

Rapid assessment of population dynamics and monitoring methods for invasive narrow clawed crayfish *Pontastacus leptodactylus* in a freshwater reservoir

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Abstract – Narrow-clawed crayfish (*Pontastacus leptodactylus*) are a data deficient invasive non-native species in the UK. Boshaw Whams (West Yorkshire, UK) contains the only known population of narrow-clawed crayfish in Yorkshire. The risk of further spread of these crayfish is high and it is important to establish the extent of the current invasion on the Generalised Invasion Curve to identify potential management options. We used a combination of methods over a 15-month period including trapping, Remote Underwater Video (RUV) and Baited RUV (BRUV) to establish the most efficient method for narrow clawed crayfish monitoring and determine annual population dynamics. There was no significant difference between the three methods in terms of detection efficiency thus we recommend a mixed approach in the future dependent on practitioner capacity. Significantly more males were observed through trapping than females and berried females were detected between February and April. A mark-recapture survey estimated the population to have a minimum size of $10,045 \pm 5602$ (95% CI) individuals in a waterbody spanning 50,000 m². Boshaw Whams Reservoir should be considered as in the ‘Containment’ or ‘Asset Protection’ stage of the Generalised Invasion Curve, and action urgently required to prevent further spread.

Keywords: Non-indigenous crayfish / Baited Remote Underwater Video / detection probability / mark-recapture

1 Introduction

The ongoing spread of invasive non-native species (*sensu* Soto *et al.*, 2024) is a major driver of biodiversity loss and economic strain globally (Roy *et al.*, 2023). Invasive non-native species have negative impacts on their new environments, and it is estimated that they cost the British economy £4 billion each year (Eschen *et al.*, 2023). Of these, invasive crayfish, can cause significant damage to irrigation structures and banks of rivers and lakes through burrowing activity and may alter community composition through predation, competition and ecosystem engineering (Holdich, 1999; Bubb *et al.*, 2004; O’Hea Miller *et al.*, 2024). In the United Kingdom (UK), the signal crayfish (*Pacifastacus leniusculus*) alone, was attributed to have caused US\$15.3 million between 2000–2020 (Kouba *et al.*, 2022). There is less information on other

invasive crayfish, and their environmental and economic impacts, including the focal species of this study, the narrow-clawed crayfish (*Pontastacus leptodactylus*). The narrow-clawed crayfish is a data deficient invasive non-native species considered native to the Ponto-Caspian region (Skurdal and Taugbøl, 2002). They are a large freshwater crayfish species found in both lentic and lotic environments but considered to be still-water specialists (Bök *et al.*, 2013). Invasive populations are widespread throughout Europe and are predicted to spread through central-western Europe under future climate scenarios (Hodson *et al.*, 2024).

There are 16 main water and sewage companies supplying the UK with water resource management, including 273 major reservoirs which account for 90% of total water storage capacity (Williams *et al.*, 2010; Durant and Counsell, 2018). These reservoirs can indirectly act as sources, sinks and stepping stones for the spread of invasive non-native species (Havel *et al.*, 2005). Reservoirs can be easily invaded due to regulated flow, low biotic diversity, and high anthropogenic

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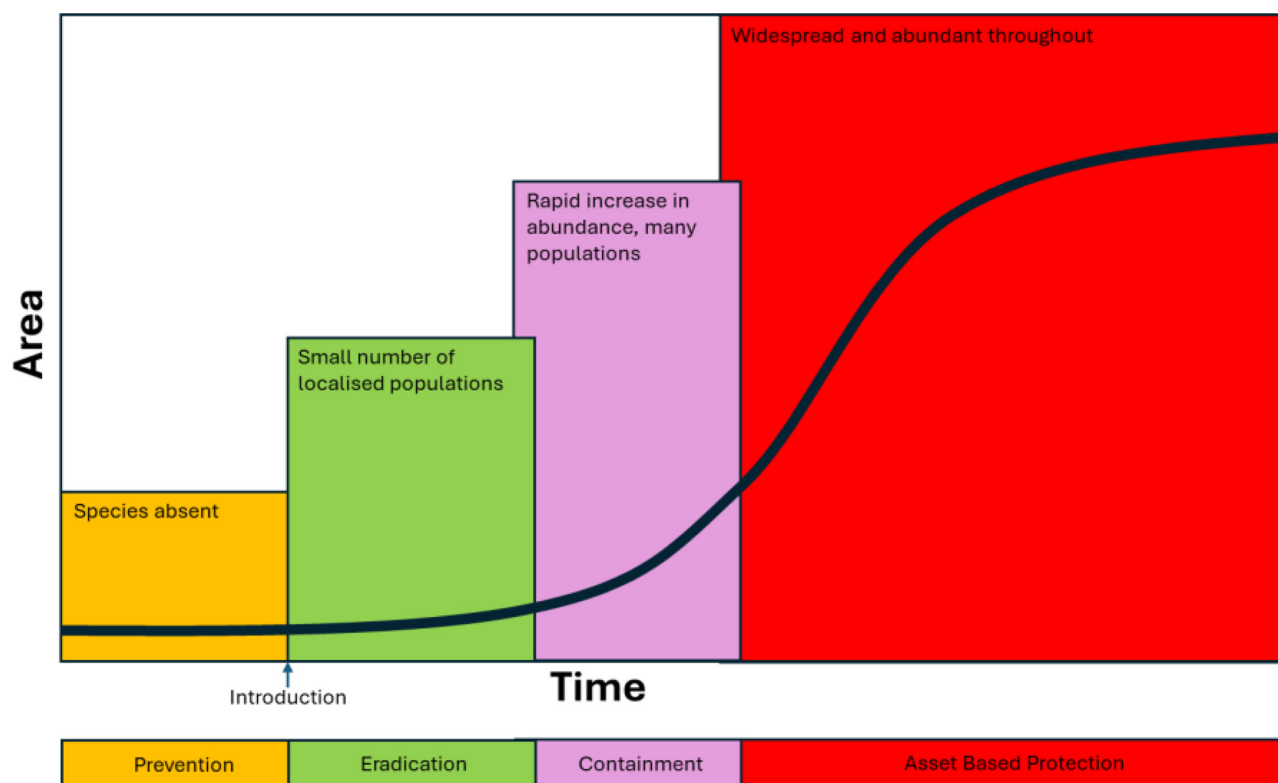


Fig. 1. General Invasion Curve for invasive non-native species, there are four stages on the curve; 1) Prevention, when the species is absent from the asset, 2) Eradication, when populations are small and isolated, 3) Containment, when populations are rapidly increasing, and 4) Asset protection, when there is a widespread population.

influence (Moyle and Light, 1996; Havel *et al.*, 2005; Clavero *et al.*, 2013). Some reservoir sites also have high numbers of anthropogenic pathways, such as recreational activities including boating, kayaking and angling. Where they are required, compensation flows from reservoirs allows the release of water from a reservoir to the connected waterbodies downstream. In addition to compensation flows, the Reservoir Safety Act 1975 requirements include operating scour valves to maintain the safety at reservoirs. These are key biosecurity issues as a large volume of water is released into connecting waterways. The Wildlife and Countryside Act 1981 outlines responsibilities and liabilities for water companies around managing invasive non-native species at their sites. The Invasive Alien Species (Enforcement and Permitting) Order 2019 also introduced penalties for the spread of ‘species of special concern’.

The General Invasion Curve illustrates the process of invasion in a given area to categorise threat and determine possible interventions (Harris *et al.*, 2018). The key aim of the graph is to establish the threat of an invasive population on a national scale, here we apply it on a more local scale, looking at a single site. When a waterbody is invaded, management actions are often working on a time lag between invasion arrival, detection, and impact. Assessing the stage of invasion must be prioritised and determined rapidly to inform appropriate decisions following the General Invasion Curve (Fig. 1; Harris *et al.*, 2018) which guides mitigation measures along stages related to the progression of the invasion: 1)

prevention, 2) eradication, 3) containment and 4) asset protection (Harris *et al.*, 2018). Further frameworks provide summaries of management options relative to the stage of invasion, for example Robertson *et al.* (2020). Failure to enact appropriate management may result in further invasive non-native species spread and increased cost of management interventions (Cuthbert *et al.*, 2022). Appropriate management is relative to the stage of invasion of the population, and can include different key forms of management, including pathway management and population suppression (Robertson *et al.*, 2020). It is important to note that these frameworks and curve can be applied at different spatial scales, thus whilst assessing one site within this study, when considering management options, it is imperative to understand the overall spread and impact of the species, especially at a catchment/regional scale, with connected waterbodies potentially facilitating further spread in the absence of anthropogenic pathways.

