State of the ART: Using artificial refuge traps to control invasive crayfish in southern California streams

Joseph N. Curti1,4, C. Emi Fergus2,5, and Angela A. De Palma-Dow3,6

1University of California, Los Angeles, 610 Charles E. Young Drive South, Los Angeles, California 90095 USA
2Oak Ridge Institute for Science and Education, c/o USEPA Pacific Ecological Systems Division, 200 Southwest 35th Street, Corvallis, Oregon 97333 USA
3Lake County Water Resources Department, 255 North Forbes Street, Lakeport, California 95453 USA

Abstract: Invasive species are a widespread threat to stream ecosystems across the planet. In Southern California, USA, the invasive red swamp crayfish Procambarus clarkii (Girard, 1852) poses a significant threat to native aquatic fauna. Studies have suggested that artificial refuge traps (ARTs) resembling crayfish burrows can be used to remove invasive crayfish, but, to date, no studies have focused on optimizing ART design and deployment to maximize crayfish catch. This month-long study tested the effect of modifications on ART diameter, color, and soak time on P. clarkii catch effectiveness across 160 traps. We evaluated catch data by creating multiple candidate generalized linear mixed models predicting P. clarkii catches with different modeling parameterizations and a priori hypothesized predictor variables. During the study period, ARTs removed a total of 240 red swamp crayfish with no incidental bycatch. Larger P. clarkii (2–6-cm carapace length) were found more frequently in 5.1-cm-diameter traps, and smaller P. clarkii (1–4 cm) were found more frequently in 2.5-cm-diameter traps. Catch numbers varied between trap types, with black-colored 5.1-cm-diameter traps removing the greatest amount of the total P. clarkii caught in the study (mean = 0.27, SD = 0.29; 35% of the total caught) and black-colored 2.5-cm-diameter traps removing the least amount (mean = 0.09, SD = 0.55; 12% of the total). Further, ART deployment duration was an important predictor variable for candidate models, where ARTs with 4-d and 7-d deployment durations had lower catch/unit effort than traps with 1-d and 2-d deployments. This factorial experiment is the 1st study to suggest specific design modifications to ARTs that optimize invasive red swamp crayfish removal without incurring non-target incidental bycatch. This study demonstrates that ARTs can be a valuable tool for conservation managers interested in restoring streams through invasive crayfish removal, especially where there are sensitive biological resources.

Key words: Procambarus clarkii, bycatch, tube trap, mechanical trapping, ARTs, stream restoration, crustacean, freshwater management

Aquatic invasive species (AIS) are of concern in freshwater systems across the globe, and they have been studied on every continent except Antarctica (Lodge et al. 2012, Thomsen et al. 2014). The ecological impacts most often associated with AIS include decreases in native aquatic species abundances, especially for macrophytes, zooplankton, and fish (Gallardo et al. 2016). The economic impact of AIS are also substantial, primarily stemming from controlling the invading species (Chandra and Gerhardt 2008).

In the Malibu Creek watershed, located in the Santa Monica Mountains of Los Angeles County, California, USA, the presence of the invasive red swamp crayfish Procambarus clarkii (Girard, 1852) has widespread and long-lasting impacts on local faunal assemblages (Klose and Cooper 2012). No species of crayfish are native to the Malibu Creek watershed, but P. clarkii, introduced from multiple sources across the US (Quan 2014), have been observed there since 1924 (Holmes 1924). Procambarus clarkii remains one of the most abundant AIS in the watershed (Riley et al. 2005, Garcia et al. 2015), and their establishment in southern California has resulted in the decline of regional native faunal species, such as the California newt (Taricha torosa Rathke, 1833; Gamradt and Kats 1996, Kerby et al. 2005, Riley et al. 2005, Kats et al. 2013, Delaney and Riley 2019), California.
tree frog (Pseudacris cadaverine Cope, 1866; Riley et al. 2005, Delaney and Riley 2019), and Baja California tree frog (Pseudacris hypochondriaca) Hallowell, 1854; Riley et al. 2005, Delaney and Riley 2019). Further, P. clarkii have led to declines in benthic macroinvertebrate assemblage diversity and abundance (Klose and Cooper 2012, García et al. 2015) while promoting nuisance disease-vector species, such as mosquito (Anopheles spp.) larvae (Bucciarelli et al. 2019). In addition, crayfish can also negatively affect streamwater quality when they construct burrows in the stream banks. This burrowing behavior can lead to channel instability and erosion (Correia and Ferreira 1995), and it has been associated with cyanobacteria bloom occurrence (Yamamoto 2010). Finally, the presence of P. clarkii can lead to decreases in periphyton biomass because of both consumptive and non-consumptive clipping, and these behaviors can alter food-web dynamics by leading to decreases in periphyton-associated invertebrates (Klose and Cooper 2012).

To mitigate the impacts of P. clarkii to stream ecosystems, conservation managers and researchers have often used passive baited minnow traps to reduce crayfish abundances (Larson and Olden 2016, Holdich et al. 2017, Manfrin et al. 2019). Typically, passive baited minnow traps are constructed of steel or vinyl-coated steel mesh in the shape of a cylinder with an opening funnel at each end and measure ~42 cm long and 2.5 cm in diameter at the openings. In southern California, the use of passive baited minnow traps to remove P. clarkii has resulted in measures of stream community recovery (Kerby et al. 2005), such as increased amphibian survival during seasonal droughts (Kats et al. 2013) and increased diversity of benthic macroinvertebrate communities (García et al. 2015). Further, a modeling study has indicated that in southern California increased efforts to remove crayfish via mechanical trapping increases the likelihood of long-term persistence of aquatic breeding newts (Milligan et al. 2017).

Successful management of invasive crayfish populations using passive baited minnow traps requires consideration of many factors, one of which is optimizing trap design to prevent capture bias (i.e., to target crayfish of all size classes and sexes). Eradication of invasive crayfish is more likely under unbiased trapping management regimes (Stebbing et al. 2014), but baited minnow traps are known to exhibit bias towards trapping large adult male crayfish (Gherardi et al. 2011, Larson and Olden 2016). This inherent bias can have counterintuitive effects on a management program because it can lead to increased density of juvenile crayfish populations in the absence of large adult males (Skurdal and Qvenild 1986). Some studies have found that modifications in opening size (Stuechel 1991) and mesh size (Peay and Hiley 2001) can reduce inherent bias of traps. Further, other studies suggest that bias can be avoided by deploying multiple types or designs of mechanical traps simultaneously (De Palma-Dow et al. 2020).

In addition to sampling bias, traditional passive baited minnow traps can be a troublesome tool for researchers and managers because of their inability to discriminate between target and non-target species. Bycatch of non-target organisms can be an unintended consequence of any manual trapping program, such as reported by Mangan et al. (2009) and Swartz and Miller (2018). Although one could take a conservation-management perspective to rationalize that the long-term benefit of invasive crayfish removal justifies the temporary impact on non-target taxa, removal projects should aim to maximize crayfish removal while minimizing or eliminating non-target bycatch. There is, therefore, a need for additional research into trap types that could be used in combination with baited minnow traps to aid in the removal of juvenile and female crayfish while also minimizing impact on native aquatic species.

