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RESEARCH PAPER OPEN ACCESS

Burrowing and soil dependence in the invasive crayfish *Faxonius immunis* under simulated drought conditions

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Abstract – The invasive calico crayfish *Faxonius immunis* digs burrows into banks and pond sediments. Burrowing behaviour is a crucial trait for the ecological success of crayfish because the burrow provides shelter and keeps humid conditions during dry periods; therefore it can be of aid for management purposes to understand under which conditions the species is not able to dig its burrows. In standardized lab experiments, adult *F. immunis* individuals were placed in a closed container containing water saturated sediment and left there for a simulated two-week drought period in three separate experiments. Survival rate, volume, shape, number of burrows and the ability to seal the entrance were noted and compared between different sediments, status of the major chelae and for the different sexes. *F. immunis* was able to survive the two-week experimental drought on all sediments. The survival rate was lowest for male crayfish on sand sediment. Results show that silt sediment allowed burrowing behaviour whereas the species was not able to dig a burrow in sand and gravel sediments. Female *F. immunis* had a higher tendency towards building cavern shaped burrows and had larger burrow volumes and seal diameters. A majority of dug burrows had a sealed entrance. As there were no burrows in sand or gravel, the management approach that uses habitat modification by gravelling sediments of invaded waters has a high potential to support the efforts in managing this invasive species in ponds.

Keywords: Species management / habitat modification / sediment / survival rate / conservation

1 Introduction

The success of invasive alien species (IAS) is linked to species-specific ecology (Karatayev *et al.,* 2009). As IAS are one of the biggest threats to global biodiversity (Butchart *et al.,* 2010), understanding the ecological traits that give them an ecological advantage over native species plays a key role within the development of management strategies. In the invasive alien crayfish species (IACS) *Faxonius immunis*, commonly known as the calico crayfish, invasion success is linked to the ability to feed on a wide variety of invertebrates and macrophytes as well as its strongly r-selected life history (Chucholl, 2012). *F. immunis* shows a high invasive potential when it invades small shallow ponds and lakes, realizing high population densities (Herrmann *et al.*, 2019) and having a strong impact on the macroinvertebrate community through its high feeding rates (Chucholl and Chucholl, 2021, Herrmann *et al.*, 2022). Martens (2016) identified that *F. immunis* can survive harsh conditions such as droughts or frost in its burrows. Other *Faxonius species* (formerly known as *Orconectes*) are able to enter the hyporheic zone without constructing burrows (Larson *et al.*, 2009). This is another specific trait linked to the invasion success of this IACS in Central Europe. Although *F. immunis* is classified in North America as a tertiary burrower or poor-burrowing species (Hobbs and Hart, 1959; Berrill and Chenoweth 1982), the species has been found to better persist in intermittent or ephemeral habitats of its native range than some congeners like the virile crayfish *Faxonius virilis* by using simple burrows for several months (Bovbjerg 1970). The ability to withstand desiccation by dwelling in vertical burrows has been identified as a crucial trait linked to invasion success in other IACS before, as proven for *Procambarus clarkii* or *P. virginalis* (Kouba *et al.*, 2016). The triggers that initiate burrowing behaviour are species-specific (Peeters *et al.*, 2024). By burrowing, the crayfish change their environment, acting as ecosystem engineers which play a key role in aquatic invertebrate communities (Statzner *et al.*, 2000). For anthropogenic waterways, constructed burrows in pond banks or dams can decrease dam stability, as Haubrock *et al.* (2019) have shown for *P. clarkii*. IACS, which form high population densities and therefore high burrow densities in banks or dams, can cause considerable damage to these structures.

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Sanders *et al.* (2024) show significant erosions of creek banks caused by *Pacifastacus leniusculus* in lowland streams in England, causing increased fine sediments in the water. Lemmers *et al.* (2021) suggest that an increased risk of dike breaches in peatland areas and enhance sedimentation rates in ditches and canals was caused by the burrowing activity of IACS.

