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Traps and netting, better together than alone: an innovative approach to improve *Procambarus clarkii* management

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Abstract – The red swamp crayfish *Procambarus clarkii* is the most widespread invasive crayfish in Europe, and responsible for a plethora of negative impacts on aquatic ecosystems. Most capture methods used for controlling crayfish populations have a bias towards the capture of adults, however, the removal of the young-of-the-year crayfish (YOY) may be essential for achieving effective control of invasive populations. This paper analysed the crayfish caught during a management campaign carried out in five permanent stream pools from southern Spain. We compared size structure, CPUE and sex-ratio obtained with two control methods: cylindrical traps (a method commonly used in crayfish management) and horizontal hauls using a fine-mesh net (inspired by zooplankton sampling techniques). Horizontal hauls showed a higher selectivity for catching YOY and higher efficiency (eight-fold) than traps. The combined use of both gears increased total catch by 46%. Our results suggest that YOY may be sharply underestimated if only cylindrical traps are used. The YOY cohort represented 60% of the total catch during the management campaign. Therefore, active netting with a fine mesh may be a complementary method to the use of traps in order to manage invasive populations of *P. clarkii* and may provide a better understanding of the structure and dynamics of invasive crayfish populations.

Keywords: Crayfish / control / YOY / river / juvenile

Résumé – Pièges et filets, mieux ensemble que seuls: une approche innovante pour améliorer la gestion de *Procambarus clarkii*. L'écrevisse rouge de Lousiane *Procambarus clarkii* est l'écrevisse invasive la plus répandue en Europe et responsable d'un large éventail d'impacts négatifs sur les écosystèmes aquatiques. La plupart des méthodes de capture utilisées pour capturer et contrôler les populations d'écrevisses ont un biais en faveur de la capture des adultes, cependant, l'élimination des jeunes écrevisses de l'année (YOY) peut être essentielle pour parvenir à un contrôle efficace des populations envahissantes. Cet article a analysé les écrevisses capturées au cours d'une campagne de gestion de deux semaines menée dans cinq bassins de cours d'eau permanents du sud de l'Espagne. Nous avons comparé la structure de taille, la CPUE et le sex-ratio obtenus avec deux méthodes de contrôle: les pièges cylindriques (une méthode couramment utilisée dans la gestion des écrevisses) et les traits horizontaux à l'aide d'un filet à mailles fines (inspiré des techniques d'échantillonnage du zooplancton). Les traits horizontaux ont montré une plus grande sélectivité pour la capture de YOY et une efficacité plus élevée (huit fois) que les pièges. L'utilisation combinée des deux engins a augmenté les captures totales de 46%. Nos résultats suggèrent que YOY peut être fortement sous-estimé si seuls des pièges cylindriques sont utilisés. La cohorte YOY représentait 60% des captures totales pendant la campagne de gestion. Par conséquent, le filet actif à mailles fines peut être une méthode complémentaire à l'utilisation de pièges afin de gérer les populations envahissantes de *P. clarkii* et peut fournir une meilleure compréhension de la structure et de la dynamique des populations d'écrevisses invasives.

Mots-clés : Écrevisse / contrôle / YOY / piscine fluvial / juvénile

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1 Introduction

Managing populations of many aquatic invasive alien species remains an unsolved problem today. For many invasive species from inland waters (*e.g.*, crayfish, freshwater mussels, and many fish) there is a lack of effective eradication and control methods compatible with the maintenance of uses (*e.g.*, irrigation or drinking water for humans, livestock or wildlife) and preservation of native accompanying species (Dana *et al.*, 2019). Although prevention and eradication maximises the efficiency of management, once aquatic invasive species have colonized an aquatic ecosystem, eradication seems feasible only for isolated or highly reduced populations (Wizen *et al.*, 2008; Gherardi *et al.*, 2011). As a consequence, population control (*i.e.*, reduction of population size under an impact threshold) may become the most realistic approach to restore the ecosystem diversity and function (Panetta and Gooden, 2017) but must be maintained indefinitely to be effective (Dana *et al.*, 2010).

The red swamp crayfish (*Procambarus clarkii*) is native to Northern Mexico and the southern central region of the USA (Hobbs, 1972), and has been introduced into several countries from different continents, being particularly ubiquitous in southwestern Europe (Gonçalves *et al.*, 2015; Souty-Grosset *et al.*, 2016). *P. clarkii* shows some biological features typical of an invader, such as early maturity, generalist and opportunistic feeding, rapid growth rates as well as a relatively high fecundity in comparison to other crayfish species (Gherardi, 2006). The invasion of this species is associated with a plethora of impacts, including predation, disease transmission to native species, habitat alteration, and economic damage (Geiger *et al.*, 2005). *P. clarkii* has shown a rapid spread in Europe since its introduction in 1972 in the SW of Spain (Habsburgo-Lorena, 1979), thus becoming one of the most widely distributed invasive crayfish in southern and western Europe (Souty-Grosset *et al.*, 2006). The particular biology of *P. clarkii* (a dioecious and highly fertile species that takes refuge in deep galleries into clayey sediments) often impedes eradication, since a single pair of specimens may be sufficient to reinvade the managed habitat.