Boshaw Whams, a Yorkshire Water owned reservoir in Holmfirth, West Yorkshire, United Kingdom, contains the only known population of invasive narrow-clawed crayfish in Yorkshire. This population was illegally introduced around 2014, and local anglers started to report them as a nuisance in 2019 (pers. comm Huddersfield Angling Club). Although the impact that other invasive non-native crayfish have on narrow-clawed crayfish within their native range has been studied (Hudina *et al.*, 2016; Lele and Pârvolescu, 2017), *Pontastacus leptodactylus* is a data deficient species regarding its invasion dynamics and ecological impacts. Thus, given the data

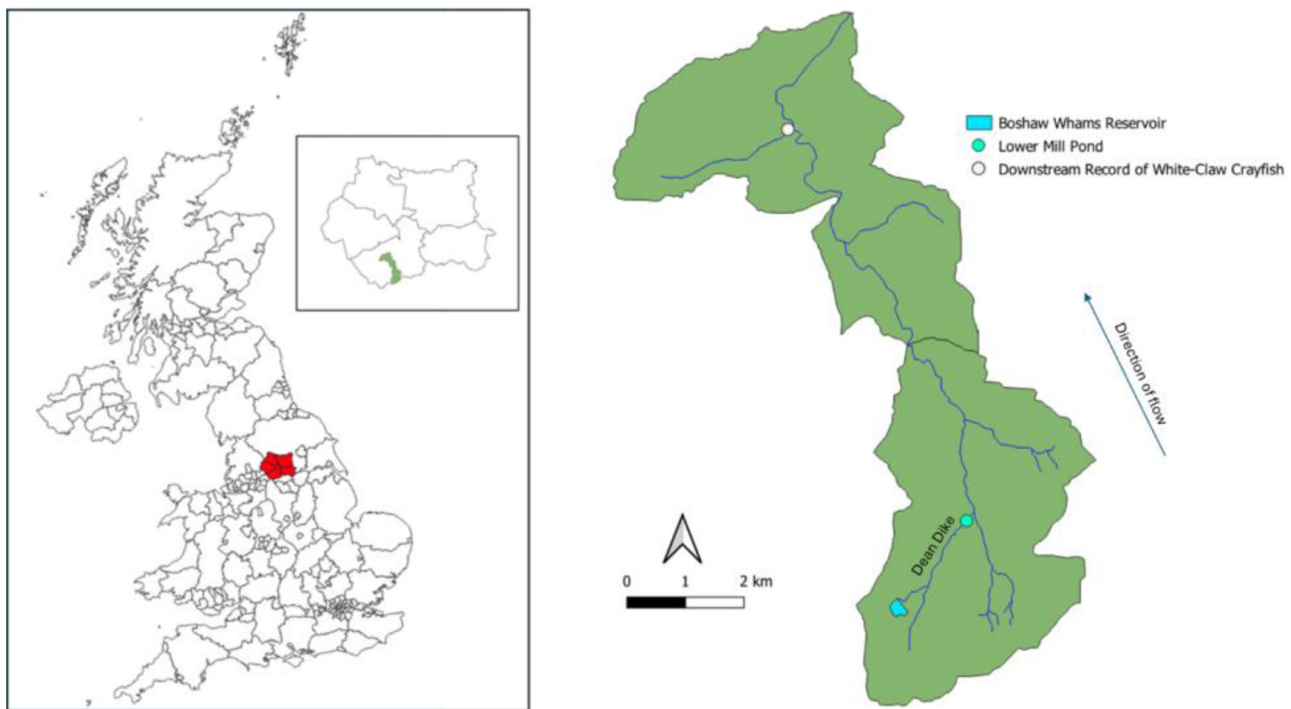


Fig. 2. Map showing Boshaw Whams Reservoir location and downstream waterbodies as well as closest population of native white-claw crayfish (*Austropotamobius pallipes*) species.

deficiency of the species' invasion ecology and the likelihood of further spread (Hodson *et al.*, 2024) our overarching aim was to rapidly assess the stage of the invasion on the Generalised Invasion Curve to advise management at this study site. In doing so, we tested two bait types and compared traditional (trapping) monitoring methods with Remote Underwater Video (RUV) and baited RUV (BRUV) for efficiency in detecting presence/absence and abundance dynamics of narrow-clawed crayfish throughout the year at Boshaw Whams reservoir. We then used mark-recapture to estimate population size and characterise reproductive ecology over a year. Finally, we provide comments on the economic resources needed to assess a crayfish invasion in a small reservoir and how to optimise invasion related costs.

2 Methods

2.1 Study site

Boshaw Whams (53°32'N; 001°46'W) (Fig. 2) is a freshwater reservoir, and is used for angling and boating recreational activity, located near to Holmfirth in Kirklees, West Yorkshire, United Kingdom. The reservoir is situated at an altitude of 300 m and has a circumference of ~ 900 m and a maximum depth of ca. 6 m. The reservoir is stocked with triploid rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) monthly from March to July with a final stocking in September, on an annual basis, with approximately 200 fish stocked per event (Huddersfield Angling Club, pers. comm.). There is a wooden jetty along one side of the reservoir with the remaining sides consisting of a grass bank with a gradual incline above the water and cobbles below. A

population of native white-clawed crayfish has been reported at Armitage Bridge (Fig. 2) WoC ID: WK9180 (for *A. pallipes*, observation date: 2022) (Ion *et al.*, 2024) approximately 10 km downstream from Boshaw Whams reservoir.

Twice a year a scour valve test is conducted to ensure that the reservoir is managed in compliance with the Reservoir Safety Act (1975). During a scour valve test, water is released from the reservoir into Upper House Dike, which is 250 m long and then flows directly into Dean Dike. Dean Dike is a small stream that runs through woodland, Strahler order 2 from Boshaw Whams reservoir. Dean Dike is 1.5 m wide at the widest point and flows for 1 km before entering Lower Mill Pond. The banks consist of woody vegetation and are bordered by farmlands.

2.2 Bait comparison

Method comparison between bait types and equipment types were completed to determine best operating procedures for detecting crayfish and method efficiency. This data was also used to describe the population dynamics in relative abundance over the course of a year. To compare bait types, crayfish trapping was conducted between October 2022 and February 2024 using collapsible fladen crayfish traps (570 mm × 290 mm, 25 mm mesh size). Bait comparison tests were conducted within a subsection of these surveys between October 2022 and June 2023, when both dry meat flavoured dog food and wet poultry flavoured cat food were used in the traps. Up to 49 traps were deployed per survey, all traps were deployed for 18 h overnight. Half of the traps were baited with dry food and deployed on one side of the jetty and the other half were baited with wet food and deployed on the other side of the

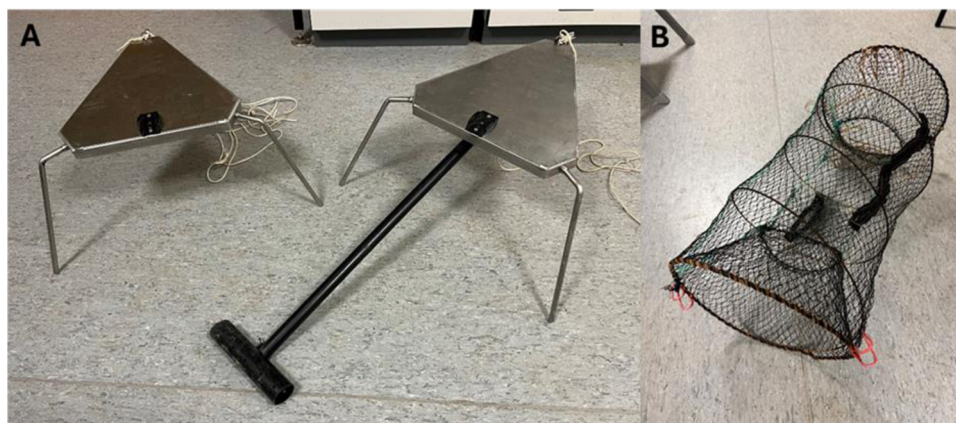


Fig. 3. A) Photograph of the Remote Underwater Video (left) and Baited Remote Underwater Video (right) rigs used in the surveys and B) a standard crayfish trap used throughout the surveys (570 mm × 290 mm, 25 mm mesh size).

jetty. The side of the jetty the bait type was deployed on was alternated monthly. The jetty split the two bait types by approximately ten meters, and the olfactory dispersal of bait plumes was not enough to cause overlaps. The catch per unit effort (CPUE) *i.e.*, – total catch per trap per night was determined for both bait types. All crayfish caught were removed from the waterbody and either euthanised with an overdose of MS-222 or brought to the facilities at the University of Leeds. A paired t-test was used on square root transformed CPUE to assess differences between in CPUE wet and dry bait types. Olfaction plays a key role in crayfish foraging (Willman *et al.*, 1994) thus we predicated that wet bait would have a higher CPUE due to the scent diffusing more rapidly.