F. immunis was first detected in the Upper Rhine area in 1993 (Gelmar *et al.*, 2006). With it now spreading along the Rhine River and its adjunctive rivers and ditches, colonizing reachable habitats and building high population densities in slow moving or stagnant waters, it is now a serious cause of bank erosion and increases the risk of dike breaches. The species survives any drying of waters by burrowing into the banks or ground sediments, and returning to the water as levels rise again. As *F. immunis* is able to colonize isolated pond complexes by overland migration (Herrmann *et al.*, 2018), the species is a growing threat where there are ecologically naive communities inhabiting ponds created for amphibian conservation. This is causing serious problems to the local pond community with increasing crayfish density (Herrmann *et al.*, 2022). The combination of high survivability and high feeding rates at different trophic levels makes *F. immunis* a serious danger for rare and endangered species. Rare amphibian species, which are to be protected under the European Bird's and Habitats Directive (European Economic Community, 1992) such as *Rana dalmatina*, *Hyla arborea* or *Triturus cristatus* can no longer be conserved in ponds invaded by *F. immunis*. Given this, crayfish management is needed to ensure the ecological function of conservation areas for threatened amphibian species. As management of crayfish in conservation ponds is mostly done using artificial shelter traps, increasing the success of those traps is a key trait to a successful management.

Sediment type is known to affect crayfish burrowing success, as Dorn and Volin (2009) showed for *Procambarus fallax and Procambarus alleni*. Gravelling ground beds showed beneficial effects on calico crayfish density and is used as an effective management approach against *F. immunis* in small ponds to increase trap success (own unpublished data). To understand the underlying systematics and behavioural traits linked to this management approach, experiments to investigate the effects of different sediment types on the burrowing ecology of *F. immunis* under experimental drought conditions were conducted.

2 Materials and methods

For the three experiments, silt sediment as well as crayfish were taken from a pond located in a conservation area with more than ten ponds in the city of Rheinstetten, south of Karlsruhe, Germany (WGS 84: 48.9731, 8.2948). The conservation area in Rheinstetten is a relevant habitat of rare amphibian species like the European tree frog *Hyla arborea*, the northern crested newt *Triturus cristatus* and the agile frog *Rana dalmatina* (Beck and Partner, 2014), all of which are listed in the EU directive 92/43 EEC (European Economic Community, 1992). The ponds are also habitat for rare invertebrate species such as great silver water beetle *Hydrophilus piceus*. As some of the ponds have already been manipulated with gravelled or sanded pond beds, local sediment was taken from the same pond the crayfish were taken, where there was not yet any manipulation of the sediments. The initial condition has been silt grounds with dense macrophytes, which changed after crayfish invasion towards silty ground and turbid waters. Crayfish were caught using baited funnel traps. After collecting the crayfish, they were translocated to the lab and placed into aquariums for a one-week acclimatization period. A majority of the caught crayfish individuals already have been caught with partly missing appendages due to autotomy and only crayfish without visible injuries were used in the experiments.

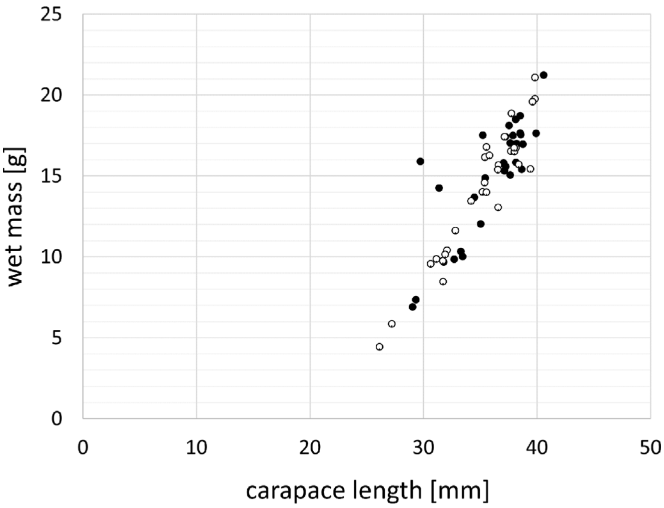

Fig. 1. Size to mass relations for female (black dots) and male (white dots) crayfish used for the sediment and shape experiments ($n = 60$).

Gravel and sand were sourced from a nearby gravel quarry. The grain size of each sediment used was <0.063 mm for silt, 0.063–2 mm for sand and 8–16 mm for gravel sediment.

2.1 Experimental design and container handling

The experiments were carried out in a lab at the University of Education in Karlsruhe between September and December 2019. The light–dark ratio was set to 12 h light using clock timers. The temperature in the lab was constant 20 °C and was checked daily using digital temperature loggers. White plastic containers (L × W × H = 222 × 195 × 195 mm) were filled with the corresponding soil to a 100 mm filling height. The surface of the soils was graded, and the sediment was slowly saturated with tap water. Overflowing water was taken out with lab tissues. The containers filled with sand and gravel were also saturated with tap water until the sediment was fully saturated, whereafter the overflowing water was also removed.

