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Design and testing of a trap removing Chinese mitten crabs (*Eriocheir sinensis*, H. Milne Edwards, 1853) from invaded river systems

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Abstract

The Chinese mitten crab is one of the top invasive species in Europe. In Flanders (Belgium), they are associated with river ecosystem degradation, especially the loss of aquatic vegetation and associated ecosystem services. Management measures have therefore been put in place to reduce the number of crabs migrating between the sea and freshwater areas and ultimately control the population. Although we are still long way from the goal, a low-cost method has been applied to successfully catch migrating crabs. In this article, we outline the design and functioning of the trap. We monitored the population in a lowland river, measured migration speeds and calculated crab densities. With over 1 million crabs caught in 2 years, the trap proved to be very effective. Median anadromous (spring) and catadromous (autumn) migration speeds were 0.69 and 0.96 km day^{-1}, respectively. Anadromous migrating crab density was calculated to be up to 3.20 ind. m^{-2} river bed. Resident crab density was calculated to be up to 2.05 ind. m^{-2} river bed. We conclude that this trap is a very useful tool for water managers to catch Chinese mitten crabs in rivers and discuss the pathways towards reducing the population and protect the entire freshwater catchment.

KEYWORDS

crab density, crab population, fish ladder, fisheries, invasive species, migration speed, river management

1 | INTRODUCTION

Invasive alien species are major drivers of the loss of biodiversity and associated ecosystem services. The economic costs of these invasions, in Europe alone, have been estimated to be 12 billion euro each year, with a strong likelihood of increasing in the coming years (European Environment Agency [EEA], 2012). Not surprisingly, applied ecological research on invasive alien species populations is considered by the EEA as one of the most urgent nature conservation issues. Member states are obliged to take measures to eradicate these species. The Chinese mitten crab (*Eriocheir sinensis*, H. Milne-Edwards, 1853 [Decapoda: Varunidae]) is one of the 49 species listed in EU Regulations (EU Regulation No 1143/2014).

The crabs were first observed in Europe in the German river Aller in 1912, and before long were reported in other European countries including Belgium, France, the Netherlands, Sweden and the U.K. In less than 50 years, these crabs have spread across Europe and are seemingly thriving in many of the locations they had invaded (Herborg, Rushton, Clare, & Bentley, 2003), often causing ecological problems in river networks and estuaries. They are omnivorous and opportunistic and feed on almost any organic food source they can find, which may pose a threat to the resident fauna and flora

(Rogers, 2000; Schoelynck et al., 2020). Burrowing activities often make river beds and banks more susceptible for erosion which can induce resuspension of sediment (increase of turbidity, decrease of light availability) and which may influence the release of nutrients and pollutants that are stored in the sediment (Wang, Xu, Wang, & Kosten, 2017). They feed on and compete with native invertebrates, which can lead to loss of biodiversity (Lewandowski & Hupfer, 2005; Wojcik-Fudalewska, Normant-Saremba, Dmochowska, & Fowler, 2015). They also cause economic problems due to their damaging (or even destroying) of river banks, dikes and other infrastructure by burrowing activities (Dittel & Epifanio, 2009), blocking water intake systems (Hieb & Veldhuizen, 1998), and potentially transferring parasites by functioning as a secondary host causing diseases in humans and animals (e.g., *Paragonimus westermani* Kerbert [Trematoda: Paragonimidae]) (Majoros & Miklos, 2012).

The issues caused are partly a result of their omnivorous feeding and catadromous life cycle - they breed and hatch only in the salty water of estuaries and the coast and, as they grow, they migrate long distances inland along freshwater bodies such as rivers and canals (Herborg et al., 2003). In their native range, they have been found to migrate over 1,400 km inland along the Yangtze River (Dittel & Epifanio, 2009) and even in Europe (Germany), they have been observed travelling 15 km in a single day (Panning, 1939). The carapace of the crab can reach a width of 8 to 10 cm (Rudnick, Hieb, Grimmer, & Resh, 2003), which makes it one of the largest freshwater invertebrates.

Upon reaching a suitable body size, adult individuals migrate during autumn all the way back to the nearest saline water, finish maturing reproductively, breed and die after doing so. Their offspring then begin the same semelparous life-cycle. This migratory behaviour means that the crabs can affect salt, brackish and freshwater ecosystems within a single lifespan, which is especially important as the number of *E. sinensis* that survive each year can be very high. In Flanders (Belgium), Chinese mitten crabs were caught as bycatch during fish surveys using fyke nets in the Scheldt River in 1995, 1997 and 2008. During the surveys in the nineties, only a few mitten crabs were recorded. Ten years later, however, *E. sinensis* had spread throughout the estuary and more than 50 crabs can now be caught per fyke net per day (Stevens, Van den Neucker, Buysse, & Coeck, 2010). However, this is only a fraction of the population since most crabs will pass the fykes. Although true population number estimates are hard to come by and on the whole unknown, in the first 6 months of 1935, nearly 3 and a half million crabs were caught at one dam on the Weser River of Germany (Panning, 1939), and just over 60 years later in 1998, 750,000 crabs were caught in just 2 hr of hand-fishing on the river Elbe, Germany (Gollasch, Minchin, Rosenthal, & Voigt, 1999). With such high numbers of an invasive, omnivorous species, water managers have reasons to suspect dramatic impacts on the environments they invade (Brodin & Drotz, 2014; CMCWG, 2003; Hanson & Sytsma, 2008; Messiaen et al., 2010).

