Research Article

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

Angela A. De Palma-Dow[1,2,*], Joseph N. Curti[1] and C. Emi Fergus[3]

[1]*Mountains Restoration Trust, 3815 Old Topanga Canyon Rd., Calabasas, CA 91302, USA*
[2]*Lake County Water Resources Department, 255 N. Forbes St., Lakeport, CA 95453, USA*
[3]*National Research Council, C/o USEPA Western Ecology Division, 200 SW 35th St, Corvallis, OR 97333, USA*

Author e-mails: *Angela.DePalma-Dow@lakecountyca.gov (AAD), joey.nikko.curti@gmail.com (JNC), emifergus@gmail.com (EF)*

**Corresponding author*

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Abstract

The invasive red swamp crayfish poses a significant threat to physical habitat quality and biodiversity of aquatic communities in western U.S. streams. With no natural predators or competitors, crayfish can consume adult, juvenile, and egg forms of native fish, amphibians, and benthic macroinvertebrates. In addition, crayfish can destroy physical structures and disrupt nutrient and sediment dynamics by burrowing into banks and increasing turbidity. Mountain Restoration Trust has managed crayfish populations in the Santa Monica Mountains for almost a decade, yet evaluation of trap type effectiveness has remained a constant source of uncertainty in overall management efforts. In this two-week field experiment, we compared 12 trap designs including refuge traps, baited pyramid traps, and baited minnow traps with different colors and opening sizes to determine which traps caught the most crayfish and least bycatch. There were significant differences observed across the traps tested in the number of crayfish, chub, and tadpoles caught. The most effective trap for catching crayfish were both mesh traps, the Promar mesh 503 trap (mean daily crayfish catch = 1.9, SE = 0.24) and the Promar mesh 501 trap (mean daily crayfish catch = 1.2, SE = 0.26). The least effective traps, that caught more bycatch than crayfish, were the painted-black Gee Minnow trap (mean daily chub bycatch = 3.3, SE = 0.98) and the customized Pyramid trap with 5.1 cm openings (mean daily chub bycatch = 3.2, SE = 1.30). When managing for crayfish in southern California, arid-environment streams, we recommend deploying a combination of the Promar mesh 503 trap, the Promar mesh 501 trap, and/or the black Promar (2.5 cm). The combination of these traps can maximize crayfish catch efficiency and limit negative impacts on native fish and tadpole bycatch.

Key words: stream management, tube trap, minnow trap, bycatch, trap efficiency, crustacean

Introduction

Aquatic invasive species pose a significant risk to the ecological form and function of valuable aquatic resources such as streams and lakes. Non-native, invasive crayfish negatively impact food webs, exert direct and indirect effects on other biota, and are fully capable of survival in anthropogenically degraded stream systems (Gherardi et al. 2011). Invasive crayfish can negatively affect stream water quality when they construct burrows in the stream banks (Correia and Ferreira 1995), leading to channel instability and erosion, and contributing to increased turbidity and nutrient resuspension through bioturbation (Yamamoto 2010; Klose and Cooper 2012). The opportunistic and omnivourous red swamp crayfish (*Procambarus clarkii* Girard, 1852) (herein "crayfish") has been observed in the Santa Monica Mountains region since the 1960s and remains one of the most abundant, non-native, invasive species in the Malibu Creek watershed (Riley et al. 2005; Garcia et al. 2015; Loureiro et al. 2015). The establishment of crayfish populations in this region has resulted in the decline of regional native species such as California newt (*Taricha torosa*), California red-legged frog (*Rana draytonii*), and arroyo chub (*Gila orcuttii*) (Milligan et al. 2017; Quan et al. 2014; Kats et al. 2013; Delaney et al. 2011; Riley et al. 2005; Kerby et al. 2005; Gamradt and Kats 1996). Historically, there are no native crayfish in this region, suggesting that the native aquatic organisms are likely unable to compete or avoid this aggressive invader, which can displace native species and reduce their overall abundance through predation on adult, juvenile, and egg life stages (Gamradt and Kats 1996; Loureiro et al. 2015; Milligan et al. 2017). Removal of crayfish is a well-documented method to reduce populations and diminish the negative impacts the species can cause once it becomes established (Stebbing et al. 2014; Kerby et al. 2005). One generally successful method to remove non-native crayfish is by means of manual trapping and subsequent removal from the system. However, implementing a crayfish removal management strategy for streams inhabited by sensitive native species requires a thorough investigation of what capture methods will limit bycatch while simultaneously providing effective catch capability.

Trap design can be the ultimate determinant of an effective method of catching desired target species while limiting catch of non-target species (Mangan et al. 2009). Few studies have singly focused on crayfish trap efficiency (Holdich and Sibley 2003) and to our knowledge, only one has included an investigation into the effects of trap method with non-target catch (Mangan et al. 2009). Furthermore, there have been very few examples of successful invertebrate eradication efforts in North America, and none has been reported in Europe (Genovesi 2005; Gherardi et al. 2011; Stebbing et al. 2014). According to Tobin et al. (2014) the highest rate of eradication success belongs to the Diptera and Lepidoptera orders, and the management controls responsible include mass trapping, lure and kill and biomanipulation (Tobin et al. 2014). Similarly, Gherardi and Panov (2006) have listed chemicals such as organophosphate, organochlorine, and pyrethroid insecticides as being effective on smaller organisms, but the impact of these chemicals in arid, low-precipitation areas is uncertain. While also not feasible in some Southern California stream systems, drawdown and other habitat manipulation techniques have been considered useful management tools (Kerby et al. 2005) as well as biomanipulation through the introduction of predaceous fish (Holdich et al. 1999). While largemouth bass are already introduced in some the stream systems in our study area, their impact on crayfish is unknown, but probably not effective enough to provide control benefits. Local management of crayfish in Trancas Creek in the Santa Monica Mountains has demonstrated that while trapping did not eradicate a local crayfish population, it was successful in maintaining low population numbers that allowed native California newt (*Taricha torosa*) populations to rebound (Milligan et al. 2017; Kats et al. 2013). Further, some studies have found success of crayfish removal in lentic systems through a combination of mechanical trapping and through management of the legal take of crayfish predator species (i.e. large predatory fishes) through limitations on maximum size of take and lower bag limits (Hein et al. 2006). Compared to management strategies including biocides and hydromodification (i.e. changing drainage and flow regimes), trapping has the least impact on other species while still removing abundances of crayfish that result in benefits for native species (Milligan et al. 2017; Kats et al. 2013; Kerby et al. 2005). Therefore, these trap types can be speculated to be the most ecologically effective method of crayfish control, although specific studies investigating this are limited.

