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Research Article

Successful control of invasive crayfish (*Pacifastacus leniusculus*) by intensive trapping in a small lake

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Abstract

Despite strict regulations, invasive alien species (IAS) pose an increasing threat to native ecosystems. In aquatic environments, difficulties in early detection of invasions make it challenging to control the spread of species such as freshwater crayfish, and hence, effective measures are often needed to eradicate already established populations. We investigated the efficacy of intensive trapping in eradication of signal crayfish (*Pacifastacus leniusculus)* from a small, isolated lake using a Before-After-Control-Impact (BACI) design with data from three control lakes. Five years of intensive biannual removal of crayfish catch in the target lake resulted in a collapse of the crayfish population, in contrast to increasing test catches in the control lakes. A temporary recovery of the population followed within four years after stopping the removal, but a short-term continuation of the intensive trapping reduced the population to apparent extinction. While small crayfish (< 60 mm in total length) were not effectively caught by the size selective traps, the trial apparently succeeded in limiting the adult crayfish and their reproduction below a critical threshold. Our results support the previous findings that complete direct removal of individuals may not be necessary for successful eradication. Climate-induced reproductive failure and low availability of suitable habitat likely supported our eradication success, highlighting the importance of environmental conditions in invasive species management. Our results emphasise the need for removal projects to be well targeted, long-term, and adequately resourced. Less selective traps catching also small crayfish would need to be developed for enhancing the invasive crayfish species management.

Key words: BACI, eradication, management of invasive species, signal crayfish

Introduction

Since invasive alien species (IAS) continue to spread despite strict legislations and vigorous regulation attempts (e.g., Pyšek et al. 2020), effective control and eradication measures are still needed to protect native ecosystems and species. Eradication or restriction of spread of established IAS is challenging, especially in aquatic environments where species can be cryptic for a long time and may spread widely before they are detected (Piria et al. 2017). Freshwater crayfish are a widely spread IAS group which has expanded to new areas through several pathways including intentional introductions, aquaculture escapees, and aquarium releases (Kouba et al. 2014; Lodge et al.

2012). Spread of new invasive crayfish species continues outside their native ranges, and already established species are spreading still in spite of strict restrictions in national and international levels (Chucholl 2016; Kouba et al. 2014). Since invasive crayfish compete with native crayfish (Westman et al. 2002), spread lethal diseases (Bohman et al. 2006), and affect whole ecosystem (Twardochleb et al. 2013; Usio et al. 2006) effective controlling measures are needed.

Total crayfish eradication, where all individuals are removed, may be possible in small, isolated watercourses using chemicals, total draining or even manual collection if the population is not established and widespread (Bonelli et al. 2017; Peay 2009; Stebbing et al. 2014). It is widely recognised that in larger watercourses, the total eradication of a well-established and widespread crayfish population is almost impossible due to the complexity of the system. (Gherardi et al. 2011). Still, controlling of crayfish population density might be possible by intensive trapping (Hansen et al. 2013; Hein et al. 2007; Moorhouse et al. 2014), and partial removal could benefit native biota as the effects of crayfish are density dependent and vary between taxa (Hansen et al. 2013; Nishijima et al. 2017; Carvalho et al. 2022; Galib et al. 2022). However, the relationship between abundance and impact is not necessarily linear as it has been found to vary case specifically from linear to non-linear with different thresholds (Matsuzaki et al. 2009; Jackson et al. 2015; Vander Zanden et al. 2017). Mechanical removal using traps does not require chemicals or expensive equipment, nor does it harm other aquatic biota, so if it is sufficiently effective in relation to the investment, it would be a good tool for the manager’s toolbox.

Signal crayfish, *Pacifastacus leniusculus* (Dana, 1852), is among the most widespread invasive crayfish in the world (Kouba et al. 2014), and it is listed as an invasive alien species of European Union concern (EU 2016/1141). It is intentionally spread to thousands of watercourses in Sweden and Finland (Ruokonen et al. 2018) to replace lost native noble crayfish (*Astacus astacus* (Linnaeus, 1758)) stocks. It has caused massive declines in the noble crayfish populations and negatively affected other native biota (Jussila et al. 2021; Ruokonen et al. 2014). Intensive trapping is one the few ecologically and socially feasible methods to limit the spread of invasive crayfish in the invaded waters (Gherardi et al. 2011) and it is also a potential method to eradicate small populations without harming other biota (Bonelli et al. 2017). However, results on the efficacy and long-term effects of intensive trapping on signal crayfish populations are still limited.