To address concerns of sampling bias and bycatch, some studies have explored the use of artificial refuge traps (ART) as a supplementary conservation and management tool. ARTs are typically constructed of either natural (Warren et al. 2009, Kusabs et al. 2018) or artificial materials (Peay et al. 2006, Green et al. 2018, O’Connor et al. 2018) that replicate the form and function of crayfish burrows by providing refuge from predation during sensitive periods in their life history (Barbaresi et al. 2004). ARTs typically reduce (if not completely eliminate) impacts to native aquatic species by including opening holes on one end where bycatch can escape. Efforts to compare ARTs with passive baited minnow traps have shown mixed results. Some studies report no difference in crayfish catch between ARTs and minnow traps (Walter 2012). Other studies report either greater (Green et al. 2018) or lower (De Palma-Dow et al. 2020) crayfish catch in ARTs than minnow traps. However, crayfish caught in ARTs have not been found to be biased towards a particular size class or sex (Walter 2012, Green et al. 2018, De Palma-Dow et al. 2020), and preliminary use of the traps suggest that gravid female P. clarkii may prefer these traps to traditional mechanical trap types (De Palma-Dow et al. 2020).

Despite the advantages of using ARTs to manage P. clarkii populations, most research has focused exclusively on comparing the efficiency of ARTs to passive baited minnow traps. Little work has been done to discern the elements of individual ART construction and deployment required to optimize P. clarkii catch and minimize bycatch. The objectives of our study were to test the effects of ART trap design and deployment time on P. clarkii management. Specifically, we assessed the effects of ART design and length of deployment on: 1) amount of P. clarkii catch; 2) bycatch of onsite native aquatic species, including Baja California tree frog juveniles and adults and Arroyo Chub (Gila orcuttii Eigenmann and Eigenmann, 1890); 3) bias towards crayfish of a particular size and sex; and 4) ability of ARTs to preferentially catch gravid female P. clarkii. Overall, we expected
that ARTs would be effective, unbiased methods for catching and removing *P. clarkii*, that ART design elements would be important factors in *P. clarkii* catch, and that there would be negligible bycatch over the course of the study. For objective 1, we predicted that traps with greater opening diameters and, therefore, greater overall surface area would catch more *P. clarkii*. For objective 2, we predicted there would be 0 instances of non-target bycatch. For objectives 3 and 4, we predicted that ARTs would catch roughly equal numbers of male and female crayfish of all carapace lengths that are regularly observed during mechanical trapping (carapace length: ~1–6 cm). Further, we predicted that of female crayfish caught, ~2% would be gravid, based on findings from previous ART work in southern California (De Palma-Dow et al. 2020).

**METHODS**

Through a factorial ART sampling framework, our study experimentally tested whether the duration of deployment, opening diameter, and trap color affected *P. clarkii* catches. We fabricated 160 traps of 4 trap types and deployed them in situ within a southern California stream with known *P. clarkii* populations. We then used iterative generalized linear modeling to analyze data on *P. clarkii* catch by trap type.

**Sampling design**

Sampling occurred between 5 August and 2 September 2019, and sample sites were located within Malibu Creek, Los Angeles County, California, USA (approximate centroid: 34.082719°N, –118.708496°W). Malibu Creek is a perennial stream system that flows ~21.6 km from the San Fernando Valley of Los Angeles to the Santa Monica Bay. The dominant vegetation at the site is willow (*Salix* spp.), California sycamore (*Platanus racemosa* Nutt.), cottonwood (*Populus* spp.), and broadleaf cattail (*Typha latifolia* L.). We selected the sampling period to coincide with the peak time of year when *P. clarkii* are gravid, based on regional historic trapping and removal (JNC, unpublished data). We also chose the sampling period because precipitation events in southern California are rare following the end of the water year on ~1 April, after which submerged ARTs are unlikely to be disturbed by high-velocity stream flow.

We established two ~100-m sampling reaches between downstream (34.08123°N, –118.70493°W) and upstream (34.08283°N, –118.70836°W) portions of the study stream (Fig. 1). Sampling reaches were selected based on 3 criteria. First, we quantified physical stream habitat composition (length of pools, riffles, runs) and total area for each sampling reach (Flösi et al. 1998) to select reaches with similar habitat composition. Second, we selected sampling reaches if a priori visual-encounter surveys indicated the presence of crayfish. Finally, we selected reaches where no previous crayfish management efforts (i.e., trapping) had occurred within ~300 m during the past 5 y. These selection criteria minimized potential effects of habitat differences and past AIS removal efforts on crayfish catches in the study.

**Trap design, placement, and sampling schema**

We determined which elements of ART design and deployment to investigate by reviewing data from 10 y of *P. clarkii* management in the same watershed (JNC, unpublished data) and reviewing recommendations from the literature and personal communications (L. Havens, University of North Carolina, Chapel Hill, North Carolina, personal communication; J. Notar, Duke University, Durham, North Carolina, personal communication). Further, we only considered design elements that could be conceived of by any conservation manager and purchased from a general hardware supply store. We chose ART diameter as a design element to test based on recommendations found in Green et al. (2018), which discussed the potential for tube diameter to target specific size classes of crayfish. The Green et al. (2018) study also informed our decision to test duration of ART deployment because of their discussion on adapting soak length to the seasonal abundance of crayfish. We chose to test ART color, as a measure of contrast of the trap with the surrounding substrate, based on the known importance of crayfish vision in both antagonistic interactions between male crayfish (Bruski and Dunham 1987) and in crayfish homing behavior to their burrows (Fernández-de-Miguel and Aréchiga 1992). We excluded tube length following results of De Palma-Dow et al. (2020) that found no relationship between ART tube length and crayfish catch.

Our trap design was based on similarly constructed traps introduced by Green et al. (2018) and De Palma-Dow et al. (2020). We fabricated the ARTs with materials sourced from a general hardware store. Traps were built with either 2.5- or 5.1-cm-diameter, schedule 40 PVC pipe and either black or white waterproof duct tape (Gorilla Tape®, Gorilla Glue Company, Cincinnati, Ohio) for a total of 4 trap types: 2.5-cm black (hereafter referred to as BLKTube2.5), 2.5-cm white (Tube2.5), 5.1-cm black (BLKTube5.1), and 5.1-cm white (Tube5.1). Traps included 5 consecutive 6-in long PVC tubes joined together with duct tape to form a rigid and horizontally flat trap (Fig. 2A, B). We sealed 1 end of the ART with duct tape and left the other end open to allow crayfish to enter the trap. We drilled two to three 2-mm holes into the closed end of each individual pipe to allow water to drain through when removed from the stream. We constructed handles with 16-gauge rebar tie wire fastened to the outer PVC pipes of each trap and tied braided mason line to this wire. To ensure traps were not dislodged or lost, we secured the mason line to a lawn stake embedded in the stream bank.

ARTs were placed in pool and run habitats to fully submerge the traps and avoid high-flow riffle and cascade areas
that tend to have lower crayfish abundance (Peay et al. 2009). Five replicates of each of the 4 trap types and 4 deployment durations (1, 2, 4, and 7 d) were placed randomly within each sampling reach, for a total of 80 traps/sampling reach (160 traps total). We chose the number of traps and trap replicates based on a preliminary power analysis that suggested that increasing the number of observations (e.g., by increasing the number of overall traps) would improve our ability to detect the effect of trap deployment time on crayfish catch. To address the potential effect of trap density on crayfish catch, we placed traps 1 to 3 m from other traps (Mangan et al. 2009, Peay et al. 2009, Green et al. 2018). Traps with 1-d deployments were redeployed after checking each day; traps with 2-d deployments were checked after 2 d and redeployed 1 additional time in a given trapping week; and traps with 4- and 7-d deployments were only checked once in a given trapping week. With the exception of 7-d traps, ARTs were removed from the water in between trapping weeks and stored on stream banks.

