Title

Determination of Chinese mitten crab, Eriocheir sinensis, year-class strength through investigation of their reproductive life history

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Publication Date

2008-04-08

Final Report 2003 – 2005

Determination of Chinese mitten crab, *Eriocheir sinensis*, year-class strength through investigation of their reproductive life history

We have attempted to determine the environmental factors that may regulate the year-class strength of the invasive mitten crab, *Eriocheir sinensis*. Specifically, we are attempting to correlate the environmental factors that are involved in crab larvae (zoeae) survivorship, thus determining the numbers of mitten crab adults that occur in successive years. This type III life history suggests that under optimal conditions, the more zoeae survive, more adults will occur in 3-4 years.

In order to develop a sound management plan for the California population of Chinese mitten crab, it is essential to understand its life history. Many aspects of the mitten crab life history, including migration, growth and reproduction are strongly regulated by environmental parameters. If these environmental components can be identified, they might be used as predictors for mitten crab population dynamics and year-class strength. We recently published a life cycle for the California population of Chinese mitten crab (Rudnick, et al., 2005). In this publication, we outlined what is currently understood of the catadromous life cycle of this crab. This life history model also postulates environmental factors that mediate each of the phases of the life cycle (Fig. 1) and discusses the potential predictors of adult year-class strength.

During the development of this model, we identified major gaps in our understanding about the life cycle of this species, including: 1) how environmental conditions drive population dynamics, and whether these conditions can be used as predictors of year-class strength. The goal of this proposal is to close these information gaps, develop reliable predictors of mitten crab abundance and provide information that will assist in better monitoring and control of impacts of the Chinese mitten crab.

In order to study the population dynamics of the mitten crab zoea, we developed "An illustrated key to the brachyuran zoea of the San Francisco Bay Estuary" (Rice & Tsukimura, 2007). This allowed the investigation of the zoea abundance of *E. sinensis* using plankton tows provided by the CaDFG (Neomysis and Clark-Bumpus Tows). With this tool, we were able to determine that later stage *E. sinensis* zoea are present only after San Francisco Bay temperatures rise above 11.7º C. In addition, planktivore abundance appears to limit the time zoea are viable in the water column, creating a window between which zoea populations may influence juvenile or adult populations.