2.3 Gear comparison

We test the potential of Remote Underwater Video (RUV) and Baited Remote Underwater Video (BRUV) surveys as an alternative to trapping (Fig. 3).

B/RUV surveys were conducted once a month between March 2023 and February 2024. The BRUV was baited using wet poultry flavoured cat food. Both cameras were deployed at separate locations within the reservoir, not simultaneously, for 1 hour, using a GoPro HERO10 Black (GoPro, Inc., USA) recording at 30 frames per second with 1080p resolution. Cameras were deployed between 12:00 and 14:00 before traps as narrow clawed are active during both day and night (Skurdal and Taugbøl, 2002) and this allowed for suitable light levels for video analysis. They were also deployed at different times to avoid interference between gear types. All footage was manually reviewed by the same observer noting the maximum number of individuals present in frame throughout the deployment (MaxN).

Monthly trapping was conducted as describe in Section 2.2. The CPUE for trapping was calculated by taking the total number of crayfish caught in traps and dividing it by the total number of traps (number of crayfish per trap). To account for the different time of deployment taken for each gear we also compared the detection probability of each gear to accurately compare gear. CPUE was calculated and compared between

each of the gears to assess the effectiveness of B/RUVs at detecting crayfish to traditional (trapping) methods. Detection probability of each gear was calculated Eq. (1). Due to high number of zero observations delta-X corrections were applied to normalise the dataset (Madzivanzira *et al.*, 2021; Nawa *et al.*, 2024), we therefore used ANOVA to compare CPUE and detection probability between gear. A chi-squared test was used to establish if there was a relationship between the number of crayfish caught in traps and the detection probability of either the RUV or BRUV.

$$\text{Detection Probability} = \frac{\text{Deployments observing crayfish}}{\text{Total Deployments}} \quad (1)$$

2.4 Mark-recapture survey

A mark-recapture experiment was conducted in March 2023 following the methods of Guan (1997) and using trapping protocols described previously to obtain an estimate of the total population size of the crayfish present within the reservoir. An important assumption for mark-recapture surveys is that there is no immigration or emigration (Rabeni *et al.*, 1997). Boshaw Whams is an isolated reservoir with little external influence and no other populations of narrow-clawed crayfish locally. Forty-nine traps were deployed daily over a three-day period. Each trap was checked at 24 hours intervals and all crayfish present within the traps were removed, and morphometric measurements taken for all crayfish, measuring the carapace length (mm), carapace width (mm), total length (mm), claw length (mm) and mass (g). After measuring, a triangular segment was cut from the tail, changing the segment of tail that had a segment removed each day so that the date of capture could be identified on any recaptures. Each marked crayfish was returned to the waterbody in a similar location as to where it was captured. Tail marks on crayfish are distinct and have durability for between two and three moults (Nowicki *et al.*, 2008).

All crayfish captured during the monthly trapping events (total 10 months) conducted after the mark-recapture survey were also checked for marked tails. Chapman's corrected

mark-recapture formula (Eq. 2) with a normal approximation for 95% confidence interval was then used to estimate the population size to help mitigate bias under low recapture numbers.

$$N = \frac{((M + 1) * (C + 1))}{(R + 1)} - 1 \quad (2)$$

where N is the estimated population size, M is the number of marked individuals, C is the total captured after marking and R is the number recaptured.

2.5 Population dynamics

Monthly trapping was used to gain an understanding of the population dynamics at the reservoir. Traps were deployed as described in Section 2.2. After June 2023 all traps were baited solely with wet cat food. All traps were deployed in the afternoon and left overnight for 18 hours. Traps were retrieved, noting the number of individual crayfish in each trap, the sex of each crayfish and if females were berried. Morphometric measurements were taken for all crayfish as described in Section 2.4. The air temperature was recorded during each survey to compare how season and temperature effected the population dynamics and CPUE.

A chi-squared test was conducted to assess the male/female sex ratio in the trapped individuals. Two linear regressions F-tests with were conducted to establish whether number of crayfish removed over time and air temperature affected the trapping CPUE, all model assumptions were checked via QQ plots.

2.6 Economic costs

In order to compare the economic costs of the different survey methods, the economic costs were calculated using the initial equipment and startup costs in combination with the annual cost to conduct monthly surveys (S3). Economic costs of assessing the population dynamics of narrow-clawed crayfish at one reservoir site were calculated first by identifying the equipment needed for surveys using; 1) traps, 2) RUV, 3) BRUV and the initial startup costs. The monthly cost of each survey was then calculated, accounting for travel to and from the site, car hire, fuel costs (one journey required for camera surveys but two for trapping surveys), bait, and surveyor time (at a minimum rate of £12/ hour). The values presented here were typical for the survey undertaken by the University of Leeds and fuel and distances are calculated appropriately, distance from the University of Leeds to Boshaw Whams is 48 km. The initial costs and monthly costs were then scaled up to establish the total costs for 12 months' worth of surveys for each of the three different gears. The costs for each method are assessed and presented as either initial one-off costs or continuous monthly costs.

3 Results

3.1 Bait comparison

For baited traps, there was no significant difference between the catch per unit effort (CPUE) obtained by the two

bait types, dry dog food and wet cat food ($t=1.23$, $df=8$, $p=0.25$).

3.2 Gear comparison

There was no significant difference between the CPUE of any of the three gears (trapping, RUV, BRUV) (ANOVA, $F=0.979$, $p=0.388$; Fig. 4, Tabs. 1 and 2). There was also no significant difference between the detection probability of any of the three gears (trapping, RUV, BRUV) (ANOVA, $F=0.066$, $p=0.936$; Fig. 5, Tabs. 1 and 2).

There was no relationship between the number of crayfish caught in traps and the detection probability of either camera method ($\chi^2=1.550$, $df=1$, $p=0.2131$). The cumulative removal of crayfish from the waterbody after each trapping survey did not bias the results.

3.3 Mark-recapture experiment

A total of 286 crayfish were marked over a three-day trapping period (Tab. 3). Over the six-month period following the initial marking survey 384 crayfish were trapped, ten of these were recaptured marked individuals (3.5% of those marked). The current population size of narrow-clawed crayfish at Boshaw Whams reservoir is estimated at $10,045 \pm 5602$ (95% CI) individuals in a 50,000 m² reservoir, equating to approximately 0.20 crayfish per meter squared.

The distinctiveness of marks on crayfish varied over time. Markings on the tails of individuals recaptured closer to the initial experiments were clear, but after a six-month period the markings on the tails of some individuals became fainter and less distinct (S1) after potential healing and moulting. All captured individuals were thoroughly checked to identify any potential markings, and we are confident that no marked individuals recaptured were missed.

3.4 Population dynamics

We deployed a total of 682 traps at Boshaw Whams reservoir during this survey. In which, 756 crayfish were captured, of these 490 were males, 266 females and 30 of which were berried. Carapace length ranged from male 22.5–99.0 mm and females: 23.8–79.1 mm (Fig. 6). Traps caught significantly more males than females ($\chi^2=66.370$, $df=1$, $p<0.05$), and these trends are visible when comparing the monthly CPUE (Fig. 6).