**Procambarus clarkii removal and data collection**

Captured *P. clarkii* were removed from ARTs and ethically euthanized by freezing before measuring and recording. We recorded measurements of carapace length (length from the rostrum to the end of the cephalothorax; Correia and Costa 1994) to the nearest cm and recorded sex and reproductive status of females. We made notes if crayfish were found in molt or copulating while in the ARTs. Collection methods were approved by regional California Department of Fish and Wildlife staff, and it was determined that all project activities were covered under a California State Fishing License.

**Determining physical and chemical habitat at sampling locations**

We took measurements of the physical and chemical stream environment to control for potential differences between sampling reaches in our data analysis, and we took

---

**Figure 1.** Map of sampling sections detailing artificial refuge trap placement by type. Sampling location in the Malibu Creek watershed, Los Angeles County, California, USA (inset map). There were 20 of each trap type placed in each section (*n* = 40, 160 total traps). Approximate start and stop coordinates: 34.08123°N, −118.70493°W and 34.08283°N, −118.70836°W.
stream habitat measurements to control for the potential association of vegetation type and crayfish abundance and distribution, following Moreira et al. (2015) (Table S1). We took water chemistry measurements at 3 locations along the length of each stream reach during the middle of each sampling week for the duration of the study. Measurements were collected with a YSI Professional Pro Plus meter (Yellow Springs Instruments, Yellow Springs, Ohio) and included water temperature, total dissolved solids, dissolved oxygen, ammonium (NH4-N), and pH. The multiparameter probes were calibrated according to the manufacturer’s specifications, with dissolved oxygen, NH4-N, and pH calibrated before each sample collection and the conductivity probe calibrated once at the beginning of the study. At the same time as recording the water-chemistry measurements, we also collected air temperature of the nearest weather station to the sampling site (TPGC1) from the National Weather Service (https://www.weather.gov/).

We collected stream physical characteristics once at the time of trap placement at each separate trap location. We used a meter stick and measuring tape to collect stream depth and wetted width and a hemispherical densiometer to measure canopy openness at a randomly selected cardinal direction. Additional measurements of stream habitat included dominant substrate through pebble counts (Harrelson et al. 1994) and the dominant overstory vegetation species.

To determine if there were differences in the physical structure (e.g., the percentage of pools, runs, and riffles) and chemical composition (e.g., water-quality measurements) of stream sampling reaches, we performed Wilcoxon rank sum tests (non-parametric independent t-tests) on stream habitat measurements and 2-way analysis of variance (ANOVA) on water chemistry measurements between stream reaches and by week (Fig. S1). We excluded riffle features from analyses—traps were not placed in riffles because their average depth did not allow for traps to be submerged. We assessed correlations between environmental variables using Pearson’s method to identify highly correlated variables ($r > |0.8|$) and to select the variables to include in the model.

**Iterative generalized linear modeling**

We used different model parameterizations and combinations of predictor variables to develop multiple candidate models to predict *P. clarkii* catch, our 1st study objective, and to explore potential relationships between individual measures of the chemical and physical environment with *P. clarkii* catch. We developed separate models for male, female, and total *P. clarkii* catches and evaluated model performance with Akaike Information Criterion (AIC; Burnham and Anderson 2002). Models with the lowest AIC scores were deemed the best fitting models given the data, and candidate models were compared based on difference in AIC scores from the top ranked model ($\Delta$AIC). Data processing and analyses were completed using R software (version 3.6.3; R Project for Statistical Computing, Vienna, Austria). Generalized linear mixed effects models were built using R package glmmTMB (version 1.0.2.1; Brooks et al. 2017).

To identify a simple, parsimonious model predicting *P. clarkii* catch, we iteratively built a series of models by adding...
a priori hypothesized model parameterizations: generalized linear Poisson regression, zero-inflated Poisson, zero-inflated Poisson with random effects by trap ID, and modeling trap deployment times as an offset. Poisson distributions are suited to analyzing count data (Bolker 2008), and we used generalized linear Poisson regression as the base model to predict P. clarkii catches. We built the remainder of the candidate models as zero-inflated Poisson regressions because of the large number of observations with no catches in our dataset. Zero-inflated Poisson regression accommodates excess 0 counts in the data by modeling 2 processes: a Poisson count model and a binomial log model predicting presence/absence of crayfish catch (i.e., the 0 counts). To accommodate possible dependencies in resampling because of redeploying the same traps multiple times during the study period, we built an alternative model that added trap ID as a random mixed effect (Bolker et al. 2012). To account for differences in trap deployment times, we added a time offset parameter to the zero-inflated Poisson model with trap ID as a mixed effect. The time offset transforms point counts of captured crayfish into rates by taking the log of the time the trap had been deployed in the field. It is a common practice to use rates instead of counts when sampling effort is uneven (e.g., when trap types have been left out for different lengths of time) (Gardner et al. 1995, LaPoint et al. 2013, Reitan and Nielsen 2016). See Appendix S1 for more detailed information about our statistical framework.

Our models also examined whether ART design and physical and chemical variables were related to P. clarkii catch. To determine if variations in trap color or opening diameter were related to P. clarkii catches, we included trap type as a predictor in the models. We included stream reach as a variable in the model to account for possible differences in crayfish counts between sampling reaches. Site-specific environmental variables of stream habitat and water chemistry were also included in the models. Stream habitat variables included habitat type (pool vs run), pebble count, and % canopy openness. Stream chemistry variables included water temperature, conductivity, pH, dissolved oxygen, NH4-N, and total dissolved solids. We averaged stream chemistry values by stream section for each sampling week and matched them to P. clarkii observations by stream section and the trap removal week. Mean pH was estimated from stream pH values that were converted to H+ to calculate the mean on a linear scale and then converted back to pH. We excluded highly correlated variables from the same model and scaled predictor variables by taking the difference from the mean and dividing by the standard deviation. Rescaling the predictor variables placed their values on a comparable scale so that we could evaluate the relative magnitude of their effects on P. clarkii catches together. We tested whether there were interactions among trap diameter, color, and deployment duration on mean crayfish catches for the total number of catches and by sex by performing 3-way ANOVA tests. Details on the statistical modeling framework are provided in the supporting information.

**Deployment time effect on P. clarkii catch**

To further explore the effect of deployment time on P. clarkii catch, we evaluated our catch per unit effort (CPUE), or the total crayfish catch divided by the deployment time, for the different ART deployment times. Because our CPUE data represent rates rather than counts and, therefore, did not meet normality assumptions for parametric analysis, we performed a Kruskal–Wallis test (the non-parametric equivalent to the 1-way ANOVA) to evaluate the relationship between CPUE and deployment time. We evaluated differences in mean CPUE across the 4 trap types visually and with a Kruskal–Wallis test to evaluate if there was a certain ART configuration that maximized management effort relative to the total amount of crayfish removed.