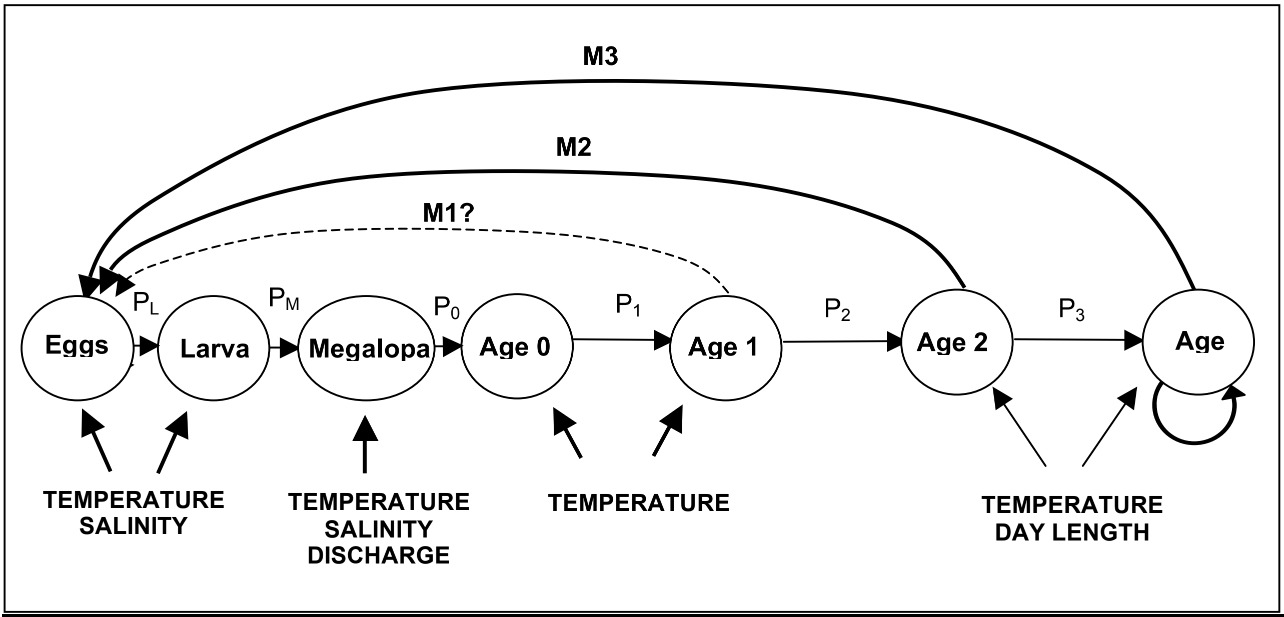

Figure 1. Mitten Crab Life History for California Population
Life stages are indicated in block letters (zoea stages are indicated by roman numerals) and possible environmental stimuli are indicated in boxes (Rudnick et al., 2005).

In an effort to detail the activities of the Chinese mitten crab in California, we developed a life history model (Fig. 1; Rudnick, et al., 2005). This model was designed to identify the idiosyncrasies of the California mitten crab population. In addition, during the construction of the model, we identified large gaps in our understanding of the mitten crab life history. Below is a synopsis of the model with relevant questions that require immediate addressing.

Mitten Crab Life History Model

The mitten crab is catadromous, meaning that the larvae hatch and develop in saline water, then metamorphose into juveniles that migrate upstream into freshwater tributaries of San Francisco Bay to mature into adults. The mitten crab may spend between 1 and 5 years in freshwater before maturing to adulthood (Panning, 1938; Ingle, 1986). In the late spring or early summer the mitten crabs reproductively mature. In the late summer and fall, these adults migrate downstream into brackish water. While in brackish water, the mitten crabs mate and oviposit eggs, which are carried by the female until they hatch. It is believed that the crabs undergo one reproduction cycle and die.

Larvae

Mitten crabs typically have one prezoea and five zoeal stages (Buhk, 1938; Anger, 1991; Kim and Huang, 1994; Montú et al., 1996; Tullis, per. comm). Mitten crab zoeae are euryhaline; however, they still require at least 16-17 ‰ NaCl or above 50% seawater (SW) concentrations to survive in the later zoeal stages (Anger, 1991). Temperature plays an important role in both survival and rate of development of mitten crab larvae. Lower water temperatures slowed development of zoeae and total time through metamorphosis in the laboratory and temperatures below 9°C were lethal (Fig. 2, after Anger 1991). Laboratory observations of mitten crab zoea suggest that zoeae are immobile or barely active at 12°C (Tullis, pers. comm.). The minimum time that *E. sinensis* larvae remain in each of the five zoeal stages appear to be 5 days at 18°C and 6-8 days at 15°C (Anger, 1991).

Based upon these temperatures, it is assumed that mitten crab larval development requires 1.5 – 2 months (Fig. 2). The warmer temperatures of China are not typical of the San Francisco Bay/Delta system and thus larval growth and development needs to be examined to determine how the mitten crab larvae are behaving throughout this region. Colder temperatures are often found in the San Francisco Bay/Delta System, which might influence the timing and survivorship of mitten crab larvae. To confound matters, it is possible that within one breeding cycle, two distinct brood classes may be developed. Larvae that settle prior to the winter temperature decline and those that hatch and settle afterwards. This would create two size classes of juvenile crabs during the same reproductive cycle. We are currently calibrating the role of thermal tolerance on mitten crab zoea survival. Further analysis of survivorship will be correlated to adult year-class strength in an attempt to create a predictive model for adult year-class strength.