Trap design, color, and placement, in addition to local habitat characteristics and bait type, are important variables to consider when planning an efficient trapping-based management scheme. Previous research has shown that baited minnow traps tend to lure and catch large male crayfish although these trap types have been the preferred method of sampling in many population and distribution studies (Stuecheli 1991; Gherardi et al. 2011). There is an absence in the literature regarding the effect of funnel-opening size and trap type and/or trap color on capture rate. Funnel-opening size alone, however, does influence capture results (Stuecheli 1991), with larger openings catching larger, male crayfish over juveniles or smaller females.

Understanding the influence of different trapping devices on the catch of native and invasive species is valuable for management, especially in habitats where the likelihood of impacting bycatch is a fundamental concern due to the presence of sensitive or endangered species. Therefore, our study compares the crayfish and non-crayfish catch across different trap types that include both baited and passive catch designs. We examine whether trap type affects the number, size, and sex ratio of crayfish caught during the study. We also investigate whether specific trap features, such as color and funnel-opening size, influence catch patterns across trap types. In this study, we use the terms “trap efficiency” or “trap effectiveness” to represent which traps are effective at capturing crayfish while capturing minimal bycatch. Our approach included a two-week, field-based comparison study to analyze passive trap effectiveness in a Santa Monica Mountain stream, Las Virgenes Creek, Calabasas, CA.

Figure 1. Placement of traps compared in study in Las Virgenes Creek within Malibu Creek State Park. Inset shows specific study location within a regional context. Section locations were selected based on their representativeness of habitat types occurring over the entire reach (i.e. amount of riffle, runs and pools being comparable) and presence of suitable habitat for trap placement and visual observance of crayfish, tadpoles and native chub.

Materials and methods

Study Site

Sample sites were located in three separate sections within a one-mile reach of Las Virgenes Creek (Figure 1) in the Malibu Creek watershed of the Santa Monica Mountains (Los Angeles, CA, USA). These sites were not previously trapped. Each stream section contained a similar proportion of pool, riffle, and run habitat (Supplementary material Table S1). Habitat types followed distinctions by Flosi et al. (2010). Sections were included only if they contained crayfish, and the two native bycatch species: Baja California tree frog tadpoles (*Pseudacris hypochondriaca*, herein “tadpoles”) and arroyo chub (herein "chub"), as confirmed by visual identification during stream habitat delineation prior to the start of this study.

Traps were placed only in pools and runs, as riffles were usually too shallow to completely submerse traps and flow was too fast for crayfish activity (Peay et al. 2009). Three replicates of each trap type, except for two each of the pyramid trap types, were placed randomly in each 75 m stream section, for a total of 102 traps. Traps were separated by a minimum of one meter from one another (Peay et al. 2009; Mangan et al. 2009). Traps placement was geo-referenced using a GPS unit (Garmin GPS map 62 stc; Figure 1). Traps were allowed to soak for 24 hours based on industry standard soak times used in similar studies and to account for higher nocturnal activity of crayfish (Klose and Cooper 2012; Mangan et al. 2009; Stuecheli 1991). Catch was recorded and bait replaced once daily Monday through Friday during the two-week study period. All crayfish caught were sexed, measured, and once removed, ethically euthanized by freezing. Crayfish total length was determined by measuring individuals from the rostrum to the end of the telson. Values for total length are approximately twice the more widely used measure of crayfish carapace length that is measured from the rostrum to the posterior end of the carapace (Stein 1977). Chub were measured and grouped into one of three size class categories, small/juvenile (≤ 60 mm), medium adult (61–89 mm), and large adult (89–150 mm) according to O'Brien et al. (2011). Tadpoles were counted and, along with chub or any other native bycatch, were immediately returned to the creek. Any mortality due to trap catch was recorded. These 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.

Trap types tested

The traps that were tested in this experiment are commercially available, easily modified or constructed using common materials available at any local hardware store. The study compared catch between six base trap models and designs, with additional modifications to some traps to identify color/size effects on catch (Table 1). Some of the base style traps tested are currently being used in invasive crayfish removal efforts in nearby creeks or have been used in previous crayfish trap or abundance studies in the area. We compared the catch efficiency of six trap models (Figure 2) and modified color or opening size in some trap models to total 12 different trap types (Table 1).

Modifications were made to test for the effect of color and opening size as determining factors driving patterns in catch. All traps, except for the tube traps, were baited with two to five pieces of Purina True Instinct salmon and tuna flavored dog food; which contains both dry "kibble" and dehydrated meaty chunks. Bait was placed into the attached bait pouch, if

Table 1. Trap specifications describing the standard base trap models and modified traps used in this study. All traps were given a soak time of 24 hours. * indicates if trap attribute was modified to fit testing parameters.

Trap ID Code	Base Model Brand and Description	Material	Requirements	Color	Opening size	# Traps Per Section	Total # Traps In Study
PROMAR (BLACK 2.5 cm)	Promar TR-601 Minnow / Funnel Trap, 22.2 × 45.7 cm	Vinyl coated wire mesh	> 25.4 cm water depth	Black	2.5 cm	3	9
PROMAR (SILVER 2.5 cm)				Silver*	2.5 cm	3	9
PROMAR (BLACK 10.2 cm)				Black	10.2 cm*	3	9
GEE MINNOW (SILVER 2.5 cm)	Gee Minnow / funnel Trap, 22.9 × 44.5 cm	.64 cm Galvanized steel wire	> 25.4 cm water depth	Silver	2.5 cm	3	9
GEE MINNOW (SILVER 10.2 cm)				Silver	10.2 cm*	3	9
GEE MINNOW (BLACK 2.5 cm)				Black*	2.5 cm	3	9
CUSTOM PYRAMID (5.1 cm)	Custom Pyramid trap with three openings at bottom corners, PVC opening at top for fish to escape	.64 cm square metal mesh	> 61 cm depth, shoreline anchor nearby (i.e. branch or root)	Grey	5.1 cm*	2	6
CUSTOM PYRAMID (10.2 cm)				Grey	10.2 cm*	2	6
PROMAR MESH 501 (“ProMSH501”)	Promar TR-501, 45.7 × 25.4 cm	Red fabric mesh, metal end frames	> 128 cm depth, low flow	Red	6.4 cm	3	9
PROMAR MESH 503 (“ProMSH503”)	Promar # TR-503 61 × 30.5 cm	Black polyethylene netting	> 33 cm depth, low flow	Black	14 cm (slack)	3	9
Tube Trap (15.2 cm)	Custom refuge, “Tube” traps, 5.1 cm diameter	Black PVC pipes taped together in-line	> 7.6 cm depth, flat area in sediment with rock/ weight to keep trap submerged	Black	5.1 cm diameter / 15.2 cm long	3	9
Tube Trap (30.5 cm)				Black	5.1 cm diameter / 30.5 cm long	3	9
Total number of traps deployed							102