In this study, we examined the long-term impact of intensive removal by trapping on the signal crayfish population of a small, isolated lake. We used a before-after-control-impact (BACI) design to control for influence of natural variation and environmental factors on changes in signal crayfish population, by using crayfish trapping data from three control lakes at the same period.

Materials and methods

Study lakes and crayfish trapping

The signal crayfish removal study was conducted in Lake Slickolampi which is an oligotrophic forest lake in southern Finland (60°01′N; 23°34′E). It has surface area of 4.2 ha, shoreline of 1000 metres and a maximum depth of 5 metres. Most of the littoral area of the lake is soft mud bottom, partly covered by submerged large woody debris, aquatic vegetation, and detritus, while only minor part of the bottom consists of rocks, stones, and gravel (Westman et al. 2002). Lake Slickolampi was among the first signal crayfish introduction sites in Finland, and its crayfish population was extensively studied from 1970 to 2015 (e.g., Westman et al. 2002). The first studies focused on establishment of signal crayfish population and on competition with the native noble crayfish, which was present in the lake. Signal crayfish outcompeted noble crayfish after 30 years of coexistence in late 90s (Westman et al. 2002). Subsequent test trappings have focused on monitoring the effects of different harvest intensities on the population of signal crayfish to optimise crayfish commercial value of crayfish production (*unpublished*).

In Lake Slickolampi, crayfish population monitoring trapping was conducted annually along the entire lake shoreline using Evo-type funnel traps (Westman et al. 1979) baited with roach, *Rutilus rutilus* (Linnaeus, 1758), in August. The mesh size of the trap was 8 mm, selecting individuals roughly above 60 mm in total length. The traps were set close to the shore at every 5 meters distance by attaching them to a nylon line. Traps were set in the evening and collected the next morning. Between 1970 and 2003, the whole shoreline was trapped twice per year, at the beginning and in the middle of August. From 2004 onwards trapping was conducted once a year on mid-August. Trappings involved two successive nights with ca. 200 traps per night each year. Between 1970 and 1991 trapping was monitoring of crayfish population and all individuals were released back to lake. Crayfish smaller than 10 cm (1992–1994) and 9 cm (1995–2000) were released back to lake (Westman et al. 2002), larger individuals were removed from the lake to test the effect of different harvest sizes on the crayfish population. Starting from year 2001, the purpose of trapping changed from population management to a trial of eradication, and all caught signal crayfish were removed from the lake. However, in 2007–2010, and 2013 no trappings were done due to resource limitations.

All three control lakes are notably larger than Lake Slickolampi, but long term data for small lakes are not available as signal crayfish were mainly introduced to large lakes in Finland (Erkamo et al. 2010). The introduction of signal crayfish, with the aim of establishing new crayfish fisheries, began in control lakes in the late 80s or early 90s. Introductions were done to certain areas of lakes where monitoring trappings were done yearly.

Lake Kukkia (61°19′N; 24°41′E) is an oligotrophic lake with a total area of 4 390 ha, mean depth 5.2 m, and maximum depth of 35 m. Littoral area in Ikaloistensaari introduction site (ca. 500 m long stretch of shore) is mostly covered with cobbles and boulders. Signal crayfish introductions started there in 1989. Monitoring trapping was conducted using Evo funnel traps by the staff of Finnish Game and Fisheries Research Institute yearly in late July or early August. On average, trapping effort was 156 trap nights a year. After crayfish population was established and reproduced well naturally (ca. 1998 onwards), most of caught larger crayfish (> 10 cm) were taken to be introduced to other areas of the lake or to other lakes.

Lake Roine (61°24′N; 24°3′E) is a clear water meso-oligotrophic lake with a total area of 5 459 ha. Signal crayfish introductions started in 1989 in the stony shores across the lake. In 1992–2006 introduction sites were trapped annually using funnel traps (on average 377 trap nights a year) by local fisheries managers or water owners following the standard method (Erkamo et al. 2010). Starting from 2007, crayfish CPUE is based on records of crayfish trappers catches (mean CPUE of 15–20 persons yearly, on average 334 trap nights a year). In 1999, crayfish trapping was opened for public, and crayfish above 10 cm were mostly taken for consumption.

Nyystölä Bay of Lake Päijänne (61°33′N; 25°35′E) has the surface area of 700 ha with a maximum depth of 30 m. It is classified as oligotrophic, and most of littoral area in the introduction site is covered with cobbles and boulders. Signal crayfish was introduced in 1992–1994, and introduction sites were trapped annually by the staff of Finnish Game and Fisheries Research Institute (later Natural Resources Institute Finland) in late July. Other trapping was prohibited in the area of introduction during the years of the study.