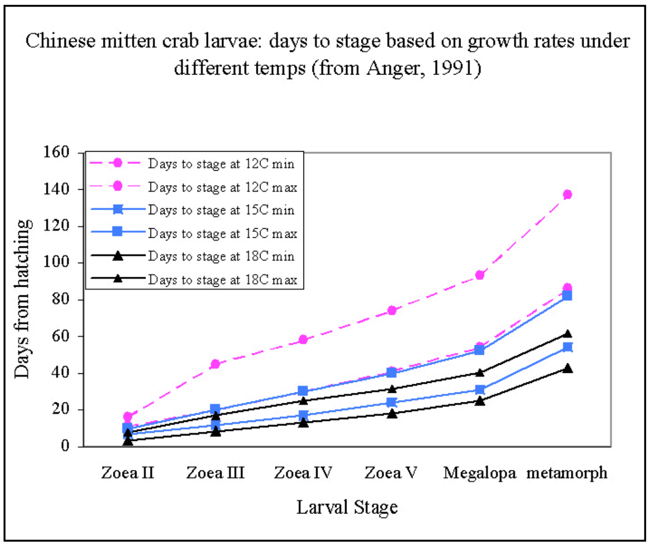

Figure 2. Range of time required for *Eriocheir sinensis* larval development at various temperatures.
Data was extracted from Anger (1991) and demonstrates the importance of water temperature on the rate of zoea development. Presented in Rudnick et al, 2005.

In San Francisco Bay the majority of ovigerous crabs are found between December and March (Rudnick et al., 2003). As egg development is likely temperature dependent (Rudnick et al., 2005). We are analyzing plankton tows in San Pablo Bay to determine the time of existence and abundance of zoea in the San Francisco Bay. We have analyzed plankton samples from 1997 – 2005. Our analyses of *Neomysis* and Clarke-Bumpus plankton trawl contents (ongoing CA DFG trawl) indicate that the zoea are in abundance in temperatures above 11.7°C (Fig 3.). These data support earlier research that *E. sinensis* zoea survive only above 12°C (Anger, 1991).

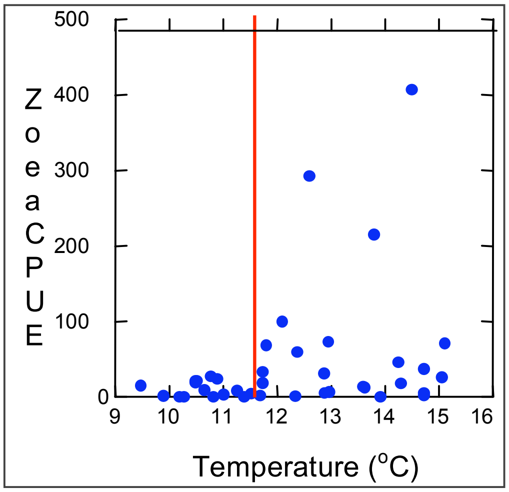

Figure 3. ***Eriocheir sinensis*** **monthly zoeae densities (Dec. – Apr.) vs. temperatures recorded from the USGS continuous monitoring gauge at PSP.** A significant difference was found between means above and below 11.7°C ($p = 0.04$), suggesting 11.7°C may be a thermal tolerance threshold.

Our analyses of *Neomysis* plankton trawl contents (ongoing CA DFG trawl) indicate that zoeae are present from December to June, with highest abundances in March and April (Fig. 4). These higher abundances relate to the temperature after which San Francisco Bay waters rise above 11.7º C. The zoea abundance falls in May and June as the zoea develop through their stages to megalopa (post-larvae) and as a result of their type III survivorship.