provided (e.g. Promar mesh traps), otherwise the bait was placed into the center of the trap. Four of the base traps were minnow trap designs with varying mesh material, size, and funnel openings. Three base trap types were made of rigid steel mesh material, silver steel, and black vinyl coated wire, and two were made with a more flexible polyethylene netting material: the black cylindrical (Promar 503) and red mesh (Promar 501) minnow traps. Two traps were custom made by Mountains Restoration Trust: the pyramid trap modified from its standard 5.1 cm opening size to 10.2 cm opening size and the tube or refuge trap, constructed of a series of either 15.2 cm or 30.5 cm long black PVC tubes. The rational for the construction and deployment of the tube trap was to identify a potential catch method that did not require bait and that did trap target species and allowed all bycatch species an escape. The tube trap mimics a burrow or hole made by crayfish in stream sediments or algae beds and was based on a design described in a study by Peay et al. (2005) but similar to those used in Green et al. (2018) and O’Connor et al. (2018).

Determining Habitat Condition

Several abiotic parameters were sampled once within each section and at each trap site, at the beginning of the two-week study. This preliminary monitoring was to identify if there were differences in the water quality

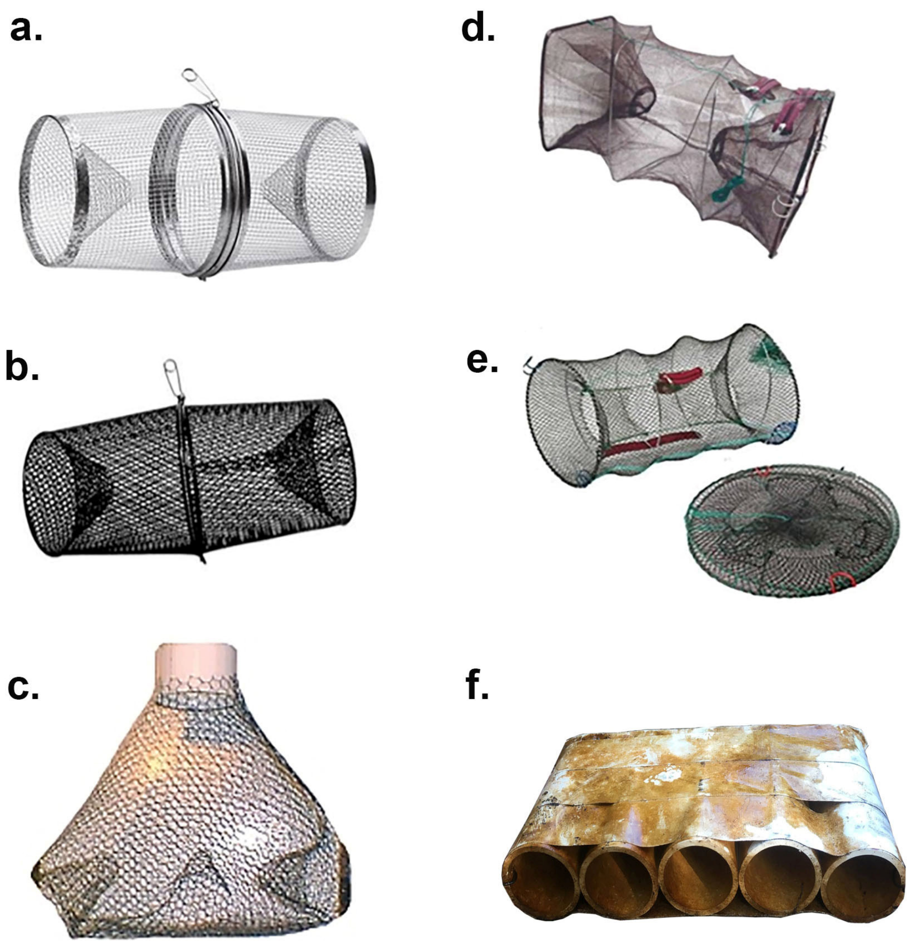

Figure 2. Six standard, base trap types used in this study; a = Steel silver Gee Minnow trap, b = Vinyl coated black Promar Minnow trap, c = Mountain Restoration Trust custom design pyramid trap, d = Collapsible red square mesh Promar 501 trap, e = Colapsible cylindrical black mesh Promar 503 trap, and f = Mountain Restoration Trust custom PVC tube/refuge traps. Specific modifications to these traps to create the 12 types tested are provided in Table 1.

environment between sections and trap placement locations before placing traps. Parameters measured included air temperature, water temperature, total dissolved solids (TDS), flow/discharge (CFS), dissolved oxygen, nitrate, and pH. Abiotic parameters were selected to ensure consistency in ambient stream conditions within and among trap sections. We used an ANOVA test to identify any differences in these predictor abiotic environmental variables measured during trap placement and resulting crayfish catch. Habitat variability between stream sections was tested using a Chi-square goodness-of-fit test to identify if any differences existed in the habitat composition (percent of pools and runs) between sections. A separate Chi-square was conducted to identify any differences in total crayfish catch between stream sections. All analyses were performed in R (R Core Team 2017).

Analysis of trap type effects on catch

We performed zero-inflated Poisson regressions to examine the effect of trap type on total mean counts of crayfish, chub, and tadpole catches separately. To evaluate model fit, we used likelihood-ratio-tests to compare the goodness-of-fit of the models with trap type to an intercept-only null model with no predictors. To determine specific differences in catch between each trap type, we performed post-hoc mean comparison tests using Tukey adjustments for multiple comparisons. In addition, we performed Chi-square goodness-of-fit analyses to determine whether mean catch counts differed from expected count proportions, assuming equal proportions of catch among crayfish, chub, and tadpoles by trap type. This analysis was important to include in order to identify not only the most effective trap for crayfish but to identify the worst type of traps for catching bycatch, an important factor for any aquatic invasive species manager.