**Evaluating ART catch bias**

To examine whether there were differences in the sex and size characteristics of P. clarkii caught in the different ART configurations, our 3rd study objective, we performed chi-square tests of independence in R. We tested for differences in observed and expected ratios of P. clarkii counts by sex and 5 size classes (1–2, 2–3, 3–4, 4–5, and 5–6 cm) across trap diameters (2.5 and 5.1 cm), color (black and white), and deployment duration (1-, 2-, 4-, and 7-d) schemes separately.

**RESULTS**

Our analysis of physical and chemical stream characteristics showed that the 2 sampling reaches were similar in physical habitat but had different water chemistry. The percentages of pool, run, and riffle habitat did not differ between the 2 stream reaches (independent t-tests, p = 0.6, 0.7, and 0.7, respectively; Table 1). Stream water temperature, dissolved oxygen (%), total dissolved solids, and NH4-N differed by both stream reach and week number (Table S2, Fig. S1). Stream pH did not differ between reaches but did change over time during the study. In contrast, stream conductivity varied by stream reach but was relatively static over time during the study. We included stream reach and water chemistry as predictors in our models, given the observed environmental differences between sampling reaches.

We captured a total of 240 P. clarkii during the study period. Of these, 117 were male and 123 were female. Removed P. clarkii had carapace lengths between 1 and 6 cm. Approximately 83% of trap visitations had 0 catches (1061/1279 observations). Over the course of the study, 2 P. clarkii were observed molting within the BLKtube5.1 ART traps, 1 pair of P. clarkii were found copulating near a trap opening
within a BLKtube2.5 ART trap, and a single gravid *P. clarkii* was found within a Tube5.1 ART trap. Crayfish were predominately found alone in traps, with only 27/1279 observations having >1 crayfish in a single trap. Of these 27 observations, 81% (22) had 2 crayfish, 15% (4) had 3 crayfish, and 4% (1) had 4 crayfish within the tube trap. No bycatch was observed in any of the traps during the study period.

We found *P. clarkii* catches were similar between stream reaches. Mean numbers of total *P. clarkii* caught did not differ between stream reaches (Wilcoxon test, $W = 209,277$, $p = 0.18$), nor did we observe differences in the number of male and female catches between stream reaches (log likelihood $X^2_1 = 2.62$; $p = 1.0$). There was a difference in carapace length distributions (5 size classes) between stream reaches ($X^2_4 = 17.45$; $p < 0.01$), but there was not a clear trend of 1 stream reach having larger *P. clarkii* than the other stream reach.

### Crayfish catch models

The top fitting model to predict both total *P. clarkii* catch and male *P. clarkii* catch was a zero-inflated Poisson regression that included random mixed effects by trap ID, an offset for trap deployment time, trap type (color + diameter), and mean pH (Tables 2, S3). For total *P. clarkii* catch, this model had similar model fit to the candidate model that included the same model parameterizations, trap type, and NH$_4$-N ($\Delta$AIC = 0.3). Total *P. clarkii* catches were negatively associated with mean pH and positively associated with mean NH$_4$-N in these separate models (Table S5). However, the relative magnitude of the effects of pH and NH$_4$-N in the models were small ($\beta_{\text{pH}} = -0.21$ and $\beta_{\text{NH}_4\text{-N}} = 0.21$, respectively), such that an increase in pH of 0.1 resulted in a decrease in *P. clarkii* catches by 0.08, and an increase in NH$_4$-N by 0.1 mg/L resulted in an increase in *P. clarkii* catches by 0.07. Male crayfish catches were negatively associated with mean pH. Stream reach and habitat type (pool vs run) did not improve model fit to predict *P. clarkii* counts.

The top fitting model to predict female *P. clarkii* catch was a zero-inflated Poisson regression with random mixed effects by trap ID (Table S4). Including trap type in the models did not improve model fit and resulted in higher

---

Table 1. Percentage and length (m) of pool, riffle, and run stream habitats of sampling sections in Malibu Creek, Los Angeles County, California, USA, in August 2019, prior to start of the study. Total length of Section 1 = 100.69 m, and total length of Section 2 = 104.48 m (difference of 3.79 m).

| Section | Habitat | Length (m) | % of total length |
|---------|---------|------------|-------------------|
| 1 Pool  | 33.52   | 33.29      |
| 1 Run   | 39.46   | 39.19      |
| 1 Rifle | 27.71   | 27.52      |
| 2 Pool  | 50.38   | 48.22      |
| 2 Run   | 37.24   | 35.64      |
| 2 Rifle | 16.86   | 16.14      |

Table 2. Candidate models predicting total crayfish counts with Akaike Information Criteria (AIC) and Bayesian Information Criteria (BIC). Model parametrization included generalized linear model with a Poisson distribution, zero-inflated (ZI) Poisson regression, model with random effect of trap ID (TrapID$_\text{random}$), and model with trap deployment time as rate (time$_\text{offset}$). Environmental predictors were added to the base model and evaluated by the difference in AIC from the model with the lowest AIC score ($\Delta$AIC). Smaller values indicate better model fit. ART = artificial refuge trap, TDS = total dissolved solids, DO = dissolved oxygen.

| Model | Log likelihood | BIC    | AIC    | $\Delta$AIC |
|-------|----------------|--------|--------|-------------|
| Poisson regression | -679.8 | 1366.8 | 1361.7 | 83.2 |
| ZI Poisson | -677.0 | 1368.4 | 1358.1 | 51.2 |
| ZI Poisson + TrapID$_\text{random}$ | -647.0 | 1315.5 | 1300.1 | 21.6 |
| ZI Poisson + TrapID$_\text{random}$ + ART type | -637.9 | 1318.7 | 1287.8 | 9.3 |
| ZI Poisson + TrapID$_\text{random}$ + time$_\text{offset}$ + ART type (“Base model”) | -637.1 | 1317.1 | 1286.2 | 7.7 |
| Base model + pebble | -637.1 | 1324.2 | 1288.1 | 9.6 |
| Base model + habitat type | -637.0 | 1324.1 | 1288.0 | 9.6 |
| Base model + TDS | -636.9 | 1323.9 | 1287.8 | 9.4 |
| Base model + canopy openness | -636.7 | 1323.5 | 1287.4 | 8.9 |
| Base model + stream section | -636.5 | 1323.2 | 1287.1 | 8.6 |
| Base model + mean conductivity | -636.1 | 1322.3 | 1286.3 | 7.8 |
| Base model + water temperature | -636.2 | 1322.4 | 1286.3 | 7.8 |
| Base model + DO | -633.6 | 1314.3 | 1281.2 | 2.7 |
| Base model + NH$_4$-N | -632.4 | 1314.8 | 1278.8 | 0.3 |
| Base model + pH | -632.2 | 1314.5 | 1278.5 | 0.0 |
AIC scores. In addition, there were no stream habitat type or water chemistry variables that improved model fit to predict female catch.

**Effect of trap deployment duration on *P. clarkii* CPUE**

In contrast with our prediction that traps with longer soak times would capture greater numbers of crayfish/unit of time, trap deployment duration had only a weak effect on total CPUE. Traps with 1- and 2-d deployments had slightly greater CPUE compared with longer deployment times (Fig. 3). However, the low observed CPUE values were not different among deployment treatments nor among trap types (Kruskal–Wallis, $H_3 = 3, p = 0.39$), most likely because of the large number of 0 counts.