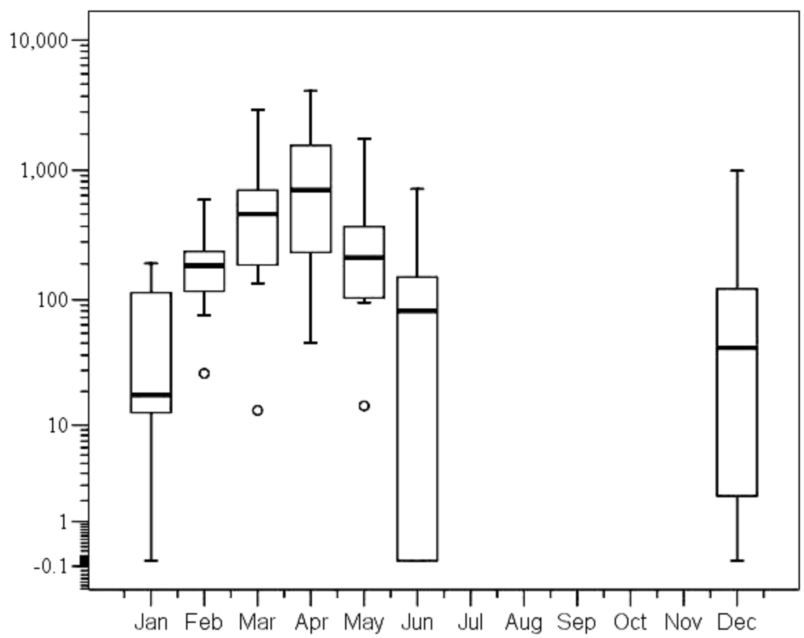

Figure 4. ***Eriocheir sinensis*** **zoeae abundance by month in San Pablo Bay, 1998 – 2004.**

We separated the zoea abundance data into zoea stage data (Fig 5). All zoeae that were found in December and January were stage I; the only stage II zoeae found in February were during 2003. In March, only stage I (84.7%), stage II (12.6%), and stage III (2.7%) zoeae were present in the samples, and no stage IV or V were found. Nearly half of the total zoeae seen in April were later stages: stage II (22.3%); stage III (19.7%); and stage IV (3.5%). Stage V zoeae first appeared in April, and in May comprised 3.8% of the total zoeae (Fig. 5). These data indicate larvae growing into stage II zoea are rare before March. This late appearance of stage II may be due to the temperature tolerance of zoea. San Francisco Bay temperatures do not rise above 11.7°C, a temperature below which zoea do not appear to survive.

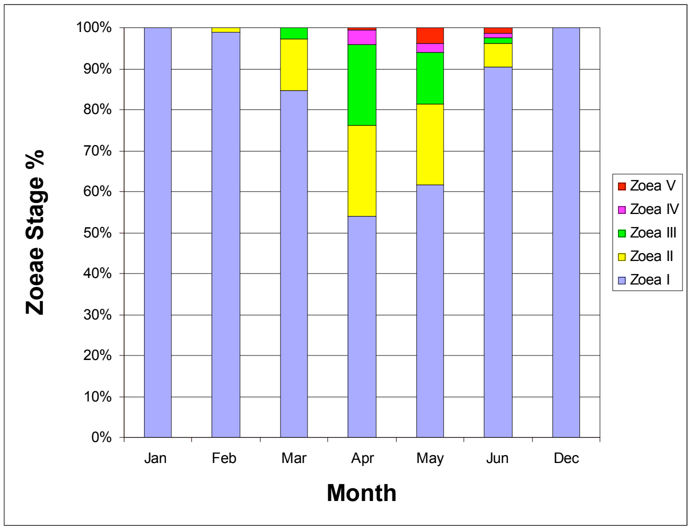

Figure 5. *Eriocheir sinensis* zoeae stages (cumulative %) identified December – June, from CDFG zooplankton samples from San Pablo Bay, 1998 – 2004.

Initial attempts at correlating water temperatures and adult year class strengths were performed by assuming 12°C as a critical thermal point based upon Anger (1991). For north San Francisco Bay tributaries, mitten crab abundance (as a measure of catch per unit effort (CPUE) was overlaid onto seasonal water temperature means (Fig. 6).