To determine if trap color or size opening influenced mean catch counts, we performed separate Chi-square goodness-of-fit tests. We excluded both tube trap types from our analysis on size opening because their design (i.e., refuge trap with multiple openings) is inherently different from the other trap types and therefore would not be appropriate to compare.

We performed non-parametric Wilcoxon rank-sum tests (i.e., Mann-Whitney) to assess whether there were significant differences in sex of mean crayfish caught in total during the study and across individual trap types. To identify if there were any differences among size of crayfish caught per trap type we performed a Kruskal-Wallis test and post-hoc Dunn test for multiple comparisons across all possible groups of trap type and catch size.

A Wilcoxon rank-sum test was used to identify significant relationships between mean catches and habitat type, specifically catch in pools *vs*. runs. We also wanted to identify any interaction effects between bycatch and crayfish catch, as it is important to know if a bycatch species tends to avoid or enter a trap with crayfish or vice versa. To test if there were any associations among trap types with crayfish and bycatch, we performed Spearman's correlation tests (two-tail) between crayfish, chub, and tadpoles by each trap type.

Results

Over the two-week trap study duration, 502 crayfish, 704 arroyo chub, 74 tadpoles, and 3 odonate larvae were caught across all trap types (Table S2). No other species were caught during the duration of this trap study, although in other areas of the creek, mosquito fish *(Gambusia affinis),* western toad (*Anaxyrus boreas*), and American bullfrog (*Lithobates catesbeianus)* have been observed. Odonate larvae were caught in Gee Minnow (2.5 cm), Promar mesh 501 and Pyramid (10.2 cm). Promar (silver 2.5 cm) and Pyramid (10.2 cm) each had a single arroyo chub mortality. Four female crayfish carrying eggs were collected, two from Promar mesh 501 trap and two from Tube Trap (30.5 cm). During the study period, one Promar mesh trap was removed from the creek by an animal but was found a day later and re-deployed. Some of the mesh traps, both Promar mesh 503 and Promar mesh 501 trap designs, had zipper malfunctions, but were able to be fastened in the field to prevent crayfish escapes when submerged. Comparing the abiotic environment during initial trap placement revealed no overall significant findings for crayfish catch (F-value range = 0.26–3.09, p-value range > 0.05), chub (F-value range 0.01–3.7, p-value range > 0.06) and mostly for tadpoles (F-value range = 0.08, p-value range = 0.06–0.81) which were significantly related to water depth (negative, F-value = 3.9, p-value = 0.05) and TDS (positive, F-value = 39.3, p-value = 0.01). Results from these multiple ANOVA tests generally indicate that the initial placement of traps were all similar in their environmental abiotic features and did not affect catch of crayfish and chub. In addition, we found no significant difference in total crayfish counts among replicate stream sections at the close of this study with section A, B, and C having caught a total of 170, 157, and 175 crayfish, respectively (X^2 = 1.03, p-value = 0.60, df = 2).

Comparisons in trap type catch for crayfish, chub and tadpoles

When testing mean catches between trap types, the zero-inflated Poisson regression models with trap type as a predictor fit the data better than the null models without trap type included. These results, based on the likelihood-ratio-tests for crayfish (X^2 = 257.67, p-value < 0.01, df = 24), chub (X^2 = 354.39, p-value < 0.01, df = 22), and tadpoles (X^2 = 57.31, p-value < 0.01, df = 18) indicate there were differences in mean catches between trap type when comparing among crayfish, chub, and tadpoles (Figure 3). The Promar mesh trap model 503 caught the greatest mean number of crayfish during the study compared to all other non-mesh traps, although it was not significantly different from the Promar mesh trap 501 in crayfish catch (Table S2).

Across all trap types, we found significant differences between observed frequencies and expected proportions of crayfish, chub, and tadpole catches (X^2 = 410, p-value < 0.001, df = 2) indicating that catch distributions did differ among all the species observed in the study. The majority of chub were caught in the Pyramid (5.1 cm) and Gee Minnow (Black 2.5 cm) traps. Tube Trap (15.2 cm) and Pyramid (10.2 cm) traps caught the least amount of chub during the study, catching only two adult chub. Promar mesh 501, while effective for catching crayfish, also caught the most tadpoles along with the Promar (silver 2.5 cm) and Gee Minnow (silver 2.5 cm).

There was an effect of trap color and opening size on the number of crayfish caught. Specifically, we found that black colored traps caught the most crayfish followed by silver and red (X^2 = 103, p-value < 0.01, df = 2).

