

Optimizing Northern Crayfish *Orconectes virilis* Control Methods in Arizona Streams



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Executive Summary

The northern crayfish (*Orconectes virilis*) is an invasive species in Arizona that has numerous deleterious effects on the native flora and fauna. Control methods have been attempted in the past with little thought to the efficiency and effectiveness of particular methods. A popular control method involves trapping; however, effectiveness varies due to crayfish activity and temporal susceptibility to traps. We investigated the life history of three introduced populations of *O. virilis* within Arizona streams using mark-recapture methods. The goal was to use information on survival and reproduction to model crayfish populations, and then use sensitivity analyses to examine life history stages where crayfish could be targeted to maximize control and eradication efforts. A summary of our study is as follows:

- Initially four sites in Arizona were chosen to investigate northern crayfish life histories. Two of the sites were in southern Arizona: The San Pedro River at Charleston located between Tombstone and Sierra Vista, and Bear Creek located about 8 km west of Coronado Pass on the south side of the Huachuca Mountains. Bear Creek was later eliminated from the study as the northern crayfish population was too small for valid statistical estimations of life history characteristics. The other two sites were located in the White Mountains: Silver Creek near Show Low, and Porter Creek near Pinetop-Lakeside. At each site, a stream segment length of about 20 -50 m was studied.
- Sample sites were monitored for a year to obtain site-specific northern crayfish life history information. A sampling event consisted of 2-3 days of sampling every 4-6 weeks. Mark-recapture methodologies were used to monitor crayfish populations, and basic water quality information was obtained as well from the sites.
- A combination of Cormack Jolly Seber (CJS) open population and robust models within program MARK, and program R were used to model population dynamics.
- Dip netting, electrofishing and minnow trapping were used to capture northern crayfish at each of the sites. Of the three capture methods, the minnow trap was the most successful across all conditions. The electrofisher and dip net were impractical

because both are dependent on water clarity, whereas a minnow trap captured northern crayfish in all water conditions. It was clear that the electrofisher and dip net methods were completely unsuccessful.

- Based on mark-recapture and estimates on the probability of recapture, it appears that the best time to implement crayfish control efforts is in the fall prior to the onset of colder temperatures at which northern crayfish become inactive. It is not clear at what temperature northern crayfish become inactive, but we believe it to be in the range of 10-12° C. Both male and female crayfish are more active in the fall (mating season) and abundance is low compared to the previous months.
- It has been reported that traps are biased towards male northern crayfish. We did not see a consistent pattern of a sex bias, however we cannot rule out that the traps captured a biased selection of size or sex of northern crayfish.
- Based on length frequency data, field collections, and observations, the northern crayfish in Arizona reproduce only once annually.
- Our information on the reproduction or potential fecundity of northern crayfish was based on individuals that were collected in the wild in berry (eggs attached) as well as from crayfish that were brought into the lab and subsequently laid eggs. Counts of pleopod eggs ranged from 1-662, while the range of juveniles surviving to the 3rd instar (free swimming stage) was 46-416 per individual.
- Based on our survival and reproduction estimates our population models indicated that crayfish populations at the three sites were not viable. It is possible that the particular sites chosen were population sinks and are supported by immigration. Variances around our estimates of survival and reproduction were fairly large. Thus in a simulation where survival values were randomly drawn from a distribution with large variance, the odds are great that a low survival value would be eventually drawn causing the population to decline significantly. Despite the shortcomings of the modeling approach the mark-recapture results provided some valuable information.

- We believe that the primary reason that the simulated population models were not viable was the high level of variance around the survival estimates. High variance was a result of few recaptures (generally 10% or less) and highly variable population size. To improve crayfish survival and recapture estimates, as well as to estimate population densities, we suggest a mark-recapture program using a robust sampling approach concentrated during spring and fall periods.
- Emigration may be an important means to supplement populations in specific stream segments. In Silver Creek, precise location data was available before and after recapture for 73 northern crayfish. Forty-five northern crayfish had a net downstream movement, 22 moved upstream, and 6 had no net movement, indicating a general trend for downstream movement. Thus it was possible that downstream migrants kept the population viable. We tested the effect of an annual addition of 20 mature female emigrants on the population simulation for Silver Creek, and it resulted in a viable population.

Introduction

The northern or virile crayfish (*Orconectes virilis*) is a nuisance aquatic species thought to have entered Arizona through bait-bucket introductions and from deliberate introductions to control aquatic weeds (Dean 1969). Arizona is the only state that has no native crayfish. The negative effects of nonindigenous crayfishes on native flora and fauna are well documented (reviewed in Lodge et al. 2000). Crayfish can significantly reduce the abundance of macroinvertebrates, aquatic vascular plants, and mollusks (Fernandez and Rosen 1996, Childs 1999). The northern crayfish can prey on vertebrates such as juvenile Sonoran mud turtles (*Kinosternon sonoriense*), leopard frogs (*Rana chiricahuensis*), as well as newborn narrow-headed garter snakes (*Thamnophis rufipunctatus*: Fernandez and Rosen 1996). Northern crayfish can also compete with and prey on many fish species, such as Little Colorado spinedace (*Lepidomeda vitatta*: White 1995), and rainbow trout (*Onchorynchus mykiss*: Hepworth and Duffield 1987).

The efficacy of currently-available control methods and effects of this species on native Arizona fish and wildlife were reported in Childs (1999) and Hyatt (2004). However, little is known about the life history and tolerances of the northern crayfish itself, especially those life history characteristics that might make it vulnerable to control in Arizona. Most life history information about the northern crayfish comes from studies of northern lakes and investigations of their potential of these crayfish for aquaculture (Momot and Gowing 1977a, 1977b, 1977c). Previous Arizona studies examined northern crayfish diet and effects on ecosystems (Fernandez and Rosen 1996, Childs 1999, Carpenter 2005), and autumn distribution according to water temperature (Childs 1999).

Northern crayfish reproduce once a year in their native habitat. Both sexes reach maturation at age 1 (Momot 1967). Mating occurs in the fall with young produced the following spring. During the fall mating season, females develop a prominent white color on the ventral side of their telson, identified as the glair gland (Thorp and Covich 2001). Glair glands develop in females prior to egg extrusion and provide a mucus-like coating (glair) that helps secure the eggs to their abdomen. Cold weather is needed for ovarian development, with most crayfish becoming inactive over winter. When the female lays eggs they remain attached; once hatched, the young usually go through three molts before they are free swimming, usually in June (Thorp and Covich 2001). Male crayfish have two forms (I, II). The mature male form (I) is identified

by modifications to the first two pleopods for sperm delivery and the presence of prominent ischial hooks on legs 3 and 4 which are absent in the other form (Momot 1967, Thorp and Covich 2001). Form II males are sexually inactive. Mature male crayfish have an annual cycle where they molt to a non-reproductive form (II) in the spring and then back to the reproductive form I by the fall. The northern crayfish is generally considered a tertiary burrower; they usually remain in open water and move into burrows only during certain times (Thorp and Covich 2001). Northern crayfish create small depressions under rocks or short shallow burrows along the banks, for brooding eggs, to escape desiccation, and as a refuge from predators.

Although northern crayfish can significantly impact native ecosystems where it has invaded, few techniques have been successful for their control (Childs 1999, Hyatt 2004). In some northern systems invasive rusty crayfish (*Orconectes rusticus*) were controlled with intensive trapping and the use of smallmouth bass (*Micropterus dolomieu*; Hein et al. 2007). However, this method would not be feasible in Arizona, as smallmouth bass are not native, and could possibly create additional problems if they were introduced more widely. Thus our approach concentrated on mechanical means of capture that are readily available.

The effectiveness of most control efforts has not been evaluated. Our approach considered how resource managers might make best use of volunteers for control efforts. For example, say a volunteer group is willing to control northern crayfish at a site; but can donate only a limited effort. How can a manager best use this time and effort to maximize impact on crayfish? When should volunteers focus their efforts, and what methods should they use? Our goal is to identify methods and timing for crayfish removal to have the greatest impact on populations. Additionally we aim to provide a level of effort required to reduce crayfish abundance to some acceptable level or eradicate them and evaluate the likelihood of success.

Population viability analysis (PVA) is commonly used to model threatened and endangered populations to determine how best to use resources to ensure the viability of populations (Beissinger and McCullough 2002). Population viability analysis in conjunction with sensitivity or elasticity analyses can be used to identify specific life stages where individuals in a population are particularly vulnerable (McLeaod and Saunders 2001, Reed et al. 2002). By identifying particular life history stages that have an inordinate effect on a populations viability, one can then direct resources more efficiently and effectively to enhance a population's viability. The same concept has been used to control pest species, with the exception that the desired outcome is to create non-viable populations. This approach has been used with a variety of pest

organisms, including a plant St John's wort (*Hypericum perforatum*: Buckley et al. 2003), the Indian house crow (*Corvus splendens*: Brook et al. 2003), slugs (*Deroceras reticulatum*: Shirley et al. 2001), foxes (*Vulpes vulpes*: McLeaod and Saunders 2001), thrips (*Frankliniella occidentalis*: Wang and Shipp 2001) and locusts (*Locusta migratoria*: Scanlan et al. 2001). To control or eradicate a population the PVA concept identifies what life history stage should be targeted, and when control efforts should take place to have the greatest impact on a population. For example Govindarajulu et al. (2005) found that to have the greatest effect on population growth rates of the invasive bullfrog (*Rana catesbeiana*), metamorphs should be culled in the fall. We planned to use the same approach to optimize control and or eradication of northern crayfish in Arizona streams.

Techniques for suppressing crayfish can be extremely labor intensive, costly, or ineffective. Therefore, identifying the most vulnerable life stages of the northern crayfish is important for applying control methods with maximum impact and cost effectiveness. We had two objectives for this study: (1) to examine survival and relative abundance of life-history stages of the northern crayfish in Arizona and (2) to use this information in a model to identify the life stage and season for applying control measures to maximize the impact on northern crayfish populations.

Methods

Initially four sites in Arizona were chosen to investigate northern crayfish life histories (Figure 1). Two of the sites were in southern Arizona: The San Pedro River at Charleston located between Tombstone and Sierra Vista, and Bear Creek located about 8 km west of Coronado Pass on the south side of the Huachuca Mountains. Bear Creek was later eliminated from the study as the northern crayfish population was too small for valid statistical estimations of life history characteristics. The other two sites were located in the White Mountains: Silver Creek near Show Low, and Porter Creek near Pinetop-Lakeside. At each site, a stream segment length of about 20 -50 m was studied.