Among control methods, passive gears such as cylindrical traps and funnel traps have been widely used for catching several crayfish species (Policar and Kozák, 2005; Scalici *et al.*, 2010; Paillisson *et al.*, 2011; Moorhouse *et al.*, 2013; Green *et al.*, 2018). Other passive physical methods such as dams have been successfully used to contain the upstream advance of *P. clarkii* in rivers (Dana *et al.*, 2011; Rosewarne *et al.*, 2013). Artificial refuges (*e.g.*, islands of bricks or tubes attached to a metal base) have been used to encompass the catch of smaller individuals and females that are frequently excluded by traps (Dana *et al.*, 2010; Green *et al.*, 2018). Among the active methods, active search (*e.g.*, night viewing) or electro-fishing may be useful only in transparent shallow waters (Dana *et al.*, 2010). Chemical methods (*e.g.*, pyrethroids or bleach) may be effective (Peay *et al.*, 2006; Bunk, 2017), but their toxicity, persistence, scarce selectivity, banning or use restrictions and negative social perception are usually incompatible with the conservation of accompanying threatened species and uses. Hand removal after pond drawdown has shown effective results with different crayfish species (Kozák and Policar, 2003; Stebbing *et al.*, 2012; Chadwick, 2019). This method is useful in small ponds or streams but may be unfeasible for preserving certain uses or species. Biological control (based on fish predation) mostly affects small or soft individuals (Aquiloni *et al.*, 2010), but its intensity and frequency are hard to manage. Most passive methods showed a bias towards catching adult crayfish (Scalici *et al.*, 2010). Young-of-the-year crayfish (YOY) may pass through the mesh of the traps or are dissuaded to enter the traps, and are hardly observable during active search (hand removal, electrofishing, etc.) (Dana *et al.*, 2010; Coignet *et al.*, 2012). Dragging with a fine-mesh size reported high captures of YOY in a reservoir from southern Portugal invaded with *P. clarkii* (Adão and Marques, 1993). Hand-netting, kick sampling and surber sampling have been also tested for detecting *Pacifastacus leniusculus* (Gladman *et al.*, 2010). Other methods capable of capturing all size classes include the use of bracken bundles, which is a traditional Maori method used to sample *Paranephrops planifrons* in New Zealand. This method can be used in turbid waters and at a wide range of depths, and does not require expensive equipment or specialised expertise (Kusabs and Quinn, 2009). Having a method capable of capturing YOY will allow to get information on the recruitment period of the population in a specific site. Also, the decline of the YOY cohort could jeopardise the population viability in the medium term. Therefore, the combination of different methods may be a suitable solution to encompass the different crayfish cohorts in control and eradication plans (Loppnow and Venturelli, 2014).

In this study, the crayfish caught during a management campaign carried out in five permanent stream pools from southern Spain was analysed. We compared size structure, CPUE and sex-ratio obtained with two control methods: cylindrical traps (a method commonly used in crayfish fishery and management) and horizontal hauls using a fine-mesh net (inspired by zooplankton sampling techniques). Finally, we discuss the feasibility of incorporating techniques specifically adapted to catch YOY as an approach to improve management efficiency of invasive populations of *P. clarkii*.

2 Material and methods

2.1 Area of study

The study was conducted in five permanent pools in a temporary stream at Conil de la Frontera (Cádiz, S Spain; 36°18′N; 6°8′W; 10–12 m.a.s.l.), in September 2011. This temporary stream shows a lotic water regime with floods during torrential rains but keeps several permanent pools (lentic regime) during the dry season (between late spring and early autumn). The pools were selected to account for the maximum habitat variability observed in the field (Tab. 1). The shape of the ponds was approximately elliptical, with a surface substrate predominantly formed by a clay layer of approx. 20 cm on a compact sandy substrate. Thus, the area of the pool i (Ai) was estimated as the surface area of the equivalent ellipse: $Ai = \pi \times a \times b$, where a and b are the major and minor semi-axis of the pool, respectively. The pool volume (Vi) was estimated as half of the volume of the resulting ellipsoid: $Vi = (2/3) \times \pi \times a \times b \times D$, where D is the mean depth. Bottom features were homogeneous across sites.

Table 1. Characteristics of stream pools in which the management of *Procambarus clarkii* was carried out.