There is thus an outstanding need for actual population estimates for the various sites and countries around the world where *E. sinensis* has spread to. If maintained and standardised over time such figures not only provide a much-needed baseline to lay out specifically what population sizes water managers are dealing with and allow formulating and evaluating management targets, it may also further expose whether there are cyclic population dynamics. Finding out the root of any such cycles could go on to indicate control measures aiming to prevent cycles progressing beyond their lower levels, a common goal when dealing with pest situations (Begon, Townsend, & Harper, 2008). In this article, we present the design and functionality of a trap specifically built to catch Chinese mitten crabs during periods of migration. We demonstrate it can be used for management and monitoring purposes and to calculate crab migration speeds and population densities, which are prime parameters for modelling population dynamics. Its use to mitigate and potentially reduce crab populations is discussed.

2 | MATERIAL AND METHODS

2.1 | Design and functioning of the trap

The trap was specifically designed to catch crabs when they were migrating through rivers. It works in both directions, so anadromous and catadromous migrating individuals can be caught. The trap consists of a custom made stainless steel rectangular container. The length was equal to the width of the cross-section between the two river banks (on our site: 8.0 m × 0.4 m × 0.4 m; Figure 1a,b). At the centre of the top of the container, a longitudinal slit was made and the resulting metal valves are partly folded inside to create a permanent opening of 15 cm wide. Two ramps were constructed at both longitudinal sides of the container using perforated stainless steel plates. The angle between the ramp and the river bottom was approximately 45 . At both lateral sides, two circular holes (diameter = 200 mm) are drilled in which a PVC tube of exactly the same diameter fits. The inner side of the PVC tubes was coated with stainless metal mesh wire to create grip. The tubes run diagonally to both river banks (approximately 30) and end at the top of two storage containers that were located on each river bank. The trap itself was submerged and was screwed onto a horizontal concrete platform on the bottom of the river.

Migrating crabs crawling over the river bottom have to climb up the ramps because they cannot pass under or around the trap. Once at the top, they slip into the valve and sink to the bottom of the container. Because of their low ability to swim, they cannot escape. The only two exits are the PVC tubes which they climb up and fall into the storage containers from which escape is impossible.

2.2 | Installation and testing in situ

The trap was installed between 19 and February 23, 2018 in a fish ladder on the Kleine Nete River, a tributary of the Scheldt River, near the town of Grobbendonk (Belgium; 51 11′35.3″N 4 45′23.1″E) (Figures 1b and 2). This site was primarily chosen because it is a

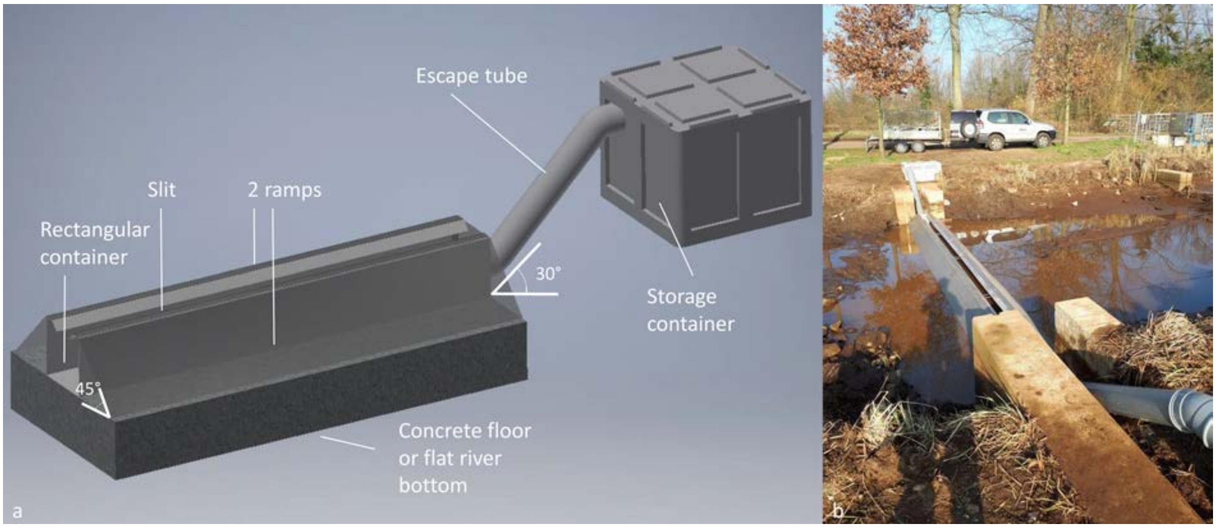
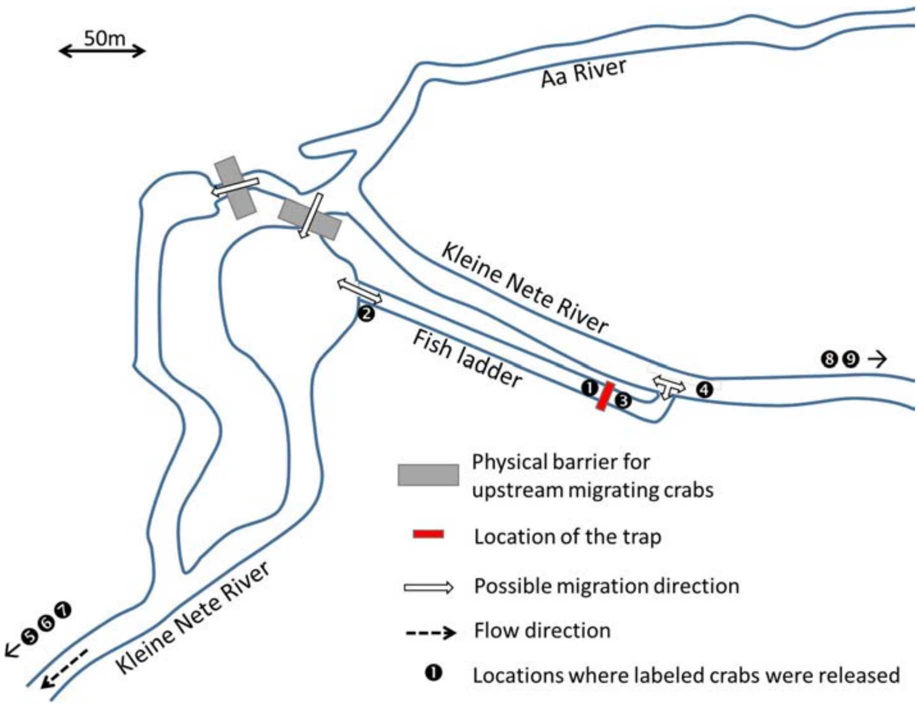