The sampling site in the San Pedro River a dynamic system with highly variable flow was located at an approximate elevation of 1200 m above mean sea level. The San Pedro River contained many non-native species (all found at our sampling site) including largemouth bass (*Micropterus salmoides*), yellow bullhead (*Ameiurus natalus*), channel catfish (*Ictalurus punctatus*), green sunfish (*Lepomis cyanellus*), mosquitofish (*Gambusia affinis*), common carp

(*Cyprinus carpio*), and bullfrog. The native fishes present at our sampling site in the San Pedro included the desert sucker (*Catostomus clarkii*), and longfin dace (*Agosia chrysogaster*).

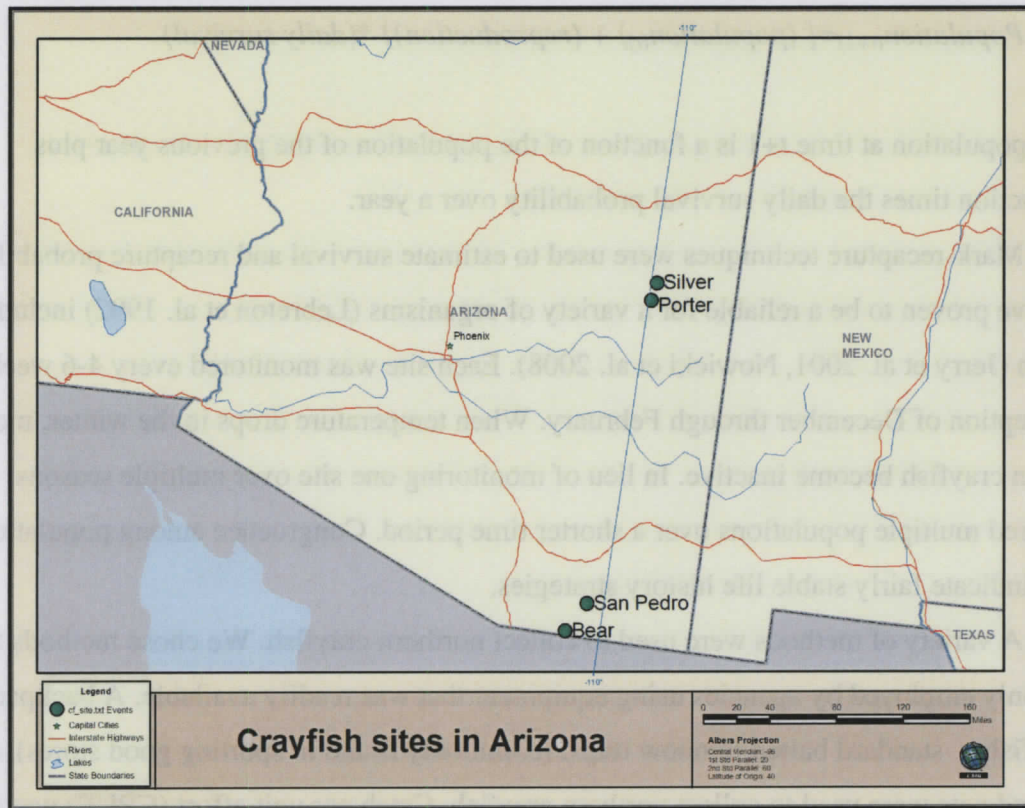


Figure 1. Location of sample sites to study northern crayfish life history in Arizona

The sampling site in Porter Creek was located in the White Mountains, in Pinetop/Lakeside at an elevation of approximately 2000 m above mean sea level. Porter Creek flows from a reservoir (Scott Lake), and has a variety of nonnative species, including bullfrog, green sunfish, black bullhead (*Ameiurus melas*), and fathead minnow (*Pimephalas promelas*).

The sampling site in Silver Creek a spring-fed stream also in the White Mountains of Arizona, was east of Show Low at an elevation of approximately 1860 m above mean sea level. Fishes present in Silver Creek included Apache trout (*Oncorhynchus gilae apache*), speckled dace (*Rhinichthys osculus*), bluehead sucker (*Catostomus discobulus*), western mosquitofish, and fathead minnow. A hatchery for Apache trout, operated by the Arizona Game and Fish Department was located at the headwaters of the creek.

Sample sites were monitored for a year to obtain site-specific life history information. We developed simple linear models to simulate population dynamics of the northern crayfish at each site based on survival and reproduction. An example of the basic population model is presented below:

$$Population_{(t+1)} = [(population_{(t)}) + (reproduction)] *(daily\ survival)$$

Where population at time $t+1$ is a function of the population of the previous year plus reproduction times the daily survival probability over a year.

Mark-recapture techniques were used to estimate survival and recapture probabilities as they have proven to be a reliable for a variety of organisms (Lebreton et al. 1992) including crayfish (Jerry et al. 2001, Nowicki et al. 2008). Each site was monitored every 4-6 weeks with the exception of December through February. When temperature drops in the winter, most northern crayfish become inactive. In lieu of monitoring one site over multiple seasons, we monitored multiple populations over a shorter time period. Congruence among populations would indicate fairly stable life history strategies.

A variety of methods were used to collect northern crayfish. We chose methods that were commonly employed by agencies using equipment that was readily available. A backpack electrofisher, standard baited minnow traps, (commonly found in sporting good stores), and dip nets/hand nets were used to collect northern crayfish. Catch per unit effort (CPUE) was recorded for each method used. The idea was to identify the most effective method and evaluate effects of external factors such as season, sex, temperature, and water velocity on catch rates. Estimates of recapture probabilities can be used to maximize effectiveness of collection methods.

On each sampling event water temperature ($^{\circ}\text{C}$), specific conductivity ($\mu\text{m S/cm}$), and pH were measured using a handheld monitor (EC-400-Exstik[®] by Extech). Total hardness (CaCO_3) was measured with a Hach Model 5B test kit. Water velocity and flow were also calculated when possible (flows >0.1 m/second) using a flow probe (FP202, Global Water Instrumentation Inc.). Flow for the San Pedro River site was obtained from the United States Geological Survey (USGS), as a gauge was located just upstream of our sampling site.

A sampling event consisted of 2-3 days of sampling every 4-6 weeks. Minnow traps were the primary means of collecting northern crayfish, as traps were not dependent on water clarity for use. Both dip netting and electrofishing were dependent on the water clarity, as one had to see crayfish for these methods to be effective. Crayfish have a different response to an electric

current than fish. Fish can be attracted to the current (taxis) and go into tetany (muscle paralysis) or narcosis, while crayfish do neither (Alonso 2001). Crayfish generally will attempt to escape the electric field by with rapid tail flips. Crayfish are not attracted to the anode, nor are they generally stunned by the electric current. Minnow traps were baited with either dead fish or small cans of fish-based cat food. The number of traps used varied from 10-14 in the San Pedro River, 8-9 in Porter Creek, and 10-14 in Silver Creek. One to 3 traps were generally set outside the designated sampling area to check for crayfish that might have moved outside of the study site. During the sampling event, traps were set out in the evening on the first day of sampling and checked in the morning. The traps were then reset by early afternoon the second day, left overnight again, and checked the following morning (day 3). During June when northern crayfish were abundant and CPUE was high, traps were checked multiple times throughout the day.

All northern crayfish collected above 13 mm (carapace length) were sexed and carapace length recorded before being released. Northern crayfish above 18 mm were marked with individually numbered visible implant (VI Alpha tags) fluorescent elastomer tags (Northwest Marine Technology Inc., Shaw Island, Washington, USA) injected into abdominal tissue (Parkyn et al. 2002). Only crayfish collected within the defined sampling site were tagged. Those caught outside the defined study site were examined for previous tags and those not previously marked were released without being tagged. Male crayfish were identified as to their form (Form I, II) and females were observed for glair gland development.

For each minnow trap set we measured the water depth and the sex ratios of crayfish captured in each trap. To determine if the traps were sex biased we used a matched pairs t-test, by sample date and site. To test if there was a difference in length between the sexes we conducted a matched pairs t-test using the mean length by sample date and site.

Apparent survival and recapture probabilities were estimated using program MARK (White and Burnham 1997). Apparent survival is the probability of surviving between successive sampling occasions, with the assumption that the animal has not permanently emigrated from the sampling site. Permanent emigration is indistinguishable and treated the same as mortality. Thus emigration was not included in the population model. Both Porter Creek and the San Pedro River were intermittent downstream of our sampling sites. Thus any northern crayfish that had moved downstream of the sampling site were effectively removed from the population and had most

likely died. The recapture probability is the probability of an individual being captured at a site given that it is alive.

Our field sampling protocol was designed with the intent to use the robust model within program MARK to obtain survival and recapture probabilities. A robust model involves sampling at two temporal scales incorporating a closed population and an open population component (Nichols 2005). With a closed population component (consecutive days of sampling), population size can be estimated. The closed population model assumes there is no reproduction, emigrations or deaths during this time period, i.e. the population is stable. These assumptions for a closed population cannot be made when sampling is every four to six weeks, migration, death and reproduction could occur during the time interval. Using an open population model one can only estimate survival and recapture probabilities.

The few northern crayfish recaptures in spring and early summer of 2007 proved problematic. With so few recaptures, program MARK was unable to arrive at a solution based on the robust model parameters. Consequently, we resorted to using an open population model (Cormack Jolly Seber [CJS]) within program MARK to estimate apparent survival and recapture probabilities for all three sites (Cormack and Alpizar-Jara 2005, Nichols 2005). The CJS model does not differentiate between emigration and death, nor provide population estimates, thus we could not include emigration/immigration in subsequent population models, nor estimate population size.

A variety of different candidate models were developed within MARK using the CJS framework to estimate survival and recapture. Within the convention of Program MARK apparent survival is represented by “ Φ ”, and recapture probabilities by “ p ”. We use this notation throughout this paper. We used parameter size adjusted Akaike’s Information Criterion (AIC_c) values to identify the best model based on maximum likelihood (Burnham et al. 1995, Burnham and Anderson 1998). Candidate models tested included various permutations with factors such as sex, sampling date, length (at first capture), flow, and temperature. Once the most parsimonious model(s) was selected within MARK, we then used Markov Chain Monte Carlo (MCMC) sampling (~30,000 - 50,000 samples) in a Bayesian framework to estimate model parameters. Maximum likelihood values generated from the model with the most support in MARK were used as prior beta estimates and standard errors for the MCMC analysis (Brooks 1998). The MCMC analyses results in distributions of possible solutions for survival and recapture probabilities. MCMC posterior distributions were examined using Convergence

Diagnostic and Output Analysis software (CODA[®]: Best et al. 1995, 1997) within the freeware program R (version 2.6.2, R Development Core Team 2007) to optimize the MCMC sampling and to ensure that stationarity and convergence was reached. The CODA program is a way to analyze results from MCMC posterior distributions to ensure that enough samples were run in the MCMC and that an acceptable solution was reached. Our population simulations used these posterior distributions of survival probabilities. In a population simulation, random survival values are selected from the appropriate posterior distribution generated from MCMC sampling, as opposed to using means and standard deviations.