After the preparation of containers each used crayfish was measured taking its carapace length (CL), its sex, the status of both of its major chelae and its wet body mass (wm) prior to its placement in the container. The sex ratio was set to 1:1. The crayfish used in the experiments had a mean carapace length of 34.07 ± 4.29 mm. The mean wet body mass (wm) of the individuals used in sediment and burrow structure experiments was 14.58 ± 3.78 g (Fig. 1). The prepared containers were placed on the ground for the time of the experiment.

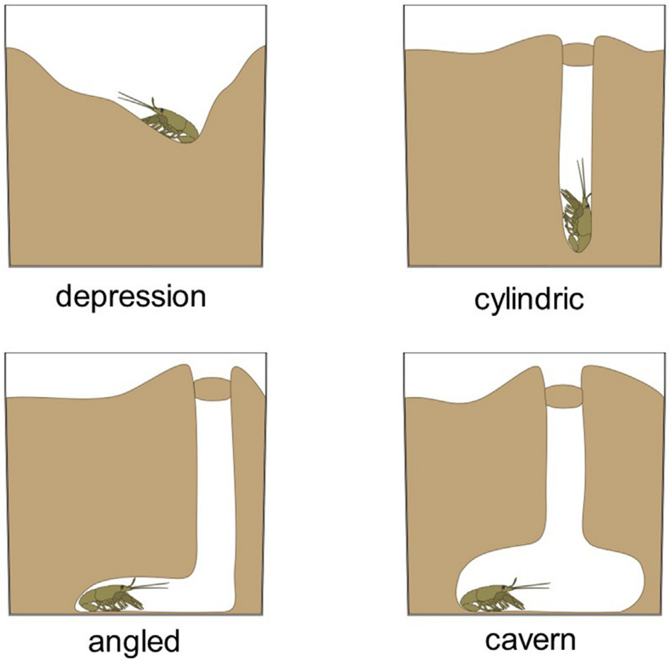

Fig. 2. Classification of burrow types created by *F. immunis* at simulated drought experiments.

The containers were checked daily and changes in the vital status of the crayfish (alive or dead), the number of visual burrow entries, burrow attempts and visibly sealed entries were noted, temperature and air humidity measures were taken using data loggers. Every crayfish individual only participated in one experiment. After each experiment the containers were cleaned for use in the next upcoming experiment.

Dead crayfish were taken out of the experiment. After a two-week period, the experiment ended and crayfish were taken out of the containers, crayfish with sealed burrows remained in their burrow during the foaming process. The dug burrows were filled with two-component polyurethan foam (Soudal 2K-Polyurethan). The casts were given 24 h to harden and then taken out of the sediment containers for further measurements and they were classified into four shape types of burrows for comparison (Fig. 2).

2.2 Sediment dependence (I)

To study the dependence on sediment structure, 30 prepared containers were placed on the lab floor in a randomized order. Ten containers were filled with silt sediment taken from the pond, 10 were filled with washed sand and 10 were filled with washed gravel. After all crayfish were placed into the containers and all data was taken like described before, the silt and sand treatment were given an initial burrow for each container which was approximately 5 mm deep. This method was also used by Kouba *et al.* (2016) and led to successful burrow initiation. After that, the simulated drought period of two weeks started and data was collected daily at the same time.

2.3 Missing chelae (II)

To examine the relevance of the major chelae for successful burrowing, 30 containers were prepared following the described method and filled with silt sediment from the pond. Crayfish with intact major chelae were placed in 10 containers, 10 containers were inhabited by crayfish with one major chelae intact and 10 containers contained crayfish with both major chelae dropped due to autotomy. Again, the sex ratio was set to 1:1. All female individuals were adult and showed signs of maturity (glare glands).

2.4 Statistics

Burrow casts were measured with callipers. Burrow volume was taken by noting their water displacement in a scaled beaker glass while filling it slowly with a discard-gauged graduated beaker. The volumes were compared to the size of the corresponding crayfish that inhabited the burrow. The survival data of crayfish was converted to a Kaplan-Meier survival rate for each treatment. Those rates were compared using chi-square-tables. All received parameters were tested for differences between the treatments, sexes or physical states, respectively.