**Effect of ART type on *P. clarkii* catch bias by size and sex**

In support of our expectation that ART design elements would be important factors in *P. clarkii* catch, our top performing models to predict total and male *P. clarkii* catches indicated that ART type was related to catch counts. Our chi-squared tests for independence to examine the effects of separate ART characteristics on catches showed an effect of trap diameter on total catches ($X^2_1 = 28.45, p < 0.001$) and male catches ($X^2_1 = 29.75, p < 0.001$). However, there were no differences in effect of ART color on total or male catches ($X^2_1 = 1.31, p = 0.25$ and $X^2_1 = 0.42, p = 0.52$, respectively). We did not observe an interactive effect between trap size and color on total, male, nor female catches (Table S6).

We did not observe an interactive effect between trap size and deployment duration in affecting *P. clarkii* catches for total nor female catches (Table S6). However, we did observe a positive interaction between trap size and deployment duration on male catches such that larger diameter traps and longer deployment durations had greater numbers of male catches. In addition, there was a positive interaction between trap color and deployment duration on total catches such that black traps with longer deployment durations caught more *P. clarkii* catches in total.

Size of *P. clarkii* caught in the ART traps was different among trap diameter size ($X^2_5 = 78.51, p < 0.001$). For traps with 5.1-cm openings, larger *P. clarkii* (mean = 4.29 cm, SD = 0.67) were more likely to be caught compared with smaller *P. clarkii* (no crayfish ≤1 cm in carapace length were observed in the larger diameter traps). In contrast, for traps with 2.5-cm openings, smaller *P. clarkii* (mean = 3.38 cm, SD = 0.67) were more likely to be caught compared with larger sized *P. clarkii* (no crayfish >5 cm in carapace length were observed in the smaller diameter traps; Fig. 5). There were no differences in *P. clarkii* size distributions between male and female crayfish ($X^2_5 = 4.70, p = 0.45$; Fig. S2).

Overall, there was no difference in catches of male (M) and female (F) *P. clarkii* during the study (1M:1.05F; $X^2_1 = 0.15$, 0.05). The traps with 5.1-cm-diameter openings (BLKTube5.1 and Tube5.1) caught the highest number of total *P. clarkii* (mean = 0.27 and 0.25, respectively) and male *P. clarkii* (mean = 0.15 and 0.13) out of the ART configurations examined (Fig. 4). Number of female catches did not differ among ART types. We did not observe interactions between trap diameter size and deployment duration in affecting *P. clarkii* catches for total nor female catches (Table S6). However, we did observe a positive interaction between trap size and deployment duration on male catches such that larger diameter traps and longer deployment durations had greater numbers of male catches. In addition, there was a positive interaction between trap color and deployment duration on total catches such that black traps with longer deployment durations caught more *P. clarkii* catches in total.

![Figure 3. Bar plots of mean catch per unit effort (CPUE) and standard errors for total, male, and female crayfish catch by soak treatment (d).](image-url)
However, the sex ratio of *P. clarkii* was different among ART types ($\chi^2_3 = 8.70, p = 0.03$). We observed more females than males in the small diameter traps: BLKTube2.5 (1M:2.5F) and Tube2.5 (1M:1.5F). Inversely, we observed more males than females in the large diameter traps: BLKtube5.1 (1M:0.76F) and Tube5.1 (1M:0.89F).

### DISCUSSION

This study tested the effects of ART design and deployment time on invasive *P. clarkii* removal. Our data suggest that both design and deployment duration can influence trapping efficacy for *P. clarkii*, and the findings from this study can be used to improve stream restoration efforts.
throughout the distributional range of invasive red swamp crayfish.

When considering ART efficacy from a management perspective, 4 factors are critically important: the overall effectiveness of the trap for long-term removal, whether or not ARTs capture *P. clarkii* of all sexes and sizes, the bycatch of non-target organisms, and the amount of effort needed to deploy traps relative to the amount of *P. clarkii* removed. In our 30-d study, a total of 240 invasive crayfish were removed from the focal reaches of our study stream in southern California. Based solely on the amount of crayfish removed during the study period, our results are more similar to studies reporting low catch of invasive crayfish in ARTs (Krieg et al. 2020) than studies that report the removal of a substantial proportion of crayfish populations by ARTs (Green et al. 2018). When considering available data from studies comparing ARTs to other trap types, there is disagreement on whether or not ARTs perform better than standard baited minnow traps (e.g., Green et al. 2018, De Palma-Dow et al. 2020). This disagreement suggests that other factors specific to study design might lead to differences in ART performance.

A primary goal of this study was to understand the effects of trap design and deployment time on invasive crayfish catch success. Trap diameter was an important factor determining the amount of crayfish caught within a trap, and BLKTube5.1 was the best performing trap throughout the study period. These data suggest that ARTs with larger diameters catch more crayfish and have a higher variance in the sizes of crayfish removed. These findings agree with research on white-clawed crayfish (*Astrotomobius pallipes* Lereboullet, 1858) in the United Kingdom (Peay et al. 2006), which demonstrated the positive relationship between opening size in breezeblocks (concrete blocks with pre-constructed holes that provide the same overall function as ARTs in this study) and crayfish size. Specifically, they found that ARTs with 30-mm openings caught more crayfish and crayfish of a wider range of size classes when compared with ARTs with 10- and 15-mm openings. The relationship between trap diameter and crayfish size is logical, given that larger crayfish can inhabit traps with greater total volume but may not be able to physically occupy the smaller trap diameters (i.e., no crayfish with 5–6-cm carapace length were observed in traps with 2.5-cm diameters). Further, considering average *P. clarkii* burrow diameters of 5.1 cm (Souty-Grosset et al. 2014), and that they are known to occupy the burrows of conspecifics (Gherardi et al. 2002, Ilhéu et al. 2002, Barbaresi et al. 2004), it follows that *P. clarkii* may preferentially seek the larger diameter ARTs that are similar to their typical burrow size.

The results from this study suggest that ART color is not an important factor in crayfish catch. Black-colored traps with 5.1-cm openings caught more crayfish than white 5.1-cm traps, but the difference was negligible, and the trap color—crayfish catch pattern was opposite for traps with 2.5-cm openings. Given the ability of crayfish to distinguish color (Wald 1968), their sensitivity to polarized light (Tut- hill and Johnsen 2006), the effect of polarized light on sight- ing distance and target contrast (Marshall and Cronin 2014), and previous research that demonstrated an effect of trap color on *P. clarkii* catch (Hyatt 2003), we expected that color would play a large role in ART catch efficiency (i.e., that the effect of color would be non-random for crayfish catch). It is possible that the effect of color treatments was confounded by natural stream processes in our study. Periphyton routinely built up on traps, which reduced the contrast of the ARTs with the natural stream substrate. However, we did not find differences in crayfish counts between white and black traps with 1-d deployment periods (Wilcoxon rank-sum test *W*= 51,396, *p*= 0.88) where we would expect to see greater differences in color contrasts. To control for differences in contrast of ARTs against stream substrate, future studies can use a luminance meter to provide quantitative measures that can better inform how color affects ART catch.