Females carrying young were recorded between February and April (Tab. 4). The range of carapace lengths for berried females was 44.8–79.1 mm (Fig. 6).

There was no relationship between cumulative number crayfish removed and trapping CPUE ($F(1,13)=0.2356$, $p=0.6355$) and air temperature did not have a relationship with CPUE ($F(1,13)=1.273$, $p=0.2796$).

3.5 Economic costs

Trapping had the lowest initial set-up cost, but the highest survey costs and the highest 12-month survey cost (Tab. 5) compared to RUV and BRUV.

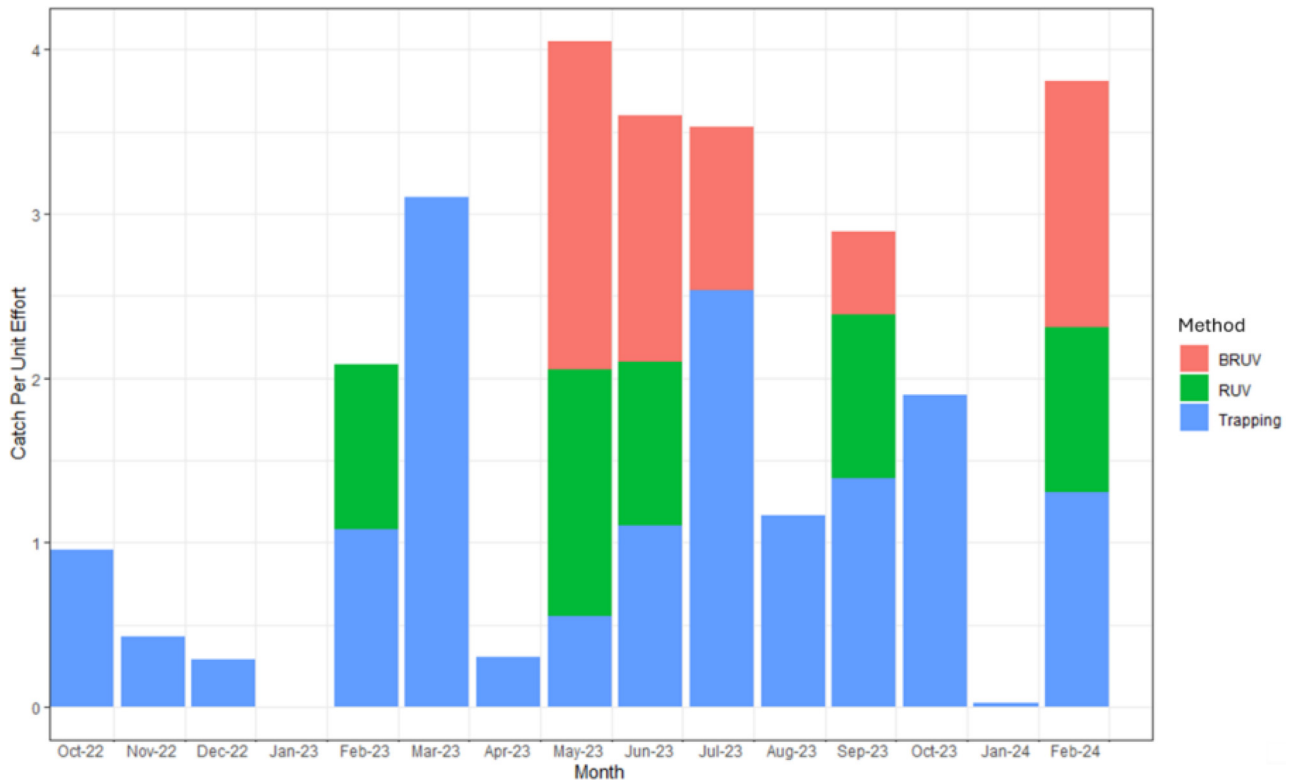


Fig. 4. Monthly Catch Per Unit Effort (CPUE) of narrow-clawed crayfish (*Pontastacus leptodactylus*) for Baited Remote Underwater Video (BRUV), Remote Underwater Video (RUV) and trapping surveys. CPUE for BRUV and RUV is the sum of MaxN (maximum number of individuals in frame at a single moment in deployment) divided by the number of deployments for each survey. CPUE for trapping is the total number of crayfish caught divided by the number of traps deployed for each survey.

Table 1. The average Catch Per Unit Effort (CPUE) and detection probability of each crayfish surveying methods.

Gear	Dates deployed	No. surveys	Total deployed	Detection probability	CPUE
Trapping	October 2022–February 2024	15	682	0.46 ± 0.25	1.11 ± 0.87
RUV	March 2023–February 2024	9	15	0.53 ± 0.39	0.67 ± 0.75
BRUV	April 2023–February 2024	8	14	0.43 ± 0.47	0.86 ± 0.57

4 Discussion

This study aimed to rapidly assess the population ecology of narrow-clawed crayfish (*Pontastacus leptodactylus*) at Boshaw Whams reservoir. Here we provide the first year-round monitoring data of population dynamics of a narrow-clawed crayfish invasion in the UK and report a large and established population at Boshaw Whams reservoir. All tested monitoring methods (traps and B/RUVs) had comparable efficacy in detecting narrow-clawed crayfish in this reservoir. Narrow-clawed crayfish are highly abundant in this reservoir which may have masked the differences in surveying methods. We recommend a multi-method approach to monitoring as well and suggest that biodiversity managers assess their capacity for monitoring (cost, people time, accessibility) and specific information needs to inform the best approach to designing and monitoring campaign for narrow-clawed crayfish.

4.1 Bait comparison

We predicted that due to wet food solubility that it would have a higher efficacy in attracting crayfish (Willman *et al.*, 1994) but in this instance there was no difference in CPUE between bait type. There is a high degree of variation in bait efficiency with some reporting no difference (Somers and Stechey, 1986), whilst other studies have concluded both that wet bait achieved higher CPUE (Beecher and Romaine, 2010) or that dry bait achieved a higher CPUE (Rach and Bills, 1987). We opted to use wet cat food for the remainder of the surveys due to the ease of use in distributing into mesh pouched to place in the traps. However, it is likely that the amino acid content of the bait, scent plume diffusion and physical properties of the water body all mediate efficacy (Westerberg and Westerberg, 2011).

Table 2. Monthly Catch Per Unit Effort and Detection Probability and water quality parameters for each surveying method. Trapping CPUE is the total number of crayfish caught in traps, divided by the total number of traps deployed. Both RUV and BRUV CPUE is the sum of MaxN for all B/RUV deployments made during a survey (maximum number of individuals on screen throughout a deployment) divided by the total number of camera deployments for each gear.

Month / Year	Trapping detection probability	Trapping CPUE	BRUV detection probability	BRUV CPUE	RUV detection probability	RUV CPUE	No. traps	Survey date average air temp (°C)
Oct-22	0.50	0.96					22	16.0
Nov-22	0.31	0.43					35	6.1
Dec-22	0.20	0.29					35	6.1
Jan-23	0.00	0.00					49	7.1
Feb-23	0.61	1.08			1.00	1.00	49	4.0
Mar-23	0.80	3.10					49	8.6
Apr-23	0.27	0.31	0.00	0.00	0.00	0.00	49	14.0
May-23	0.41	0.55	0.50	2.00	1.00	1.50	49	19.0
Jun-23	0.47	1.10	0.50	1.50	1.00	1.00	49	17.0
Jul-23	0.86	2.53	1.00	1.00	0.00	0.00	49	17.0
Aug-23	0.39	1.16	0.00	0.00	0.00	0.00	49	16.0
Sep-23	0.65	1.39	0.50	0.50	0.50	1.00	49	13.0
Oct-23	0.69	1.90					49	12.0
Jan-24	0.02	0.02	0.00	0.00	0.00	0.00	49	0.7
Feb-24	0.61	1.31	1.00	1.50	1.00	1.00	49	10.0