Statistical analysis

A Before-After-Control-Impact (BACI) design (e.g., Underwood 1992) was used to detect the effect of total crayfish removal in Lake Slickolampi. We used a generalized linear mixed model (GLMM) with Gaussian distribution to reveal differences in crayfish catch between before and after crayfish removal at one impact and three control sites. GLMMs are robust to unbalanced data sets (Pinheiro and Bates 2006), which allows use of several control sites. Period (Before-After) and treatment (Control-Impact), and their interaction were used as fixed factors in the model. Years 1995–2000 were treated as Before, when the crayfish populations were well established also in control lakes and when trapping and catch treatment were comparable in all lakes, and the period of same length from 2001to 2006 following the start of the eradication, was treated as After. Site (each study lake) was used as a random factor to involve lake specific variation. Our main interest was the interaction term (Period*Treatment) the significance of which would

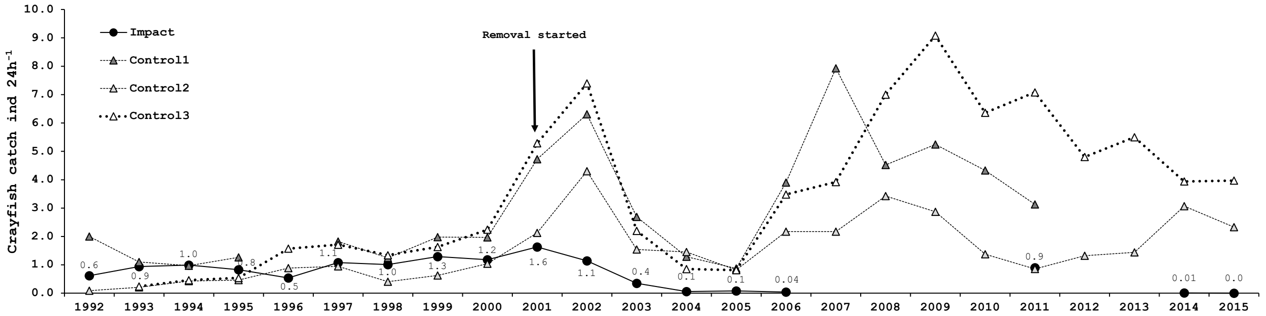

Figure 1. Crayfish catch (ind. 24h^{-1}) for the impact lake and three control lakes. Crayfish removal started 2001 at impact lake, marked with an arrow. The before (1995–2000) and after (2001–2006) periods used in the analysis are marked with vertical lines in the figure.

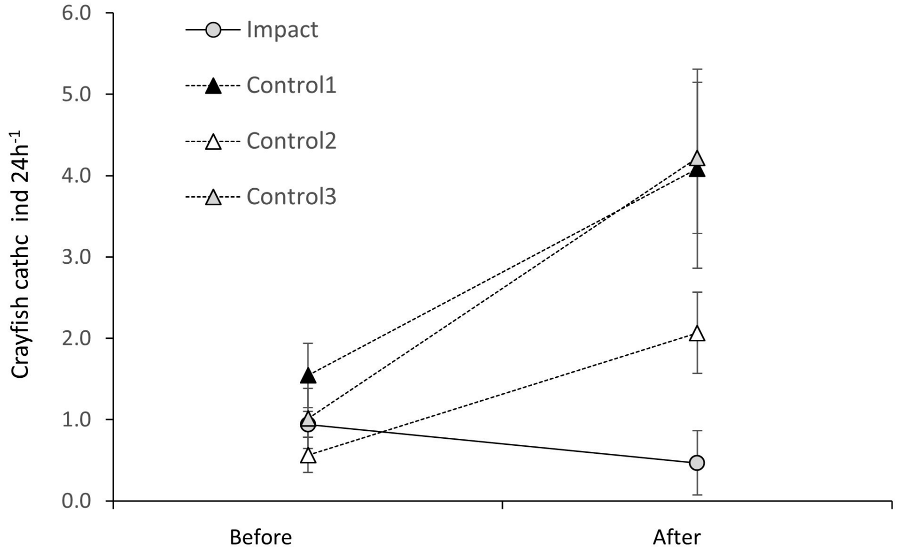

Figure 2. Mean crayfish catch (ind. 24 h^{-1}) before (1995–2000) and after (2001–2006) removal trapping for the impact and control lakes. Error bars show the 95% confidential intervals.

