Biological Conservation 159 (2013) 521–529

Contents lists available at SciVerse ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

A fish-passable barrier to stop the invasion of non-indigenous crayfish

Roy M. Frings [a,*,1], Susanne C.K. Vaeßen [b,1], Harald Groß [c], Sebastian Roger [a], Holger Schüttrumpf [a], Henner Hollert [b]

[a] Institute of Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, 52056 Aachen, Germany
[b] Department for Ecosystem Analysis, Institute for Environmental Research, RWTH Aachen University, Worringerweg 1, 52074 Aachen, Germany
[c] Edelkrebsprojekt NRW, Neustraße 7, 53902 Bad Münstereifel, Germany

ARTICLE INFO

Article history:
Received 11 January 2012
Received in revised form 3 December 2012
Accepted 8 December 2012
Available online 6 February 2013

Keywords:
Crayfish
Invasion
Barrier
Pacifastacus leniusculus
Flight response
Swimming

ABSTRACT

The invasion of non-native signal crayfish into European ecosystems has resulted in a drastic reduction of native European crayfish, with adverse effects on ecosystems and fisheries. This study aimed to determine whether native crayfish can be protected by physical barriers that do not hinder fish migration, but prohibit the upstream migration of non-native crayfish. Laboratory experiments were carried out to test a barrier design consisting of a gently-inclined, smooth, prismatic, cross-channel structure. Barrier efficiency appeared to depend on barrier roughness, barrier slope and flow velocity directly above the barrier crest. The maximum barrier slope that can be climbed by crayfish decreases with increasing flow velocity in a non-linear way. This observation is in agreement with the physics of crayfish locomotion as demonstrated by applying Newton's laws of motion to crayfish. Contrary to general acceptance, signal crayfish do deliberately deploy their swimming capacities to pass barriers, proving the general belief that crayfish only swim as an escape response to be untrue. This suggests that crayfish are able to pass all barriers regardless of barrier slope or barrier roughness if the flow velocity is below the maximum velocity against which crayfish can swim. Nevertheless, physical crayfish barriers are an effective method to protect indigenous crayfish in streams with sufficiently high flow velocities. Promising barrier locations are pre-existing structures such as fish ladders alongside weirs, where flow velocities are controlled, sedimentation risks are low, maintenance is done regularly and the bed profile is suitable to connect barriers to.

1. Introduction

The invasion of non-native signal crayfish (*Pacifastacus leniusculus*; Dana, 1852) into European ecosystems has resulted in a drastic reduction of native European crayfish (Holdich et al., 2009; IUCN, 2012), such as the gourmet crayfish *Astacus astacus* (Linnaeus, 1758). In addition, signal crayfish were observed to have a negative impact on populations of invertebrates (e.g., Usio et al., 2009), macrophytes (e.g., Usio et al., 2009), benthic fish (e.g., Guan and Wiles, 1997; Bubb et al., 2009) and pelagic fish (e.g., Griffiths et al., 2004; Peay et al., 2009). Furthermore, the invasion of signal crayfish leads to a reduced water quality (Hänfling et al., 2011) and increases sediment-related flood risks (Harvey et al., 2011). Problems started in 1959 (Abrahamsson, 1973), when signal crayfish were brought from America to Europe as a food species, but continue today (e.g. Skov et al., 2011). Signal crayfish are not only competitively superior to native crayfish (e.g., Söderbäck, 1991, 1995), they also transmit the crayfish plague *Aphanomyces astaci*, a fungal disease harmless to signal crayfish but lethal to native crayfish (Unestam, 1972; Alderman and Polglase, 1988). When signal crayfish intrude into a watershed, downstream populations of native crayfish are exposed to the plague due to transport of spores by flowing water, whereas both downstream and upstream populations are exposed due to migration of infected crayfish.