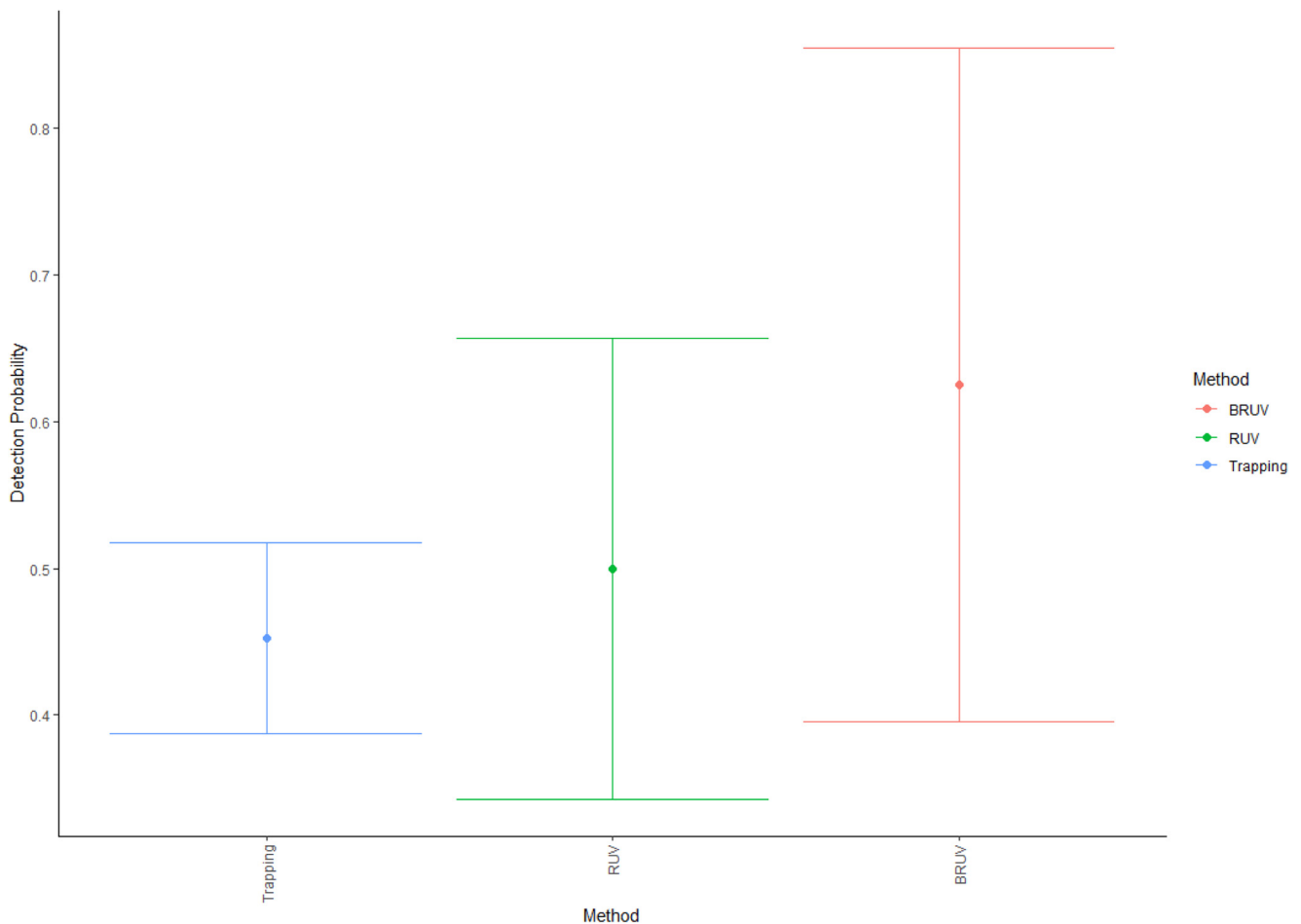
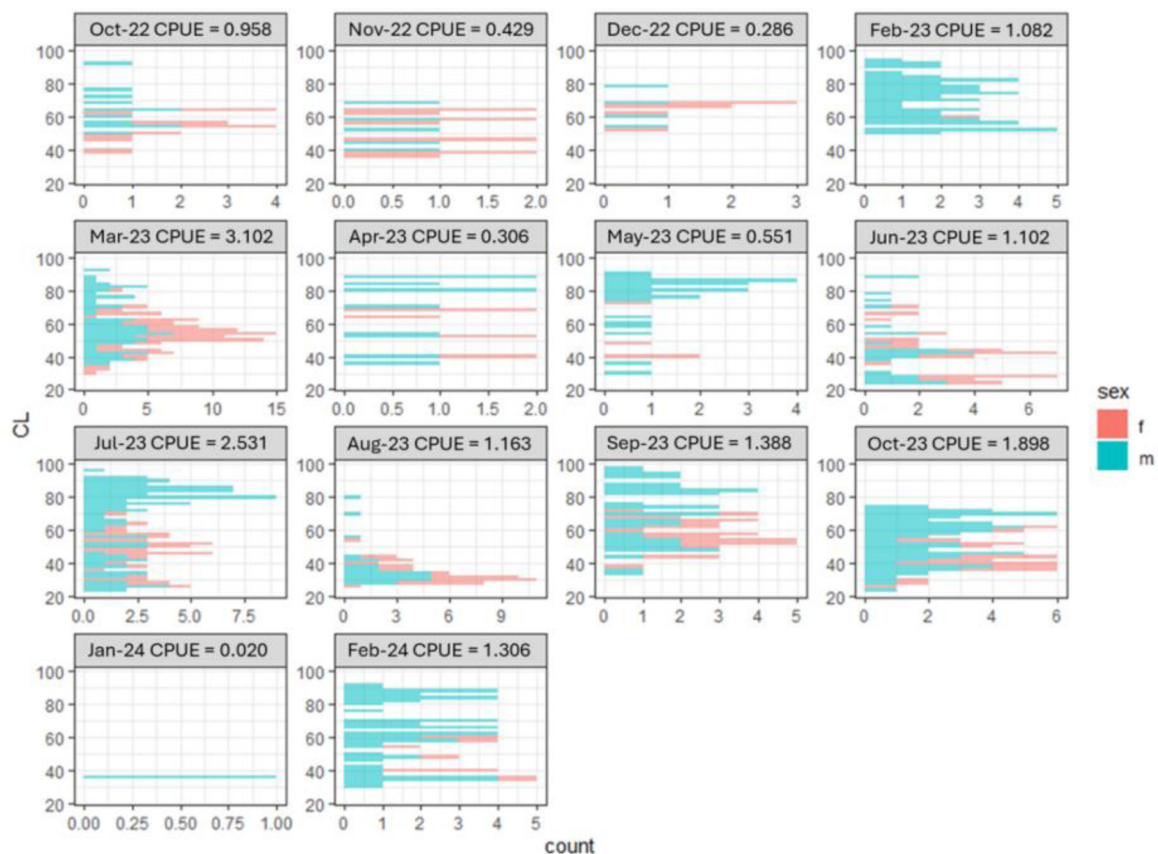


Fig. 5. Mean detection probability for Baited Remote Underwater Video, Remote Underwater Video and trapping of narrow-clawed crayfish (*Pontastacus leptodactylus*). Error bars are the standard error of detection probability for each method.

Table 3. Mark-recapture experiment summary of narrow-clawed crayfish (*Pontastacus leptodactylus*) at Boshaw Whams reservoir. Three-day trapping and marking period highlighted in green.

Date	Total caught	Males	Females	Total recaptured
31/03/2023	152	78	74	n/a
04/04/2023	78	43	34	0
05/04/2023	56	37	19	0
06/04/2023	39	29	10	1
29/04/2023	15	10	5	0
26/05/2023	27	23	4	0
30/06/2023	54	26	28	2
01/08/2023	124	88	36	3
01/09/2023	57	28	29	1
13/10/2023	68	43	25	3

**Fig. 6.** Histograms comparing the monthly sex ratios and size distributions with catch per unit effort.

4.2 Method comparison

All trialled methods had comparable detection probability therefore in relatively clear, still-waters we would recommend any of the methods for detecting presence/absence of invasive crayfish populations. To assess relative abundance, we recommend a multi-method approach as traditional trapping as the MaxN value from the B/RUV setups provides a conservative estimate of abundance whereas trapping can provide more nuanced information regarding population demographics. Our results are similar to other attempts to compare novel monitoring methods to traditional approaches

in freshwaters in that there is not a one size fits all monitoring method, but rather, specific methods may be better suited dependent on the question. For example, [Castañeda *et al.* \(2020\)](#) found that underwater cameras were more time consuming than snorkel surveys but that cameras were better for detecting rare freshwater fish species. Thus, choice of monitoring methods depends on what information the surveyor is aiming to achieve.