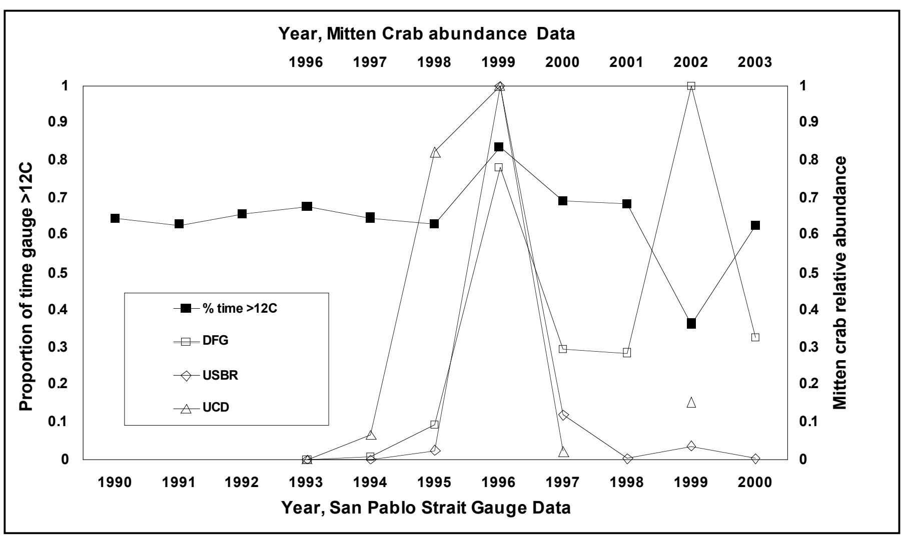

Figure 6. North San Francisco Bay adult mitten crab abundances (CPUE) and San Pablo Bay temperatures expressed as % time >12°C (November – June)
A warmer winter in 1996 overlays a high adult year class in 1999.

When the adult year-class strength is overlaid upon temperature data, mitten crab adults appear to be year class 2, or those in their third year of life, suggesting that the crabs are at least three years old. In the winter of 1999, an exceptionally cool winter occurred, however, 2002 was a strong year-class. The life history model is thus more complicated than simply relating to larval water temperature and adult abundance.

We have also looked at the outflow data for a decade and found a visual correlation with two peak years of adult mitten crab abundance (Fig. 7). These data indicate that adult mitten crabs are likely year-class 3 (in their 4th year) animals. These data appear to conflict with the predictions we have found using water temperature data. Interestingly, outflow and water temperatures are not correlated ($r^2 = 0.0502$; $y = -1x10^{-5}x + 13.754$).

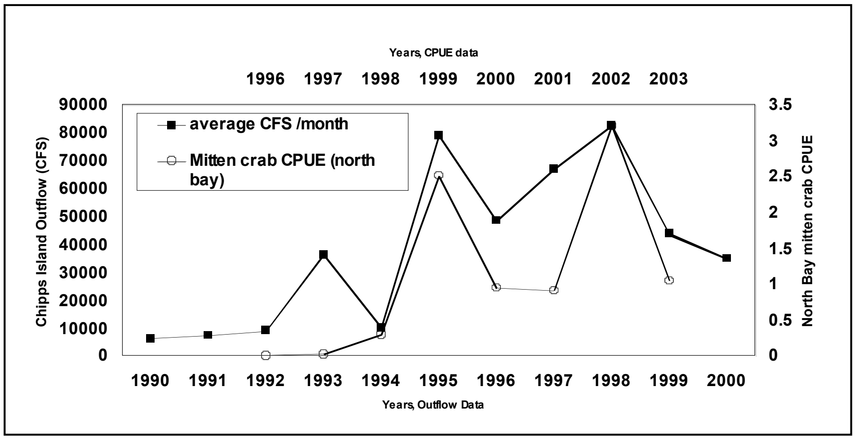

Figure 7. Correlation of Outflow at Chipps Island (CFS) and Adult Mitten Crab Abundance

Additional examination of the *Neomysis* and Clarke-Bumpus trawls conducted by CaDFG, has indicated that on high outflow years there are higher numbers of zoea present in San Pablo Bay (Fig. 8). During high outflow years, salinities in bay waters decline. We hypothesize that the planktivorous fish, unable to tolerate the lower salinities, are in lower densities, thus lowering predation pressures on crab larvae and increasing adult crab populations in subsequent years. The mitten crab larvae are euryhaline and therefore able to tolerate changes in salinity and survive in a temporary refuge defined by lower salinity (Anger, 1991). Therefore, we suggest that the zoea populations are inversely related to adult populations 4 years later.