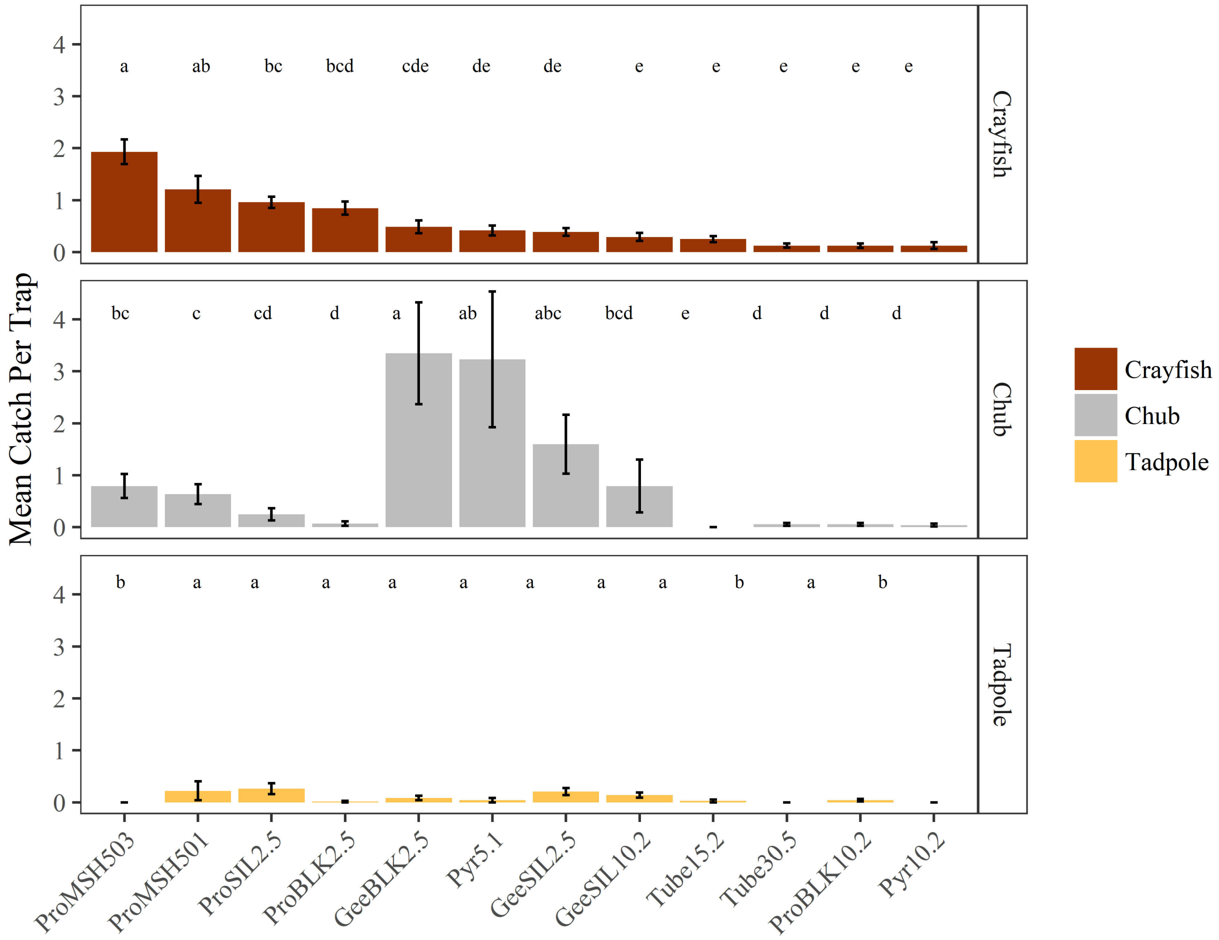

Figure 3. Mean catch per trap type with standard errors. Letters indicate significantly different mean counts within groups.

Further, traps with 2.5 cm openings caught the most crayfish, and traps with 5.1 cm and 10.2 cm openings caught the least number of crayfish (X^2 = 207, p-value < 0.01, df = 3).

Trap type effects on crayfish sex and size

There were not significant differences between male and female counts when comparing the mean for all traps combined (Wilcoxon rank-sum test W = 326640, p-value = 0.35, Figure 4). In addition, we found no significant differences in male and female crayfish catches within individual trap types (Wilcoxon rank-sum test range W = 1152–2701, p-value range = 0.7–1.0).

We did observe differences across trap types in their effectiveness for catching crayfish of different sizes (Kruskal-Wallis X^2 test = 864, p-value < 0.01, df = 119, Figure 5). Both mesh traps caught a greater proportion of the larger 9 cm and 10 cm size of crayfish compared to other crayfish sizes. In contrast, Promar (silver 2.5 cm) and Promar (black 2.5 cm) caught similar amounts of crayfish across size classes.

For bycatch of chub, there was a significant effect of trap type on size of chub caught (Kruskal-Wallis X^2 test = 266, p-value < 0.01, df = 35, Figure 6). The Promar mesh trap caught significantly more small-sized chub (mean

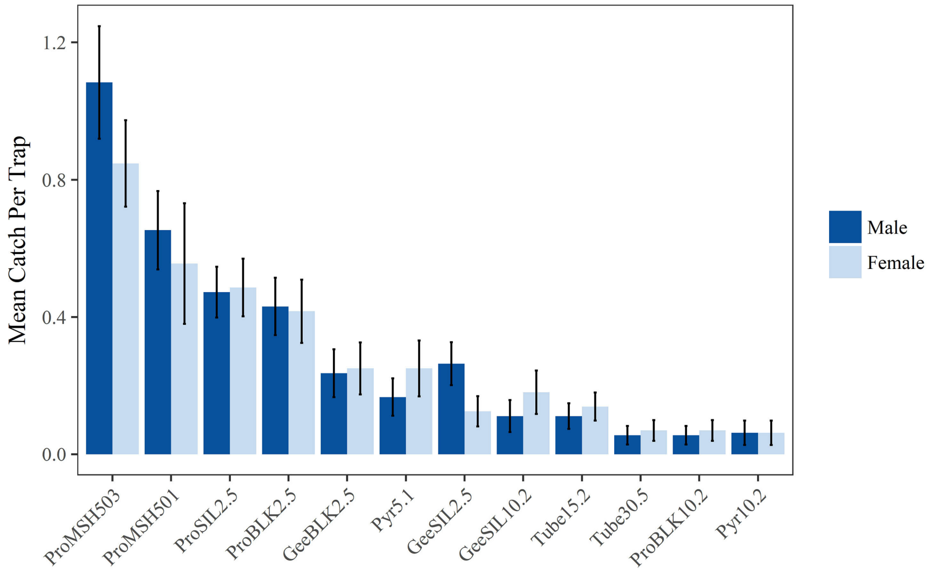

Figure 4. Mean crayfish catch per trap by sex. Bars indicate standard error.

catch = 0.40, SD = 0.10) than large-sized chub (mean catch = 0.01, SD = 0.01). However, across all other trap types there was no significant difference in the size of chub caught. Tadpoles were not grouped by size class and no adult frogs were caught in traps during this study.

Habitat and species interaction effects on catch

Across all trap types, crayfish were more likely to be caught in pools than runs ($W_{crayfish}$ = 91088, p-value < 0.05). Although this was not observed with chub (W_{chub} = 80546, p-value = 0.20) nor tadpoles ($W_{tadpole}$ = 81692, p-value = 0.23) that were caught equally among pools and runs (Figure 7). Crayfish catches were not correlated with chub catches (r = 0.05, p-value 0.10) nor tadpole catches (r = –0.02, p-value = 0.58) across all trap types.