FIGURE 1 Schematic representation of the trap (a) and a picture from the trap installed at the fish ladder in Grobbendonk (Belgium) on the Kleine Nete River (b). The water level was temporarily lowered to install the trap and take the picture

FIGURE 2 Map of the location of the trap on the fish ladder bypassing the Kleine Nete River around a functioning watermill that forms a physical barrier for upstream migrating animals (fish, crabs, etc). The Aa River is a tributary to the Kleine Nete River. Locations where labeled crabs were released is keyed to the text and to Table 1



known migration route for crabs and because weirs could be adjusted to temporarily divert the water to the main channel instead of flowing through the fish ladder (which facilitated its installation). The fish ladder was 210 m long, 8–10 m wide and 0.9 m deep near the location of trap and flow velocity was on average 0.40 m s^{-1}. A centrifugal pump was installed in the river, spraying fresh water in both storage containers during 1 min each 80 min. The water was immediately drained again through holes in the bottom of the storage containers. The aim of this is to flush the animal excrements and prevent the crabs from drying out and dying. This is done from an animal welfare perspective, as well as to avoid odour nuisance.

To check the effectiveness of the trap, two mark-recapture field experiments were performed. On April 27 and May 4, 2018, two groups of 100 freshly caught juvenile crabs were labelled with nail varnish on their carapaces (method after Gilbey, Attrill, & Coleman, 2008). The first group of 100 crabs (❶; numbers are keyed to Figure 2 and Table 1) were released just 1 m downstream of the trap, but they were set back a few meters because of the prevailing current. The second group (❷), carrying a different colour, was released at the downstream end of the fish ladder, approximately 166 m downstream of the trap. The second experiment was initiated on November 13, 2019 and two groups of 50 freshly caught adult

TABLE 1 Overview of the mark-recapture field experiments, the number of *E. sinensis* individuals that were re-captured after their release and the duration before the first were re-caught

Experiment number	Distance away from trap	Number of crabs initially released	% re-captured after release	Number of days before first re-captured
Spring migration 2018 - anadromous				
❶ Trap effectiveness	1 m downstream	100	73%	1
❷ Trap effectiveness	166 m downstream	100	60%	1
❺ Migration speed	1.5 km downstream	100	32%	2
❻ Migration speed	5 km downstream	100	15%	8
❼ Migration speed	10 km downstream	100	16%	9
Autumn migration 2019 – catadromous				
❸ Trap effectiveness	14 m upstream	50	52%	1
❹ Trap effectiveness	90 m upstream	50	30%	3
❽ Migration speed	6.5 km upstream	50	20%	4
❾ Migration speed	25 km upstream	50	24%	9

Notes: Experiment numbers are keyed to Figure 2.

crabs were labelled with two different colours of nail varnish. The first group (❸) was released 14 m upstream of the trap. The second group (❹) was released 90 m upstream of the trap and upstream of the junction with the fish ladder and the main channel of the Kleine Nete. Although the majority of the flow goes into the fish ladder, downstream migrating crabs have the choice of taking the fish ladder (and potentially being caught), or moving further down the main channel and pass the water mill without being caught (Figure 2). After the releases, both storage containers were checked daily over 3 weeks for the coloured crabs.

2.3 | Measuring migration speed

To measure the migration speed, another mark-recapture field experiment was done, but using different colours. In spring, two groups of 100 juvenile crabs were labelled on April 27, 2018 and one group on May 4, 2018 and released 1.5 km (❺), 5 km (❻) and 10 km (❼) downstream the trap. In autumn, two groups of 50 adult crabs were labelled on November 13, 2019 and released 6.5 (❽) km and 25 km (❾) upstream of the trap (note that also these crabs have the choice of taking the fish ladder or following the main channel downstream). After the releases, both storage containers were checked daily for the coloured crabs over 5 weeks. The migration speed of each crab that was caught was calculated by dividing the travelled distance (m) with the respective number of days before recapture.

2.4 | Monitoring of migration

Since the installation of the trap in February 2018, the storage containers were emptied frequently (weekly or shorter during migration periods and biweekly or longer outside migration periods). The number of crabs were counted and weighed. Frequently, a subsample of 100 randomly picked intact crabs (i.e., not missing any limbs) were weighed individually (fresh weight), carapace width (i.e., the distance between the fourth lateral spines from the eyes) was measured with digital callipers, and sex ratio and presence or absence of visible fur (setae) on the chelae was noted. Juvenile mitten crabs are defined as crabs less than 2.5 cm carapace width (Panning, 1939; Rudnick et al., 2005). Statistical differences in biometric data between migration periods were calculated using Mann–Whitney U-tests (none of the biometric datasets were normally distributed). In order to check if there were changes in the distribution of the sample datasets between years, two-sample Kolmogorov–Smirnov tests were used. The ratio between the wet weight and the carapace width was calculated according to Equation 1:

$$FW = aCW^b \tag{1}$$

with FW = fresh weight (g) and CW = carapace width (mm). The correlation strength between both parameters and its significance were tested with Kendall correlation tests. All statistical tests were performed in R 3.3.2, using the package "stats" (R Development Core Team, 2016).

