxy for Estuarine Salinity

Water diversion from the Sacramento-San Joaquin Delta increased dramatically after World War II [*Reisner*, 1988]. We use the Fort Point winter-spring salinity data from 1922 to 1952 to calibrate the tree ring reconstruction of salinity because the salinity data are stationary in mean and variance over this period and they are highly coherent with the natural and undisturbed blue oak record of precipitation over this interval. Serious modifications to the estuary did, of course, occur before 1952 [*Nichols* et al., 1986], but they do not appear lo have dramatically altered the January-July average salinity measured at Fort Point from 1922 to 1952.

A regional average of the five most proximate blue oak chronologies was used as a predictor in bivariate regression with salinity at Fort Point for the 1922–1952 time interval:

$$Y_t = 3.455 - 6.509X_t \qquad (1)$$

where Y, is the estimated January-July salinity average at Fort Point in parts per thousand (‰) for year *t*, and X, is the corresponding ring-width value for the regional blue oak chronology in year *t*. The regional blue oak chronology is a proxy for the combined effects of regional precipitation and streamflow and explains 81% of the January-July salinity variance during the 1922–1952 calibration period (R^2adjusted = 0.81; Figure 3). This transfer function (equation 1) was used to estimate January-July salinity at Fort Point for all years from 1604 to 1997.

The diversion-impacted salinity data from 1953 to 1994 were used to verify the high-frequency interannual variability of this reconstruction. The tree ring estimates of salinity are highly correlated with observed salinity at Fort Point from 1953 to 1994 ($r = 0.70$, $P < 0.0001$). Even with the anthropogenic trend in salinity, the reconstruction passes most standard verification statistics used to evaluate dendroclimatic reconstruction fidelity (for example, the reduction of error = 0.37, but the paired t-test on observed and reconstructed means and the coefficient of efficiency both fail because they are sensitive to differences in mean).

There is a significant linear trend of +0.06‰ per year in the observed January-July average salinity data from 1953 to 1994 ($P = 0.0679$; Figure 3), while the trend from 1922 to 1952 is slightly negative and not significant (−0.03‰ per year; $P = 0.5005$). Some of this post-diversion salinity trend might be linked to natural variations in atmospheric circulation, changes in the seasonal runoff maxima, and coastal zone upwelling [*Peterson* et al., 1989]. But most appears to reflect the diversion of up to 50–60% of winter-spring streamflow from the Delta [*Nichols* et al., 1986].

The anthropogenic impact on salinity extremes and trend after circa 1952 can be detected through comparison with winter-spring precipitation over California or the tree ring reconstruction of salinity. The observed precipitation and reconstructed salinity series both lack a significant linear trend for the period from 1953 to 1994. The 1953–1994 trend in December-April precipitation for a regional average of California climatic divisions 1, 2, 4,