Discussion

Characteristics of the most effective traps

Many studies, review papers, and technical reports have emphasized the need for research relating to improved trap design in mechanical removal of invasive crayfish, yet there is an apparent absence of comparative studies on trap design (Larson and Olden 2016; Gherardi et al. 2011; Peay and Hiley 2001). The goal of this study was to identify the trap design or designs that are most effective at catching crayfish while minimizing bycatch. In this study, we were able to identify the overall best design for catching crayfish as the Promar mesh traps. The Promar mesh 503 trap caught roughly 28% of all the crayfish but only 8% of the chub (with no mortality) and did not catch any tadpoles, while the Promar mesh 501 trap caught 17% of crayfish, 7% chub, and 22% of the tadpoles. In addition, both mesh traps were relatively effective at catching crayfish of all size classes and not biased towards one sex. It appears the design of these traps,

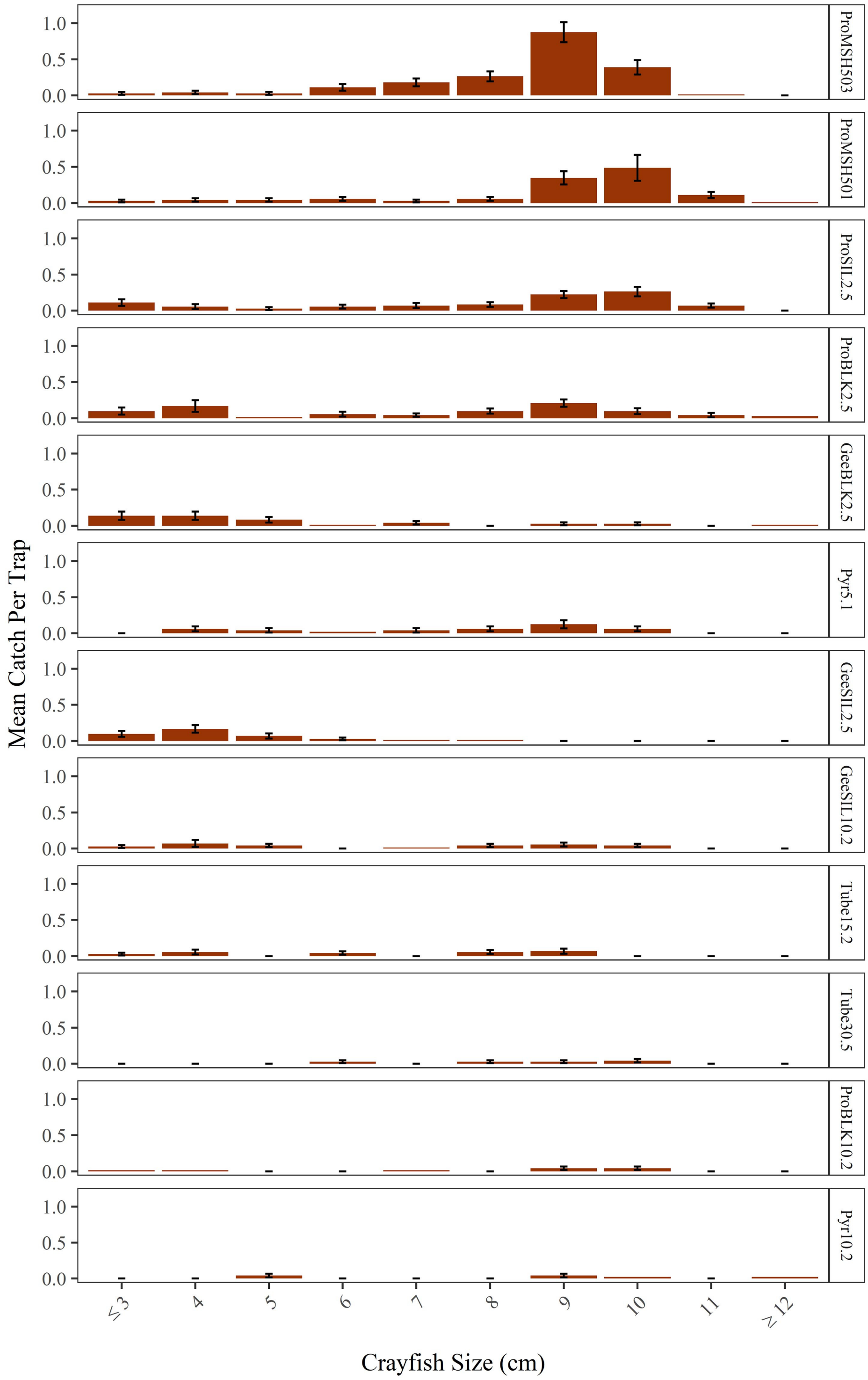

Figure 5. Mean crayfish counts by size (cm) class across twelve trap types with standard error bars.

specifically the mesh size and material, make them adept at catching crayfish while remaining large enough that smaller chub or tadpoles can exit the trap. The Promar mesh 503 trap is also larger in volume than the other traps in the study, the custom Pyramid traps excluded, which has been suggested as a feature of catch-efficient traps (Stebbing et al. 2014). The hanging bait bag feature of these traps might aid in the longevity of the bait and its associated odor within the stream. This in turn, may provide a