Pool	Area (m^2)	Mean depth (m)	Volume (m^3)	Conductivity ($\mu S\,cm^{-1}$)	Water temperature (°C)
P1	190	0.25	129	298	17.9
P2	38	0.61	61	268	18
P3	8	0.8	17	301	18
P4	276	0.78	575	519	18
P5	59	1.04	163	280	17.8

Fig. 1. Trapping methods used: foldable cylindrical crayfish traps (‘traps’) (a); detail of baited traps left in one of the managed pool (b); and fish keeping net used during horizontal hauls (‘netting’) (c-d).

2.2 Methods tested

We combined the use of foldable cylindrical traps (hereinafter ‘traps’) and horizontal hauls with a fine-mesh net carried out on foot (hereinafter ‘netting’) (Fig. 1). Traps are one of the most commonly used methods to study and control crayfish populations, whereas netting was inspired by techniques used in zooplankton studies (*e.g.*, Moscatello and Belmonte, 2004; Seminara *et al.*, 2008; Florencio *et al.*, 2014). Traps had two entrances (0.07 m diameter) at the extremes, and measured 0.5 m long, 0.3 m diameter, and 5 mm square mesh. Traps were left in the pool banks and attached to the nearest bush or branch to facilitate their further collection by the field worker. A floating foam (*i.e.*, a piece of a pool noodle commonly used in swimming pools) was introduced inside the traps to avoid the drowning of non-target species. Traps were baited with cat food, that was placed inside pet bird drinkers to avoid their consumption by crayfish arriving from outside the trap and to favour slow release of the bait. We placed between one and nine traps per pool, depending on the pool size. Netting was conducted on foot with a foldable, cylindrical fish keeping net. This net has a 0.47 m diameter, 1 mm mesh size and is 3 m long. This length provided a high evacuation surface that compensated for the small mesh size, thus preventing water (and eventually also the catch) from bouncing off the main opening. During netting, repeated sweeps or trawls were implemented through the entire water mass (depths ranged between 0.25 and 1.04 m), including the water layer just above the sediment surface to the water surface. The net was also swept through the marginal vegetation (Gladman *et al.*, 2010). Netting was repeated in each pool as many times (three to seven netting sessions, depending on the pool) as necessary until no more crayfish were caught in at least once netting session. Each netting session lasted three minutes and included the filtration of both the proximity of the benthos and the water mass. The same person proceeded in all pools to reduce the variability due to the sampler. During each netting session, the operator frequently retraced the own steps, thus filtering the recently resuspended sediment.

Before sampling, large submerged objects (mainly branches from riverside trees) were removed or pruned for full accessibility. Since traps mesh had a larger diameter, they were used first in each pool. The traps were used during two weeks (eight consecutive working days) and revised daily, whereas the netting was performed once in each pool: at day four in pool 2 (P2); at day five in pools 1 (P1) and 3 (P3); at day seven in pool 4 (P4); and at day eight in pool 5 (P5). Traps were revised and emptied each day before the netting. Once the netting sessions were completed, traps were left again in the pools until the next day and checked daily according to Coignet *et al.* (2012), and crayfish were collected for further analysis (see below). The netting was performed between 11.30 and 13 h. Given that these methods are not selective, the non-target species that were accidentally caught were immediately returned to the pool. For traps, bycatches were determined to the species level except for aquatic insects. During netting, bycatches couldn’t be quantified but were identified to the order level.

2.3 Data collection

Crayfish were counted, sexed and their cephalothorax length (CL, from the tip of the rostrum to the carapace posterior portion) measured with a vernier caliper. Crayfish were divided into two size classes, YOY (CL $\leq$ 22 mm) and adults (CL $>$ 23 mm), according to Figiel *et al.* (1991), which is rather similar to the size proposed by Huner (2002): 21 mm if female and 24 mm if male. Sex ratio was calculated as the ratio between the number of males divided by the number of females. All the captured crayfish were transported cold and were air-frozen according to ethical standards (RSPCA, 2003) after measurements. Catch per-unit-effort (*CPUE*) was used as a proxy of method efficiency and was calculated for each pool as the total number of crayfish caught divided by the accumulated effort. Previous studies often considered the effort as the period that the gears were 'working' (*i.e.*, submerged) multiplied by the number of gears used. However, this effort measure may not fully represent the operational costs (real time spent to trapping or netting), and material costs (traps, net, bait, transport, ice, etc.). Accordingly, in this study we considered two measures of effort, and calculated *CPUE* as follows:

- Considering the effort as the number of traps (N_{traps}) used in each pool *Pi* during the sampling period (T_{trap}) or the number of netting sessions ($N_{netting\ sessions}$) used in each pool *Pi* during the sampling period ($T_{netting}$). This way, we calculated $CPUE_{traps,Pi}$ and $CPUE_{netting,Pi}$ for each sampling day, *i.e.*, $T_{trap} = T_{netting} = 1$ day (Eqs. (1) and (2)).
- Considering the operational effort as the time, T', spent in the field by an experienced worker during trap placement, collection of each trap from the pool, collection of catches and discard of non-target species in each pool *Pi* (T'_{traps}) or the time spent during each netting session plus the time spent to revising the catch and separating the crayfish from non-target species ($T'_{netting\ sessions}$). In our study, T'_{trap} was ca. 0.25 h/trap but $T'_{netting\ sessions}$ widely varied depending on the catch abundance (for example, we spent ca. 0.13 h/netting session when no crayfish were caught, but increased up to 0.5 h/netting session when crayfish were abundant). This way, we calculated catch per unit of operational effort, $CPUOE_{traps,Pi}$ and $CPUOE_{netting,Pi}$ (Eqs. (3) and (4)).

$$CPUE_{traps,Pi} = \text{crayfish}/(N_{traps} \times T_{trap}) \tag{1}$$

$$CPUE_{netting,Pi} = \text{crayfish}/(N_{netting\ sessions} \times T_{netting}) \tag{2}$$

$$CPUOE_{traps,Pi} = \text{crayfish}/T'_{traps} \tag{3}$$

$$CPUOE_{netting,Pi} = \text{crayfish}/T'_{netting\ sessions} \tag{4}$$

2.4 Statistical analysis

The variables CL and sex ratio did not follow a normal distribution (Kolmogorov–Smirnov test), nor was there homogeneity of variances (Levene's test). Consequently, differences in the overall CL and sex data (all pools) between methods were analysed using the Mann–Whitney *U* test. For each method, we also compared the size distribution and sex among the different pools using the Kruskal–Wallis test, and pairwise comparisons were made using the Mann–Whitney *U* test. The Friedman test was used to analyse significant differences in $CPUOE_{traps}$ among the different pools. In this case, post-hoc analysis was developed using Wilcoxon pairwise test. Spearman rank correlation analysis was used to analyse the correlation significance of $CPUOE_{trap}$ with time for each pool. In the case of netting, the generalised linear model (GLM) procedure was used to compare the catch pattern obtained during consecutive netting sessions among the different pools: the number of crayfish caught was the dependent variable, the pool was used as the fixed factor and the number of netting sessions was set as a covariate. Depletion curves were obtained for the catch obtained during consecutive netting sessions for each pool using an exponential model ($\text{catch} = a \times e^{(-b \times \text{netting session})}$), where the parameters *a* and *b* are the initial catch and the decline rate, respectively. Finally, we assessed whether the netting implementation affected the catch obtained with traps. For this purpose, we compared $CPUE_{trap}$ before and after netting implementation with the univariate GLM procedure: $CPUE_{trap}$ was the dependent variable whereas the pool and the trapping period (before/after netting) were considered as fixed factors. The pond P5 was excluded for this analysis because netting was implemented in the last campaing day and no catch data with traps were available after netting. In all analyses, differences were considered significant when the *p*-value ≤ 0.05. Statistical analyses were performed using SPSS® (version 15.0) and PAST (version 4.02; Hammer *et al.*, 2001).

3 Results

A total of 1487 crayfish were caught (801 with the traps and 686 by netting) (Tab. 1). Considering all pools together, CL was significantly lower ($p < 0.0001$, Mann–Whitney *U* test) in netting ($Q_1 = 15$ mm; median = 15 mm; $Q_3 = 16$ mm) than in the traps ($Q_1 = 22$ mm; median = 26 mm; $Q_3 = 29$ mm) (Fig. 2). YOY showed a contribution of 25% and 96% for the traps and netting, respectively. In two of the ponds the traps caught a high percentage of YOY (P2 = 79% and P3 = 100%; Tab. 2). Sex ratio did not show significant differences between methods (mean sex ratio ± SD = 1.1 ± 0.7 in the traps and 2.75 ± 1.8 in netting) (Tab. 2). When both methods were considered together, sex ratio showed a slightly higher contribution of males than females (males/females = 1.1). External sexual structures were undifferentiated in 97% of juveniles with CL $\leq$ 15 mm.

Among the different pools (P), CL was also significantly different, both for the traps and netting ($p < 0.0001$, Kruskal–Wallis test). For the traps, median CL values ranged between 15 and 51.5 mm (P1 = 28 mm; P2 = 20 mm; P3 = 15 mm; P4 = 27 mm; and P5 = 51.5 mm). Post-hoc pairwise comparisons showed significant differences between all pairs of pools excepting for P1 *vs.* P4, P1 *vs.* P5 and P4 *vs.* P5. For netting, median CL values showed a lower range (P2 = P3 = 15 mm; P1 = P4 = 16 mm; P5 = 17 mm). In this case, pairwise analysis revealed significant differences in median CL between P2 *vs.* P3, P2 *vs.* P4, P2 *vs.* P5, P3 *vs.* P4, and P3 *vs.* P5.