2.5 | Calculation of crab densities

The monitoring data were used to calculate crab densities in the Kleine Nete River network. Crab densities are calculated for two different situations: (a) density of the upstream migrating juveniles in the area downstream of the trap, and (b) the resident population in the ecosystem upstream of the trap if they were not removed by the trap (therefore a "hypothetical" resident population density, but realistic for the situation in the Kleine Nete River if no management efforts were being undertaken).

The density of the upstream migrating juveniles in the area downstream of the trap was calculated by dividing the average number of crabs caught per day (ind. day^{-1}) during the 2018 and 2019 spring migration with the weighted average migration speed of juveniles (m day^{-1}). This gives the number of crabs per unit m river (ind. m^{-1}), which is then divided by the average width of the river reach downstream of the trap (8.4 m; derived from available GIS datasets) to calculate the crab density (ind. m^{-2}), assuming a homogenous distribution of the animals across the area.

Calculating the resident population density in the ecosystem upstream of the trap accounts for upstream migrating juveniles entering the area, downstream migrating adults leaving the area and the residence time of the population in the freshwater ecosystem. The calculation was based on some assumptions. The resident lifespan of the species in Western European freshwater is estimated to be 4 years, during which we assume the population decays exponentially with a constant mortality rate *m* (Dittel & Epifanio, 2009). To estimate this constant mortality rate *m*, we have to assume a constant immigration number N_0 during the 4-year residence period since only 2018 and 2019 data were available. A constant immigration number is actually not realistic and large differences exist between years. The mortality rate and resident population were therefore calculated with the 2018 dataset (as a lower estimate) and again with the 2019 dataset (as an upper estimate), both with the measured data and with data corrected for trap effectiveness (Table 1). Given our assumptions, the total resident population was calculated using Equation 2:

$$N = N_0 \sum_{i=0}^{3} e^{-i\,m\,\text{years}} \tag{2}$$

in which N is the total resident population, N_0 is the immigrating population, and m is mortality rate. The mortality rate is calculated using Equation (3):

$$m = -\log \frac{N_4}{N_0} \cdot \frac{1}{4\,\text{years}} \tag{3}$$

in which m is the mortality rate, N_4 is emigrating population, and N_0 is immigrating population.

To estimate a corresponding population density, the resulting population numbers were divided by the total river network surface area upstream of the trap, which was calculated from available GIS datasets (only streams larger than Strahler 1 were taken into account since many small ditches are dry for most of the year), and assuming homogenous distribution of the animals across the area. This was calculated for the upstream area of the Kleine Nete alone (682,564 m^2) and for the upstream area of Kleine Nete and Aa combined (1,128,502 m^2) since it was not known how the population is distributed over both rivers (Figure 2).

