The current status of \textit{Pacifastacus leniusculus} (Dana, 1852) and their effect on aquatic macroinvertebrate communities in Hungarian watercourses

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Abstract

The freshwater crayfish \textit{Pacifastacus leniusculus} is among the most widespread invasive crayfish species in Europe. \textit{Pacifastacus leniusculus} invaded Hungary around 1998 and here we investigated the recent expansion of this species and its impact on other aquatic macroinvertebrates. The colonization of watercourses throughout Europe by the signal crayfish resulted in negative impacts on the present aquatic communities. Our investigation (i.e. in Rába, Pinka, Gyöngyös-stream, Répce, Arany-stream and Strém systems) revealed that the distribution range of signal crayfish is still in expansion in the western part of Hungary and in all likelihood impacting the aquatic communities in these watercourses. Our results obviously demonstrated that signal crayfish densities were highest in habitats with gravel or coarse particulate organic matter, which seems to reflect a species-specific habitat preference. Our investigation proved that the presence of \textit{P. leniusculus} had negative effects on a number of protected species such as \textit{Calopteryx virgo} and \textit{Onychogomphus forcipatus} next to a significant negative effect on the Odonata and Trichoptera species richness as well as on the abundances of Ephemeroptera, Odonata and Trichoptera. Our study in Hungary supports the notion of the significant negative impact of signal crayfish on native freshwater invertebrate communities throughout Europe. In order to assess whether these impacts are restricted to fast flowing waters only, an adequate monitoring plan providing more knowledge on this species with respect to biotic and abiotic preferences and aquatic macroinvertebrate composition is required.

Key words: habitat preferences, signal crayfish, invasion, impact on aquatic invertebrates, protected macrofauna species

Introduction

Since 1959, \textit{Pacifastacus leniusculus} has been introduced to over 20 European countries (Kouba et al. 2014) and its range expansion is the widest among invasive crayfish in Europe (Chucholl 2016; Ruokonen et al. 2018). The first observation of \textit{P. leniusculus} in Hungary was made in 1998 in the western part of the country, e.g Gyöngyös-stream (Kovács et al. 2005, Puky and Schád 2006). The species arrived in Hungary most probably through...
Crayfish species, like *P. leniusculus*, affect their physical and chemical environment (Reynolds and Souty-Grosset 2012; Freeland-Riggert et al. 2016). They modify abiotic conditions through either bioturbation (Albertson and Daniels 2016; Lodge et al. 2012; Early et al. 2016) and burrowing (Holdich et al. 2009; Pöckl 1999; Kholodkevich et al. 2005). As signal crayfish feed on plants, detritus, zoobenthos, fish, and other crayfish (Guan and Wiles 1998; Crawford et al. 2006; Twardochleb et al. 2013; James et al. 2015), their effects may occur at several levels of the aquatic ecosystem through predation and competition.

The most recent publication on the distribution of this species in Hungary contains data for the period up to 2015 (Ludányi et al. 2016) and according to this investigation the species mainly occurred in calcic, upland-hilly, medium and large sized watercourses in the western part of the country. That study also mentioned that signal crayfish prefer habitats where current velocity is between 0.3–0.4 ms⁻¹ (Ludányi et al. 2016). As *P. leniusculus* continues to colonize many watercourses, negative effects on aquatic macroinvertebrate communities are also expected as has been observed in the rivers Gwash, Chater and Clyde in the UK after colonization by this species (Mathers et al. 2018; Crawford et al. 2006). Turley et al. (2017) and Ruokonen et al. (2018) also revealed that *P. leniusculus* can negatively impact the species richness of other aquatic macroinvertebrates. Usually, invasive crayfish impact macroinvertebrate communities via direct predation (Nyström et al. 2001; Jackson et al. 2014; James et al. 2014) and indirectly through destruction of habitats (Griffiths et al. 2004). To what extent these effects also occur in Hungarian watercourses is still unknown, which is troublesome as observations by BioAqua Pro Ltd. show that the signal crayfish occurs in locations where many protected macroinvertebrate species used to occur (BioAqua Pro Ltd. database).