The other major component of our population model was reproduction. A measure of reproduction is essential for adequately modeling population dynamics. For our population models we used the number of free-swimming juveniles per female as a reproductive measure, as this incorporates mortality of eggs, hatching, and the first 2 molts.

A field and laboratory approach was used for estimating the number of attached eggs and the number of free-swimming juveniles. In the spring we collected females with eggs at each site, and counted the number of attached eggs. To estimate the number of free-swimming juveniles produced by individual females, crayfish were collected in the fall and maintained in the lab over winter with the hope that they would then produce eggs and subsequently free-swimming juveniles the following spring. Crayfish need 4 months of cold water (less than 12° C) and darkness for ovarian development and egg laying (Aiken 1969, Portelance and Dubé 1995). Approximately 43 female crayfish were placed in a cool room (12° C), while others (n = 80) were kept at ambient laboratory temperature. Crayfish were monitored for eggs produced and or the number of free-swimming crayfish produced (3rd instar). All eggs that are laid do not remain attached to the female, nor do all attached eggs hatch and survive to become free-swimming juveniles (Dean 1969, Momot and Gowing 1977a).

The percentage of females that reproduce was another important factor to incorporate in our population models. Unfortunately, we had little confidence that we could use our laboratory measurements to estimate this factor. We did not know if northern crayfish had mated prior to collection or not. All females developed glair glands in the laboratory (indicative of being mature), but not all subsequently extruded eggs. It is very difficult to measure the percent of females that reproduce in the wild. In the spring when females extrude their eggs, they are less susceptible to capture (Hazlett et al. 1979), and of those that are captured without eggs, it is unknown whether they have reproduced or not without dissection. Mitchell and Smock (1991) in

Virginia observed that 55 % of age 1 northern crayfish females collected in November extruded eggs, while Weagle and Ozburn (1972) estimated that 65% of females reached maturity during the first year in a northwestern Ontario population northern crayfish. For the proportion of females reproducing within a population we used a random normal distribution created with a mean of 0.60 and a standard deviation of 0.05 based on values reported in the literature (Weagle and Ozburn 1972, Mitchell and Smock 1991). Each female in the simulated population was assigned an individual offspring value (number of offspring produced) for each year of the simulation. The offspring value was randomly drawn from a distribution based on the measured mean and standard deviation of free-swimming young obtained from our laboratory experiment. As population simulations were only based on females, we used half of the estimated young hatched (assuming equal sex ratios). For population simulations we used random daily survival values drawn from the posterior distributions created in the MCMC procedure equivalent to the number of days between sampling intervals. All population modeling and simulation was conducted in program R. Program R code and annotation for population models are provided in Appendix B.

The population model used for each site depended on the results of the most parsimonious model(s) selected within program MARK. Thus each site had a slightly different population model. The same reproductive values (percent reproducing and free-swimming juveniles produced) were used for each site and population model simulations; however survival rates varied by site. One of the simplest population models was one where survival rates did not vary across sampling dates or by sex. In this simple model, annual survival was estimated by simply taking the product of a random sample of 365 survival values from the posterior survival distribution for that site. This is the basic population model that was used for Silver Creek and Porter Creek.

A slightly more complicated model was required for simulating populations within the San Pedro River. Time (sampling date) was a significant factor on survival, thus for modeling the population we had to account for varying survival probabilities among sampling dates. Using a linear based population model, apparent survival was divided into 22 time blocks that corresponded with the 22 intervals between sampling. We randomly selected daily survival values equivalent to the number of days between sampling intervals from the MCMC posterior survival distributions (created from 30,000 values) generated from the most parsimonious model identified within Program MARK.

Results

Water quality results are summarized in Table 1. Flow measurements from Porter Creek were lacking for most sample events as the flow was rarely above 0.01m/s, the minimum water velocity recorded by our meter. Flow values for San Pedro were obtained from the USGS gauge, and downloaded from the World Wide Web (<http://water.usgs.gov/>) (Figure 2). The San Pedro River generally had higher pH, specific conductivity and total hardness than the other two sites. Temperature readings could be quite variable depending on the time of day. For example, on July 25, 2007, water temperature in Porter Creek ranged from 15.5 °C at 7:25 am, to 25.1 °C by 11:27 am.

Table 1. Range of physical measurements at each sample site

Site	pH	Specific Conductivity (µmS)	Temperature (°C)	Total hardness (CaCO ₃ mg/l)
San Pedro River	8.2 – 10	274 - 499	11 - 29	154 – 239
Porter Creek	7.0 - 9.48	78.8 - 270	2.4 – 28	103 – 205
Silver Creek	7.1 - 9.4	93.8 - 155	6.0 - 26	68.4 - 103

Crayfish collection

Of the three methods for capturing northern crayfish the minnow trap was the most successful across all conditions. The electrofisher and dip net were impractical because both are dependent on water clarity, whereas a minnow trap captured northern crayfish in all water conditions. It was clear that the electrofisher and dip net methods were completely unsuccessful, so we did not statistically test their effectiveness compared to the minnow trap. Crayfish were not collected at any of the sites in July as a result of high water.

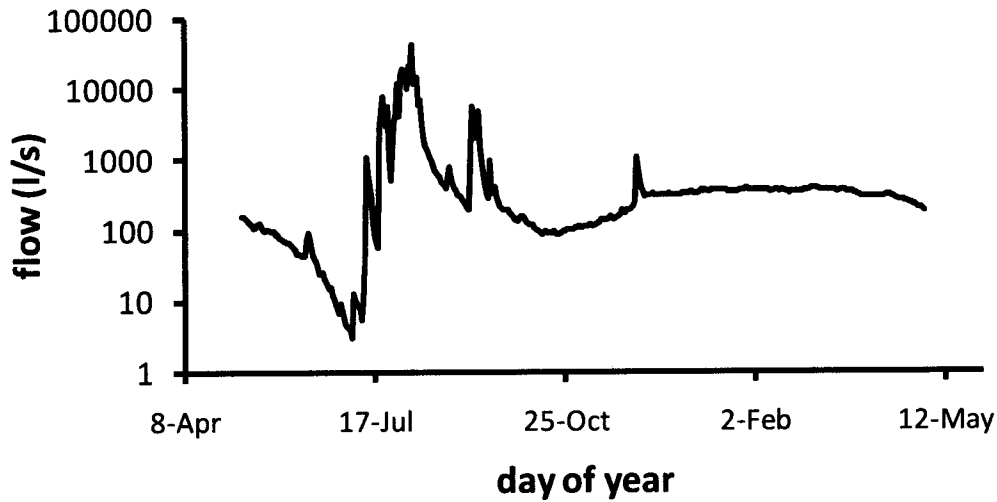
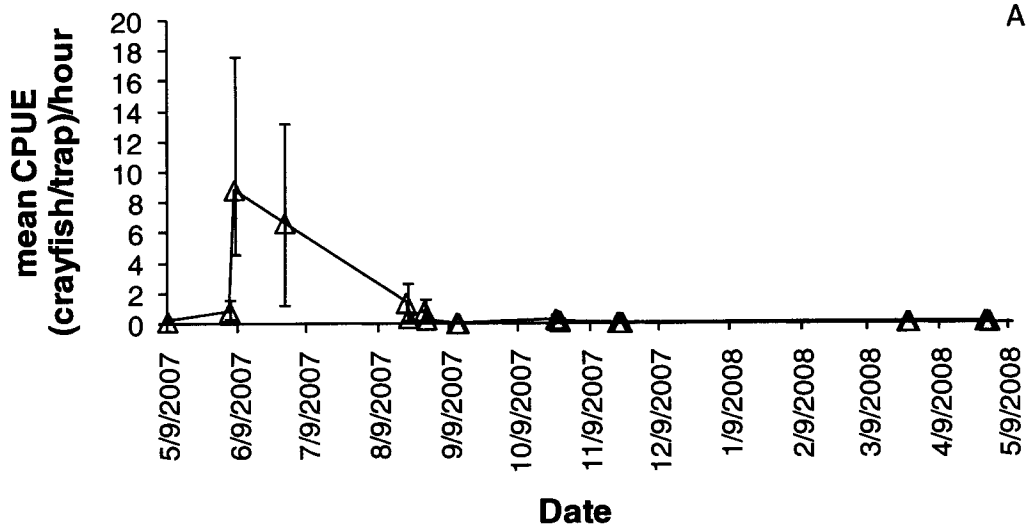


Figure 2. Mean daily water flow in the San Pedro River at the Charleston USGS monitoring gauge from 8 May 2007 to 1 May 2008, the length of our study.

We marked 832, 704, and 908 crayfish at San Pedro River, Porter Creek, and Silver Creek respectively. Mean CPUE changed dramatically throughout the year (Figure 3). Silver Creek and Porter Creek had similar temporal patterns in mean CPUE (Figures 3).