$CPUE_{traps}$ ranged between 0.6 and 9.7 crayfish trap^{-1} d^{-1}, whereas $CPUE_{netting}$ was 1.0–54.6 crayfish (netting session)$^{-1}$ d^{-1}. Significant differences were found in $CPUE_{traps}$ among the different pools ($p < 0.0001$, Friedman test). Pairwise comparisons revealed significant differences in $CPUE_{traps}$ between all pairs of pools (*p*-values ranged between 0.012 and 0.043, Wilcoxon test) excepting for P1 *vs.* P3 and P3 *vs.* P5. The GLM procedure revealed that the netting implementation did not affect the $CPUE_{traps}$ either for adults or YOY. Significant differences in $CPUE_{traps}$ were evident only for the factor 'pool' ($p = 0.032$ and 0.008, for adult and YOY crayfish, respectively).

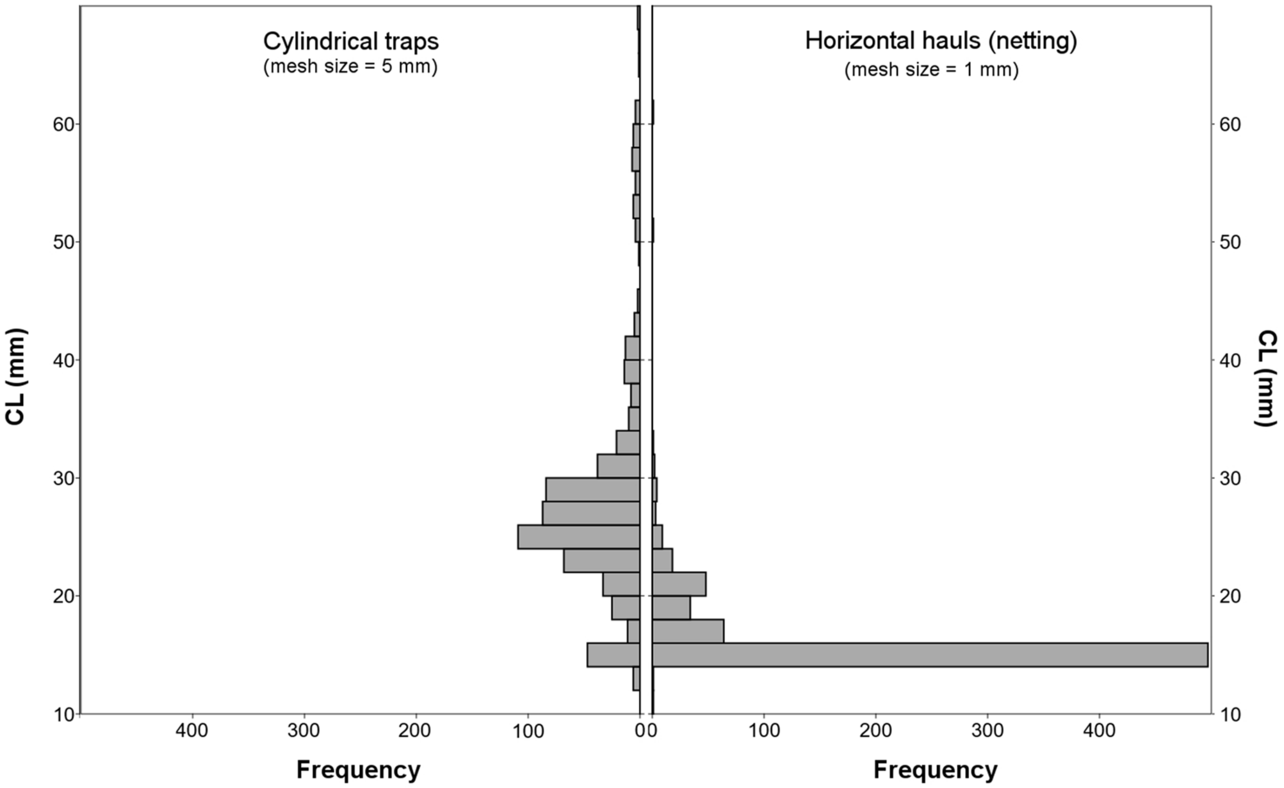

Fig. 2. Numbers of crayfish per size class (as their size frequency distribution) of the total catch of baited traps *versus* netting.

Table 2. *CPUE*, *CPUOE*, contribution of YOY (%) to total catch and sex ratio obtained with the two control methods tested in stream pools during the control campaign.