indicate that the crayfish CPUE change between the periods in the impact lake differs from that in the control lakes. Crayfish trapping data have been collected over a long period at all study sites, but six years before and six years after the start of eradication were selected for the analysis to provide a balanced dataset. Model assumptions were checked visually from QQ plot. We performed the analysis following (Pardini et al. 2018) using the lmer function in the lme4 package (Bates et al. 2015), and we used Satterthwaite's degrees of freedom method to test statistical significance of interaction in the lmerTest package (Kuznetsova et al. 2017) in R (R Core Team 2021).

Results

The crayfish catch in Lake Slickolampi varied from 0.5 to 1.3 individuals per trap per night in Before-period (Figures 1 and 2). A total of 1 268 crayfish were caught in total and removed during the six years long After-period, and CPUE decreased gradually from 1.6 to 0.04 crayfish per trap per night

(Figure 1). In control lakes, the mean crayfish catch varied from 0.7 to 1.7 during before period and increased during after period varying from 1.2 to 2.7 (Figures 1 and 2). The variation in crayfish catches was clearly similar in the control lakes during the follow-up years (Figure 1) with clear increases and decreases in CPUE. However, no permanent collapse of catches was observed. Notably, the population in Lake Slickolampi declined immediately in the next year (2002) after the eradication started in 2001, whereas in the control lakes the catches peaked in that year.

The GLMM model explained 0.395 of the variance in the crayfish catch. No significant differences in mean crayfish catch between ControI and Impact (F = 3.566, p = 0.200) or Before and After period (F = 1.840, p = 0.182) were found but an interaction between period (BA) and treatment (CI) was significant (F = 5.615, p = 0.023). The estimated mean crayfish catch decreased from 1.0 to 0.6 in impact site, while in control sites it increased from 1.3 to 2.9.

In 2011, after four years without trapping in Lake Slickolampi, the catch was again quite high (CPUE 0.9), and 383 crayfish were removed from the lake (Figure 1). In 2014, after two years without trapping, the catch was 0.01 crayfish per trap per night and caught few crayfish were removed. In 2015, no crayfish were caught in the traps (Figure 1). In the control lakes, catches varied after the period analysed, but with no clear signs of population collapse (Figure 1).

Discussion

After five years of removing all the crayfish caught, the catch in Lake Slickolampi dropped to almost zero, indicating a dramatic decline in the crayfish population. Over the same period, mean crayfish catches increased in all control lakes, indicating that the decline was at least partially caused by total removal of caught crayfish. We observed a clear synchronous variation in catches in the control lakes which was most likely related to large-scale effect of climatic factors which limited the reproductive success of crayfish in certain years (Heinimaa and Pursiainen 2008). In 2002, crayfish catches peaked synchronously in the control lakes whereas in Lake Slickolampi catch declined after several years of slow increase, indicating that intensive trapping has had an immediate impact on the crayfish population.

In a long-term crayfish removal experiment, Perales et al. (2021) found that catch rates of rusty crayfish, *Faxonius rusticus* (Girard, 1852) declined by 95% after 8 years of removal and remained at a low level for 11 years after the removal period. In our study, mean crayfish catches declined rapidly after the start of total removal. After five years of removal, the mean catch was 0.04 crayfish per trap, which was only 2.5% of the catch in the first year of removal. Our trapping effort of ca. 400 trap nights per year covering the whole shoreline at 5 meters intervals twice a year, can be considered a high effort.

However, after the four-year pause in trapping, the catch was again surprisingly high (CPUE 0.9) in 2011. Hence, in contrast to Perales et al.

(2021), the crayfish population in Lake Slickolampi was able to recover from removal within four years. The trap (Evo funnel trap) used is size selective (Ulikowski et al. 2017), and the remaining few small crayfish (< 50–60 mm in total length) most probably grew to catchable size and reproduced to some extent. Since females of 50–60 mm can reach maturity in one year (Westman et al. 1999), reproduction could have taken place during the trapping pause, when perhaps one or two new year classes were capable of recruiting to catchable size. In 2011, all 383 caught crayfish were removed. In 2014, trapping continued after a two-year pause, and the very few crayfish caught (CPUE 0.01) were removed, and no crayfish were caught in 2015 despite the high trapping effort.