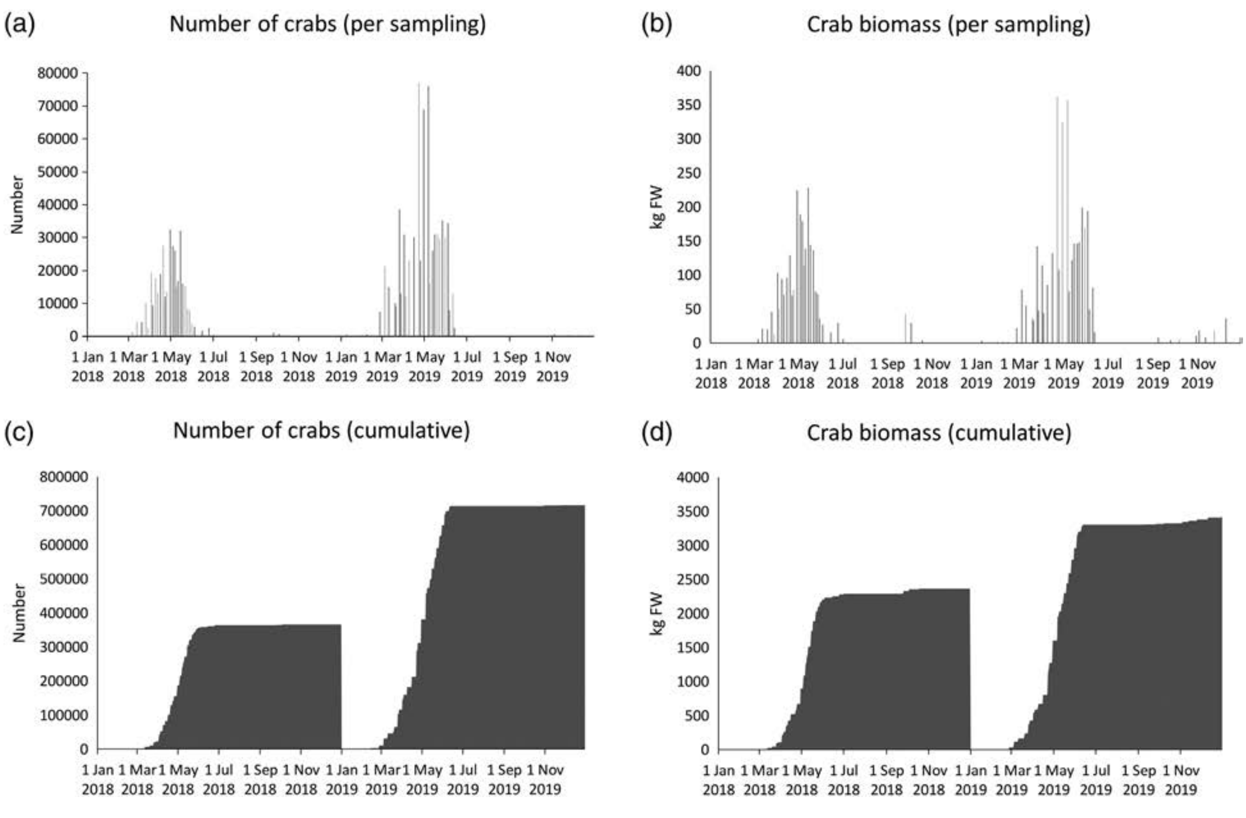


FIGURE 3 Total number and total fresh weight (FW) of *Eriocheir sinensis* individuals caught in the trap in Grobbendonk (Kleine Nete, Belgium) for four consecutive migration periods (two in 2018 and two in 2019). Data are presented per sampling event (a,b) and cumulative over time (c,d). Because of technical problems with the weir of the fish ladder, data for autumn 2018 may be an underestimation

3 | RESULTS

The proved to be effective in spring (Table 1). Up to 73% of the coloured juvenile crabs were re-caught after 14 days and the first ones already after 1 day. The crabs that were released further downstream to measure migration speed were trapped again a few days later and in smaller numbers. Between 15 and 32% were re-caught after 21 days, and the first after 2 to 9 days for the short and long distance, respectively. This resulted in migration speeds between 0.46 and 1.11 km day^{-1}, with a median speed of 0.68 km day^{-1}.

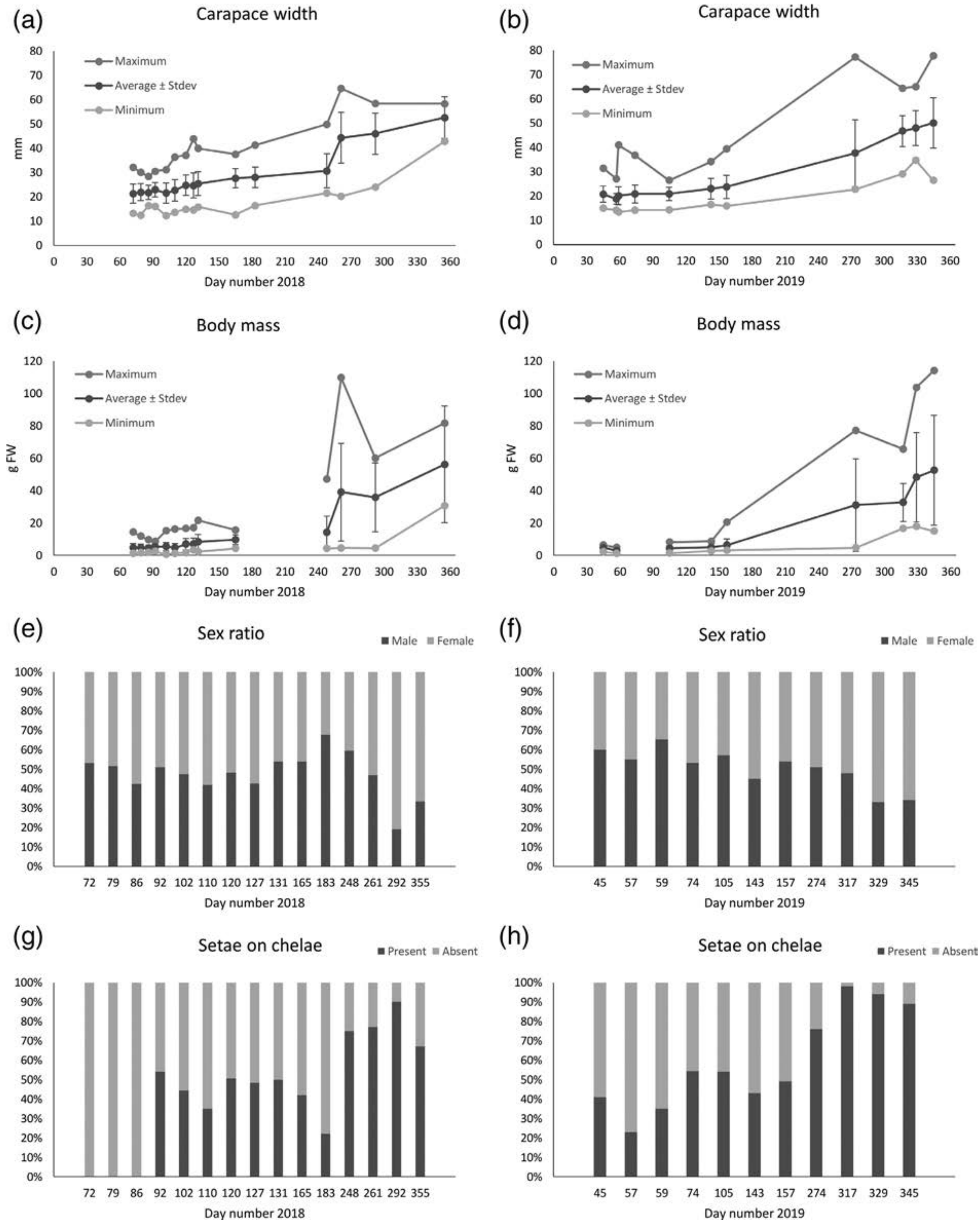


FIGURE 4 Biometric data of *Eriocheir sinensis* individuals caught over 2 years in the Kleine Nete near Grobbendonk (Belgium): carapace width in mm (a,b), body mass in g fresh weight (FW) (c,d), sex ratio (e,f) and presence of setae (g,h)

The effectiveness was less in autumn (Table 1). Only half (52%) of the coloured mature crabs released upstream of the trap were re-caught, and just over a quarter (30%) of the crabs released upstream of the junction. The first crabs were re-caught after 1 day. The crabs that were released further upstream to measure migration speed were trapped again a few days later in smaller numbers. Twenty percent and 24% were re-caught after 35 days, and the first after 4 to 9 days for the short and long distances, respectively. This resulted in migration speeds between 0.22 and 2.78 km day^{-1}, with a median speed of 0.96 km day^{-1}.