Another unexpected outcome of our study was the difference in ratios of male and female crayfish between traps, with females more likely to be found in smaller traps and males more likely to be found in larger traps. This skew between male and female crayfish by trap opening size is surprising because adult male crayfish tend to dominate all aggressive interactions except those with maternal females at burrowing sites (Peeke et al. 1995), and juvenile crayfish show no observable pattern between crayfish sex and dominance at shelter resources (Figler et al. 1999). Considering that female crayfish reach maturity at ~3-cm carapace length (Alcorlo et al. 2008) and that pre-gravid maternal females can successfully dominate aggressive interactions (Peeke et al. 1995), it is possible that a disproportionate number of pre-gravid maternal female crayfish occupied 2.5-cm traps. However, reproductive status was only noted when female crayfish were gravid, and no data on pre-gravid maternal females were collected (e.g., through inspection of glair glands). Additionally, this pattern was not observed in 5.1-cm traps, so we are unable to explain this observation. Furthermore, some research indicates that larger crayfish intruders maintain dominance at shelter resources (Figler et al. 1995, Issa et al. 1999). However, our study only recorded data on which crayfish occupied ARTs and not the exchange of dominance between previous and current burrow occupiers. It is worth noting that trap type did not improve model fit for the female-only crayfish models, which suggests that female red swamp crayfish do not exhibit a preference for trap diameter size nor color; however, this is a somewhat conflicting result given observed differences in the ratios of male and female crayfish in traps of different diameters. Future studies could use underwater videography to document crayfish behavior over time at ARTs to...
further investigate the relationship between ART opening size and crayfish sex.

With regards to bycatch of non-target organisms, ARTs can generally be deployed in areas with sensitive species, such as salmonid young of year or juvenile amphibians, because they do not have a trapping mechanism that prevents non-target species from escaping (De Palma-Dow et al. 2020). On the other hand, in locations where native and non-native crayfish are sympatric, ARTs may be useful for monitoring native populations (e.g., Peay et al. 2006) while removing invasive populations (e.g., Green et al. 2018). Our study had no incidental take of non-target organisms, which echoes findings of previous research that deployed similar ARTs in a nearby stream (Dagit 2020). Further, studies of passive baited traps that report both crayfish catch and bycatch (e.g., Mangan et al. 2009, Swartz and Miller 2018) provide further evidence that ARTs are a better choice for removing non-native crayfish. However, it is worth noting that data on bycatch are limited because studies using minnow traps or other passive baited trap types often do not report their bycatch.

Another objective of this study was to determine if ARTs could be used to preferentially target gravid female crayfish. This question was primarily motivated by the observation that all gravid female crayfish observed in the trap comparison study by De Palma-Dow et al. (2020) were found within ARTs. Further, it has been suggested that targeted removal of gravid female crayfish can increase the overall success of eradication projects by decreasing crayfish recruitment (Holdich and Domaniewski 1995). Surprisingly, during the course of this study, we caught only a single gravid female crayfish. It is possible that gravid female abundance was naturally lower at this study site or reproductive phenology differed from the stream reach used in previous studies. When compared with historical trapping data from this region using a variety of different passive baited traps (JNC, unpublished data), we did not find evidence to suggest that ARTs perform better than any other crayfish trap in targeting gravid female crayfish.

Finally, to address the amount of effort needed to deploy traps relative to the amount of P. clarkii removed, we found that traps left out for longer (4– and 7-d) soaks were ~½ as effective at removing crayfish as traps left out for shorter (1- and 2-d) soaks. These findings suggest that managers who have limited time and resources to dedicate to invasive species removal should focus on consecutive days of trapping as opposed to leaving traps out a week at a time. These findings could be a result of low shelter fidelity in P. clarkii (Figler et al. 2005). Instead of an additive effect of trap soak time on crayfish catch where, for example, familiarity with shelter resources leads to more crayfish occupying any given resource, it is hypothesized that crayfish instead occupy the resource that is closest to the location where they last foraged (Barbaresi and Gherardi 2006).

As with any conservation tool, ARTs should be deployed in management contexts where they can provide the most benefit. In stream systems where sensitive species might otherwise be negatively impacted by the use of minnow traps, ARTs may be beneficial in reducing numbers of invasive crayfish without causing incidental bycatch of a state or federally listed or sensitive species. In management contexts where native aquatic species are not vulnerable to the effects of mechanical trapping, ARTs can be used in combination with baited minnow traps to maximize crayfish removal efforts. Although ARTs are not a panacea for P. clarkii removal, they represent a valuable trap for any invasive crayfish maintenance and control program when used in combination with other more effective traps (e.g., baited minnow traps) and in contexts where managers need to begin implementation immediately, require flexibility on when and how often traps are checked, and are operating in areas where sensitive native taxa are present.

ACKNOWLEDGEMENTS

Author contributions: JNC, AAD, and CEF conceived of the study design. JNC built study traps and conducted field data collection. CEF implemented statistical analyses and generated most figures in R. JNC wrote the manuscript, and AAD and CEF provided comments and feedback.

Funding for this study was provided by an Integrated Regional Water Management 2016 grant (Grant Agreement #4600011488) awarded to the Mountains Restoration Trust. This manuscript has been subjected to United States Environmental Protection Agency review and has been approved for publication. The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the United States Environmental Protection Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The authors wish to thank R. Kosugi, M. Fiege, E. Gomez, G. Chiuz, R. Burnap, and A. Shy-Sobol for assistance in trap construction, placement, and data collection. Further, we thank R. Householder for trap schematics and illustrations and K. Gaston for project maps. We thank J. Notar and L. Havens for early discussions on crayfish vision that informed trap color selection and G. Bucciarelli for feedback on early versions of the manuscript. We acknowledge D. Lefer and California State Parks staff for assistance in permitting for this project. Finally, we also thank 2 anonymous reviewers for their thoughtful comments that improved the manuscript.

LITERATURE CITED

Alcorlo, P., W. Geiger, and M. Otero. 2008. Reproductive biology and life cycle of the invasive crayfish Procambarus clarkii (Crustacea: Decapoda) in diverse aquatic habitats of southwestern Spain: Implications for population control. Fundamental and Applied Limnology: Archiv für Hydrobiologie 173:197–212.

Barbaresi, S., and F. Gherardi. 2006. Experimental evidence for homing in the red swamp crayfish, Procambarus clarkii.
Bulletin Français de la Pêche et de la Pisciculture 380–381: 1145–1154.

Barbaresi, S., E. Tricarico, and F. Gherardi. 2004. Factors inducing the intense burrowing activity of the red-swamp crayfish, Procambarus clarkii, an invasive species. Naturwissenschaften 91:342–345.

Bolker, B. 2008. Ecological models and data in R. Princeton University Press, Princeton, New Jersey.

Bolker, B., M. Brooks, B. Gardner, C. Jennett, and M. Minami. 2012. Owls example: A zero-inflated, generalized linear mixed model for count data. (Available from: https://groups.nceas.ucsb.edu/non-linear-modeling/projects/owlsv/RIPEU/owlsvpdf/)

Brooks, M. E., K. Kristensen, K. J. van Benthem, A. Magnusson, C. W. Berg, A. Nielsen, H. J. Skaug, M. Mächler, and B. M. Bolker. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. The R Journal 9:378–400.