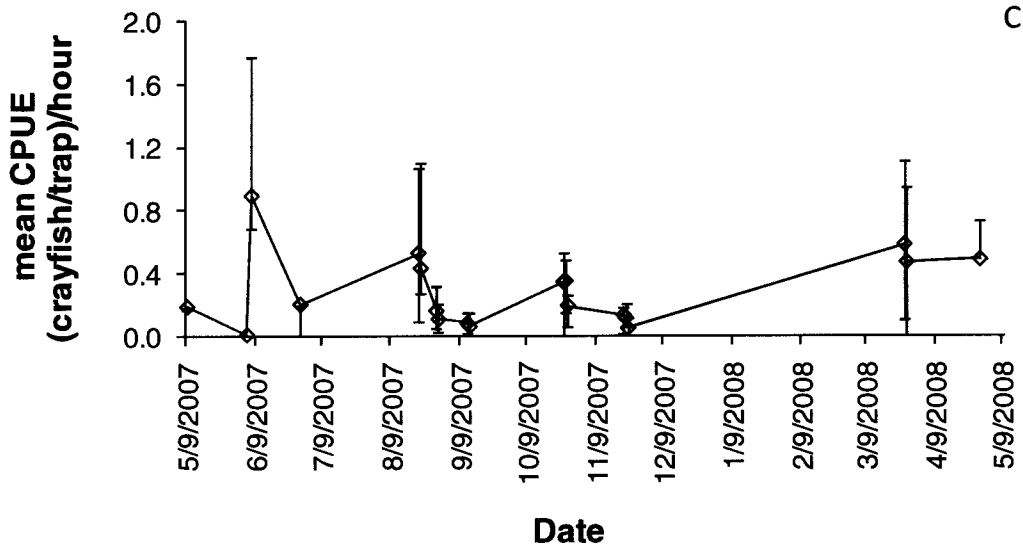
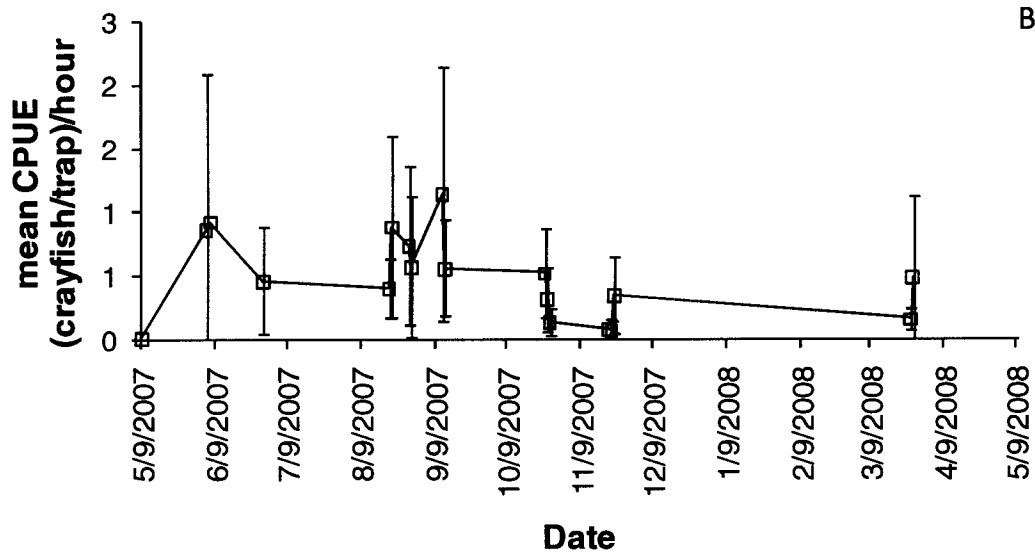


Figure 3. Mean catch per unit effort of northern crayfish by date at San Pedro River (A), Porter Creek (B), and Silver Creek (C), Arizona, from minnow traps (error bars are standard deviations)

Sex ratio

Combining all methods of capture across all sites, there was no significant difference in the number of males or females captured across sites (Paired *t*-test; $P = 0.4904$; Table 2). For each trap the number of crayfish caught was recorded as well as the sex of each. We examined the mean percentage of females per trap across time by site (Figure 4). In a matched pairs two-tailed *t*-test, minnow traps set in Silver Creek averaged significantly more females ($\bar{x} = 5.1$) than males ($\bar{x} = 3.3$; $P < 0.001$). In the San Pedro River mean number of each sex caught in minnow

trap sets was not a significantly different ($P = 0.225$), while in Porter Creek, more males on average ($\bar{x} = 3.08$) were caught than females ($\bar{x} = 2.08$) in minnow trap sets ($P = 0.0019$).

Table 2. Crayfish sex ratio by site

Site	Females	Males
Bear Creak	39	36
Porter Creek	318	431
Silver Creek	503	374
San Pedro	518	478

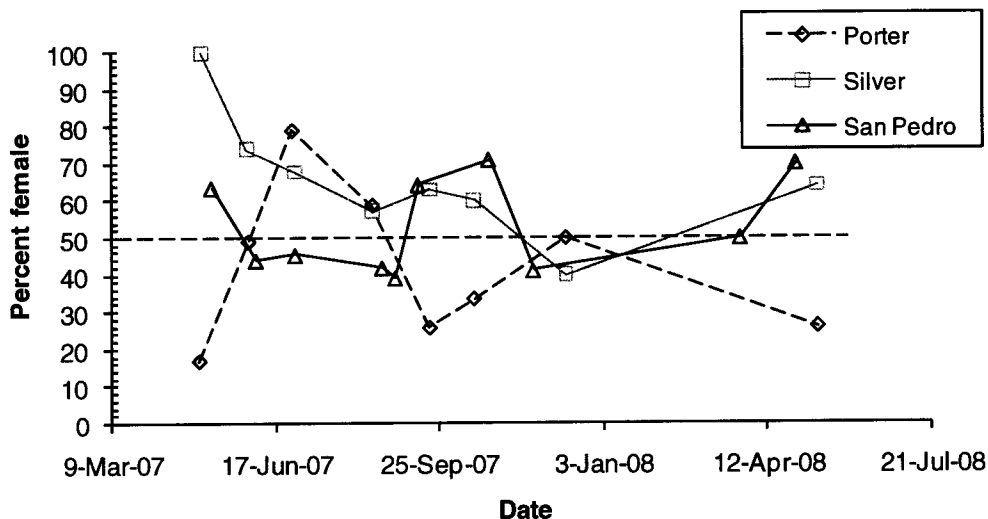


Figure 4. Mean percent female northern crayfish collected from minnow traps at three sites in Arizona, grouped by sampling event.

Growth

Growth rate of northern crayfish was fairly constant, May through October (Figure 5). In the San Pedro River, two cohorts were present during the first two sampling periods (Figure 5, top). Northern crayfish from the previous year were generally greater than 32 mm carapace length and were differentiated from young-of-the-year by size. After July, there appeared to be a single size cohort present in the San Pedro River. Crayfish length frequency distributions of Porter Creek and Silver Creek showed a pattern of two different cohorts only within the first sample occasion. We looked at growth in more detail in the San Pedro River. Of 13 crayfish recaptured after 25 October 2007, none had increased in length (thus no molting).

Female crayfish (mean carapace length = 34.4 mm) were significantly larger than males (mean carapace length = 32.8 mm) in Silver Creek (matched pair t -test: $DF = 14$, t -ratio = -2.28,

$P = 0.0380$). There was no significant difference between sexes at Porter Creek (matched pair t -test: $DF = 15$, t -ratio = 0.664, $P = 0.518$), or in the San Pedro River (matched pairs t -tests: $DF = 15$, t -ratio = -1.57 = 0.137, $P = 0.137$).

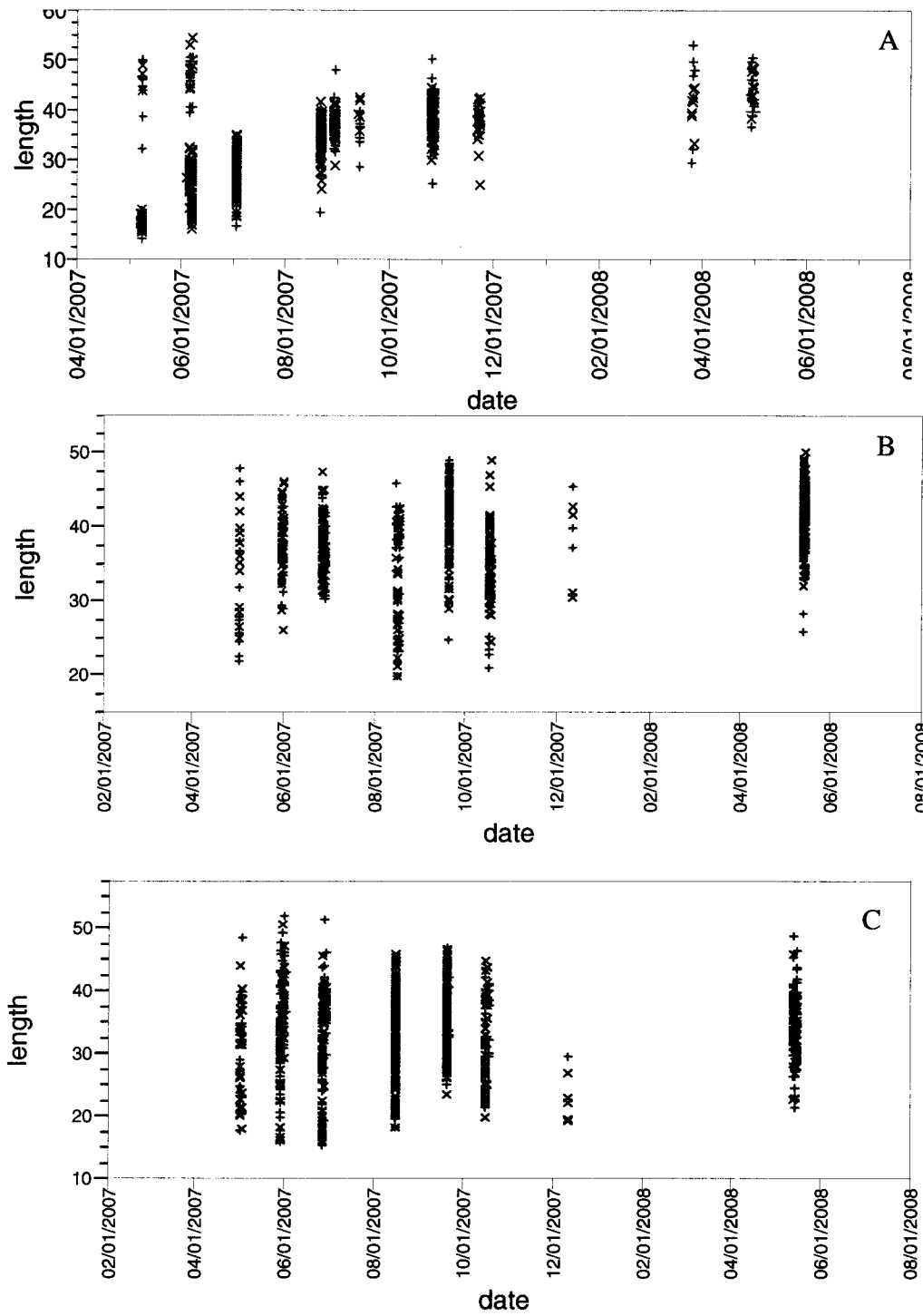


Figure 5. Length of crayfish collected in A) San Pedro River, B) Porter Creek and C) Silver Creek (x = male, + = female).

Reproduction

Juvenile crayfish were only observed from approximately May through the end of June, suggesting that northern crayfish have only one reproductive season a year. We had little success collecting crayfish with attached eggs at our sites in spring.