Trapping can be a time-consuming method which may or may not require entering waterbodies. Furthermore, it requires a minimum of two days of staff time to conduct a single survey, which can limit the total number of surveys that can be

Table 4. Monthly trapping and crayfish morphometrics on the Narrow Claw Crayfish (*Pontastacus leptodactylus*) at Boshaw Whams Reservoir.

Month / Year	Total caught	Male	Female	Berried female	Mean carapace length $\pm$ SD	Mean carapace width $\pm$ SD	Mean total length $\pm$ SD	Mean claw length $\pm$ SD	Mean weight $\pm$ SD
Oct-22	23	10	13	0	59.3 $\pm$ 11.6	31.6 $\pm$ 7.0	115.5 $\pm$ 21.3	43.0 $\pm$ 17.7	60.2 $\pm$ 31.2
Nov-22	15	5	10	0	51.6 $\pm$ 10.6	27.0 $\pm$ 6.0	101.4 $\pm$ 21.3	32.0 $\pm$ 9.2	40.3 $\pm$ 22.6
Dec-22	10	4	6	0	64.1 $\pm$ 7.8	34.0 $\pm$ 4.7	126.4 $\pm$ 14.7	46.2 $\pm$ 13.2	67.6 $\pm$ 24.4
Jan-23	0	0	0	0					
Feb-23	53	52	1	1	69.1 $\pm$ 12.6	37.3 $\pm$ 7.7	131.8 $\pm$ 23.3	58.7 $\pm$ 20.5	89.5 $\pm$ 47.0
Mar-23	152	78	74	26	57.0 $\pm$ 13.2	30.3 $\pm$ 7.9	110.5 $\pm$ 24.0	41.5 $\pm$ 17.6	55.7 $\pm$ 35.9
Apr-23	15	10	5	2	65.6 $\pm$ 17.0	35.5 $\pm$ 9.7	128.1 $\pm$ 32.0	53.0 $\pm$ 22.9	84.1 $\pm$ 56.4
May-23	27	23	4	0	70.5 $\pm$ 17.7	38.5 $\pm$ 10.3	136.6 $\pm$ 32.9	63.1 $\pm$ 24.9	106.5 $\pm$ 59.0
Jun-23	54	26	28	0	44.2 $\pm$ 16.6	22.6 $\pm$ 9.5	87.9 $\pm$ 33.0	28.7 $\pm$ 17.1	29.2 $\pm$ 36.4
Jul-23	124	89	35	0	60.5 $\pm$ 20.6	31.9 $\pm$ 11.9	117.3 $\pm$ 39.2	47.6 $\pm$ 26.5	69.4 $\pm$ 58.2
Aug-23	57	28	29	0	36.7 $\pm$ 10.30	18.6 $\pm$ 6.3	71.3 $\pm$ 19.3	20.5 $\pm$ 7.5	13.3 $\pm$ 17.7
Sep-23	68	42	26	0	66.2 $\pm$ 16.0	35.3 $\pm$ 9.4	129.5 $\pm$ 28.5	55.5 $\pm$ 27.9	79.6 $\pm$ 57.5
Oct-23	93	68	25	0	51.5 $\pm$ 13.2	27.2 $\pm$ 7.67	100.5 $\pm$ 24.3	36.3 $\pm$ 16.5	48.6 $\pm$ 32.5
Jan-24	1	1	0	0	36.6	17.5	69.5	17.9	9.0
Feb-24	64	54	10	1	59.7 $\pm$ 18.6	31.6 $\pm$ 11.0	114.7 $\pm$ 33.7	48.4 $\pm$ 26.0	64.9 $\pm$ 54.1

Table 5. Total cost for each method for monthly surveys over 12 months of surveying, where method is deployed once a month.

Monitoring method	Total initial cost	Monthly cost	12 months of survey cost
Trapping	£494.41	£293.02	£4010.65
RUV	£611.00	£146.36	£2367.32
BRUV	£631.04	£146.96	£2394.56

conducted in a fixed timeframe. Cameras therefore provide an alternative survey method which, although initially costly, can reduce the amount of labour needed to complete the surveys and allow video data to be assessed at any time in the future, thus removing immediate time constraints – especially in remote locations (Ebner *et al.*, 2014; Castañeda *et al.*, 2020; Broom *et al.*, 2023). Video data still requires human time to assess but developments in artificial intelligence image recognition may remove this barrier (Siri *et al.*, 2024).

Lighting and water turbidity can limit the effectiveness of RUV as this hampers the capacity to obtain usable video (Ebner *et al.*, 2014; King *et al.*, 2018), this was not an issue for our surveys at Boshaw Whams as the nature of the reservoir meant that underwater visibility averaged >1 m for all surveys. Crayfish species are largely nocturnal thus the need for overnight sampling has been a barrier to developing rapid surveying methods, besides eDNA approaches, due to light level limitations (Fanjul-Moles and Prieto-Sagredo, 2003; Mallet and Pelletier, 2014). Narrow-clawed crayfish show high feeding intensity during both day and night (Skurdal and Taugbøl, 2002) and were regularly observed on the cameras. Studies must account for these limitations when designing and deploying RUVs for crayfish monitoring to avoid wasted effort and costs.

4.3 Mark-recapture experiment

The mark-recapture experiment indicated that there were over ten-thousand narrow-clawed crayfish individuals in the reservoir (one per 5 metres squared (0.20 crayfish/m²)).

Considering only 10 individuals were recaptured, representing 3.5% of all trapped individuals after the mark-recapture event, this data is likely unreliable but offers an indication of the extremely high density of crayfish. This is reinforced by the large confidence intervals post Chapman correction implementation. There is limited information about the densities of narrow-clawed crayfish found in waterbodies in their native range. However, in comparison to other invasive crayfish populations in lotic waterbodies (signal crayfish; *Pacifastacus leniusculus*) in the UK, they are much lower ($3\text{--}20/\text{m}^2$ (Guan and Wiles, 1997), $20/\text{m}^2$ (Bubb *et al.*, 2004), $21\text{--}110/\text{m}^2$ (Chadwick *et al.*, 2021)).

Trapping and marking can have a short-term negative effect on crayfish recapture chances (Nowicki *et al.*, 2008), with marked individuals potentially having a negative association with traps and avoiding them. Individuals found over six months after the marking event only had faint markings (S1). This is supported by other studies which found that markings from mark-recapture events tend to last two to three moult cycles (Nowicki *et al.*, 2008).

4.4 Population dynamics

The narrow-clawed crayfish population in Boshaw Whams is established, detectable throughout the year and reproducing at small sizes. The number of male narrow-clawed crayfish caught was 1.84 times higher than females. This sex bias may be a result of the aggressive behaviour of larger males resulting in females and smaller males avoiding the traps (Momot and Gowing, 1977; Holdich, 2002; Hein *et al.*, 2007;

Hilber *et al.*, 2020). Except for January 2023, crayfish were caught each month throughout the year with an increase in CPUE between March and May (2023), which was also when the first observations of berried females occurred. In their native range berried females can be found between December and May (Cilbiz, 2020) and reproduction generally occurs in cold water between 7–12 °C (Farhadi and Harhoglu, 2018). In our study most berried females were caught during these months and a small number of berried individuals were observed in subsequent months. In their native range females reach sexual maturity at 64.3 mm total length but spawning only occurred for crayfish with a total length $\geq$ 82 mm (Berber and Mazlum, 2009). This is smaller than the total length of the smallest berried individual found in the present study (carapace length: 44.8 mm, total length of 90.8 mm), suggesting that reproduction happens at smaller sizes in the invasive range.

Our monitoring campaign did not appear to have had an impact on the population size at Boshaw Whams reservoir. Despite removing over 700 crayfish there was no negative trend in the monthly CPUE which indicates that removal of crayfish did not bias our results. This is due to the relatively low monthly trapping effort (Peay, 2001; Green *et al.*, 2018).