Bruski, C. A., and D. W. Dunham. 1987. The importance of vision in agonistic communication of the crayfish Orconectes rusticus. I: An analysis of bout dynamics. Behaviour 103:83–107.

Bucciarelli, G. M., D. Suh, A. D. Lamb, D. Roberts, D. Sharpton, H. B. Shaffer, R. N. Fisher, and L. B. Kats. 2019. Assessing effects of non-native crayfish on mosquito survival. Conservation Biology 33:122–131.

Burnham, K., and D. Anderson. 2002. Model selection and multimodel inference: A practical information-theoretic approach. Springer, New York, New York.

Chandra, S., and A. Gerhardt. 2008. Invasive species in aquatic ecosystems: Issue of global concern. Aquatic Invasions 3:1–2.

Correia, A., and A. Costa. 1994. Introduction of the red swamp crayfish Procambarus clarkii (Crustacea, Decapoda) in São Miguel, Azores, Portugal. Life and Marine Sciences 12A:67–73.

Correia, A., and O. Ferreira. 1995. Burrowing behavior of the introduced red swamp crayfish Procambarus clarkii (Decapoda: Cambaridae) in Portugal. Journal of Crustacean Biology 15:248–257.

Dagit, R. 2020. Crayfish removal trap evaluation final technical memo. Resource Conservation District of the Santa Monica Mountains, Los Angeles, California. (Available from: www.fs.usda.gov/treesearch/pubs/20753)

De Palma-Daw, A., J. Curti, and E. Fergus. 2020. It’s a trap! An evaluation of different passive trap types to effectively catch and control the invasive red swamp crayfish (Procambarus clarkii) in streams of the Santa Monica Mountains. Management of Biological Invasions 11:44–62.

Delaney, K., and S. Riley. 2019. Monitoring aquatic amphibians and invasive species in the Mediterranean Coast Network—2017 Annual Report: Santa Monica Mountains National Recreation Area. Natural Resource Report NPS/MEDN/NRR—2019/1884. Natural Resource Stewardship and Science, National Park Service, United States Department of the Interior, Fort Collins, Colorado. (Available from: https://irma.nps.gov/DataStore/DownloadFile/619805)

Fernández-De-Miguel, F., and H. Aréchiga. 1992. Sensory inputs mediating two opposite behavioural responses to light in the crayfish. Journal of Experimental Biology 164:153–169.

Figler, M. H., G. S. Blank, and H. V. S. Peeke. 2005. Shelter competition between resident male red swamp crayfish Procambarus clarkii (Girard) and conspecífic intruders varying by sex and reproductive status. Marine and Freshwater Behaviour and Physiology 38:237–248.

Figler, M. H., H. M. Cheverton, and G. S. Blank. 1999. Shelter competition in juvenile red swamp crayfish (Procambarus clarkii): The influences of sex differences, relative size, and prior residence. Aquaculture 178:63–75.

Figler, M. H., J. E. Finkelstein, M. Twum, and H. V. Peeke. 1995. Intruding male red swamp crayfish, Procambarus clarkii, immediately dominate members of established communities of smaller, mixed-sex conspecifics. Aggressive Behavior 21:225–236.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins. 1998. California salmonid stream habitat restoration manual. 4th edition. Wildlife and Fisheries Division, California Department of Fish and Game, Sacramento, California. (Available from: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=22610&inline)

Gallardo, B., M. Clavero, M. I. Sánchez, and M. Vilá. 2016. Global ecological impacts of invasive species in aquatic ecosystems. Global Change Biology 22:151–163.

Gamradt, S. C., and L. B. Kats. 1996. Effect of introduced crayfish and mosquitofish on California newts. Conservation Biology 10:1155–1162.

Garcia, C., E. Montgomery, J. Krug, and R. Dagit. 2015. Removal efforts and ecosystem effects of invasive red swamp crayfish (Procambarus clarkii) in Topanga Creek, California. Bulletin, Southern California Academy of Sciences 114:12–21.

Gardner, W., E. P. Mulvey, and E. C. Shaw. 1995. Quantitative methods in psychology. Psychological Bulletin 118:393–404.

Gherardi, F., L. Aquiloni, J. Diéguez-Uribeondo, and E. Tricarico. 2011. Managing invasive crayfish: Is there a hope? Aquatic Sciences 73:185–200.

Gherardi, F., E. Tricarico, and M. Ilhéu. 2002. Movement patterns of an invasive crayfish, Procambarus clarkii, in a temporary stream of southern Portugal. Ethology Ecology & Evolution 14:183–197.

Green, N., M. Bentley, P. Stebbing, D. Andreou, and R. Britton. 2018. Trapping for invasive crayfish: Comparisons of efficacy and selectivity of baited traps versus novel artificial refuge traps. Knowledge and Management of Aquatic Ecosystems 419:15.

Harreln, C. C., C. L. Rawlins, and J. P. Potonyk. 1994. Stream channel reference sites: An illustrated guide to field technique. RM-GTR-245, Rocky Mountain Forest and Range Experiment Station, Forest Service, United States Department of Agriculture, Fort Collins, Colorado. (Available from: https://www.fs.usda.gov/treesearch/pubs/20753)

Holdich, D. M., R. Gydemo, and W. D. Rogers. 2017. A review of possible methods for controlling nuisance populations of alien crayfish. Pages 245–270 in F. Gherardi and D. M. Holdich (editors). Crayfish in Europe as alien species: How to make the best of a bad situation? 1st edition. A. A. Balkema, Rotterdam, The Netherlands.

Holdich, D. M., and J. C. J. Domaniewski. 1995. Studies on a mixed population of the crayfish Austropotamobius pallipes and Pacifastacus leniusculus in England. Freshwater Crayfish 10:37–45.

Holmes, S. J. 1924. The genus Cambarus in California. Science 60:358–359.

Hyatt, M. W. 2003. Investigation of crayfish control technology: Final report. Cooperative Agreement No. 1448-20181-02-J859. Arizona Game and Fish Department, Phoenix, Arizona.
Artificial refuge traps to control invasive crayfish

J. N. Curti et al.

(Available from: https://www.usbr.gov/lc/phoenix/biology/azfish/pdf/CrayfishFinal.pdf)

Ilhêu, M., P. Acquistapace, C. Benvenuto, and F. Gherardi. 2002. Burrowing activity of the red-swamp crayfish in a temporary stream in Portugal. Freshwater Crayfish 13:609.

Issa, F. A., D. J. Adamson, and D. H. Edwards. 1999. Dominance hierarchy formation in juvenile crayfish Procambarus clarkii. The Journal of Experimental Biology 202:3497–3506.

Kats, L. B., G. Bucciarelli, T. L. Vandergon, R. L. Honeycutt, E. Mattiasen, A. Sanders, S. P. D. Riley, J. L. Kerby, and R. N. Fisher. 2013. Effects of natural flooding and manual trapping on the facilitation of invasive crayfish-native amphibian coexistence in a semi-arid perennial stream. Journal of Arid Environments 98:109–112.

Kerby, J. L., S. P. D. Riley, L. B. Kats, and P. Wilson. 2005. Barriers and flow as limiting factors in the spread of an invasive crayfish (Procambarus clarkii) in southern California streams. Biological Conservation 126:402–409.