In order to investigate the potential impact of *P. leniusculus* on aquatic macroinvertebrates and protected species in particular we analysed both their occurrences in time and space using the database of BioAqua Pro Ltd. During different projects in Hungary in the last decades, macroinvertebrate data were collected and stored in the BioAqua Pro Ltd database and this information allowed us to: i) update the distribution area of the invasive freshwater crayfish *P. leniusculus* in Hungary, ii) to determine the relationship between crayfish abundance and abiotic and biotic conditions and iii) to evaluate possible threats of *P. leniusculus* to aquatic macroinvertebrate communities in general and to protected species in Hungary specifically.

**Materials and methods**

**Data sets**

The dataset of BioAqua Pro Ltd contained 378 sampling events at 137 locations throughout the western part of Hungary since 1993. We selected
macroinvertebrate samples from different water types ranging from calcic to siliceous bedrock, upland-hilly and lowland waters, and varying in size from very small to very large. These features have been derived from the Hungarian river basin management plan (http://www2.vizeink.hu/). From this database, we selected abiotic and biotic features of the sampling location, the presence or absence of *P. leniusculus* and macroinvertebrate abundance data. Out of the 137 locations, 81 comprised calcic, upland-hilly medium sized watercourses, 47 locations comprised calcic, upland-hilly large sized watercourses and 9 locations comprised upland-hilly siliceous small watercourses. We investigated 18 different abiotic and biotic habitat types based on the protocol of AQEM consortium (2002).

**Sampling**

For our analyses, we used both quantitative and qualitative macroinvertebrate samples that have been collected since 2005 by BioAqua Pro Ltd. The quantitative aquatic macroinvertebrate samples were taken by the company in line with the protocol of National Biodiversity Monitoring System, which is in fact a “multihabitat sampling” method (Juhász et al. 2009; Cheshmedijev et al. 2011; Nieuwenhuis 2005). In short, prior to the sampling we determined the relative abundance of the different microhabitats and sampled different microhabitats in proportion to their presence at the sampling location and determined prior to the sampling. We applied the “kick and sweep” technique (Juhász et al. 2009; Letovsky et al. 2012) with a standard dip net (with a 950 µm mesh fabric and a 25 × 25 cm metal frame) to collect the animals. Every location contained three independent samples (= 3 sections). Relative abundances of the collected species were expressed as the average of their abundance values in the three sections.

A standard hand net was used to collect qualitative samples, but not taking into account the size of the sampled area, thus only a species list was generated with presence and absence data.

In every case, when quantitative samples were taken, information was recorded on a field form about the abiotic and biotic habitat composition (Table 1), water depth, water velocity. The following taxonomic groups were collected from the sampled material for further identification up to the species level in the laboratory: Hirudinea, Ephemeroptera, Gastropoda, Bivalvia, Trichoptera, Coleoptera, Heteroptera, Plecoptera, Odonata, and Malacostraca. The bigger sized animals (native crayfishes, bivalves, snails) were identified in the field and returned to the water, while smaller animals were classified in the field into groups and bottles containing 70% ethanol. These invertebrates were identified in the laboratory using a Nikon SMZ 1000 microscope.

**Data analysis**

We used Quantum GIS 2.18 software to map the observations of *P. leniusculus* in the three different water types mentioned above. To visualize the expansion...
Table 1. The investigated habitat types and their explanation.

| habitat type          | habitat subtype               | explanation                                      | size fractions |
|-----------------------|-------------------------------|--------------------------------------------------|----------------|
| abiotic habitats      | hydropetric                   | bedrock outcrop                                  | > 40 cm        |
| megalithal            | natural macrolithal          | coarse cobbles, head-sized cobbles                | > 20–40 cm     |
| artifical macrolithic constructions | mezolithal           | coarse blocks, head-sized cobbles                | > 20–40 cm     |
| microlithal           | artificial macrolithic        | fist to hand-sized cobbles                        | > 6–20 cm      |
| akal                  | psammal / psammopelal        | sand / sand with mud                              | > 6 µm–2 mm    |
| argyllal              | biotic habitats              | roots                                            | < 6 µm         |
| macro-algae           | submerged macrophytes        |                                                   |                |
| micro-algae           | emergent macrophytes         |                                                   |                |
| living parts of terrestrial plants | xylal                    |                                                   |                |
| CPOM                  | FPOM                          |                                                  |                |
| debris                |                               |                                                  |                |

of the species, we compared the observations from 2015 onwards with those reported earlier (Ludányi et al. 2016).