The trends over 2 years were very similar: the spring migration started around beginning of March (although occasional juveniles were caught as early as January) and abruptly stopped at the end of May. The autumn migration is situated around October–November. In 2018, the total number of individuals caught was 365.000 (2,468 kg FW) during the spring migration (Figure 2). In 2019, the total number was 714,000 individuals during spring migration, which was double of that in 2018. Total mass in spring 2019 was 3,304 kg FW, which was only 25% more than in 2018. This indicates that the 2019 spring crabs were generally smaller than in 2018, which was confirmed by the biometric data (Figure 3). In autumn 2018 and 2019, a comparable number of crabs were caught: 2,011 and 2,665 individuals with a total fresh weight of 123 kg and 159 kg, respectively. These values were > 0.5% (in numbers) and > 5% (in mass) of the spring migrations. Note that one of the weirs controlling the fish ladder had a technical malfunction for a several weeks in autumn 2018. During this period, the water was more directed through the main channel instead of over the fish ladder. This may have temporarily influenced crab migration and reported 2018 values may therefore be an underestimation.

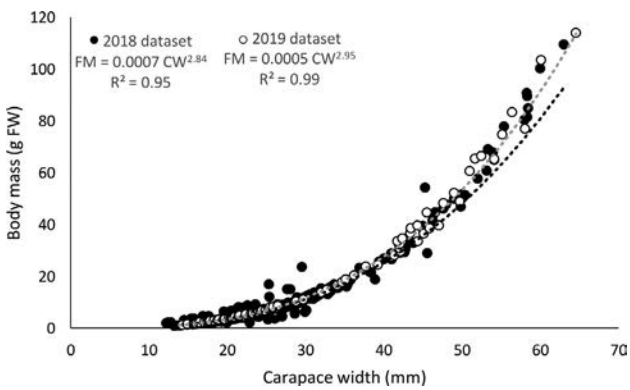


FIGURE 5 Relationship between the carapace width (mm) and the body mass (g fresh weight [FW]) of *Eriocheir sinensis* individuals caught in both years in the Kleine Nete near Grobbendonk (Belgium)

Carapace width (Figure 4a,b) and crab fresh weight (Figure 4c,d) both increased gradually over time, with a notable jump around day 250 and patterns were similar for 2018 and 2019. The average crab size and fresh weight in spring 2018 (measured over 100 days after the start of the migration) were 23.4 ± 4.5 mm and 5.8 ± 3.2 g, significantly (p = 2.2e^{-16} for carapace width and p = 1.067e^{-14} for crab fresh mass) larger and heavier than in 2019 (20.2 ± 3.4 mm and 3.6 ± 1.5 g). In autumn (measured over the last 100 days of the year), the average crab size and fresh weight were 42.0 ± 11.2 mm and 29.7 ± 26.4 g, significantly (p = 0.01933 for carapace width and p = 9.868e^{-3} for crab fresh mass) smaller and lighter than in 2019 (45.4 ± 10.1 mm and 38.6 ± 25.3 g). The smallest and largest crab caught over the 2-year period measured 12.2 and 64.6 cm, respectively, and weighed 0.6 and 114.1 g FM, respectively. On average, the sex ratio in both years was 50:50 male:female, with variable ratios towards the end of each year (autumn migration) (Figure 4e,f). On average 32% and 44% of the crabs had furry claws in spring 2018 and 2019, respectively, compared with 79% and 90% in autumn 2018 and 2019, respectively (Figure 4g,h). The ratio between fresh weight and carapace width was significant for both years (p < 0.001) and factor b was very close to the "ideal value" 3 (2.84 and 2.95 for 2018 and 2019, respectively; Figure 5), which indicates isometric growth of the animals (Wójcik-Fudalewska & Normant-Saremba, 2016).

The density of the migrating juveniles downstream of the trap was calculated to be 1.88 and 3.20 ind. m^{-2} for 2018 and 2019, respectively (Table 2). The resident population was estimated between 0.44 and 2.05 ind m^{-2}, depending on year, whether the data were corrected for trap effectiveness and whether the area of the Aa River was taken into account.

TABLE 2 Calculated crab densities of upstream migrating juveniles for the area downstream of the trap (during spring migration of 2018 and 2019) and resident crab densities and mortality rates for the area upstream of the trap (2018 and 2019)

			Density (ind. m^{-2})		
Population	**Year**	**Dataset used**	***Kleine Nete***	***Kleine Nete + Aa***	**Mortality rate m (t^{-1})**
Migrating	2018	Measured data	1.88	na	na
Migrating	2019	Measured data	3.20	na	na
Resident	2018	Measured data	0.73	0.44	1.30
Resident	2018	Data corrected for trap effectiveness	1.10	0.66	1.08
Resident	2019	Measured data	1.38	0.84	1.40
Resident	2019	Data corrected for trap effectiveness	2.05	1.24	1.18

Notes: Resident crab densities were calculated for the area of the Kleine Nete River alone and for the combination of the Kleine Nete and tributary Aa since it is not known how the population divides between rivers. na = not applicable.