Maintaining northern crayfish in a cold room (at 10° C) did not seem to stimulate egg production in females. Only 4 out of 37 northern crayfish produced eggs after 5 months in the cold room. Interestingly, a higher percentage of crayfish kept in an unheated lab room produced eggs compared to those in the cold room. Many of the crayfish did not retain their eggs to hatching. The majority of northern crayfish that produced eggs in the lab were collected at Rose Canyon Lake, in the Santa Catalina Mountains (Pima County, AZ). These crayfish were collected later in the year (November) than other northern crayfish from the research sites that were retained for fecundity measurements. Results of the reproductive measurements are provided in Appendix A.

The number of eggs attached to pleopods was positively correlated with female carapace length, while the number of free-swimming juveniles was not (Figure 6). One female collected in July and maintained in isolation in the lab successfully extruded eggs over winter. This would suggest that females can maintain viable sperm for an extended period, potentially over one year (Reynolds 2002), or that they will produce eggs even if they are not fertilized.

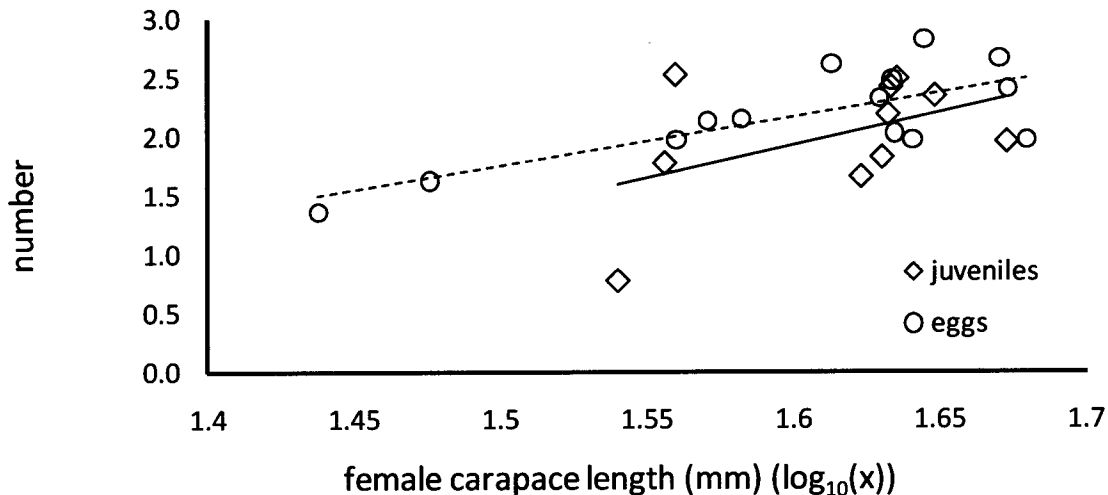


Figure 6. Female length and number of juvenile crayfish hatched (3rd instar) ($R^2 = 0.21$, $P=0.18$) and number of attached pleopod eggs ($R^2 = 0.54$, $P= 0.026$). All values $\log_{10}(x)$ transformed to approximate normality.

Mark-recapture

Program MARK – survival and capture probability

The VIA tags did not appear to affect survival or growth of crayfish. All of the marked crayfish in the lab survived (437 days) and all of the controls survived that did not escape from their containers. Three of the 12 tagged crayfish molted; two of those molted twice. Tags were retained and readable in all laboratory crayfish.

Of the 832 northern crayfish marked in the San Pedro River, 111 individuals were recaptured, and 39 of those were recaptured more than once. For the San Pedro River, twenty models were examined in program MARK (Table 3). Model 1 was the most parsimonious model based on AICc, and this was used in the MCMC analysis to determine survival and recapture probabilities. Flow was not identified as a significant factor in northern crayfish survival or recapture in the San Pedro River. There were not significant differences in survival or recapture probabilities between males and females. Apparent mean daily survival (Figure 7) and recapture probabilities (Figure 8) varied across time, with age having a significant effect on survival (Table 3). Crayfish were classified as either being age 1 or young-of-the-year based on length at first capture.

Table 3. Cormack-Jolly-Seber open population model selection result summary for northern crayfish in San Pedro River from program MARK.

	Model	AICc	Delta AICc	AICc weights	Model likelihood	Num. par.	Deviance
1	Phi (time+age) p(time+length)	970.46	0.000	0.505	1.000	46	873.85
2	Phi (time)p(time+length)	971.27	0.813	0.336	0.666	45	876.86
3	Phi (time+age+flow) p(time+length)	974.56	4.11	0.0648	0.128	47	875.75
4	Phi (time+age) p(time+length+age)	975.15	4.70	0.0483	0.0957	46	878.54
5	Phi (time+age+length) p(time)	976.97	6.51	0.0194	0.0385	46	880.36
6	Phi (time+age) p(time)	977.33	6.87	0.0163	0.0323	46	880.72
7	Phi (time+length) p(time)	979.48	9.02	0.00555	0.0110	43	889.46
8	Phi(time) p(time)	980.42	10.0	0.00346	0.0069	43	890.40
9	Phi (time+flow) p(time+length)	982.10	11.6	0.0015	0.0030	48	881.09
10	Phi (time) p(sex*time)	1000.6	30.1	0.000	0.000	65	861.27
11	Phi (sex*time) p(time)	1005.1	34.6	0.000	0.000	65	865.74
12	Phi (time+age+sex.a) p(time+length)	1007.8	37.3	0.000	0.000	67	863.83
13	Phi (sex) p(time)	1024.7	54.2	0.000	0.000	24	975.37

14	Phi (time) p(sex)	1027.9	57.4	0.000	0.000	24	978.62
15	Phi (time+age+sex*age) p(time+length+time*length)	1029.4	58.9	0.000	0.000	88	835.91
16	Phi (sex*time) p(sex)	1038.3	67.8	0.000	0.000	42	950.46
17	Phi (sex*time) p(sex*time)	1038.4	68.0	0.000	0.000	86	849.77
18	Phi (sex) p(sex*time)	1045.6	75.1	0.000	0.000	46	948.98
19	Phi (sex) p(sex)	1112.5	142	0.000	0.000	4	1104.4
20	Phi (.) p(.)	1115.5	145	0.000	0.000	2	1111.5

Phi = survival factors

p= recapture factors

flow = cubic foot per second of water

Time = sampling date

npar = number of parameters

(.) = indicates one factor for the parameter

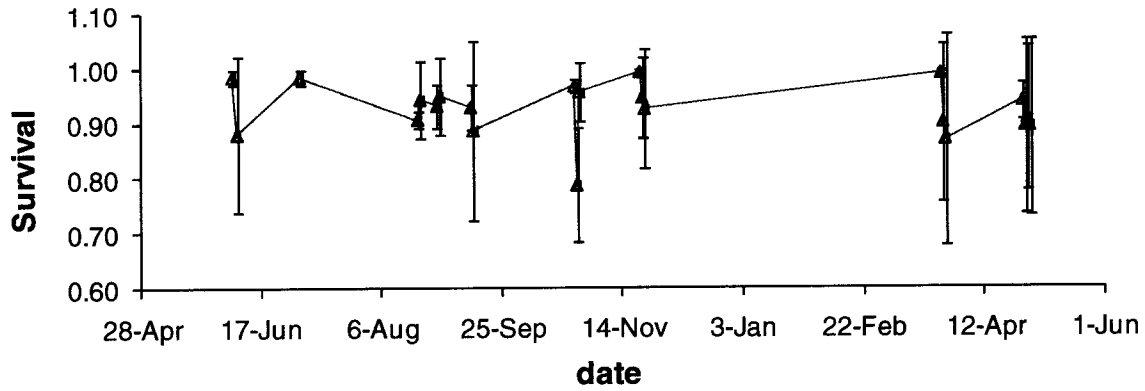


Figure 7. Northern crayfish apparent survival estimates for the San Pedro River from an MCMC analysis of the best-fitting open population model selected from Program MARK.

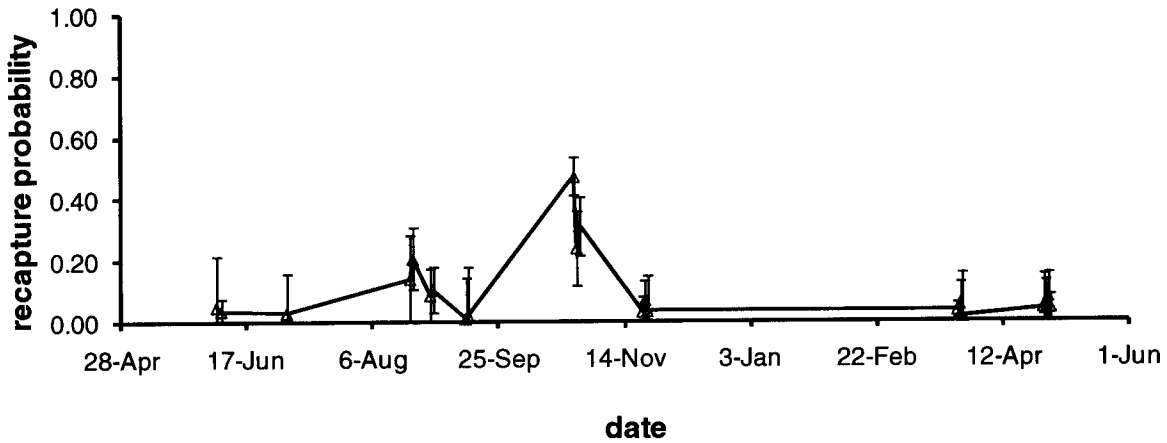


Figure 8. Recapture probability of northern crayfish in the San Pedro River from an MCMC analysis of the best-fitting open population model selected from program MARK.

Of the 704 crayfish marked within Porter Creek, 77 individuals were recaptured once and eight more than once. Sixteen open population models were examined in program MARK (Table 4). Model 1 was the most parsimonious model based on AICc, and this was used in the MCMC analysis to determine survival and recapture probabilities. Recapture probabilities varied across time (Figure 9), but survival probabilities did not. Apparent mean daily survival differed by sex. Apparent mean daily survival probabilities for female crayfish in Porter Creek was 0.9790 (SD = 0.0061347), and for males it was 0.992345 (SD=0.001519590). Although water temperature values were recorded for each sampling date, the values differed substantially depending on the time of day the readings were recorded. As a result of the high daily variance, we use mean air

temperature data from the nearest weather station (Show Low Airport) as a proxy for water temperature.