We applied stepwise linear regression with stepwise selection (combination of forward and backward selections) using the MASS packages (Venables and Ripley 2002) to find the best model by AIC, predicting the relationship between the crayfish relative abundance and the abiotic and biotic habitat variables (cover of artificial macrolithic constructions, microlithal, akal, psammal, argyllal, xylal elements, CPOM and FPOM). The response variable (relative abundance of the *P. leniusculus*) was log transformed to achieve normality. In the generalized linear models (GLMs) sampling year was entered as a random factor. For this analysis we had the quantitative sampling data of *P. leniusculus* 29 sections of 15 locations from 8 years which means that we used only habitat information of those sections where *P. leniusculus* occurred to assess the habitat parameters affecting the abundance of the species. Visualizing significant relationships jtools package (Long 2020) was used.

We used Generalized Linear Models (GLMs) to analyse the impact of the presence of *P. leniusculus* on the relative abundance of the protected species, as well as on the richness and the relative abundance of the selected taxonomic groups (Bivalvia, Coleoptera, Ephemeroptera, Gastropoda, Heteroptera, Hirudinea, Malacostraca, Odonata, Plecoptera and Trichoptera) using the lme4 package (Bates et al. 2015). Prior the analyses the distribution that best fits the data were identified using the car (Fox and Weisberg 2019) and the MASS packages (Venables and Ripley 2002). Relative abundance was followed a normal distribution, while richness was followed a Poisson distribution. We used a log link function and standard linear predictor in the case of Poisson distribution. Models on richness with overdispersed data, where greater variability (statistical dispersion) was
expected based on the model (models on overall richness, as well as on richness of the Ephemeroptera and the Trichoptera), were refitted using the sample location as a random factor, as proposed by Harrison (2014). Because of the multiple tests on the same set of data on the richness and the relative abundance of the selected taxonomic groups, we applied Bonferroni correction for the significance values (Dunn 1961). For these analyses data from 13 sampling locations of two upland-hilly, medium sized watercourses that differed in the presence of the crayfish were used (eight locations from the invaded Gyöngyös and five from the signal crayfish-free Kerca with a total of 104 sampling events). In all the models, sampling year was treated as a random factor. All analyses were completed in the R programming environment (R Core Team 2017).

Results

Distribution of *P. leniusculus*

Our data showed that *P. leniusculus* has moved further into Hungary since 2015 (Figure 1). *Pacifastacus leniusculus* occurred in 47 sampling locations corresponding to roughly 12.5% of all sampled locations and in at least 10 watercourses in western Hungary from July 2015 onwards. *P. leniusculus* had colonized a total of 20 sampling locations in 6 watercourses before 2015 (Ludányi et al. 2016) indicating that *P. leniusculus* has more than doubled its range in the last 5 years. The distribution pattern showed a clear spreading route from the river Rába towards the upper sections of the river Pinka. In addition, signal crayfish distribution in the Gyöngyös-stream, Répce, Arany-stream and Strém expanded from the upstream sections from Austria towards the downstream sections deeper into Hungary (Supplementary material Table S1).

Effect of habitat features

Our best model included four habitat variables (akal, psammal, CPOM and FPOM) and predicted a significant positive correlation between akal cover (%) and crayfish relative abundance (t = 2.576, df = 13, p < 0.01) and between CPOM cover (%) and crayfish relative abundance (t = 3.614, df = 13, p < 0.001) (Table 2, Figures 2, 3). The relationship between the crayfish relative abundance and psammal and FPOM cover was not significant.