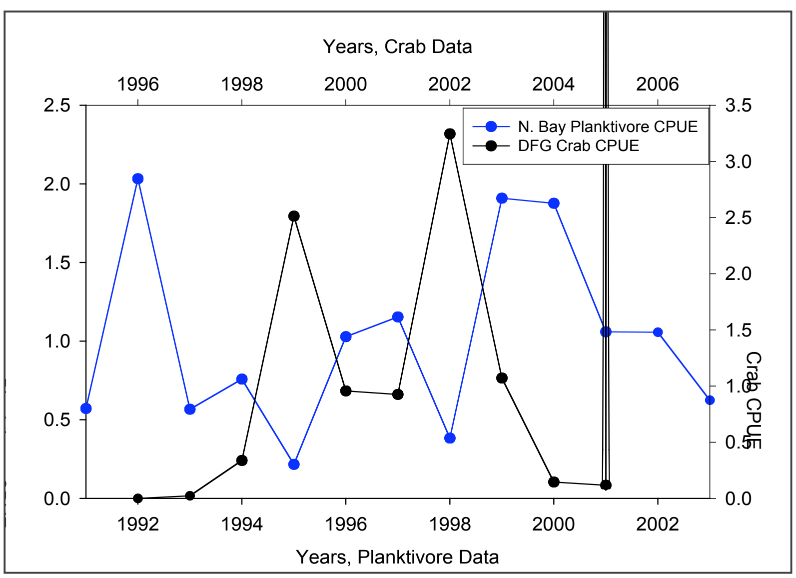

Figure 8. Comparison of planktivore abundance and adult *E. sinensis* off-set by 4 years. Initial years suggest that planktivores abundance may be inversely related to crab abundance.

Initial analyses of planktivore abundance (CaDFG) indicate that they arrive in May or June in higher abundances after Bay salinities rise to near 100% SW. Over ¾ of these planktivores are anchovies, thus we have focused on the abundance of anchovies in San Pablo Bay. We have yet to determine whether the planktivore entry into San Pablo Bay is related to temperature, salinity or daylength events.

Mitten crab zoeae density was hypothesized to directly correlate with adult abundance. Linear regression between the two variables ($N = 55$) detected a significant relationship between the adult CPUE and zoeae density, as did Pearson's correlation ($p < 0.01$; $r = 0.465$) (Fig. 9). Freshwater outflow into the San Francisco Bay Delta significantly correlates with salinity ($p < 0.0001$). Periods of high outflow caused a decrease in salinity in San Pablo Bay. Planktivore abundance in San Pablo Bay is significantly correlated with outflow ($p < 0.01$; $r = -0.375$) (Fig. 8). Monthly zoeae abundances were plotted with planktivore CPUE to determine how planktivores may be impacting zoeae (Fig. 9). Independent variation exists in both zoeae and planktivore CPUE. Northern anchovy CPUE is lowest early in the larval life history, and during this time other factors would influence larval density, such as temperature and salinity. High planktivore CPUE and low zoeae densities occur in May and June. However, neither linear regression nor Pearson's correlation detected a significant relationship between planktivore CPUE and zoeae density ($p = 0.173$; $r = 0.194$).