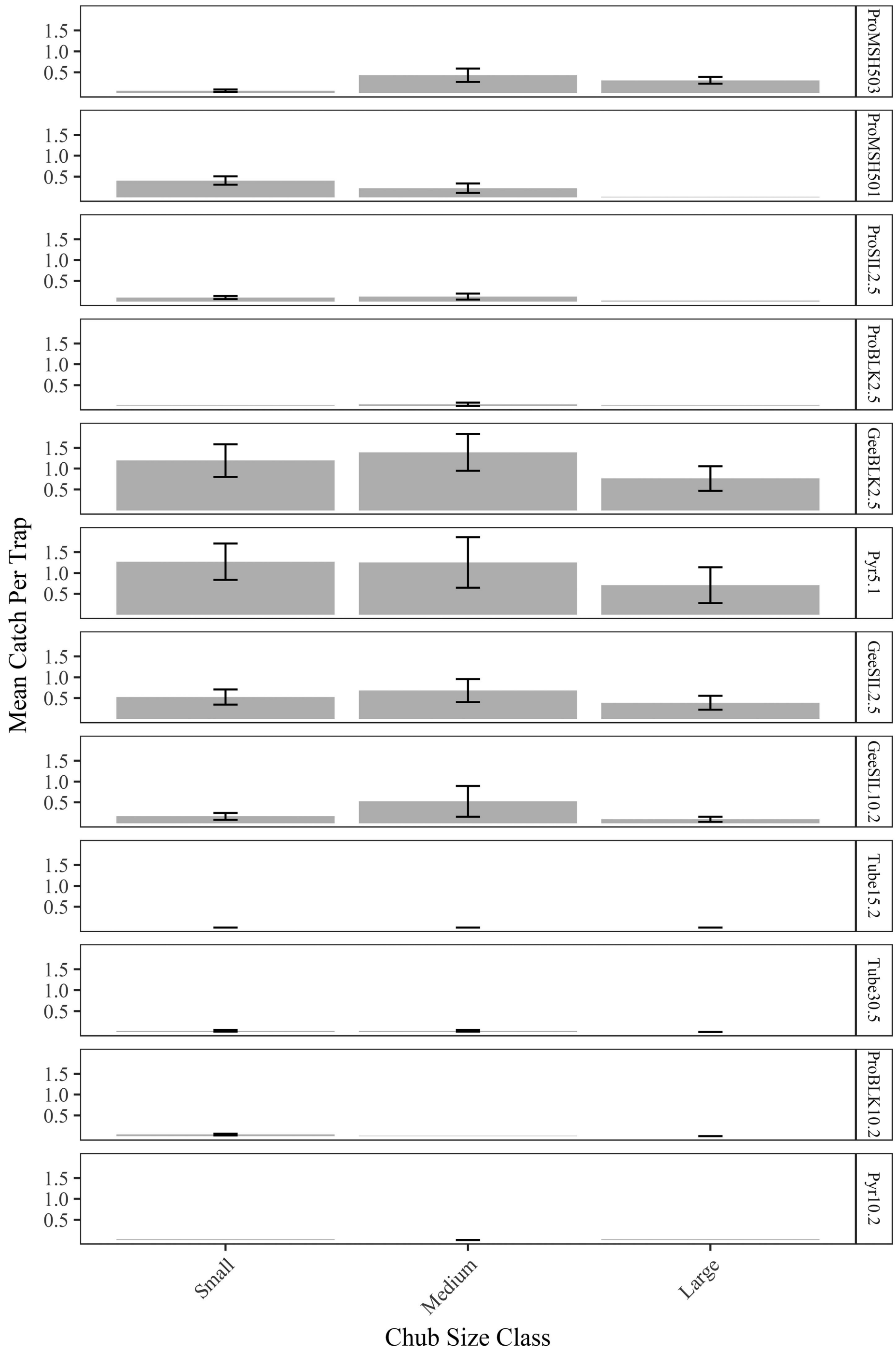

Figure 6. Mean chub counts by size class across twelve trap types with standard error bars. Size classes include small as ≤ 60mm, medium as 61–89 mm, and large as 89–150mm as described by O'Brien et al. (2011).

lure-effect that could outlast the bait placed in the bag-less traps, which could be readily consumed by trap occupants. Crayfish are considered highly sensitive to nitrogen-containing chemical compounds, such as those in meat-based dog food (Schmidt and Mellon 2011), further adding support to the extended efficacy of the Promar traps containing separate bait compartments. However, due to the separate but attached zippered bait bag, these traps take a slightly longer time to service and have more moving parts that can malfunction. Additionally, their non-metal-based

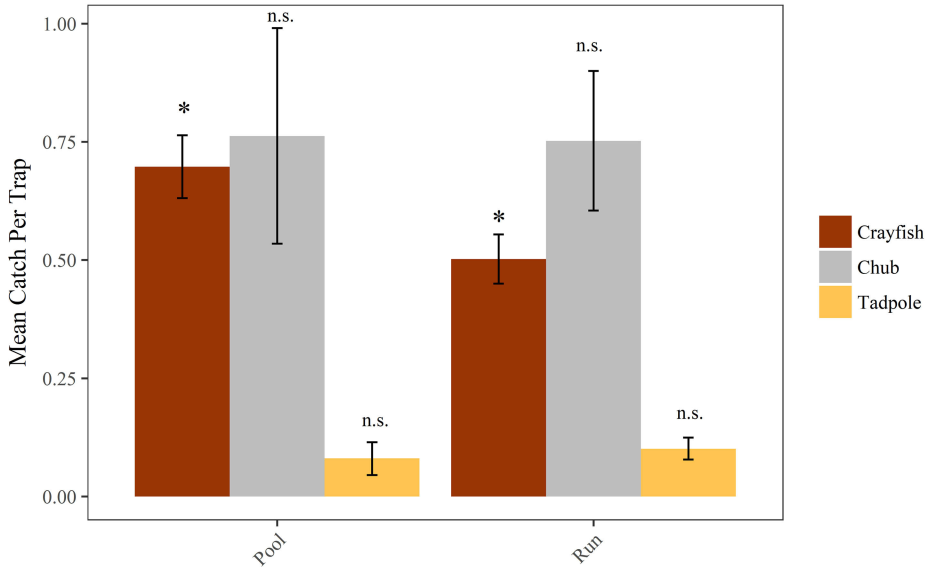

Figure 7. Mean catches by stream habitat type. Differences in mean catches between stream Pools *vs*. Runs was evaluated using Wilcoxon rank-sum tests. * P-value < 0.05.

construction suggests they will not last as long during prolonged field deployments in comparison to the steel Gee Minnow or vinyl-coated metal Promar black traps. So, while these traps were top performers in our two-week study, their service, maintenance, and replacement or repair costs need to be considered when planning to use them in longer-term management programs.

It was surprising to observe poor performances from the custom-made pyramid traps – both the Pyramid (5.1 cm) and Pyramid (10.2 cm) traps. The design of these traps was speculated to be more effective at catching crayfish because of the flat bottom and large interior volume, and they have been used for several years as part of the current management effort in other Santa Monica Mountain streams. As suggested by Mangan et al. (2009), flat bottomed traps are thought to sit more even on the substrate, making them more accessible to crayfish even in streams with cobble or uneven sediments. It is possible that the sandy composition of the stream sections in the study area might have affected the observed performance of this trap. However, for the purposes of continued management in Santa Monica Mountain streams, it was important to test the efficacy of these traps in a reach of stream that is characteristic of other streams in the watershed. Further areas of study might include identifying specific crayfish-trap behavior with changes in benthic stream topography and habitat composition.