Impact on protected species

In order to assess the potential impact of *P. leniusculus* on protected species, the occurrences of these species were compared between the invaded Gyöngyös-stream and the non-invaded Kerca stream. Despite the invasion of *P. leniusculus*, the Gyöngyös-stream still harboured many protected species comprising *Agneta elegans*, *Aquarius najas*, *Calopteryx virgo*, *Cordulegaster bidentata*, *Cordulegaster heros*, *Gomphus vulgatissimus*, *

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**Figure 1.** Distribution of *P. leniusculus* before and after 2015.

**Table 2.** The results of the best model by AIC predicting the relationship between the *P. leniusculus* relative abundance (individuals/m²) and habitat features based on 29 samples

| Habitat feature                        | Estimate | SE   | df  | t-value | p-value |
|----------------------------------------|----------|------|-----|---------|---------|
| ( Intercept )                          | 1.1305   | 0.2990 | 25  | 3.781   | 0.0009  |
| Abiotic habitat features               |          |      |     |         |         |
| > 2 mm–2 cm gravel (akal)              | 0.0143   | 0.0062 | 25  | 2.305   | 0.0297  |
| > 6 µm–2 mm sand with mud (psammal)    | −0.0105  | 0.0065 | 25  | −1.601  | 0.1218  |
| Biotic habitat feature                 |          |      |     |         |         |
| coarse particle of organic matter (CPOM)| 0.0241  | 0.0078 | 25  | 3.082   | 0.0050  |
Figure 2. The relative abundance of *P. leniusculus* in proportion of akal cover (grey area: confidence interval; black line: direction of the relationship between the variables; y-axis scale is individuals/m²).

Figure 3. The relative abundance of *P. leniusculus* in proportion of CPOM cover (grey area: confidence interval; black line: direction of the relationship between the variables; y-axis scale is individuals/m²).
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**Figure 4.** Relative abundance of *C. virgo*, *G. vulgatissimus* and *O. forcipatus* in the presence of *P. leniusculus* (± SE).

**Table 3.** The results of generalized linear models regarding abundance of protected species (bold: significant differences p < 0.05, n = 104).

| Species                     | Estimate | SE  | $\chi^2$ | p       |
|-----------------------------|----------|-----|----------|---------|
| *Calopteryx virgo*          | -14.470  | 3.866| 14.007   | < 0.001 |
| *Gomphus vulgatissimus*     | -0.395   | 2.129| 0.0344   | 0.8528  |
| *Onychogomphus forcipatus* | -6.910   | 2.163| 10.206   | 0.0014  |

Macronychus quadrituberculatus, Oligoneuriella rhenana, *Onychogomphus forcipatus*, *Ophiogomphus cecilia* and *Unio crassus*. In the Gyöngyös-stream concerned, the relative abundance of *Calopteryx virgo* (2.94 ± 1.08 ind./m$^2$ ± S.E.), *Gomphus vulgatissimus* (4.32 ± 1.66 ind./m$^2$ ± S.E.) and *Ophiogomphus cecilia* (5.58 ± 1.57 ind./m$^2$ ± S.E.) was the highest.

*Calopteryx virgo*, *C. heros*, *G. vulgatissimus*, *O. forcipatus*, *O. cecilia* and *U. crassus* occurred in the crayfish affected Gyöngyös and crayfish free Kerca as well. However, due to the low abundances of most of these protected species, a proper comparison was only possible for *C. virgo*, *G. vulgatissimus* and *O. forcipatus*. According to the GLM analysis, the relative abundance of *C. virgo* and *O. forcipatus* was significantly lower in the presence of *P. leniusculus*, while the relative abundance of *G. vulgatissimus* did not show significant relationship with the crayfish occurrence (Figure 4, Table 3).