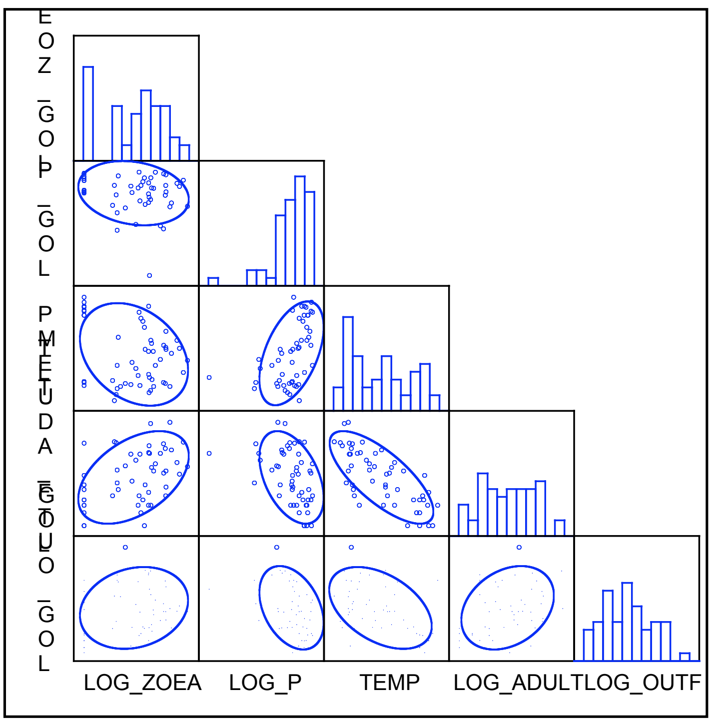

Figure 9. Multiple correlations between physical and biological variables in San Pablo Bay from December – June, 1998 – 2004. Pearson Correlation detected significant relationships between zoeae density and adult CPUE ($p < 0.01$; $r = 0.465$), and zoeae density and temperature ($p < 0.05$; $r = 0.304$); there was no relationship detected between zoeae density and planktivore CPUE ($p = 0.173$; $r = 0.194$), or zoeae density and freshwater outflow ($p = 0.183$; $r = 0.182$). A relationship exists between planktivores and freshwater outflow ($p < 0.01$; $r = -0.375$).

The current model for zoea survivorship is framed by temperature and the presence of planktivores. At one survivorship border, temperature limits survival, such that growth and development beyond stage I occurs after water temperatures rise above 11.7°C. The planktivores entering San Pablo Bay may limit the survivorship of zoea (Fig. 10). Thus, the time between temperatures rising above 11.7°C and when the anchovies enter San Pablo Bay may create a window during which mitten crab zoea can grow and development. We are hoping to test the hypothesis that the longer this temporal window, the greater number of adult crabs will be present 3-4 years later.