Method	Pool	CPUE	CPUOE (crayfish h^{-1})	YOY (%)	Sex ratio (male/female)
Cylindrical crayfish traps	P1	0.6 (0.5 ± 0.5) crayfish $trap^{-1}$ d^{-1}	1.9 (2.2 ± 2.0)	15	0.8
	P2	3.1 (3.1 ± 1.2) crayfish $trap^{-1}$ d^{-1}	10.5 (12.5 ± 4.9)	79	1.1
	P3	1.3 (1.3 ± 1.7) crayfish $trap^{-1}$ d^{-1}	4.2 (5.0 ± 6.7)	100	–
	P4	9.7 (9.9 ± 8.4) crayfish $trap^{-1}$ d^{-1}	32.5 (39.6 ± 33.5)	5	1.1
	P5	1.3 (1.3 ± 0.9) crayfish $trap^{-1}$ d^{-1}	4.3 (5.2 ± 3.6)	42	1.2
	All pools	**3.4 crayfish $trap^{-1}$**	**13.7**	**25**	**1.1**
Horizontal hauls with a fish keeping net	P1	1.0 crayfish (netting session) $^{-1}$ d^{-1}	6.4	100	–
	P2	54.6 crayfish (netting session) $^{-1}$ d^{-1}	186.3	99	0.7
	P3	7.3 crayfish (netting session) $^{-1}$ d^{-1}	42.6	100	–
	P4	37.4 crayfish (netting session) $^{-1}$ d^{-1}	182.4	89	4.3
	P5	11.7 crayfish (netting session) $^{-1}$ d^{-1}	45.7	94	3.0
	All pools	**27.4 crayfish (netting session) $^{-1}$**	**112.3**	**96**	**2.7**

Considering the net time spent in field works during the whole management campaign, *CPUOE* was eight-fold greater with netting ($CPUOE_{netting=}$ 6.4–186 crayfish h^{-1}) than with traps ($CPUOE_{traps} = 1.9$–32 crayfish h^{-1}) (Tab. 2), showing significant differences ($p = 0.03$, Mann–Whitney *U* test). No correlation was observed between $CPUOE_{traps}$ or $CPUOE_{netting}$ and pool surface. In the case of traps, $CPUOE_{trap}$ showed a slight decrease with time, except for the biggest pool (P4) (Fig. 3). The Spearman rank correlation analysis showed significant correlations of $CPUOE_{traps}$ *vs*. time only in two of the five pools studied but with opposite trends: P1 showed a significant decrease of $CPUOE_{traps}$ with time whereas P4 showed a significant increase with time (Fig. 3). For netting, crayfish were depleted after three (in P1) to seven (in P2) consecutive netting sessions. Exponential decline rates ranged between 0.26 and 0.69 crayfish/netting session. Curiously, for pools P2, P4 and P5, the number of catches increased after the first netting session and were then followed by a sharp decrease (in fact, these pools fitted better a polynomial equation than an exponential equation) (Fig. 4).

Both traps and netting included bycatches. During the whole management campaign, traps captured *Pelophylax perezi* (125 individuals), *Mauremys leprosa* (83 individuals), *Emys orbicularis* (one individual), *Anguilla anguilla* (35 individuals), *Natrix maura* (one individual), and some aquatic coleoptera belonging to the Dytiscidae family. Despite traps were revised daily, injuries were observed on *Pelophylax perezi* (occasionally) and *Anguilla anguilla* (only once), likely due to the contact of these species with crayfish or *Mauremys leprosa*. Netting bycatch mainly included aquatic hemiptera (being the most abundant *Anisops sardeus*, and occasionally corixidae species, and *Nepa cinerea*), aquatic coleoptera (several species), odonata larvae and occasionally fish (*Aphanius baeticus*). Considering that all non-target animals were returned to the ponds, some of these animals could be caught more than once.

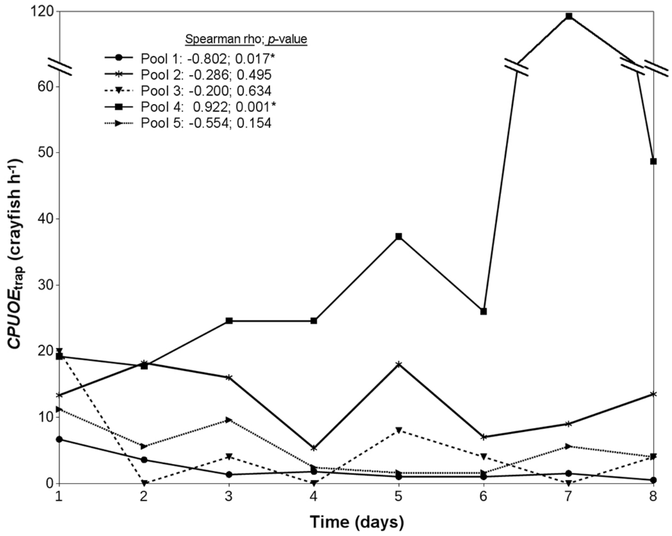

Fig. 3. Catch per unit effort obtained with traps during the course of the management campaign.