3 Results

3.1 Burrow structure

Females showed a preference for creating a cavern-type burrow (Fig. 3) whereas male individuals showed no preference in burrow-shape (Supplement 1). The performed chi-square test ($X^2 = 0.00664638$, df = 4) showed significant differences between sex and burrow type ($p = 0.003$). Seventeen of the total 30 tested individuals created a seal to their burrow. The average diameter was 17.67 mm (± 8.86 mm SD) with no significant differences between sexes (Fig. 4). The highest excavated volume was 250 mL by a male individual. No correlation between individual size and excavated soil volume was found.

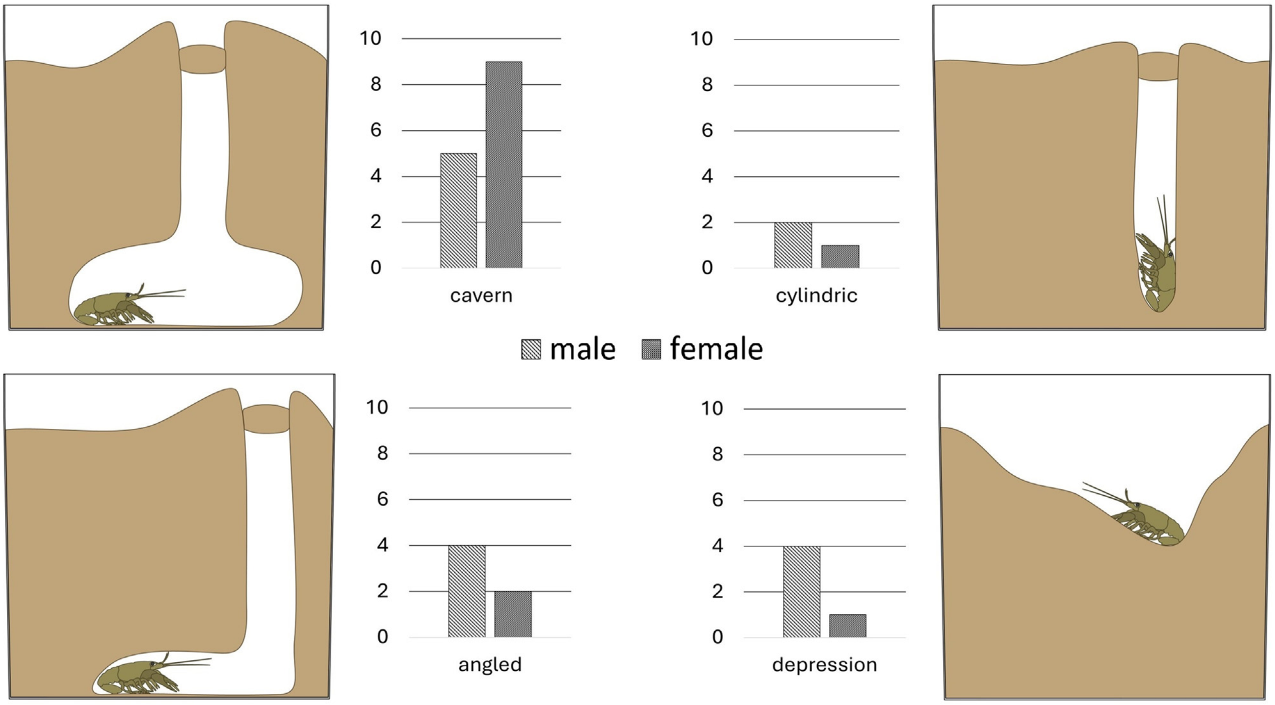

Fig. 3. Burrow shapes and sex relations (light: male, dark: female) for burrows created in silt sediment by *Faxonius immunis* during simulated drought conditions ($n = 30$).

A majority of crayfish within the chelae-experiment created a burrow in silt sediment ($n = 29$ out of 30). One female individual was found dead after the experiment without a visible burrow attempt.

3.2 Sediment

The experiment was ended after 10 days because the survival rate (ŝ) for male individuals on sand sediment reached zero (Fig. 5). All individuals with silt sediment survived the experiment and created a burrow. Four burrows of the silt group were found sealed. Nine out of 10 individuals from the gravel sediment group survived. The individuals within the sand and gravel sediment were not able to create a burrow, whereas the sand groups created a depression in the sand. Individuals with gravel sediment tried to hide between the gravel stones by pressing the abdomen in holes between the stones.