4 | DISCUSSION

4.1 | Evaluation of the trap and practical guidelines

Based on the number of crabs caught, and the results of the mark-recapture experiments, it can be concluded that the design and functioning of this trap is successful in catching and removing Chinese mitten crabs from rivers. With over 1 million individuals caught in 2 years and with no bycatch except for two toads, the trap is far more effective than any other method. A thorough literature search for earlier efforts to design a trap for Chinese mitten crabs, only resulted in the study by Boerkamp (2013), who in parallel came up with a design reminiscent of our trap. Although a similar principle was used, our design and installation solves some issues the authors in that study were confronted with, for example, the fact that our trap is permanent instead of mobile (and therefore more robust) and that it can close-off entire cross-sections.

A few other methods were described to obtain an indication of the size of a crab population in river or estuarine systems. Methods used were calculating the density of crab holes in riverbanks (Rudnick et al., 2003), visual inspection of the presence of crabs combined with manual sampling of habitats like rocks (Gilbey et al., 2008), bottom trawling (Cabral & Costa, 1999; Rudnick et al., 2003), mark and recapture experiments (Bell, Eaton, Bannister, & Addison, 2003; Gíslason, Jónasson, Pálsson, Svavarsson, & Halldórsson, 2017; Munch-Petersen, Sparre, & Hoffmann, 1982) and the use of fyke nets and/or (baited) pots (Anastácio, Marques, Águas, Wójcik-Fudalewska, & Normant-Saremba, 2018; Clark, 2011; Clark et al., 2017; Garcia-de-Lomas et al., 2010; Normant, Wiszniewska, & Szaniawska, 2000; Soes, van Horssen, Bouma, & Collombon, 2007). The first three of these techniques were used in tidal areas and were unsuitable for (small) rivers because of practical difficulties. The mark and recapture method is generally used to make a density estimation of mobile animals. However, juvenile Chinese mitten crabs molt frequently in order to grow, thereby losing their marking and therefore is not optimal either. Fyke nets are most commonly used to catch Chinese mitten crabs. Although the technique has proven effective, there are some concerns about the number of bycatch of fish (Clark, 2011; Clark et al., 2017). Modifications of the net (e.g., larger mesh size) can mitigate this, but comes with the drawback that small crabs can escape (Clark et al., 2017). In addition, the placement and emptying of the fyke nets can be tricky, which is labor intensive and time consuming. They have to be emptied on a regular basis to release vulnerable species, to avoid clogging of the net and the escape of Chinese mitten crabs by cutting the net (Garcia-de-Lomas et al., 2010). A great disadvantage of the use of all these other methods is that it is difficult, if not impossible, to cover the entire cross-sectional area of the river from bank to bank. Therefore, crabs can easily pass, which can result in a severe underestimation of the population and a suboptimal removal of individuals.

A recapture percentage in spring of between 66% and 73% is very good (e.g., Gilbey et al., 2008, found 0%–25% recapture of crabs, although their setup and environment was different). It is not clear why 100% was not retrieved, especially in the experiment where the crabs were released just in front of the trap. We have no indication or observation that they managed to pass the trap without being caught, but it cannot be excluded. If this was the case, it implies that the trap stops a significant number but not all crabs from reaching upstream parts of the river. A practical solution may be the installation of two traps behind each other, but this was not tested. Additional explanations can be disorientation after releasing them (crabs moving away from the trap), mortality, molting (which would shed off the marked carapace) or settlement (stop or delay of migration). These additional explanations were supported by the fact that the recapture percentage becomes lower if crabs are released further away from the trap and experience more challenges before again reaching the trap.

In autumn, the recapture percentage was lower with only 52% retrieval of crabs released just in front of the trap. The explanations listed above of the fate of the missing crabs still hold, although it is more likely now that adult crabs might have taken advantage of the flow to “jump” the trap, yet this was never observed. Only one-third of the crabs released in front of the junction of the main channel and the fish ladder were retrieved. With a recapture percentage of 52% at the trap, it suggests that ~40% of the population probably takes the main channel and ~ 60% use the fish ladder. Similar recapture percentages as in spring were retrieved for crabs released further away from the trap. From a management point-of-view, a lower success rate with adult crabs is not a problem since they leave the area and there should be a focus on the influx during spring.

The trap was installed on a fish ladder, which has many advantages. First, the water could be temporarily diverted to the main channel, which facilitated construction and maintenance. Secondly, the fish ladder already had a concrete platform onto which the trap could be fixed. This assured no space between the container and the river bed to avoid crabs crawling underneath the trap. It is advised that in all newly built fish ladders in areas sensitive to Chinese mitten crab invasion (see, e.g., Herborg, Rudnick, Siliang, Lodge, & MacIsaac, 2007), a platform is foreseen to install such a trap if needed. In other locations on rivers, this trap could be built after specific technical adaptations (e.g., extending the ramps deep into the sediment, although this was not tested). The construction and installation of the trap in its current location was inexpensive (around 5,500 euro), but the removal of the captured crabs is a full-time job during the period of the spring migration. The crabs were euthanized and currently treated as animal waste, which increases maintenance costs. A practical or commercial use of the biomass was sought, but not found. Sedimentation on the ramps and silting up of the container occurred a couple of times, especially after intense rain events. A sludge pump was used to clean the trap. Perforations in the bottom of the container could help flushing out the sediment, which is currently being tested and has proved to be successful, though occasional maintenance remains necessary.