Fortunately, the upstream spread of the crayfish plague is often halted by barriers such as waterfalls, culverts and dams (Alderman and Polglase, 1988; Taugbol et al., 1993; Kerby et al., 2005). Therefore, some residual populations of native crayfish have been able to survive in river headwaters. These remaining populations now are in great danger due to the implementation of the European Water Framework Directive (EU, 2000), a legally-binding agreement that requires the restoration of the ecological continuity of water bodies by 2015. This implies that anthropogenic barriers that hinder fish migration must be removed or provided with a fish ladder. It may be clear that this is beneficial for migratory fish species (e.g. salmon) and gene flow in residential species populations, but threatening to native crayfish, because it promotes the invasion

* Corresponding author. Tel.: +49 241 80 25265; fax: +49 241 80 22348.
E-mail address: frings@iww.rwth-aachen.de (R.M. Frings).
[1] The authors wish it to be known that, in their opinion, the first 2 authors should be regarded as joint First Authors.

0006-3207/$ - see front matter
http://dx.doi.org/10.1016/j.biocon.2012.12.014

of signal crayfish. Quite similar debates on the merits of connectivity versus isolation of freshwater bodies have been had in North America (Fausch et al., 2010).

If we want native crayfish to survive, measures must be taken urgently. In addition to the political challenge of stopping the ongoing introduction of non-native species to European ecosystems (cf. Keller et al., 2011), we also have to deal with the signal crayfish that have already passed through the first two stages of biological invasion – namely introduction and establishment on site – and are now in the final stage of impacting the ecosystem by spreading massively (Vander Zanden and Olden, 2008). The preferred solution is to eradicate these crayfish (e.g., Holdich et al., 1999; Sandodden and Johnsen, 2010), but available eradication methods are either extremely time consuming, ineffective or harmful to other organisms (Ellis, 2005). Partial eradication of crayfish populations has even proven to result in faster growth rates and improved body condition in the remaining population (Moorhouse and Macdonald, 2011). The only alternative solution is the management and confinement of native crayfish populations in isolated 'ark sites' (Peay, 2009), free from non-native crayfish and the threat of colonisation by non-native crayfish. Crayfish barriers can protect native crayfish in such ark sites in the hope that acceptable eradication methods against invaders will be developed soon.

In the past, some success has been achieved with electrical crayfish barriers (e.g., Unestam et al., 1972) but these were never applied widely, because they need an uninterruptible power supply, which makes them rather costly to implement in remote areas. A promising alternative are physical crayfish barriers (e.g., Thompson, 1990; Ellis, 2005; Dana et al., 2011), which are cheap, easy to maintain and do not require power supply. Physical crayfish barriers typically consist of a smooth, cross-channel vane with a height of 25–30 cm, often with an overhanging drop, that is placed vertically or slightly tilted on the river bed (Ellis, 2005). Some variants have stone walls that rise above the waterline and allow downstream water flow only over a small barrier spring (Dana et al., 2011).

A disadvantage of the present generation of physical crayfish barriers, however, is that they are not (e.g. Dana et al., 2011) or not fully (e.g. Ellis, 2005) passable for fish. Laboratory investigations with several barrier types (Ellis, 2005) show that even if barriers allow upstream migration of pelagic fish they hinder the migration of benthic fish.

Another disadvantage of existing crayfish barriers is that they are only effective against crayfish walking along the river bed. Crayfish, however, also have another way of locomotion: rapid backward swimming by flipping their tail. This type of locomotion is used as a flight reflex and is typically caused by a rapid visual stimulus from the anterior direction (Wine and Krasne, 1972; Webb, 1979). Usually, it is believed that swimming events are too infrequent and too short of duration for crayfish to breach barriers by swimming, which is supported by laboratory investigations (Webb, 1979; Light, 2005; Ellis, 2005; Foster and Keller, 2011). However, signal crayfish from a population in the Iter (Germany) were regularly found to swim distances of up to one meter in a container (Vaeßen, personal observation). This suggests that these crayfish could be able to breach physical barriers by swimming.