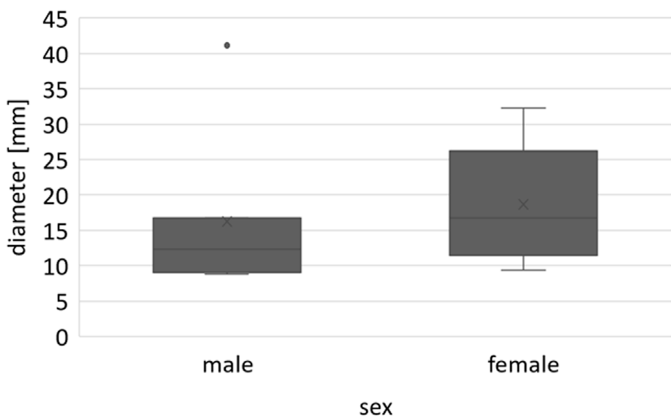

Fig. 4. Seal maximum diameters for male and female *F. immunis* ($n = 22$).

4 Discussion

The results demonstrate that the burrowing behaviour of *F. immunis* allows the species to prevent desiccation at drought events effectively by burrowing into the ground on silty sediments and surviving a two-week drought period regardless of the status of the major chelae. Therefore, even at high densities, which can cause a higher rate of autotomy, the majority of the crayfish are able to create a burrow and withstand dry conditions. This result supports the results of Bovberg (1970) describing *F. immunis* as more resistant to desiccation than *Faxonius virilis*. The desiccation capacity is also a basic requirement for the high overland dispersal of the calico crayfish in summer (Herrmann *et al.*, 2018). Female *f. immunis* showed a clear tendency towards bigger burrows. It is possible that they have a higher need for space within the burrow so they can stay beneath surface when the juveniles hatch, providing enough space to move. As some crayfish species are able to hatch outside the water as long as the humidity is high enough (Banha *et al.*, 2014), it is possible that *F. immunis* females prepare for this situation by creating bigger burrows. *P. clarkii* also builds burrows with terminal chambers (Haubrock *et al.*, 2019), like the ones described in the present study. The results in *F. immunis* show similarity to the results in