**Effect on other macroinvertebrates**

The presence of crayfish had a significant, negative effect on the number of species of Odonata ($z = -4.669$, n = 104, p < 0.0001) and Trichoptera ($z = -5.368$, n = 104, p < 0.0001) and the total number of species ($z = -2.989$, p < 0.0001).
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Table 4. The results of generalized linear models regarding number of taxa of main macroinvertebrate groups in the presence of the *P. leniusculus* (*: significant differences by Bonferroni correction, n = 104, the significance level is 0.05/11 = 0.0045).

| Main taxonomic group | Estimate | SE  | $\chi^2$ | p     |
|----------------------|----------|-----|----------|-------|
| Bivalvia             | -0.781   | 0.615 | 1.6145   | 0.204 |
| Coleoptera           | -0.779   | 0.429 | 3.2971   | 0.069 |
| Ephemeroptera        | -1.392   | 0.589 | 5.5708   | 0.018 |
| Gastropoda           | -1.139   | 0.633 | 3.2458   | 0.072 |
| Heteroptera          | -0.636   | 0.474 | 1.7976   | 0.180 |
| Hirudinea            | -0.802   | 0.485 | 2.738    | 0.098 |
| Malacostraca         | -0.043   | 0.192 | 0.05     | 0.823 |
| Odonata              | -0.883   | 0.189 | 21.796   | < 0.001* |
| Plecoptera           | -0.146   | 0.315 | 0.2147   | 0.643 |
| Trichoptera          | -2.292   | 0.427 | 28.817   | < 0.001* |
| Total                | -1.569   | 0.525 | 8.9353   | 0.003* |

Figure 5. Mean number of taxa within Odonata, Trichoptera and total number of taxa in the absence/presence of *P. leniusculus* (± SE).

$n = 104, p < 0.001$) (Table 4, Figure 5). The relationship between crayfish presents and number of species of Bivalvia, Coleoptera, Gastropoda, Heteroptera, Hirudinea, Malacostraca and Plecoptera was not significant.

The presence of *P. leniusculus* resulted statistically significant declines in relative abundance of Ephemeroptera, Odonata, Trichoptera and total macroinvertebrate relative abundance. We did not find significant relationship between the crayfish present and the relative abundance of Bivalvia, Coleoptera, Gastropoda, Heteroptera, Malacostraca and Plecoptera (Table 5, Figure 6).

**Discussion**

Our analysis showed that the distribution area of *P. leniusculus* has expanded in Hungary since 2015 and this pattern is in line with observations in other
Table 5. The results of linear models regarding abundance of taxa of main macroinvertebrate groups (*: significant differences by Bonferroni correction, n = 104, the significance level is 0.05/11 = 0.0045).

| Taxa       | Estimate | SE    | \( \chi^2 \) | p      |
|------------|----------|-------|--------------|--------|
| Bivalvia   | −12.798  | 9.066 | 1.993        | 0.158  |
| Coleoptera | −5.727   | 2.318 | 6.104        | 0.014  |
| Ephemeroptera | −145.1 | 50.2  | 8.355        | 0.004* |
| Gastropoda | −1.01    | 0.542 | 3.473        | 0.063  |
| Heteroptera| 0.126    | 2.09  | 0.004        | 0.952  |
| Hirudinea  | −3.683   | 1.629 | 5.112        | 0.024  |
| Malacostraca | −167    | 164.9 | 1.026        | 0.311  |
| Odonata    | −38.01   | 9.19  | 17.068       | < 0.001* |
| Plecoptera | −2.915   | 14.773| 0.039        | 0.844  |
| Trichoptera| −268.94  | 64.09 | 17.608       | < 0.001* |
| Total      | −639.2   | 206.3+| 9.604        | 0.002* |

Figure 6. Relative abundance of Ephemeroptera, Odonata, Trichoptera and abundance of all taxa in the presence of *P. leniusculus* (± SE).