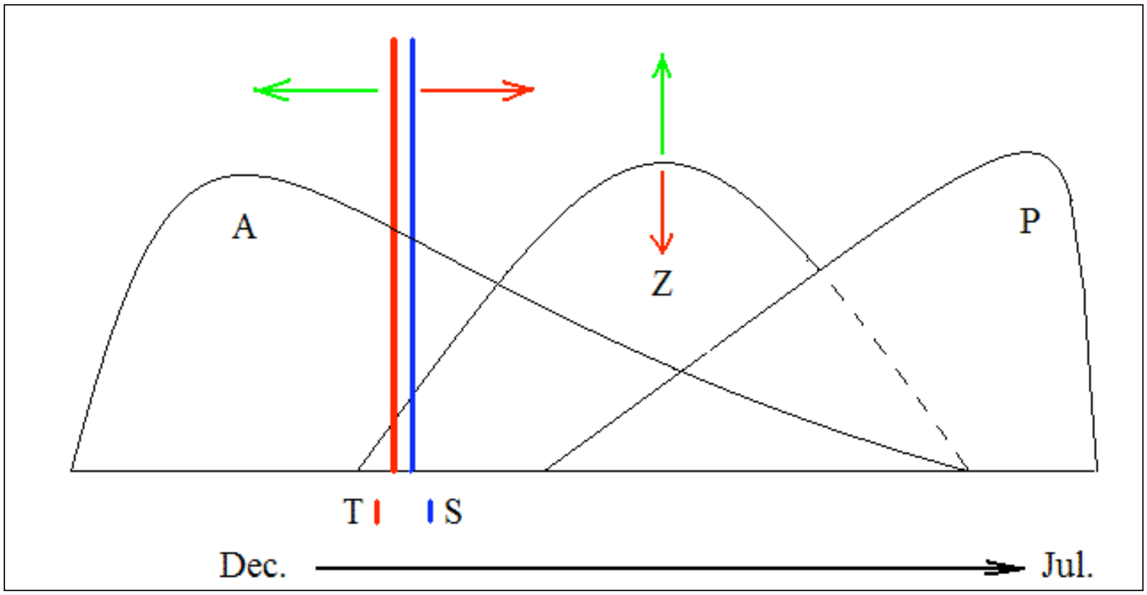

Figure 10. Model for zoeae recruitment. The number of adults that will contribute to the supply of larvae each year will depend on the number of adult crabs present when temperature (T) and salinity (S) thresholds occur. When temperature (T) and salinity (S) occur early in the season (green arrow, left) more adults (A) will contribute to the larval supply, and the zoeae density (Z) will increase (green arrow, up). When temperature and salinity occur late in the season (red arrow, right) fewer adults will contribute to the larval supply, and the zoeae density will decrease (red arrow, down). Planktivores (P) that arrive latter in the recruitment period will create predation pressure for the zoeae that remain in the system, and thus bringing an end to the recruitment period.

Patterns of zoeae development, peak densities, and annual abundance suggest that physical and biotic factors strongly influence development and survivorship of mitten crab zoeae. The timing of adult migration in relation to temperature and salinity thresholds directly affects the supply of zoeae into the system. Decreasing freshwater outflow causes salinity to increase in San Pablo Bay throughout the season, allowing planktivores to migrate into the system, and thus increase predation pressure. Physical factors and planktivores create boundaries for zoeae recruitment, between which zoeae development and survivorship are less affected. The more time that exists between these boundaries will allow larger year-classes to be recruited (Fig. 10).

1) Present data at national meeting
   a) Oct. 2004: Presentation of preliminary data to Interagency Ecological Program, Tracy, CA. "Rudnick, D. & B. Tsukimura. 2004. Preliminary results on factors affecting mitten crab abundance"
   b) Jan. 2005: Poster presentation at Annual Conference of Society for Integrative and Comparative Biology, San Diego, CA. "Rice, A. and B. Tsukimura. 2004. A key to the brachyuran zoea of the San Francisco Bay Estuary. Integr. Comp. Biol. 44:741. (Annual meeting of the Society for Integrative and Comparative Biology)"
   c) Mar. 2005, Poster presentation at the Annual meeting of the Interagency Ecological Program, Pacific Grove, CA. "Tsukimura, B., D. Rudnick, and A. Rice. 2005. Influence of Environmental Conditions on the Life History of the Invasive Chinese Mitten Crab, *Eriocheir sinensis*, in San Francisco Bay."
   d) Jul. 2005, Invited presentation (Invasive Species) at the International Crustacean Congress, Glasgow U.K. "Tsukimura, B. Rudnick, D., S.C. Blumenshine & A. Rice &. 2005. Environmental parameters as predictors of abundance of the invasive Chinese mitten crab, *Eriocheir sinensis*, in San Francisco Bay, CA, USA."
   e) Presentation at regional conference. "Rice, A., D. Rudnick, & B. Tsukimura. 2005. Monitoring larval abundance and environmental conditions to predict adult populations of the invasive Chinese mitten crab, *Eriocheir sinensis*. 26th Annual Central Calif. Research Symposium (CCRS) pp. 54."

2) Publications:
   a) Rudnick, D., T. Veldhuisen, R. Tullis, K. Heib, C. Culver, and B, Tsukimura. 2005. A life history model for the San Francisco Estuary population of Chinese mitten crab, *Eriocheir sinensis* (Decapoda:Grapsoidea). Biol. Invasions 7:333-350.
   b) Rice, A. and B.Tsukimura. 2007. An illustrated key to the brachyuran zoea of the San Francisco Bay Estuary. J. Crustacean Biology. 27:74-79.

Modifications:

1) Insufficient number of juvenile female crabs has postponed our ability to determine which environmental conditions stimulate reproduction in the mitten crabs.
2) We have started examining the planktivore populations in relation to potential predation on mitten crab zoea. The planktivore abundance is inversely correlated to freshwater outflow. These stenohaline fish are not able to tolerate decreases in salinity and may play a role in zoea survivorship.