Table 4. Cormack-Jolly-Seber open population model selection result summary for northern crayfish in Porter Creek from program MARK.

	model	AICc	Delta AICc	AICc weights	Model likelihood	Num. par.	Deviance
1	Phi(sex) p(time)	724.2	0.000	0.487	1.000	21	680.9
2	Phi (sex+length) p(time)	725.3	1.02	0.293	0.602	22	679.8
3	Phi (g*length) p(time)	725.9	1.61	0.218	0.447	23	678.2
4	Phi(.) p(time)	735.3	11.1	0.002	0.004	20	694.1
5	Phi(sex+temp) p(time+length)	741.6	17.4	0.000	0.0002	39	658.9
6	Phi(t) p(time)	739.3	15.1	0.000	0.001	38	658.8
7	Phi(sex) p(time +length)	743.2	19.0	0.000	0.000	23	695.6
8	Phi(sex+length) p(time +length)	744.9	20.6	0.000	0.000	23	697.2
9	Phi(sex) p(sex*time)	750.1	25.9	0.000	0.000	40	665.1
10	Phi(sex* time) p(time)	756.2	32.0	0.000	0.000	53	641.3
11	Phi(t) p(sex*time)	766.9	42.6	0.000	0.000	57	642.5
12	Phi(time) p(sex)	772.5	48.2	0.000	0.000	21	729.1
13	Phi(sex*time) p(sex*time)	775.5	51.2	0.000	0.000	66	629.4
14	Phi(sex*time) p(sex)	788.8	64.5	0.000	0.000	38	708.3
15	Phi(sex) p(sex)	807.8	83.6	0.000	0.000	4	799.8
16	Phi(.) p(.)	835.4	111	0.000	0.000	2	831.4

Phi = survival factors

P = recapture factors

Time = sampling date

Num. par. = number of parameters

temp. = mean daily temperature

(.) = indicates one factor for the parameter

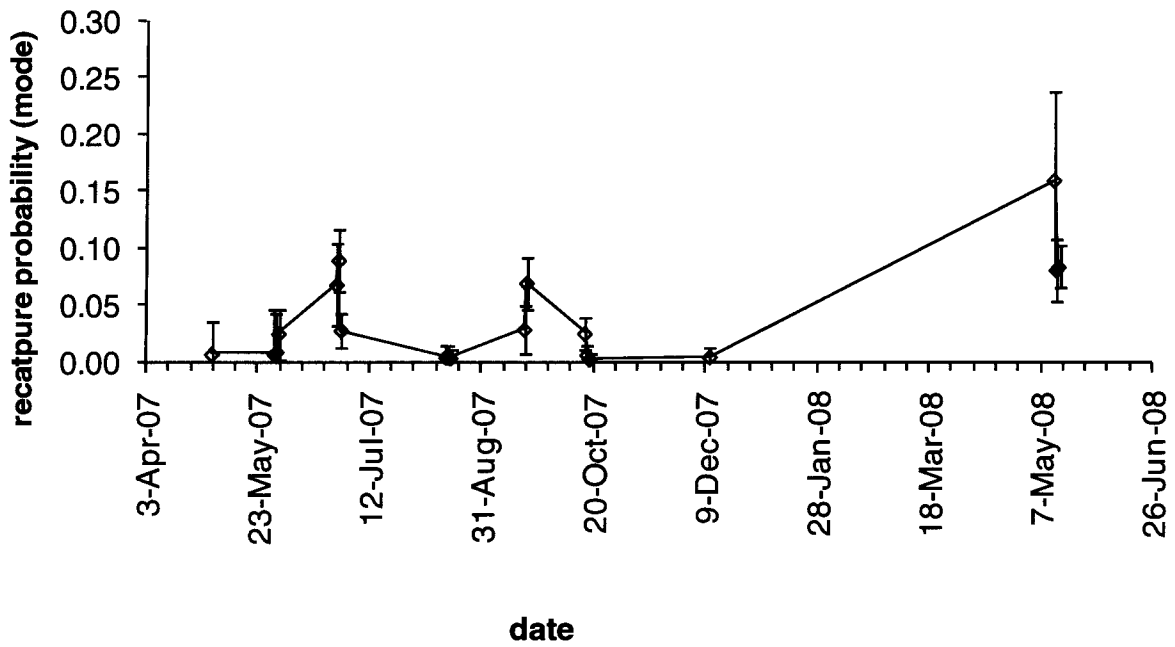


Figure 9. Recapture probabilities for crayfish within Porter Creek and standard deviations obtained from an MCMC analysis of model 1 from Table 4.

Of the 908 crayfish marked at Silver Creek, 84 were recaptured at least once, and of those 13 crayfish were recaptured 2 or more times. For Silver Creek, 15 open population models were examined in program MARK (Table 5). Model 1 was the most parsimonious model based on AICc, and this was used in the MCMC analysis to determine survival and recapture probabilities (50,000 samples). Recapture probabilities varied across time (Figure 10), but mean daily survival did not. Apparent mean daily survival differed by sex. Mean daily survival for female crayfish was 0.9876157 (SD = 0.0017400) and for males it was 0.984116 (SD=0.0025096).

Table 5. Cormack-Jolly-Seber open population model selection result summary for northern crayfish in Silver Creek from program MARK.

	model	AICc	Delta AICc	AICc weights	Model likelihood	Num. par.	Deviance
1	Phi(sex) p(time+length)	974.1	0.00	0.999	1.000	23	927.0
2	Phi(sex+length) p(time+length)	989.3	15.12	0.00052	0.0005	24	940.0
3	Phi(sex) p(time)	992.6	18.48	0.0001	0.0001	22	947.5
4	Phi(sex+length) p(time)	996.2	22.07	0.00002	0.000	24	946.9
5	Phi(time) p(time)	998.0	23.89	0.00001	0.000	40	914.5
6	Phi(sex+length) p(time*length)	1001	27.31	0.000	0.000	43	911.4
7	Phi(time+temp) p(time)	1002	27.86	0.000	0.000	41	916.3
8	Phi(time) p(sex)	1019	44.77	0.000	0.000	22	973.8
9	Phi(sex*time) p(time)	1020	45.57	0.000	0.000	60	891.7
10	Phi(sex*time) p(sex*time)	1047	72.77	0.000	0.000	78	877.1
11	Phi(.) p(sex)	1049	74.71	0.000	0.000	3	1043
12	Phi(sex)length p(time)	1049	74.76	0.000	0.000	22	1004
13	Phi(sex) p(.)	1049	74.99	0.000	0.000	3	1043
14	Phi(.) p(.)	1049	75.10	0.000	0.000	2	1045
15	Phi(sex) p(sex)	1051	76.37	0.000	0.000	4	1042

Phi = survival factors
 p= recapture factors
 time = sampling date
 Num. par. = number of parameters
 temp = mean daily temperature
 (.) = indicates one factor for the parameter

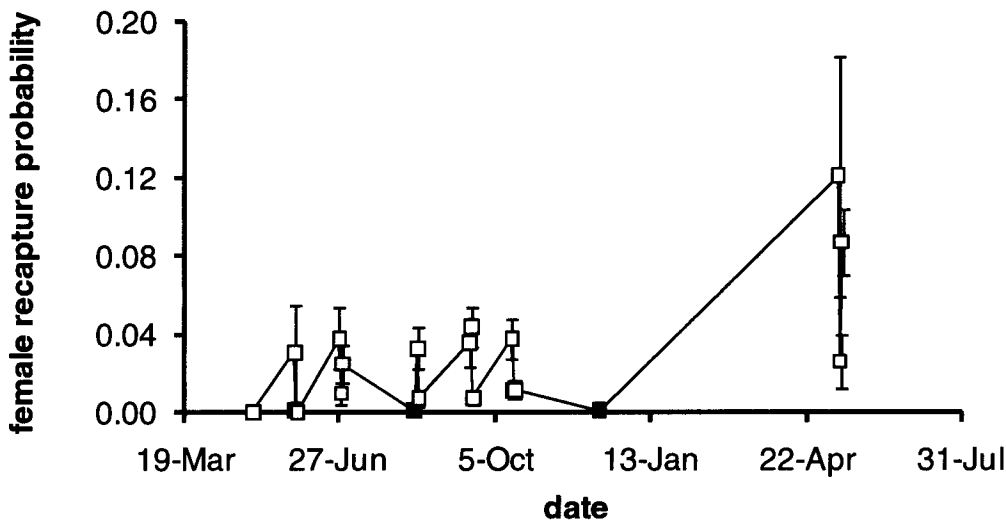


Figure 10. Recapture probabilities for northern crayfish within Silver Creek and standard deviations obtained from an MCMC analysis of the best-fitting open population model selected from program MARK. Recapture probabilities for three dates were not estimable and are indicated by a solid square and given a value of zero (31 May, 15 August, and 11 December).

Population modeling

San Pedro River

In the most parsimonious model identified in the model selection procedure within Program MARK, survival of San Pedro River crayfish was dependent on time and age with recapture dependent on time and length. The next best model was not significantly different and included the same factors with the exception of age (Table 3). For population modeling and simulation we used the simpler model (model 2), as it was not significantly different and was easier to simulate.

The linear population model simulated in R (model details in Appendix B), and based on these results shows the northern crayfish population in the San Pedro River should not be viable. Beginning with 1000 replicate populations of 5000 females, all populations went extinct after 3 years. Since the population in San Pedro does persist, either our survival estimate and/or reproduction estimate are too low. If juvenile production is doubled and daily survival modes (higher values) are used instead of a random sample of daily survival values from the posterior distribution, the population is still not viable. Even with this adjusted model, no simulated population (n=1000) was viable beyond 2 years. Any additional modifications to the population model would result in a model that would not be representative of the actual population.

Porter Creek

Based on the initial values of our population model, the crayfish population within Porter Creek does not appear to be viable. In the population simulation starting with a population of 100 female crayfish, of 1000 simulations, all went extinct by the third year. Since the population in Porter Creek does persist, either our survival estimate and/or reproduction estimate are too low. Even if 100 percent of the females are reproductively active and the number of offspring is doubled, the simulated populations are still not viable beyond the third year.

Silver Creek

In a simulation of 1000 populations, all survive 10 years, and although all of the simulated populations were in decline, none of them went extinct during the simulated time frame (Figure 11).