The objective of this study was to explore whether it is possible to construct a physical crayfish barrier that does not hinder the upstream migration of fish, but prohibits the upstream migration of non-native crayfish by all types of locomotion. In this way, protection of native crayfish species can be achieved in combination with improving fish passability, thereby meeting multiple management objectives simultaneously. In contrast to previous studies, we propose a barrier with a triangular prismatic design with inclined barrier surfaces in order to minimize impact on migrating fish (Fig. 1a). Theoretical calculations of crayfish locomotion and laboratory experiments were carried out to test the efficiency of the proposed barrier design. Particular efforts were made to determine the minimum slope needed to halt walking crayfish and the minimum flow velocity needed to halt swimming crayfish. The analyses are complemented with a discussion on the passability of barriers for fish, on constructional aspects of crayfish barriers and on potential barrier locations.

2. Theory

Basic guidelines for constructing the new barrier (Fig. 1a) can be derived by considering the forces that act on a crayfish (Fig. 2) and applying Newton's laws of motion. In the case of crayfish walking a barrier, the relevant forces are: F_m, the muscular force of the crayfish (N); F_f, the Coulomb friction force due to the friction between the crayfish legs and the barrier surface (N); F_d, the drag force exerted by the fluid (N); and $F_{G//}$ the net downslope gravity force acting on the crayfish (N). A barrier is effective if the magnitude of the forces that pull the crayfish downslope (F_d and $F_{G//}$) exceeds the magnitude of the forces that pull the crayfish upslope (F_m and F_f):

$$F_d + F_{G//} > F_m + F_f \tag{1}$$

with:

$$F_d = 0.5\rho C_d A u^2 \tag{2}$$

$$F_{G//} = (G - B)\sin(\alpha) = (\rho_c - \rho)Vg\sin(\alpha) \tag{3}$$

$$F_f = \mu(G - B)\cos(\alpha) = \mu(\rho_c - \rho)Vg\cos(\alpha) \tag{4}$$

Here, G (=$\rho_c Vg$) represents the gravity force (N), B (=ρVg) the buoyancy force (N), α the barrier slope (°), ρ_c the bulk density of the crayfish' body (kg/m^3), ρ the water density (998 kg/m^3), V the crayfish volume (m^3), g the gravitational acceleration (9.81 m/s^2), C_d the drag coefficient (–), A the frontal surface area of crayfish exposed to the flow (m^2), u the flow velocity parallel to the barrier surface (m/s) and μ the Coulomb friction factor (–). Combination of Eqs. (1)–(4) leads to the following expression:

$$\sin(\alpha) - \mu\cos(\alpha) > \frac{F_m - 0.5\rho C_d A u^2}{(\rho_c - \rho)Vg} \tag{5}$$

which shows that in order to be effective against walking crayfish, crayfish barriers must be steeper if the barrier has a high surface roughness than if the barrier has a low surface roughness. Equally, crayfish barriers must be steeper in situations with low flow velocities than in situations with high flow velocities. Flow velocity influences barrier efficiency in a highly non-linear way.

Eq. (5) also allows visualizing the effect of crayfish properties on barrier efficiency. A sensitivity analysis in which F_m, A and C_d were systematically varied keeping the other variables constant (Fig. 3) shows that the maximum slope that can be walked by crayfish under still-water conditions (u = 0 m/s) depends on the muscular strength of crayfish (F_m), but not on their body shape (represented by A and C_d). Furthermore, the maximum velocity against which crayfish can walk a barrier of a given slope increases if crayfish have a higher muscular force (F_m), a lower frontal area (A) or a more streamlined body with lower drag coefficient (C_d).

Eq. (5) cannot be used directly to determine the minimum slope and roughness needed for a crayfish barrier, because the hydrodynamic properties of signal crayfish (ρ_c, V, A, C_d), their muscle force (F_m) and the friction coefficient of the barrier surface (μ) have not been documented with sufficient detail in scientific literature. Experimental tests of the proposed barrier design therefore remain indispensable.