Trap effects on Bycatch

We discovered that while some traps were better at catching crayfish, they also varied widely in how many native species they caught. If the main management goal was to minimize bycatch and maximize crayfish catch, we needed to consider and identify the specific traps or trap features that met both these requirements. The painted Gee Minnow (black 2.5 cm) and custom Pyramid (5.1 cm) traps caught the most bycatch and also were the 5th, and 6th performer, respectively, in catching crayfish. The standard Gee Minnow trap (2.5 cm) and modified Gee Minnow (10.2 cm) were also likely to catch more bycatch than crayfish. These traps did not differ in the size of bycatch they caught, although more research is needed to identify exactly why chub might prefer these specific traps over the others. Regardless of color or opening size, Gee Minnow traps were the least effective trap for catching crayfish and minimizing native bycatch. This trap model is standard in crayfish management programs, but based on these findings for streams in the Santa Monica Mountains, the use of this trap should be reconsidered. This is especially true when programs wish to maximize crayfish removal efforts and minimize impacts to native populations.

Trap effects on size and sex

In our study, trap type was related to the size of crayfish and bycatch caught but not the sex of crayfish caught. Both Promar mesh traps with different opening sizes caught the most crayfish during the study and tended to catch a higher percentage of moderately sized (9–10 cm) crayfish compared to other size classes. It is not known if these mesh trap types preferentially capture moderately sized crayfish or if the catches reflect a higher proportion of moderately sized crayfish in the underlying population distribution. In addition, we found that the Gee minnow traps with 2.5 cm openings tended to catch smaller sized crayfish compared to the same trap type with 10.2 cm openings. This suggests that opening size of the minnow traps may preferentially catch smaller crayfish. Future studies may want to examine catch biases by trap types in relation to the underlying population structure to better inform crayfish management and control practices. In terms of crayfish sex ratios, our study did not find a significant difference in the numbers of males and females caught among all the traps tested. This result differed from other crayfish trap studies that have observed an inherent catch bias towards larger males (Green et al. 2018; Byrne et al. 1999; Holdich et al. 1995). Preferential removal of male crayfish may not be an effective approach to control invasive crayfish. In fact, previous research suggests the removal of larger males from the stream in general, encouraged smaller individuals to travel more freely, sometimes extending 200 m beyond their normal range and trapped boundaries (Moorhouse and Macdonald 2011). Compared to other studies, our trapping effort in southern California streams was less biased towards trapping large male crayfish.

Studies focusing on artificial refuge traps similar in design to the tube traps used in our study have been shown to be an effective method in comparison to other trap approaches, indicating their potential use for enhanced management of crayfish (O'Connor et al. 2018). In fact, a two-year study in England found that artificial refuge traps captured higher proportions of females to males, indicating their potential importance for targeted removal of reproductive female crayfish (Green et al. 2018). In our study, both sizes of the tube traps (15.2 cm and 30.5 cm length), caught a greater number of females than males, and of those females, half were carrying eggs or juveniles. Although these differences were not statistically significant due to the low number of crayfish caught in the tube traps, future studies may want to examine whether these preliminary patterns persist under more focused experimental designs. While Green et al. (2018) only compared artificial refuge traps and baited funnel minnow traps, our study compared across twelve different trap designs and resulted in overall less crayfish catch among all traps types, including the artificial refuge/tube trap types. Further research focused on these particular trap types (i.e., artificial refuge/tube traps) is needed to determine their application for an effective sex-specific management strategy for other invasive crayfish species, outside European streams.

Conclusion

Results of this study suggest a necessary paradigm shift from the default management practice of using a single, catch-all trap type to management practices that consider and potentially utilize a combination of different trap types to maximize catch while minimizing bycatch. While localized research is recommended to identify trap specificity needed to include in any such updated management schema, we have suggested some trap combinations that would be applicable to the regional southwest stream systems. The findings from this study can also be applied in order to encourage management that focuses on both maximizing crayfish catch and minimizing bycatch while making explicit any size or sex trapping biases. Based on the findings of this study and from over ten years of experience trapping crayfish from Southern California streams, a successful scenario might include the simultaneous deployment of two or three types of traps in the same reach of stream, a strategy proposed by researchers studying crayfish in Europe (Green et al. 2018; O'Connor et al. 2018). For example, a combination of the Promar mesh 503 trap, the Promar mesh 501 trap, and the black Promar (2.5 cm) might provide the appropriate amount of catch conditions that would remove substantial abundances of crayfish of all sizes and also have little impact on bycatch of all sizes. Deploying either length of tube trap, might be especially valuable during the reproductive season where females are more likely to seek refuge in the burrow-like tubes as opposed to a crowded and exposed minnow trap. While our study did not focus in-depth on tube traps, future research could investigate how traps perform during periods of extended soak times and if they do catch significantly more ovigerous female crayfish over time. Current state permitting guidelines, however, prevent trap-soak times longer than 24-hour periods, and some streams in California are even limited to 10-hour soaks. These time restrictions may impact crayfish catches as crayfish are the most active overnight and seek a new refuge during that time (Loureiro et al. 2015). However, in areas where sensitive species are abundant or where shorter soak times are enforced, the tube trap might be especially useful as the construction and bait-free design does not technically constitute it as a trap. Any sensitive species that enter this trap would be free to escape the trap, while invasive crayfish species might be inclined to seek refuge in these traps as our results indicate.

Adaptive management is a key feature of an effective crayfish monitoring and management plan. In some instances, the appearance of new species or the expansion into new territory might require an adjustment in the type of traps that can be used successfully while accommodating new conditions, habitats, or resident species. For example, many streams in California contain both invasive crayfish and protected, sensitive species such as California red-legged frog, foothill yellow-legged frog, and juvenile salmon species. There is a strong need for effective trapping mechanisms that have a minimized impact on native species. The research identifying traps that can both remove ecologically-significant abundances of crayfish and remain benign to the species of conservation concern is limited, but we hope our study sheds some light on this knowledge gap. Understanding the effects of different trap types on target and non-target species could be a valuable tool for managers to have in their aquatic invasive species toolbox.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Habitat information by section for trap study.

Table S2. Total number of crayfish, arroyo chub and tadpoles caught in each type of trap and associated descriptive stats.

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http://www.reabic.net/journals/mbi/2020/Supplements/MBI_2020_DePalmaDow_etal_SupplementaryMaterials.xlsx