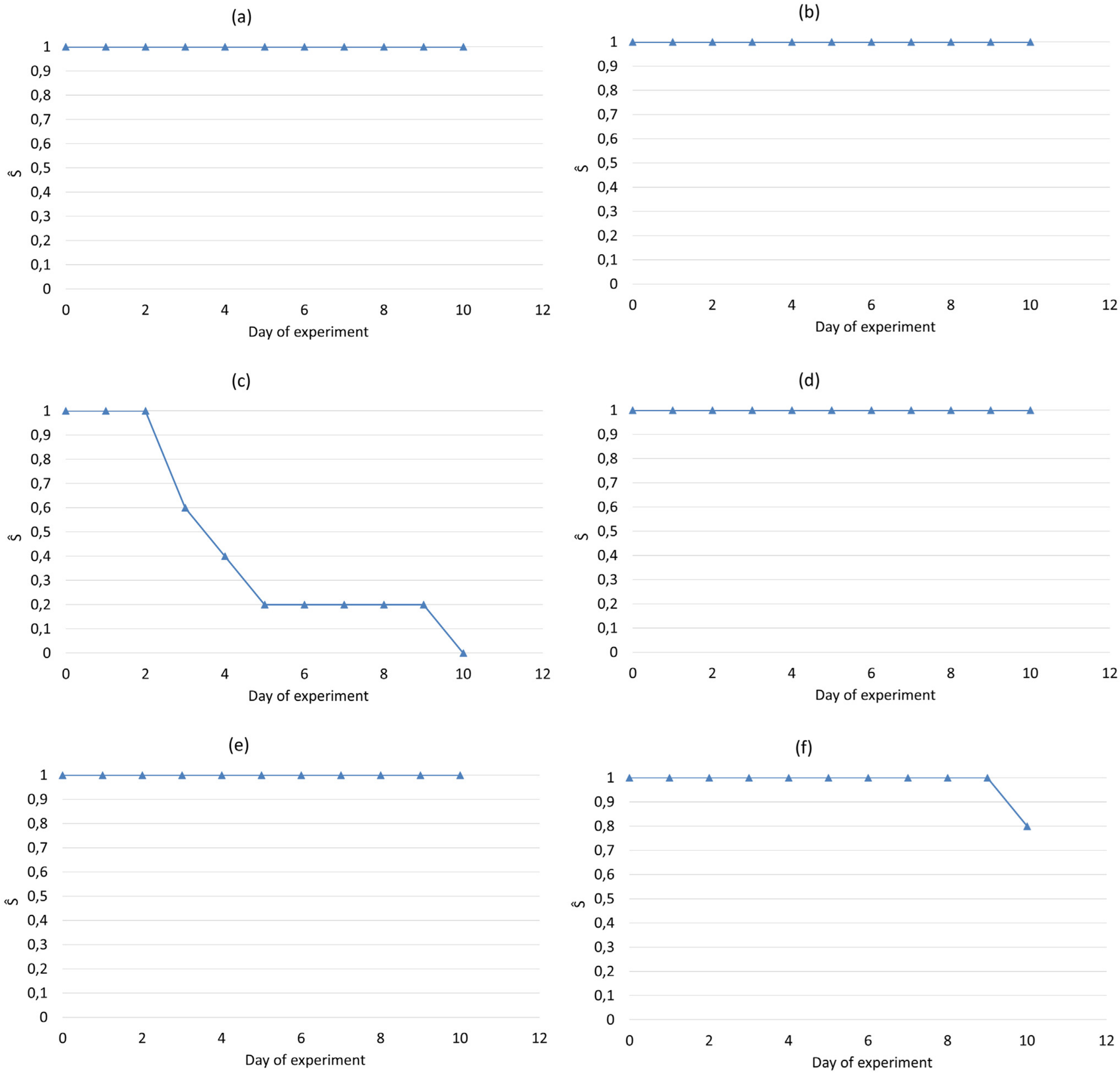

Fig. 5. Survival rate of *F. immunis* individuals for the simulated drought experiment on different sediments ($n = 30$) for mud (a,b), sand (c, d) and gravel sediments (e,f).

P. clarkii from Correia and Ferreira (1995); Ilhéu and Bernardo (1996), Gherardi *et al.* (2002) and Haubrock *et al.* (2019), where both chambered burrows and simple (cylindric, angled) burrows are present. Crayfish act as ecosystem engineers, playing a key role in aquatic invertebrate communities (Statzner *et al.*, 2000). This is becoming a conflict in anthropogenic waterways when burrows are constructed in pond banks or dams, as burrowing decreases their stability (Souty-Grosset *et al.*, 2014). IACS, which build high population densities and therefore high burrow densities in banks or dams, can cause serious damage to these structures. Lemmers *et al.* (2021) for example suggest an increased risk of dike breaches in peatland areas and enhance sedimentation rates in ditches and canals caused by the burrowing activity of some IACS. Therefore *F. immunis*, which is spreading along the Rhine river and its adjunctive rivers and ditches, colonizing every reachable habitat and building high population densities in slow moving or stagnant waters since its first detection in 1993 (Gelmar *et al.*, 2006), is a serious case considering bank erosion (Águas *et al.*, 2014, Souty-Grosset *et al.*, 2016)

Our experiments showed the species was able to burrow on silty ground, but neither on sand nor on gravel sediments. Similar results were reported by Dorn and Volin (2009) for *P. fallax* and *P. alleni*, where crayfish had the poorest burrowing success on sand sediment. Therefore, the management approach by habitat modification with gravelling the ground beds has the potential to overcome this key trait. Although the survival rate on gravel sediment was high for both male and female crayfish as they were able withstand desiccation by pressing their abdominal parts in the gaps between the rocks, it increases predation on the crayfish. Larson *et al.* (2009) described that crayfish followed the grounding water by pressing stones aside. This impression was also given by the individuals of the gravel sediment group, as the crayfish pressed their abdomen between the rocks. As artificial shelter traps are also used for the management of *F. immunis* in conservation ponds in Germany, increasing the success rate of those traps is crucial to a successful management approach. Without the ability to hide in a burrow, the traps remain the only solid chance for shelter. Using sand can show the same result on increased success of artificial shelter traps in the short term but gravel should receive priority because on sand sediments detritus builds up quicker, creating new silty grounds where the species is able to burrow once more.

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Supplementary material

The Supplementary Material is available at https://www.kmae-journal.org/10.1051/kmae/2024018/olm.

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