European countries like the Czech Republic, Austria and Latvia (Kouba et al. 2014; Hudina et al. 2017). Although the distribution area is still confined to the western part of the country, it is constantly expanding towards the Rába river and its tributaries (e.g. Pinka, Gyöngyös-stream). In addition, *P. leniusculus* was also found in the upper section of Danube and in its tributary, called Lajta (Weiperth et al. 2020). There are numerous reasons for the fast spreading of *P. leniusculus*, but one of the main reasons for the fast expansion is probably the human-mediated stocking (Weinländer and Füreder 2009). If we take into account this fact, detailed action plans and cross-border management strategies will be needed which should reduce the impact of this species on the native aquatic community (Jussila and Edsman 2020).
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**Figure 7.** The typical habitats of *P. leniusculus* in Gyöngyös-stream (A) and Strém (B).

The *P. leniusculus* populations originate from large, low-altitude rivers and show intolerance to streams with steeper slopes and higher water velocity. These kind of water types contains fine particulate fragments, like sand or mud and assume a higher amount of organic matter accumulation (Larson et al. 2012), like in Gyöngyös-stream and Strém (Figure 7). In parallel with this result, our analysis showed that the typical abiotic habitat consisted of akal (gravel of size 2–20 mm) and coarse particulate organic matter (from leaves and branches). Vedia et al. (2013) found that the abundance of *P. leniusculus* had a positive relationship with vegetation cover and with boulders. Remarkably, literature on habitat requirements for *P. leniusculus* is not unambiguous and this may be due to regional differences in their distribution area, like differences in topography, slope
features, bedrock properties and habitat composition. Our analyses also showed a relationship between the coarse particulate organic matter cover and *P. leniusculus* relative abundance. Accumulation of CPOM in watercourses automatically leads to higher food availability for aquatic macroinvertebrates feeding on this organic matter. Since macroinvertebrates are prey items for crayfish and crayfish may feed on organic matter (Doherty-Bone et al. 2018), this may be the reason for the positive correlation of crayfish densities with particulate organic matter.

Our study showed that although the signal crayfish still co-occurred with several protected species in the invaded Gyöngyös-stream, larvae of *Calopteryx virgo* and *O. forcipatus* had higher densities in stream without signal crayfish present. In consequences, some of these protected species are threatened by the presence of this crayfish. As far as we know, there are no specific studies available on the effects of *P. leniusculus* on protected species including aquatic macroinvertebrates, except for other crayfish species, like *Austropotamobius pallipes* (Ibbotson and Furse 1995; Martin-Torrijos et al. 2019). However, in the case of other Decapoda species, the biggest threat is formed by the crayfish plague (Diéguez-Uribeondo et al. 1997), which is caused by the oomycete *Aphanomyces astaci* (Schikora, 1903) and invaders like *P. leniusculus* are resistant, but it is extremely lethal for the native crayfish species (Vaessen and Hollert 2015; Ludányi et al. 2016).

As we realized, the effects of *P. leniusculus* on other protected species lacks extensive investigation, but admittedly they can yield new, interesting results. The conservation of protected species and their habitats is a current issue and information about the risk factors may help to develop protection plans for national parks or environmental protection agencies.

In their study, Ludányi et al. (2016) found that *P. leniusculus* mainly occurred in fast flowing watercourses in the western part of the country and therefore the signal crayfish mostly affected macroinvertebrates associated with this type of water. This means that 12.5% of the investigated locations are suitable for *P. leniusculus* in Hungary. Our study clearly showed that the presence of *P. leniusculus* has impact on different macroinvertebrate groups which is consistent with other investigations (Moorhouse et al. 2014; Ruokonen et al. 2014; Ercoli et al. 2015). However, the identity of the most affected groups and species depends on the water type under study. In our study, Coleoptera, Gastropoda, Bivalvia, Heteroptera, Hirudinea, Plecoptera and Malacostraca (without Decapoda) were not significantly affected by the presence of crayfish while the *P. leniusculus* had effect on groups of Ephemeroptera, Odonata and Trichoptera. No effects on molluscs were found in our study and it seems to be in line with the laboratory findings of Rosewarne et al. (2016) who found that gastropods were the least preferred prey by the signal crayfish. Our study investigated the impact of crayfish in their outdoor environment where they could actively select their food. The observed absence of any effect on
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snails may indeed indicate that other organisms are preferred prey instead. Interestingly, there are studies with pronounced effects of signal crayfish on snails (Olden et al. 2009; Twardochleb et al. 2013; Rosewarne et al. 2016) and possibly the amount of available, alternative food items play a role here with hardly any effect on snails when other food items are abundant but with strong snail effect when other food items are scarce.