4 Discussion

4.1 Improving efficiency of crayfish management

The catchability (the interaction between the target species abundance and the fishing or capture effort) may be very different among different gears for each species (Arreguín-Sánchez, 1996). In the case of *P. clarkii*, the use of traps may exclude YOY in management campaigns, however, YOY may represent a high percentage of the population (up to 100% of total catch in some of the pools studied). The protection of the immature cohort is a key parameter for long-term sustainability of commercial fisheries (Langton *et al.*, 1996; Zabel *et al.*, 2003). In fact, when the catch of the immature cohort is more than twice that of adults, the population falls below precautionary limits (Vasilakopoulos *et al.*, 2011). Inversely, promoting an intense capture of the YOY cohort could be an effective way to control of invasive crayfish populations. Therefore, the opposite to the "spawn-at-least-once" principle (*i.e.*, to catch the population over their regeneration rate, especially the immature specimens) could provide an efficient way to control crayfish invasive populations.

In the case of crayfish, there is a need to implement new controlling methods to slow the proliferation of invasive crayfish and to protect and restore aquatic ecosystems

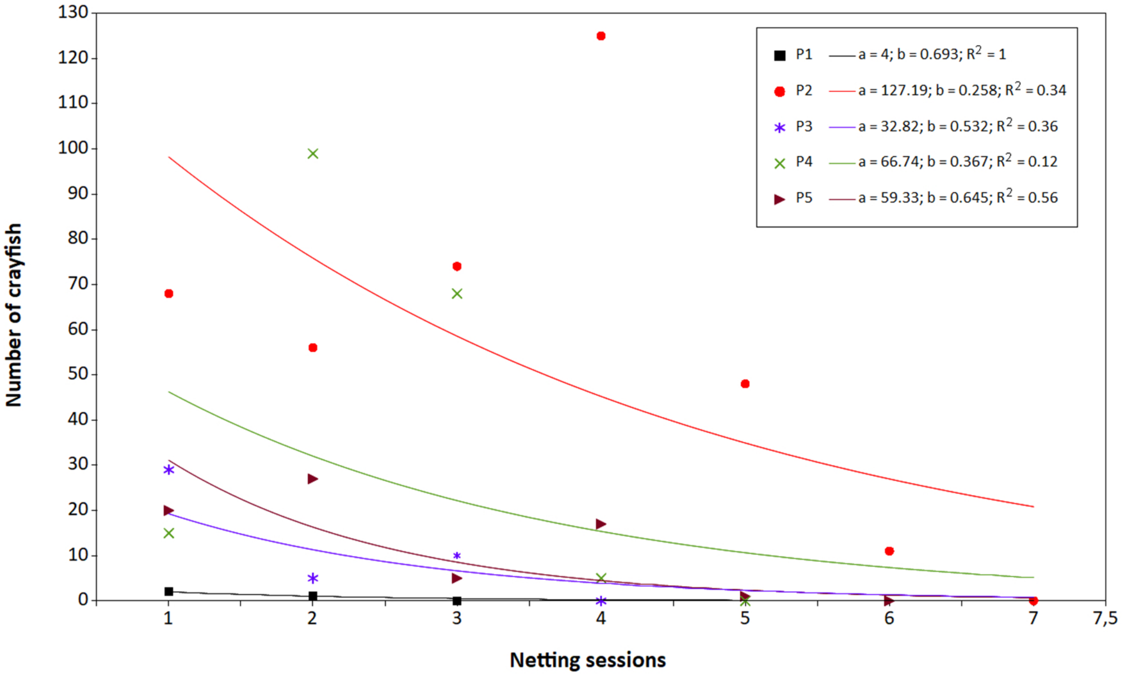

Fig. 4. Number of crayfish caught in each pool with the fish keeping net during consecutive netting sessions. The parameters of the exponential model (catch $= a \times e^{(-b \times \text{netting session})}$) used for the calculation of depletion curves are shown.

(Manfrin *et al.*, 2019). Netting, towing, dragging or filtering the water through a fine-mesh size are common techniques for zooplankton sampling (*e.g.*, Florencio *et al.*, 2014) but have rarely been used in crayfish studies (Adão and Marques, 1993). To our knowledge, this is the first time that horizontal hauls with a fish keeping net were used for catching crayfish and its efficiency evaluated. Both the opening diameter and mesh size of fish keeping net used in this study were bigger than other common gears used for zooplankton sampling in order to facilitate the catch of crayfish. The application of netting required the removal of submerged objects as a preparatory action in order to increase accessibility for workers, a key item related to feasibility of action plans (Dana *et al.*, 2019). Netting trialled in this study may be in principle useful in shallow lakes and ponds, which can be forded on foot (depth < 1 m). In case of different habitats such as rocky substrates, flowing rivers or deeper lakes, the suitability of netting should be adapted and its efficiency evaluated in relation to other control methods.