4.2 | Results of 2-year monitoring

Although observed trends in migration between the two years were similar, greater differences in total number of crabs and individual crab size and mass were observed. Parameter b from Equation 1 (Figure 5) was close to the "ideal value" of 3, which indicates isometric growth of the animals. This is an indication that the prevailing environmental conditions were suitable for the species and that individuals were in good health (Wójcik-Fudalewska & Normant-Saremba, 2016) and can therefore not explain differences between years. There have been some indications that the *E. sinensis* populations in Europe and America undergo some sort of cyclic population structure, with massive numbers found some years and very few in others, although mechanisms driving these fluctuations are currently unknown (Drotz, Berggren, Lundberg, Lundin, & Proschwitz, 2010; Gollasch et al., 1999; Rudnick et al., 2003; Rudnick, Halat, & Resh, 2000). The main possible reason which has some support basis is that of fluctuations in fresh water wash-out speed in estuaries: years with consecutively low freshwater flows due to drought are thought to be behind the establishment of a breeding *E. sinensis* population in the Thames, United Kingdom (Gilbey et al., 2008). In Flanders, 2018 and 2019 were very dry years and spring 2019 was exceptionally warm, though our limited dataset does not allow any correlative predictions.

During the autumn migration, males arrive in the estuary generally 1 month before the females and also mature faster. Small crabs also start migrating earlier than large individuals (Fladung, 2000; Soes et al., 2007). This is also clearly visible in our data where male representatives were more dominant at the beginning of the autumn migration and more female representatives were found towards the end of the autumn migration. The sex ratio was around 50:50 for juveniles during the spring migration. Adults and juveniles in the genus Eriocheir are characterized by the presence of patches of brown setae on the inner and outer surface of their white-tipped chelae, which was confirmed by our data. Adult males generally have a denser mat of setae, but there is no gender-based dimorphism in claw size (Rudnick et al., 2000). The measured migration speed of the juveniles (between 0.46 and 1.11 km day^{-1}) was slower than that found by Panning (1939). He had found that small animals, migrating from the tidal region in the lower course of the Weser, travelled a distance of 1 to 1.5 km daily and that the larger individuals, moving against the current in mid Elbe, a distance of 2 to 3 km daily. Probably, local conditions very much determine this speed. Note that conditions on the fish ladder were different than average Belgian lowland rivers of similar size (e.g., higher mean flow velocity), which may have had some influence on the results. Adult migration speed towards the sea is better documented in literature: 0.074 m s^{-1} (= 6.4 km day^{-1}) in experimental conditions (Fialho, Banha, & Anastácio, 2016), 8 to 12 km day^{-1} (Panning, 1939) and 11.5 km day^{-1} with a maximum of 18 km day^{-1} (Herborg et al., 2003) in natural conditions. This is much faster than the migration speeds measured in this study (max. 2.78 km day^{-1}). To achieve such high speeds, the adults take advantage of freshwater flow for transport to the estuary and after reaching tidal areas, benefit from ebb tides to reach coastal areas (Kobayashi, 2002). But actual studies on this putative transport mechanism have not been done. We do not know why our measured migration speeds were much slower. There might have been some influence of the methods applied (e.g., crabs can wait a few days after their release before starting migrating again). However, projecting the migration speeds found in the literature on our tested distances (6.5 and 25 km) would mean that the crabs should reach the trap again in 1–2 days, which was different to what we measured.

Crab densities were high and the density during migration was higher than the resident population density. All calculated densities were much higher (2 to 10 times) than the critical predicted threshold density value above which vegetation is likely to be negatively impacted by the crabs. This threshold value was set at 0.1–0.3 ind. m^{-2} in an experimental setup specifically designed to estimate the risk of a native plant species (*Myriophyllum spicatum*) decline due to Chinese mitten crab behaviour (Schoelynck et al., 2019), and which is in accordance with the density threshold of 0.25–0.5 ind. m^{-2} established by Jin, Xie, and Li (2001) for macrophytes in the crabs' home territory in China. A (semi) permanent reduction or even total loss of vegetation can have dramatic consequences for the aquatic ecosystem since macrophytes are ecological engineers (Schoelynck et al., 2012) that support several ecosystem functions in the river (Boerema et al., 2014; Carpenter & Lodge, 1986; Hofstra et al., 2020; O'Hare et al., 2018). A sudden loss of vegetation may induce sediment erosion, which can be intensified by the burrowing activities of the crabs and which may further inhibit vegetation recovery in the long term. In the Kleine Nete River, macrophytes are still present today, though a decrease in abundance and diversity was observed in recent years. In a large part of the nearby flowing Grote Nete River, a near total absence of macrophytes has been observed since 2013, where previously plant growth was abundant. Chinese mitten crabs were also observed in high numbers here, but not exclusively in the section where the macrophytes have lost and actual crab densities have not been measured (VMM, 2015; VMM, 2017).

4.3 | Outlook

This single trap, located in an upstream reach of one of the tributaries of the larger Scheldt River basin, will most likely not reduce the Chinese mitten crab population in Flanders. Yet it will very likely protect the area upstream of the trap, which will become clear if the number of adults migrating from that area diminishes over the coming years. However, with each female reaching the salty nursery grounds, up to 1 million eggs are released (Fladung, 2000) and thousands of new juvenile crabs will reach the trap year after year, resulting in a continuation of the water managers' Sisyphean task. Only a catchment-wide approach could effectively reduce the overall population size and improvements of the current design, functioning and strength of the trap are likely needed to allow it to functioning in larger streams with stronger currents and/or tides. The effectiveness of the trap can probably be improved by placing two or more containers behind each other at the same location, although further research is required to test this.

5 | CONCLUSION

We conclude that this type of trap is robust, relatively cheap and very successful in catching and removing Chinese mitten crabs as a river management measure, without the risk for any by-catch of fish. It also allows a systematic monitoring of population numbers and densities, which was more difficult with previous techniques such as fyke nets. Since it is not size selective, the trap can also be used as a systematic device to sample individuals over time for individual crab measurements and analyses, and it allows in situ experiments such as mark-recapture experiments.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

All data needed to evaluate the conclusions in the paper are present in the paper. Additional data is available form authors upon request.

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