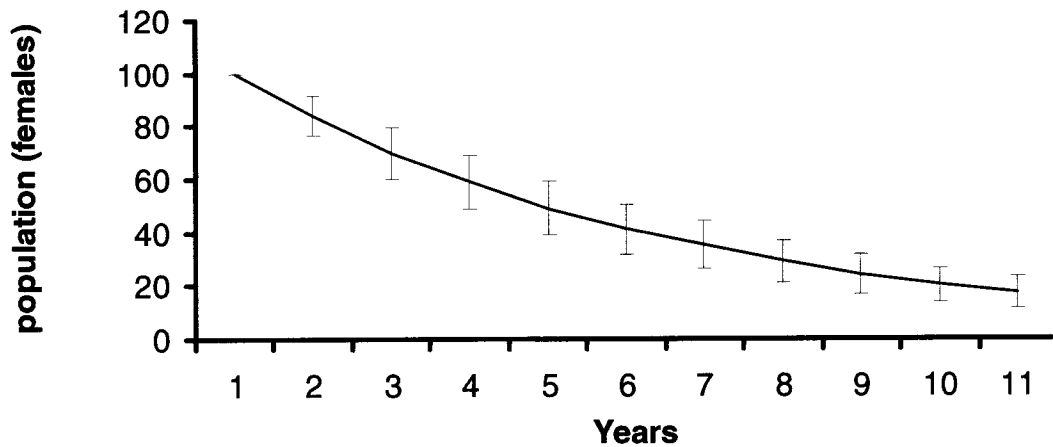


Figure 11. Mean female population size and standard deviations based on 1,000 simulations of northern crayfish in Silver Creek with a starting population of 100.

Discussion

The goal of this research was to investigate life history characteristics of the northern crayfish to determine if it was feasible to exploit certain aspects of crayfish biology that would lead to the control or eradication of these invasive populations in Arizona. The idea was to use population modeling and sensitivity analysis to achieve these goals. Our results do provide guidance on the control and eradication of crayfish populations, but not quite in the way that we envisioned. The population models and simulations did not lead to useful insights; however, an examination of the recapture rates from program MARK provide valuable information that can be used to help direct crayfish removal and control efforts.

In order to control or eradicate crayfish populations, it is important that efforts be implemented when they can have the greatest impact on the population. Targeting crayfish when CPUE is the highest may not be the most effective time to impact the population. For example, many crayfish can be captured per unit effort in late spring and early summer. However, while a greater number of crayfish can be caught in the spring, a larger proportion of the population can be captured in the fall, thus having a bigger impact on the population. Based on mark-recapture and estimates on the probability of recapture, it appears that the best time to implement crayfish control efforts is in the fall prior to the onset of colder temperatures at which northern crayfish become inactive. It is not clear at what temperature northern crayfish become inactive, but we believe it to be in the range of 10-12° C. During the fall, populations are at fairly low levels, and crayfish are active and vulnerable to trapping (high recapture rates). Northern crayfish mate in

the fall, prior to winter before the water cools off (Thorp and Covich 2001). Most of the males collected in the fall were of form 1 (reproductive form) and most of the females had visible glair glands. At this time, both male and female crayfish appear to be highly active (moving, feeding, and mating) and very susceptible to trapping. When the water temperature cools off the majority of crayfish become less active. The specific temperature that triggers a reduction in activity is believed to be around 11° C. Temperatures below 12° C are necessary for ovarian development (Aiken 1969, Portelance and Dubé 1995), while temperatures above 12-13° C are thought to be necessary for crayfish to become active in the spring (Momot 1967).

Although we were unable to estimate population size, recapture probabilities can reveal trends in population size. In general, the higher the recapture probability the lower the population size. Our recapture probabilities were generally lowest when there were many crayfish visible, in July for all three sites. When the population was large and few crayfish were marked, the percentage of marked crayfish to the overall population was low, resulting in low recapture probabilities. However, when the population was low, we could mark a greater percentage of the population, resulting in a greater recapture rate.

Recapture probability was highest in the spring for crayfish in Porter Creek and Silver Creek (Figures 9-10). This result suggests spring might be a good time to apply control efforts. However, crayfish had already reproduced at this time as evidenced by free-swimming juvenile crayfish present, which were not included in the calculation of recapture probabilities. Additionally, female crayfish with attached eggs/juveniles were less active and tended to stay hidden to protect their offspring, and consequently were less vulnerable to capture (Hazlett et al. 1979). Thus high recapture rates in the spring do not reflect the combined population of adults and very small juveniles, and concentrating removal efforts during this time would probably not be as effective as in the fall, when crayfish can be removed prior to reproduction.

The results of this investigation are dependent on the assumption that the northern crayfish captured and marked were representative of the general population. In one respect this was not true, as crayfish smaller than 18 mm carapace length were not marked. However, our results do pertain to crayfish that are susceptible to trapping. It is also unclear if the sex ratio of northern crayfish obtained primarily from minnow traps, accurately represent the sex ratio of northern crayfish in the wild. It has been reported that traps are biased towards male northern crayfish (Momot and Gowing 1977b, Somers and Green 1993). We did not see a consistent

pattern of a sex bias (Figure 3), however we cannot rule out that the traps captured a biased selection of size or sex of northern crayfish.

Our models did not find significant relationships between stream flow (volume/velocity) and temperature and northern crayfish survival. However, this does not mean these variables never affected survival. We used flow measurements collected on the day of capture, and did not sample when flow was high because flood conditions made the river unsafe to sample. Flow was also highly seasonal and the effects could have been masked by temporal differences. After the monsoon season (July), when high water flows are present, crayfish densities appeared to be significantly lower. Prior to the high flows of the monsoon season, crayfish were very abundant and easily observed; and we observed hundreds to thousands of crayfish. After high flows, there was a noticeable difference in the number and size of crayfish present. Many of the smaller crayfish may have been swept away and/or did not survive the high flows as CPUE declined and length frequency increased. Any differences that may have been related to temperature may have been accounted for in temporal differences, which were significant, as temperatures were correlated with time of year.

Based on length frequency data, field collections, and observations, the northern crayfish in Arizona reproduce only once annually. While the majority of female crayfish that were brought into the lab developed glair glands, very few actually extruded eggs, and even fewer produced free swimming juveniles (3rd instar or molt). Thus we could not reliably estimate the percentage of females that reproduced in the wild.

Our information on the reproduction or potential fecundity of northern crayfish is based on individuals that were collected in the wild in berry (eggs attached) as well as from crayfish that were brought into the lab and subsequently laid eggs. Counts of pleopod eggs ranged from 1-662, while the range of juveniles surviving to the 3rd instar (free swimming stage) was 46-416 (Appendix A). Momot et al. (1978) provides an overview of the number of attached eggs reported for northern crayfish. Attached eggs in northern crayfish populations from western Ontario have a range of 214 eggs with a maximum of 320, and in eastern Alberta the maximum was 891, while in northern Michigan the fecundity ranged from 1 to 443 (from Table 5, Momot et al. 1978). Dean (1969) reports a range of 1-1,015 for the number of pleopod attached eggs of the Conchas crayfish (*Orconectes causeyi*) in Arizona. The population described by Dean (1969) is thought to have been misidentified and is believed to be northern crayfish (Momot 1978). Dean (1969) also reports that females lay eggs within 3 weeks of the surface temperature

reaching 10° C, and females had been collected with eggs between 30 March and 15 June, and females with attached young were observed between 27 May and 24 June. Thus if female crayfish were still in berry or had juveniles attached during our sampling periods, the assumption of equal probability of capture in the CJS model would not be met and could potentially bias the results obtained in program MARK.

We found electrofishing ineffective for collecting crayfish, which contrasted with the results of others (Westman et al. 1978, Rabeni et al. 1997, Alonso 2001). The success of electrofishing was dependent on water clarity. If the water was too turbid to see crayfish on the bottom, then electrofishing was unsuccessful (July-September, December). Crayfish also did not respond in the same manner as fish to DC current. We could not adjust the levels to successfully stun and or draw crayfish to the electrode as one can with fish. Most crayfish swam away and dove down towards the substrate. Additionally, electrofishing is not an option that is commonly available to those most involved in crayfish control programs, such as volunteer groups. Electrofishing is also expensive and requires training to capture target organisms while minimizing injury to other species (Snyder 2003, 2004).

Our population models, based on the data and analyses for the three sites, resulted in the simulated populations not being viable. As the populations of crayfish have been at these sites for many years, our estimates of survival and or reproduction were likely incorrect. Either reproduction is greater, or survival was higher than estimated. However, even when reproduction was doubled in the population models for San Pedro River and Porter Creek, the simulated populations were still not viable. The CJS model used relies on certain assumptions and some of these assumptions may have been violated. We assumed that there was no emigration or immigration, or that they were equal. As this study was not designed to specifically examine movement, we can only make broad conjectures about the effects of migrants on population viability. It is possible that our estimates of survival and reproduction are correct and our site locations are sinks for crayfish, kept viable by emigration. Northern crayfish are active but the majority tends to not move much more than 0.5 m (Hazlett et al. 1974). In Silver Creek, precise location data was available before and after recapture for 73 northern crayfish. Forty-five northern crayfish had a net downstream movement, 22 moved upstream, and 6 had no net movement, indicating a general trend for downstream movement. Thus it was possible that downstream migrants kept the population viable. We tested the effect of an annual addition of 20

mature female emigrants on the population simulation for Silver Creek, and it resulted in a viable population.

The CJS model also assumes that all crayfish were equally likely to be captured. When female crayfish are carrying eggs, they are less likely to be captured (Hazlett et al. 1979). Females in berry generally find a safe refuge to allow the eggs and juveniles to develop, and consequently are inactive. We tried to account for differences associated with reproduction and crayfish inactivity by not sampling during the months of December through March. However, some females may still have had attached young after March (Dean 1969).

We believe that the primary reason that the simulated population models were not viable was the high level of variance around the survival estimates. High variance was a result of few recaptures (generally 10% or less) and highly variable population size. To improve crayfish survival and recapture estimates, as well as to estimate population densities, we suggest a mark-recapture program using a robust sampling approach concentrated during spring and fall periods. Adult northern crayfish recapture probabilities are at the highest during the spring and fall, while adult population size is probably at its lowest. Our results with mark-recapture are similar to the conclusions reached by Nowicki et al. (2008), who suggest a similar approach to mark-recapture techniques for the white-clawed crayfish (*Austropotamobius pallipes*) in Italy.

Although the population models did not provide the information that we had hoped, the research provided valuable information that will be useful for managers trying to control or eradicate the northern crayfish in Arizona. Northern crayfish reproduce only once per year, and emmigration may be an important means to supplement populations in specific stream segments. Of the methods we tested, fall minnow trap sets have the best chance of impacting crayfish populations in Arizona streams. However, we were unable to estimate if intense fall trapping would be able to control populations to a sufficient level.

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Appendix A. Northern crayfish reproduction information

The ID number was an internal lab identification number, with the exception of “wild” indicating that these crayfish were collected in the wild with eggs attached. Location indicates where crayfish were collected, and date in berry is when they were seen bearing eggs. Eggs produced presents a direct count of eggs attached to the abdomen. If there were free-swimming juveniles present they were noted, but we could not obtain an egg count in these situations.