The relatively high YOY abundance suggests that the management campaign coincided with the early recruitment period described for this species in permanent waters from southwestern Europe (Scalici and Gherardi, 2007; Alcorlo *et al.*, 2008). However, time of recruitment depends on seasonality and hydroperiod of each habitat type (Alcorlo *et al.*, 2008), consequently, the gears used in crayfish control should be adapted to such particularities. In fact, our results suggest that YOY recruitment was advanced in time compared to other studies carried out in permanent waters from similar latitudes. For example, the size histogram obtained in our management campaign resembles to that found in March by Adão and Marques (1993) in a reservoir from southern Portugal. Therefore, netting efficiency could greatly vary throughout the year, *e.g.*, when females are in the burrow with eggs/juveniles. The combined use of methods selective for YOY and adult crayfish could also help to better understand the population dynamics of each site and adapt management.

4.2 Size selectivity and efficiency of traps and horizontal hauls

The results of the present study showed that the combined use of traps and netting achieved two main benefits for management: first, a noticeable increased of total catch (47%); and second, the YOY cohort was encompassed. The selectivity of the traps for adult crayfish obtained in this study is in accordance with other studies (Scalici *et al.*, 2010; Coignet *et al.*, 2012) and could be explained by at least four reasons: (i) YOY pass through the mesh of the traps (Coignet *et al.*, 2012) or simply fall out the traps at the time of removal (authorś pers. obs.); (ii) adult crayfish can escape from netting by swimming away using repeated tailflips; (iii) the possibility of cannibalism by pre-adult and adult crayfish (Hasiotis, 1995; Aquiloni and Gherardi, 2008) may dissuade YOY to enter the traps if adult crayfish are already inside; and (iv) adult crayfish avoid netting because they remain hidden inside shelters during daytime (Correia and Ferreira, 1995; Ilhéu *et al.*, 2003) leaving their shelter at night and dawn in search of food. Therefore, the use of traps or netting alone could provide a biased information of population structure.

The high percentage of YOY obtained with active netting (96% of total catch with this method) suggest that this cohort occupy shallow and ephemeral refuges and that such refuges were easily disturbed during on-foot horizontal hauls. Little is known on the burrowing habits of the different cohorts of *P. clarkii* in field conditions and in different habitats but further knowledge on this topic would be of great help to inspire new control gears. This species constructs galleries but also occupy a broad suite of shelters (*e.g.*, brick fragments, pvc pipes) and natural refuges (Adão and Marques, 1993; Hasiotis, 1995; Ilhéu *et al.*, 2003; Alonso and Martínez, 2006). In the managed pools, the abundance of dead leaves removed during netting suggest that this resource could be also use as a temporary refuge for YOY. Submerged hollow twigs were also used as refuges (authorś personal observations). In both cases, the first netting session would serve to stir YOY from the bottom of the pool, thus favouring their capture by performing repeated net sweeps.

Our results suggest that the abundance of crayfish and the relative abundance of the different cohorts are context dependent (Coignet *et al.*, 2012), even among neighbour pools. Particular pool features (*e.g.*, resource or shelter availability, predation pressure or hydroperiod) may have affected the differences found in the total catch, *CPUE*, and the contribution of each cohort among the five pools managed. Very small pools such as P3 lacked adults but allowed some recruitment of YOY. Therefore, the joint control of crayfish in all invaded neighbour pools may help to reduce the possibility of reinvasion (Dana *et al.*, 2019).

The ratio of females to males was very similar at this time of the year, in accordance with other studies (*e.g.*, Scalaci and Gherardi, 2007; Paillisson *et al.*, 2011). With respect to YOY, external sexual structures were not developed in YOY specimens smaller than 16 mm, in accordance with Paillisson *et al.* (2011).

In terms of efficiency, netting achieved significantly higher *CPUOE* values than the traps. By considering the effort as the time spent by field workers during crayfish control operations rather than the time that the gears were working (submerged), we could get a practical and objective estimate of personnel requirements that can be helpful in planning management. As in other disciplines, there is a trade-off between staff availability and the number and complexity of management works that must be conducted. More rapid and easier field approaches are usually preferred under conditions of resource limitations. Hence, the use of time spent in completing the field works provides a useful proxy to evaluate efficiency and are the basis for estimating costs, a widespread approach in decisions taking in bio-invasions management (Dana *et al.*, 2014, 2019). Nevertheless, the use of either traps or netting alone could leave part of the population without control. But in combination, traps and active netting with a fine mesh seems promising for increasing the efficiency of *P. clarkii* control. The combination of different methods (*e.g.*, electrofishing and kick sampling) has also shown clear benefits for determining the presence of signal crayfish in rivers (Gladman *et al.*, 2010). In this report, kick sampling with a fine mesh size net was also more efficient than other control methods such as electrofishing. To confirm the effectiveness of this approach for the control of *P. clarkii* populations, further evaluation during periodic management campaigns is recommended.

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