Klose, K., and S. D. Cooper. 2012. Contrasting effects of an invasive crayfish (Procambarus clarkii) on two temperate stream communities. Freshwater Biology 57:526–540.

Krieg, R., A. King, and A. Zenker. 2020. Measures to control invasive crayfish species in Switzerland: A success story? Frontiers in Environmental Science 8:609129.

Kusabs, I. A., B. J. Hicks, J. M. Quinn, W. L. Perry, and H. Whanga. 2018. Evaluation of a traditional Māori harvesting method for sampling kōura (freshwater crayfish, Parapeneaus planifrons) and toi toi (bully, Gobiomorphus spp.) populations in two New Zealand streams. New Zealand Journal of Marine and Freshwater Research 52:603–625.

LaPoint, S., P. Gallery, M. Wikelski, and R. Kays. 2013. Animal behavior, cost-based corridor models, and real corridors. Landscape Ecology 28:1615–1630.

Larson, E., and J. Olden. 2016. Field sampling techniques for crayfish. Pages 287–324 in M. Longshaw and P. Stebbing (editors). Biology and ecology of crayfish. Taylor & Francis Group, Boca Raton, Florida.

Lodge, D. M., A. Deines, F. Gherardi, D. C. J. Yeo, T. Arcella, A. K. Baldrige, M. A. Barnes, W. L. Chadlerton, J. L. Feder, C. A. Gantz, G. W. Howard, C. L. Jerde, B. W. Peters, J. A. Peters, L. W. Sargent, C. R. Turner, M. E. Wittmann, and Y. Zeng. 2012. Global introductions of crayfishes: Evaluating the impact of species invasions on ecosystem services. Annual Review of Ecology, Evolution, and Systematics 43:449–472.

Manfrin, C., C. Souty-Grosset, P. M. Anastácio, J. Reynolds, and P. G. Giulianini. 2019. Detection and control of invasive freshwater crayfish: From traditional to innovative methods. Diversity 11:5.

Mangan, B. P., J. J. Savitski, and N. T. Fisher. 2009. Comparison of two traps used for capturing wild crayfish. Journal of Freshwater Ecology 24:445–450.

Marshall, J., and T. Cronin. 2014. Polarisation vision of crustaceans. Pages 171–216 in G. Horváth (editor). Polarized light and polarization vision in animal sciences. 2nd edition. Springer-Verlag, Heidelberg, Germany.

Milligan, W. R., M. T. Jones, L. B. Kats, T. A. Lucas, and C. L. Davis. 2017. Predicting the effects of manual crayfish removal on California newt persistence in Santa Monica Mountain streams. Ecological Modelling 352:139–151.

Moreira, F. D., F. Ascensão, C. Capinha, D. Rodrigues, P. Segurado, M. Santos-Reis, and R. Rebelo. 2015. Modelling the risk of invasion by the red-swamp crayfish (Procambarus clarkii): Incorporating local variables to better inform management decisions. Biological Invasions 17:273–285.

O’Connor, J., S. Brennan, and J.-R. Baars. 2018. Crayfish arts: An evaluation into the efficacy of artificial refuge traps for monitoring lotic white-clawed crayfish Austropotamobius pallipes (Lereboullet, 1858) (Decapoda, Astacidae) populations. Crustacea 91:297–309.

Peay, S., N. Guthrie, J. Spees, E. Nilsson, and P. Bradley. 2009. The impact of signal crayfish (Pacifastacus leniusculus) on the recruitment of salmonoid fish in a headwater stream in Yorkshire, England. Knowledge and Management of Aquatic Ecosystems 394–395:12.

Peay, S., and P. Hiley. 2001. Eradication of alien crayfish populations. R&D Technical Report WI-037/TR1. Environment Agency, Leeds, United Kingdom. (Available from: http://ea-literatureserverlife.org/archive/ealtit/4540/OBJ/preview.pdf)

Peay, S., A. Proud, and D. Ward. 2006. White-clawed crayfish in muddy habitats: Monitoring the population in the River Ivel, Bedfordshire, United Kingdom. Bulletin Français de la Pêche et de la Pisciculture 380–381:1079–1094.

Peeke, H. V. S., M. Twum, J. E. Finkelstein, and M. H. Figler. 1995. Maternal aggression in red swamp crayfish (Procambarus clarkii, Girard): The relation between reproductive status and outcome of aggressive encounters with male and female conspecifics. Behaviour 132:107–125.

Quan, A. 2014. Origins of the invasive red swamp crayfish (Procambarus clarkii) in the Santa Monica Mountains. Aquatic Invasions 9:211–219.

Reitan, T., and A. Nielsen. 2016. Do not divide count data with count data: A story from pollution ecology with implications beyond. PLoS ONE 11:e0149129.

Riley, S. P. D., G. T. Busted, L. B. Kats, T. L. Vandergon, L. F. S. Lee, R. G. Dagit, J. L. Kerby, R. N. Fisher, and R. M. Sauvajot. 2005. Effects of urbanization on the distribution and abundance of amphibians and invasive species in southern California streams. Conservation Biology 19:1894–1907.

Skurdal, J., and T. Qvenild. 1986. Growth, maturity, and fecundity of invasion by the red-swamp crayfish (Procambarus clarkii) in southern California streams. Biological Invasions 17:273–285.

Souty-Grosset, C., J. Reynolds, F. Gherardi, L. Aquiloni, A. Coignet, F. Pinet, and M. D. Mancha Cisneros. 2014. Burrowing activity of the invasive red swamp crayfish, Procambarus clarkii, in fishponds of La Brenne (France). Ethology Ecology & Evolution 26:263–276.

Stebbing, P., M. Longshaw, and A. Scott. 2014. Review of methods for the management of non-indigenous crayfish, with particular reference to Great Britain. Ethology Ecology & Evolution 26:204–231.

Stuecheli, K. 1991. Trapping bias in sampling crayfish with baited funnel traps. North American Journal of Fisheries Management 11:236–239.

Swartz, T., and J. Miller. 2018. Trapping amphibians and their predators: Tradeoffs in trap design and performance. Herpetological Review 49:238–243.

Thomsen, M., T. Wernberg, J. Olden, J. E. Byers, J. Bruno, B. Siliman, and D. Schiel. 2014. Forty years of experiments on
aquatic invasive species: Are study biases limiting our understanding of impacts? NeoBiota 22:1–22.
Tuthill, J. C., and S. Johnsen. 2006. Polarization sensitivity in the red swamp crayfish Procambarus clarkii enhances the detection of moving transparent objects. Journal of Experimental Biology 209:1612–1616.
Wald, G. 1968. Single and multiple visual systems in arthropods. The Journal of General Physiology 51:125–156.
Walter, K. 2012. An evaluation of whether artificial refuge traps or baited traps are the most effective method for trapping white-clawed crayfish (Austropotamobius pallipes) in the Creedy Yeo River, Devon. The Plymouth Student Scientist 5:443–485.
Warren, M. L., A. L. Sheldon, and W. R. Haag. 2009. Constructed microhabitat bundles for sampling fishes and crayfishes in coastal plain streams. North American Journal of Fisheries Management 29:330–342.
Yamamoto, Y. 2010. Contribution of bioturbation by the red swamp crayfish Procambarus clarkii to the recruitment of bloom-forming cyanobacteria from sediment. Journal of Limnology 69:102–111.