The results suggest that the first removal effort was sufficient to reduce the population to a very low level, and that the repeated removals some years after could drive the population even to local extirpation. Although small specimens (< 50–60 mm) were not trapped and removed, the results imply that intensive trapping of larger crayfish was effective and limited reproduction below a critical threshold. Our results support the findings of Tobin et al. (2011) and Nishijima et al. (2017) that invasive species control does not need to kill all individuals to achieve eradication success, as the Allee effect could lead to the extinction of the invader or keep population density at a low level. Our considerably high trapping effort of ca. 400 trap nights covering the whole shoreline at 5 meter intervals twice a year, might not be feasible to realise in large lakes. On the other hand, even if it is not possible to remove all individuals, ecological effects of crayfish can be reduced as effects of crayfish example on benthic macroinvertebrates are density dependent (Carvalho et al. 2022; Galib et al. 2022; Nishijima et al. 2017; Ruokonen et al. 2016). The objective of long-term management may be to minimise the ecological impact of the invader, which could also reduce the pressure for further spread as resources (e.g., food and habitat) are not limited because of lower population density.

Some aspects related to habitat availability and larger scale climatic events may have contributed to the successful removal of signal crayfish in Lake Slickolampi. The size of the initial crayfish population was rather small due to the limited availability of favourable crayfish habitat (Westman et al. 2002). Westman et al. (2002) estimated that the population size of trappable crayfish to be around 1000 individuals in the early 90's. Based on trapping CPUEs, the crayfish population size peaked in 2001 with about 1300 individuals > 60 mm in total length (Savolainen *unpublished*). Signal crayfish also inhabit deeper parts of lakes if the bottom quality is suitable consisting of hard sand, clay, rocks or boulders (Abrahamsson and Goldman 1970; Ruokonen et al. 2012). In such circumstances, if only the littoral area is trapped, some crayfish may remain in deeper areas and spread back to the littoral area. In Lake Slickolampi, however, this probably does not happen, since the bottom beyond the littoral area is very soft and muddy and all suitable crayfish habitats have been effectively trapped (Westman et al. 2002). However, this an issue that should be considered in eradication programmes, by trapping also deeper bottoms if they provide suitable habitats for the crayfish.

There was a clear decline in CPUE in all control lakes from 2003 to 2005, in parallel to what was widely observed in crayfish populations in southern Finland. Cold autumns in the early 2000's probably impaired reproduction, which led to low recruitment and was reflected in low catches a few years later (Pursiainen and Erkamo 2014). Low water temperature has documented to decrease spawning frequency and hatching of eggs of crayfish (Westman et al. 1999) and is among the main drivers of crayfish population fluctuations in Fennoscandia (Heinimaa and Pursiainen 2008; Olsson et al. 2010). Hence, it is possible that this wider failure in reproduction assisted in the success of eradication of signal crayfish in Lake Slickolampi in the early stages of the trial. In two of the control lakes, crayfish were caught by local water owners during the later stages of monitoring period and individuals longer than 10 cm were taken for consumption, which may have influenced the development of crayfish populations. However, crayfish trapping pressure in these areas was moderate and it is generally observed that Finnish crayfish stocks can tolerate the catch levels associated with crayfish trapping in the control areas (Erkamo et al. 2010). The low impact of other trapping is supported by the finding that similar fluctuations in crayfish abundance were also observed in the Nyystölänlahti control area, where all individuals were returned after catch monitoring.

Simberloff et al. (2013) concluded that eradication programs for invasive species have improved, and that the success rate is increasing. Our results also suggest that removal or at least significant restriction of signal crayfish population is possible when the trapping effort is high enough in relation to the inhabited area and the population size. However, it is necessary to continue intensive removing of crayfish for several years, then to continue monitoring every few years and take more effective actions when needed. This is particularly important if traps are size-selective, as they often are. Our example demonstrates that crayfish populations can recover quickly if removal efforts are halted too early, even if the trap catches are low. To make eradication or control more efficient, the traps used should be less selective and catch smaller crayfish as well. While comparisons of trap types have been made for effectiveness (Budnick et al. 2022), no perfect solution has been found yet, and further development is needed.

Authors' contribution

Research conceptualization: TJR, EE, JT, HH; sample design and methodology: TJR, EE; investigation and data collection: EE and TJ; data analysis and interpretation: TJR; ethics approval: TJR, EE; writing – original draft: TJR; writing – review and editing: TJR, EE, JT, HH.

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Ethics and permits

Study was conducted following national guidelines on animal welfare, and no specific ethic permit was needed for the study.

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