The number of species of the Odonata, Trichoptera and the total aquatic macroinvertebrate community were significantly lower in watercourse with crayfish, than in locations which have not been invaded yet. In our study, populations of Ephemeroptera and Trichoptera had statistically significant lower densities in the invaded watercourse. This result is completely in line with the study of Guan and Wiles (1998). The observed effect on the Ephemeroptera and Plecoptera taxa may be caused by the fact that these taxa also prefer habitats characterized by fine sediment accumulation and coarse organic matter. As a result, they strongly co-occur with the signal crayfish in these locations and thereby become a preferred food item. Nyström and Strand (1996) found that *P. leniusculus* selectively predate on sedentary taxa such as leeches (Hirudinea) and snails (Gastropoda).

Our study showed that signal crayfish *P. leniusculus* had a significantly negative impact on the native freshwater invertebrate community in western Hungary. Hence, it can be stated that signal crayfish form a real threat to Hungarian aquatic macroinvertebrate communities and threaten most of the aquatic macroinvertebrate groups which is manifested in a lower number of species and a lower species relative abundance. *P. leniusculus* is on the European list of Invasive Alien Species of Union concern ([https://eunis.eea.europa.eu/species/258987](https://eunis.eea.europa.eu/species/258987)) indicating the severeness of invasions. Yet, it seems that there is no control over the expansion of signal crayfish in Hungary. In order to assess whether these impacts are restricted to faster flowing waters, which means that surface water velocity is between 0.3 and 0.4 ms⁻¹ (Ludányi et al. 2016), only an adequate monitoring plan is required, providing more knowledge on this species with respect to biotic and abiotic preferences and aquatic macroinvertebrate composition is required. This way the most valuable aquatic habitats and communities can be protected with cross-border measures, by investigating the most affected watercourses, the occurrence of protected and non-protected aquatic species, with the main focus on the spread of the *P. leniusculus*.

Cooperation between nations could be the most effective way to address the issue of invasive species. An excellent practical example for this kind of protection can be found in Fennoscandia, where it came to fruition on different levels. The so-called controlled spreading of alien species, like *P. leniusculus*, would assure that the spreading of the species is restricted and controlled and thereby protect the native and protected aquatic invertebrate stocks through blocking the direct interactions between native species and alien crayfish species (Jussila and Edsman 2020). According to
the Swedish legislation, a possible way to attenuate the negative effect of *P. leniusculus* is the preservation of the native *Astacus astacus* populations (Jussila and Edsman 2020). As Jussila and Edsman (2020) also mentioned, Hungary has to count with the fact that alien species once established, will be nearly impossible to eradicate. In the Hungarian context, the monitoring of the affected watercourses and its tributaries and the installation of ecological barriers (Cowart et al. 2018; Krieg et al. 2021) and application of physical removal (Moorhouse et al. 2014) would be the best onset to impede the spreading of *P. leniusculus*.

In conclusion, further studies on how to stop the spreading of *P. leniusculus* and more knowledge on habitat usage and the effects of this species, especially on protected species may give clue information for management in the future.

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**Authors’ contribution**

ML: research conceptualization, investigation and data collection, data analysis and interpretation, writing, review and editing, photography; ETHMP and IR: data analysis and interpretation, review and editing; BK and ZM: research conceptualization, sample design and methodology, investigation and data collection, funding provision; AG: systematization of data, database organization; TM: data analysis and interpretation, writing – review and editing.

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**Supplementary material**

The following supplementary material is available for this article:

**Table S1.** Details of the distribution of *Pacifastacus leniusculus* in Hungarian watercourses.