4.5 Economic costs

The largest cost that goes into crayfish sampling is staff-time (Peay, 2004). We recommend that surveyors first determine their data needs such as whether rapid detection is the aim or whether population level information is needed at each stage of assessment. Beyond this, accessibility issues, economic and time constraints can also influence choice of method. In this scenario, *i.e.*, a high-density invasion in clear water, all three methods were able to detect crayfish, however, more granular information on breeding period, length frequency, sex ratio were only available with trapping. Thus, a staggered approach to monitoring where cameras are first deployed and this data used to inform trapping may be the most effective.

5 Conclusion

Boshaw Whams reservoir should be considered in the ‘Containment’ or ‘Asset Protection’ stage of the General Invasive Curve, which means there are large populations within the waterbody, but we cannot confirm that they have colonised the entire area of it. The population of narrow-clawed crayfish at Boshaw Whams reservoir is estimated to be 10,045, and breeding activity was seen between February and April. Potentially this could mean that the opportunity to eradicate this population has passed and eradication is no longer viable, however the feasibility of eradication would need to be assessed on a site and catchment specific scale, beyond the scope of this study. Narrow clawed crayfish ranges are expected to expand and shift with predicted climate change therefore mitigation of further spread is required urgently (Hodson *et al.*, 2024).

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Supplementary material

Sup. 1. Triangular notch marking used in mark-recapture survey and marks remaining on individuals captured on 13/10/2023, six months after the initial marking experiment.

Sup. 2. Boxplot showing the median and upper and lower quartiles for the Catch Per Unit Effort of surveys using cat food and dog food as bait. CPUE was calculated by dividing the total number of crayfish caught by the number of traps deployed for each survey and each bait type.

Sup. 3. Breakdown of initial set up costs for each method, per unit of method. Initial costs were calculated per trap or per camera unit.

Sup. 4. Boxplot showing the monthly variations in sizes between males and females.

The Supplementary Material is available at <https://www.kmae-journal.org/10.1051/kmae/2025017/olm>.

References

- Beecher LE, Romaine RP. 2010. Evaluation of baits for harvesting procambarid crawfishes with emphasis on bait type and bait quantity. *J Shellfish Res* 29: 13–18.
- Berber S, Mazlum Y. 2009. Reproductive efficiency of the narrow-clawed crayfish, *Astacus leptodactylus*, in several populations in Turkey. *Crustaceana* 82: 531–542.
- Bök TD, Aydın H, Ates C. 2013. A study on some morphological characteristics of *Astacus leptodactylus* (Eschscholtz 1823) in seven different inland waters in Turkey. *J Black Sea/Medit Environ* 19: 190–205.
- Broom CJ, Weyl OLF, South J. 2023. Habitat associations of imperilled fishes after conservation intervention in the Cape Fold Ecoregion, South Africa. *J Fish Biol* 102: 317–327.
- Bubb DH, Thom TJ, Lucas MC. 2004. Movement and dispersal of the invasive signal crayfish *Pacifastacus leniusculus* in upland rivers. *Freshw Biol* 49: 357–368.
- Castañeda RA, Van Nynatten A, Crookes S, Ellender BR, Heath DD, MacIsaac HJ, Mandrak NE, Weyl OLF. 2020. Detecting native freshwater fishes using novel non-invasive methods. *Front Environ Sci* 8: 29.
- Chadwick DDA, Pritchard EG, Bradley P, Sayer CD, Chadwick MA, Eagle LJB, Axmacher JC. 2021. A novel ‘triple drawdown’ method highlights deficiencies in invasive alien crayfish survey and control techniques. *J Appl Ecol* 58: 316–326.
- Cilbiz M. 2020. Pleopodal fecundity of narrow-clawed crayfish (*Pontastacus leptodactylus* Eschscholtz, 1823). *Invertebr Reprod Dev* 64: 208–218.
- Clavero M, Hermoso V, Aparicio E, Godinho FN. 2013. Biodiversity in heavily modified waterbodies: native and introduced fish in Iberian reservoirs. *Freshw Biol* 58: 1190–1201.
- Cuthbert RN, Digne C, Hudgins EJ, Turbelin A, Ahmed DA, Albert C, Bodey TW, Briski E, Essl F, Haubrock PJ, Gozlan RE, Kirichenko N, Kourantidou M, Kramer AM, Courchamp F. 2022. Biological invasion costs reveal insufficient proactive management worldwide. *Sci Total Environ* 819: 153404.