ID	Location	Length	Date in berry	Eggs produced	Date free swimming	# free swimming
15	Rose Canyon Lake	43.0	2-Jan-08		27-Feb-08	266
31	Rose Canyon Lake	41.4	20-Dec-07	4	none	
98	Silver Creek	34.7	11-Feb-08	-		6
99	Silver Creek	36.0	18-Jan-08	-		60
100	Silver Creek	43.7	19-Dec-07	-		91
101	Rose Canyon Lake	43.7	17-Dec-07	94	-	
102	Rose Canyon Lake	41.0	17-Dec-07	416	None	416
104	Rose Canyon Lake	44.5	19-Dec-07	-	21-Feb-08	223
106	Rose Canyon Lake	36.3	31-Dec-07 ^a	-	22-Feb-08	336
108	Rose Canyon Lake	38.2	19-Dec-07	140	None	
110	Rose Canyon Lake	47.8	?	93		
111	Rose Canyon Lake	47.8	24-Jan-08	-	5-Mar-08	46 ^b
113	Rose Canyon Lake	36.3	?	93		
116	Rose Canyon Lake	42.7	?	-		67
118	Rose Canyon Lake	42.9	3-Jan-08		25-Feb-08	155
119	Rose Canyon Lake	46.8	19-Dec-07	461	None	
120	Rose Canyon Lake	43.0	2-Jan-08	300	None	
122	Rose Canyon Lake	43.2	2-Jan-08	-	20-Feb-08	312
123	Rose Canyon Lake	27.4	31-Dec-07 ^a	23	None	-
124	Rose Canyon Lake	44.1	19-Dec-07	662	None	-
125	Rose Canyon Lake	47.1	?	255	-	-
127	Rose Canyon Lake	43.1	?	107	-	-
128	Rose Canyon Lake	.	19-Dec-07	397	None	-
Wild	Porter Creek	37.2	14-May-08	136	-	-
Wild	Porter Creek	42.6	14-May-08	209	-	-
Wild	Silver Creek	29.9	14-May-08	42	-	-

^a Approximate date as crayfish were not checked from Dec 24th - Dec 31st 2007.

^b this crayfish escaped its container and died before all young were free swimming

Appendix B. Population model simulation code (Program R)

Computer code was written in program Tinn-R – GUI/Editor for R language and environment Version 1.19.2.3 (<http://www.sciviews.org/Tinn-R/>).

San Pedro River

```
surv=read.table("surv.txt", header=T, sep = "\t") # MCMC posterior distributions from 30K
samples phi(t)p(t+Length)
attach (surv)

# FECUNDITY
fec<- 249.346 # fecundity
fSD<- 72.28

hatch<- (rnorm(50000, fec, fSD)) # distribution of CF hatched
ha<-round(hatch[hatch>0]) # restricts distribution to numbers above 0

NO <-15000 # starting population females
tmax <-10 # is max time step
nrep <- 10 # is number of reps

reprod<-(0.971) # % reproductively active
reprodVAR<-(0.05)^2 # by squaring SD we get variance
reproduction<-reprod*((reprod*(1-reprod))/reprodVAR)-1 # this is alpha (a) for beta
distribution
reproVAR<-((1-reprod)*((reprod*(1-reprod))/reprodVAR)-1) #this beta (b) for beta distribution
r<-rbeta(50000, shapel=reproduction, shape2=reproVAR) # % repro distribution

#####
# Yearly survival models based on daily survival values from 3 different distributions
# w = random sample from MCMC posterior probability distributions
# y = alternate using median values where MCMC values are suspect (ie low)
# xy = daily survival values using the mode from posterior probability distributions
#####

w<(prod(sample(real1,1)))*(prod(sample(real2,29)))*(prod(sample(real3,2)))*
(prod(sample(real4,26)))*(prod(sample(real5,49)))*(prod(sample(real6,1)))*
(prod(sample(real7,7)))*(prod(sample(real8,1)))*(prod(sample(real9,13)))*
(prod(sample(real10,1)))*(prod(sample(real11,42)))*(prod(sample(real12,1)))*
(prod(sample(real13,1)))*(prod(sample(real14,25)))*(prod(sample(real15,1)))*
(prod(sample(real16,1)))*(prod(sample(real17,153)))*(prod(sample(real18,1)))*
(prod(sample(real19,1)))*(prod(sample(real20,32)))*(prod(sample(real21,1)))*
(prod(sample(real22,1))) #iterate population size

# alternate survival
y<(prod(sample(real1,1)))*((median(real2)^29))*(prod(sample(real3,2)))*(prod(sample(real4,26)))*
((median(real5)^49))*(prod(sample(real6,1)))*((median(real7)^7))*(prod(sample(real8,1)))*
(prod(sample(real9,13)))*prod(sample(real10,1))*((median(real11)^42))*(median(real12))*
(prod(sample(real13,1)))*((median(real14)^25))*(median(real15))*(prod(sample(real16,1)))*
((median(real17)^153))*(median(real18))*(prod(sample(real19,1)))*((median(real20)^32))*
(median(real21))*(median(real22))

# used mode for survival values
xy<-(0.9975811)*(0.9999771^29)*(0.9976379^2)*(0.9115240^26)*(0.9999875^49)*(0.9239712)*
(0.9999850^7)*(0.9248298)*(0.9999886^13)*(0.9728144)*(0.7682214^42)*(0.9999686)*(0.9985786)*
(0.9999686^25)*(0.9999727)*(0.9923999)*(0.9999593^153)*(0.9999694)*(0.9518278)*(0.9999644^32)*
(0.9999855)*(0.9999760)

# Actual population model simulation
cf_pop<-function(NO, tmax, nrep){
#Nset is an array of population sizes for each rep (row) by time step (col)
Nset <- matrix(nrow=nrep,ncol=tmax+1) # storage space for population sizes
for(i in 1:nrep){
Nset[i,1] <- NO # for each replicate
for(tt in 1:tmax){
```



```

      z<- (if((Nset[i,tt])>0) (Nset[i,tt]) else(0)) # the if statement doesn't allow it to go below
negative numbers
      repro<- (sum(sample(ha,z))) # dropped the 0.5 adj for females in ha#
      Nset[i,tt+1] <- (round((Nset[i,tt]) + (round(repro))))*xy
    }
test<- list("Nset"=(round(Nset)))
}
test
write.table(test, file="test9.txt", quote = FALSE, sep = "\t") # outputs an external tab
delimited file
#}

cf_pop(50, 10, 50)
#####
# to run function "cf_pop", fill in data for initial population number
# (NO), years to run (tmax), the number of replications (nrep)
#####

cf_pop (NO=50, tmax=10, nrep=50)

```

Porter Creek

```

# Porter Creek
# A simple model of crayfish life history dynamics based on survival from Mark
# with MCMC of best model selected using AIC
# {Phi(g) p(t) PIM}

setwd("G:/Arizona/Crayfish/R_pop_models/Porter/MCMC_pop_models") # change working directory
result=read.table("porter_result40k.txt", header=T, sep = "\t") # MCMC data from 30K samples phi(t)p(t+Length)
attach(result) # can now call real1, real2, and randomly sample from them for population modeling

NO <-100 # starting population females
tmax <-10 # is max time step
nrep <- 10 # is number of reps
fec<- 249.346 # actual fecundity = 249.346
fSD<- 72.28 # fecundity SD

re<-(0.60) # percent female reproduce
std<-(0.05)^2 # by squaring SD we get variance
repr<-re*(((re*(1-re))/std)-1) # this is alpha (a) for beta distribution confines values between 0-1
reSD<-((1-re)*(((re*(1-re))/std)-1)) # this beta (b) for beta distribution
rpo<-rbeta(50000, shape1=repr, shape2=reSD) # % repro distribution

hatch<- rnorm(5000, fec, fSD) # distribution of crayfish hatched
ha<-hatch[hatch>0] # distr of CF hatched

cf_pop<-function(NO, tmax, nrep){
#Nset is an array of population sizes for each rep (row) by time step (col)
Nset <- matrix(nrow=nrep,ncol=tmax+1) # storage space for population sizes
for(i in 1:nrep){ # for each replicate
  Nset[i,1] <- NO
  for(tt in 1:tmax){ # for each time step
    z<- (if((Nset[i,tt])>0) (Nset[i,tt]) else(0)) # the if statement doesn't allow it to go below negative numbers
    repro<- (0.5)*(sum(sample(ha,(round(sample(rpo)*z)))) # reproduction, 0.5 because half are males
    Nset[i,tt+1] <- (Nset[i,tt]+repro)*(prod(sample(real1,365))) # iterate population size over a yr via daily survival
  }
}
test<- list("Nset"=(round(Nset)))
}

```

```

test
}
write.table(test, file="porter_n_pop3.txt", quote = FALSE, sep = "\t")# outputs an external tab delimited file
#}

```

```
cf_pop(300,10,20)
```

Silver Creek

```

surv=read.table("survival_50k_MCMC.txt", header=T, sep = "\t")
attach (surv)

```

```

fec<- 249.346 # fecundity
fSD<- 72.28 # fecundity SD

```

```

re<-(0.60) # percent female reproduce
sd<-(0.05)^2 # by squaring SD we get variance
repr<-r*(((re*(1-r))/sd)-1) # this is alpha (a) for beta distribution
reSD<-((1-re)*(((re*(1-re))/sd)-1)) # this beta (b) for beta distribution
rpo<-rbeta(50000, shape1=repr, shape2=reSD) # % repro distribution confined between 0-1

```

```

hatch<- (rnorm(50000, fec, fSD)) # distribution of CF hatched
ha<-round(hatch[hatch>0]) # restricts distribution to numbers above 0
hatch<- rnorm(5000, fec, fSD) # distr of CF hatched
ha<-hatch[hatch>0]

```

POPULATION SIMULATION

```

cf_pop<-function(NO, tmax, nrep){
#Nset is an array of population sizes for each rep (row) by time step (col)
Nset <- matrix(nrow=nrep,ncol=tmax+1) # storage space for population sizes
for(i in 1:nrep){ # for each replicate
Nset[i,1] <- NO
for(tt in 1:tmax){
z<-((if((Nset[i,tt])>0) (Nset[i,tt]) else(0)) # the if statement doesn't allow it to go below negative numbers
repro<- (0.5)*(sum(sample(ha,(round(sample(rpo)*z)))))) # reproduction, 0.5 because half are males
Nset[i,tt+1] <- (Nset[i,tt]+repro)*(prod(sample(real1,365))) # iterate population size, real1=female survival
}
}
test<- list("Nset"=(round(Nset)))
}
test
write.table(test, file="silvercreek_b.txt", quote = FALSE, sep = "\t") # outputs an external tab delimited file
}

```

```
cf_pop(100, 10, 1000)
```

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