- Durant MJ, Counsell CJ. 2018. Inventory of reservoirs amounting to 90% of total UK storage. *NERC Environmental Information Data Centre*. (Dataset). <https://doi.org/10.5285/f5a7d56c-cea0-4f00-b159-c3788a3b2b38>
- Ebner BC, Starrs D, Morgan DL, Fulton CJ, Donaldson J, Doody S, Cousins S, Kennard MJ, Butler G, Tonkin Z, Beatty S. 2014. Emergence of field-based underwater video for understanding the ecology of freshwater fishes and crustaceans in Australia. *J Royal Soc West Aust* 97: 287–296.
- Eschen R, Kadzamira M, Stutz S, Ogunmodede A, Djeddour D, Shaw R, Pratt C, Varia S, Constantine K, Williams F. 2023. An updated assessment of the direct costs of invasive non-native species to the United Kingdom. *Biol Invasions* 25: 3265–3276.
- Fanjul-Moles ML, Prieto-Sagredo J. 2003. The circadian system of crayfish: A developmental approach. *Microsc Res Tech* 60: 291–301.
- Farhadi A, Harlioglu MM. 2018. Elevated water temperature impairs gamete production in male narrow-clawed crayfish *Pontastacus leptodactylus* (Eschscholtz, 1823). *Knowl Manag Aquat Ecosyst* 419: 40.
- Green N, Bentley M, Stebbing P, Andreou D, Britton R. 2018. Trapping for invasive crayfish: comparisons of efficacy and selectivity of baited traps versus novel artificial refuge traps. *Knowl Manag Aquat Ecosyst* 419: 15.
- Guan RZ. 1997. An improved method for marking crayfish. *Crustaceana* 70: 641–652.
- Guan RZ, Wiles PR. 1997. Ecological impact of introduced crayfish on benthic fishes in a British Lowland River. *Conserv Biol* 11: 641–647.
- Harris S, Elliott C, Woolnough A, Barclay C. 2018. A heuristic framework for invasive species research planning and measurement. Developing an invasive species research strategy in Tasmania. *Record Queen Victoria Museum Art Gallery* 117: 1–13.
- Havel JE, Lee CE, Zanden JMV. 2005. Do reservoirs facilitate invasions into landscapes? *BioScience* 55: 518–525.
- Hein CL, Vander Zanden MJ, Magnuson JJ. 2007. Intensive trapping and increased fish predation cause massive population decline of an invasive crayfish. *Freshw Biol* 52: 1134–1146.
- Hilber T, Oehm J, Effenberger M, Maier G. 2020. Evaluating the efficiency of three methods for monitoring of native crayfish in Germany. *Limnologica* 85: 125821.
- Hodson J, South J, Cancellario T, Guareschi S. 2024. Multi-method distribution modelling of an invasive crayfish (*Pontastacus leptodactylus*) at Eurasian scale. *Hydrobiologia* 852: 2115–2131.
- Holdich DM. 1999. The negative effects of established crayfish introductions. In *Crayfish in Europe as Alien Species* (Gherardi, F.) Routledge. London, UK. 17p, <https://doi.org/10.1201/9781315140469>
- Holdich DM, ed. 2002. *Biology of freshwater crayfish* (Vol. 22) UK: Wiley-Blackwell Oxford, 720p.
- Hudina S, Hock K, Radović A, Klobučar G, Petković J, Jelic M, Maguire I. 2016. Species-specific differences in dynamics of agonistic interactions may contribute to the competitive advantage of the invasive signal crayfish (*Pacifastacus leniusculus*) over the native narrow-clawed crayfish (*Astacus leptodactylus*). *Mar Freshw Behav Physiol* 49: 147–157.
- Ion MC, Bloomer CC, Bărașcu TI, Oficialdegui FJ, Shoobs NF, Williams BW, Scheers K, Clavero M, Grandjean F, Collas M, Baudry T, Loughman Z, Wright JJ, Ruokonen TJ, Chucholl C, Guareschi S, Koese B, Banyai ZM, Hodson J, Hurt M, Kaldre K, Lipták B, Fetzner JW, Cancellario T, Weiperth A, Birzaks J, Trichkova T, Todorov M, Balalaikins M, Griffin B, Petko ON, Acevedo-Alonso A, D'Elia G, Śliwińska K, Alekhovich A, Choong H, South J, Whiterod N, Zorić K, Haase P, Soto I, Brady DJ, Haubrock PJ, Torres PJ, Sadrin D, Vlach P, Kaya C, Woo Jung S, Kim J, Vermeersch XHC, Bonk M, Guiasu R, Harlioglu MM, Devlin J, Kurtul I, Błońska D, Boets P, Masigol H, Cabe PR, Jussila J, Vrålstad T, Beresford DV, Reid SM, Patoka J, Strand DA, Tarkan AS, Steen F, Abeel T, Harwood M, Auer S, Kelly S, Giantsis IA, Maciaszek R, Alvanou MV, Aksu Ö, Hayes DM, Kawai T, Tricarico E, Chakandinakira A, Barnett ZC, Kudor SG, Beda AE, Vilcea L, Mizeranschi AE, Neagul M, Licz A, Cotoarba AD, Petrusek A, Kouba A, Taylor CA, Părvulescu L. 2024. World of Crayfish™: a web platform towards real-time global mapping of freshwater crayfish and their pathogens. *PeerJ* 12: 18229.
- King AJ, George A, Buckle DJ, Novak PA, Fulton CJ. 2018. Efficacy of remote underwater video cameras for monitoring tropical wetland fishes. *Hydrobiologia* 807: 145–164.
- Kouba A, Oficialdegui FJ, Cuthbert RN, Kourantidou M, South J, Tricarico E, Gozlan RE, Courchamp F, Haubrock PJ. 2022. Identifying economic costs and knowledge gaps of invasive aquatic crustaceans. *Sci Total Environ* 813: 152325.
- Lele SF, Părvulescu L. 2017. Experimental evidence of the successful invader *Orconectes limosus* outcompeting the native *Astacus leptodactylus* in acquiring shelter and food. *Biologia* 72: 877–885.
- Madzivanzira TC, South J, Ellender BR, Chalmers R, Chisule G, Coppinger CR, Khaebef FH, Jacobs FJ, Chomba M, Musando B, Mwale C, Nhiwatiwa T, Rennie CL, Richardson N, Weyl OLF. 2021. Distribution and establishment of the alien Australian redclaw crayfish, *Cherax quadricarinatus*, in the Zambezi Basin. *Aquat Conserv: Mar Freshw Ecosyst* 31: 3156–3168.
- Mallet D, Pelletier D. 2014. Underwater video techniques for observing coastal marine biodiversity: a review of sixty years of publications (1952–2012). *Fish Res* 154: 44–62.
- Momot WT, Gowing H. 1977. Results of an experimental fishery on the crayfish *Orconectes virilis*. *J Fish Res Board Can* 34: 2056–2066.
- Moyle PB, Light T. 1996. Biological invasions of fresh water: Empirical rules and assembly theory. *Biol Conserv* 78: 149–161.
- Nawa N, South J, Ellender BR, Pegg J, Madzivanzira TC, Wasserman RJ. 2024. Complex selection processes on invasive crayfish phenotype at the invasion front of the Zambezi floodplains ecoregion. *Freshw Biol* 69: 1322–1337.
- Nowicki P, Tirelli T, Sartor RM, Bona F, Pessani D. 2008. Monitoring crayfish using a mark-recapture method: potentials, recommendations, and limitations. *Biodivers Conserv* 17: 3513–3530.
- O'Hea Miller SB, Davis AR, Wong MYL. 2024. The impacts of invasive crayfish and other non-native species on native freshwater crayfish: A review. *Biology* 13: 610.
- Peay S. 2001. *Eradication of alien crayfish populations*. Bristol, UK: Environment Agency, 122p.
- Peay S. 2004. Keynote a cost-led evaluation of survey methods and monitoring for white-clawed crayfish-Lessons from the UK. *Bulletin Français de la Pêche et de la Pisciculture* 372: 335–352.
- Rabeni CF, Collier KJ, Parkyn SM, Hicks BJ. 1997. Evaluating techniques for sampling stream crayfish (*Paraneopros planifrons*). *NZ J Mar Freshw Res* 31: 693–700.
- Rach JJ, Bills TD. 1987. Comparison of three baits for trapping crayfish. *North Am J Fish Manag* 7: 601–603.
- Robertson PA, Mill A, Novoa A, Jeschke JM, Essl F, Gallardo B, Geist J, Jarić I, Lambin X, Musseau C, Pergl J, Pyšek P, Rabitsch W, Schmalensee M, Shirley M, Strayer DL, Stefansson RA, Smith K, Booy O. 2020. A proposed unified framework to describe the management of biological invasions. *Biol Invasions* 22: 2633–2645.

- Roy HE, Pauchard A, Stoett P, Renard Truong T, Bacher S, Galil BS, Hulme PE, Ikeda T, Sankaran KV, McGeoch MA, Meyerson LA, Nuñez MA, Ordonez A, Rahlao SJ, Schwindt E, Seebens H, Sheppard AW, Vandvik V. 2023. Summary for policymakers of the thematic assessment report on invasive alien species and their control of the intergovernmental science-policy platform on biodiversity and ecosystem services. Bonn, Germany: IPBES secretariat, 56 p.
- Siri D, Vellaturi G, Ibrahim SHS, Molugu S, Desanamukula VS, Kocherla R, Vatambeti R. 2024. Enhanced deep learning models for automatic fish species identification in underwater imagery. *Heliyon* 10: e35217.
- Skurdal J, Taugbøl T. 2002. Crayfish of commercial importance, *Astacus*. In: Holdich DM, ed. *Biology of Freshwater Crayfish*. Oxford, UK: Blackwell Science Ltd. pp. 467–510.
- Somers KM, Stechey DPM 1986. Variable trappability of crayfish associated with bait type, water temperature and lunar phase. *Am Midl Nat* 116: 36–44.
- Soto I, Balzani P, Carneiro L, Cuthbert RN, Macêdo R, Tarkan AS, Ahmed DA, Bang A, Bacela-Spychalska K, Bailey SA, Baudry T, Ballesteros-Mejia L, Bortolus A, Briski E, Britton JR, Buřić M, Camacho-Cervantes M, Cano-Barbacil C, Copilaş-Ciocianu D, Coughlan NE, Courtois P, Csabai Z, Dalu T, De Santis V, Dickey JWE, Dimarco RD, Falk-Andersson J, Fernandez RD, Florencio M, Franco ACS, García-Berthou E, Giannetto D, Glavendekic MM, Grabowski M, Heringer G, Herrera I, Huang W, Kamelamela KL, Kirichenko NI, Kouba A, Kourantidou M, Kurtul I, Laufer G, Lipták B, Liu C, López-López E, Lozano V, Mammola S, Marchini A, Meshkova V, Milardi M, Musolin DL, Nuñez MA, Oficialdegui FJ, Patoka J, Pattison Z, Pincheira-Donoso D, Piria M, Probert AF, Rasmussen JJ, Renault D, Ribeiro F, Rilov G, Robinson TB, Sanchez AE, Schwindt E, South J, Stoett P, Verreycken H, Vilizzi L, Wang YJ, Watari Y, Wehi PM, Weiperth A, Wiberg-Larsen P, Yapıcı S, Yoğurtcuoğlu B, Zenni RD, Galil BS, Dick JTA, Russell JC, Ricciardi A, Simberloff D, Bradshaw CJA, Haubrock PJ. 2024. Taming the terminological tempest in invasion science. *Biol Rev* 99: 1357–1390.
- Westerberg H, Westerberg K. 2011. Properties of odour plumes from natural baits. *Fish Res* 110: 459–464.
- Williams F, Eschen R, Harris A, Djeddour D, Pratt C, Shaw RS, Varia S, Lamontagne-Godwin J, Thomas SE, Murphy ST 2010. The economic cost of invasive non-native species on Great Britain. Oxford, UK: CABI Proj No VM10066, 199p.
- Willman EJ, Hill AM, Lodge DM. 1994. Response of three crayfish congeners (*Orconectes* spp.) to Odors of fish carrion and live predatory fish. *Am Midl Nat* 132: 44–51.

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