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RESEARCH PAPER OPEN ACCESS

Three crayfish species of different origin in a medium-sized river system: a new state of affairs

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Abstract – In view of contemporary changes in aquatic environments, determining the distribution of both native and emerging invasive crayfish species is increasingly important. In central Europe, the three invasive crayfish species of the signal crayfish *Pacifastacus leniusculus* (Dana, 1852), the spiny-cheek crayfish *Faxonius limosus* (Rafinesque, 1817) and the red swamp crayfish *Procambarus clarki* (Girard, 1852) are of North American origin. The spiny-cheek crayfish was first brought to the southern Baltic basin at the end of nineteenth century, and its expansion ensued rapidly. At the same time, the indigenous species of the noble crayfish *Astacus astacus* (Linnaeus, 1758) began to disappear. The spread of the signal crayfish started in the second half of twentieth century; however, it has progressed strongly in recent years. Latest studies of fish fauna in the Drwęca River system, a tributary of the lower Vistula River, have simultaneously revealed new information on the occurrence of crayfish. The most widespread was spiny-cheek crayfish found at ten sites throughout the river basin. The second alien species, the signal crayfish, was noted in four locations in the upper part of the river system, but no mixed populations were noted. A particularly valuable result of the study was the discovery of an unknown site of noble crayfish in a small stream.

Keywords: Invasive crayfish / species introduction / noble crayfish / habitat requirements / river

Résumé – Trois espèces d'écrevisses d'origine différente dans un système fluvial de taille moyenne: un nouvel état des lieux. Compte tenu des changements contemporains dans les environnements aquatiques, il est de plus en plus important de déterminer la distribution des espèces d'écrevisses invasives, qu'elles soient indigènes ou nouvelles. En Europe centrale, les trois espèces d'écrevisses envahissantes que sont l'écrevisse signal *Pacifastacus leniusculus* (Dana, 1852), l'écrevisse américaine *Faxonius limosus* (Rafinesque, 1817) et l'écrevisse de Louisiane *Procambarus clarki* (Girard, 1852) sont d'origine nord-américaine. L'écrevisse américaine a été introduite dans le sud du bassin de la Baltique à la fin du XIX^{e} siècle, et son expansion a été rapide. Dans le même temps, les espèces indigènes d'écrevisses nobles *Astacus astacus* (Linnaeus, 1758) ont commencé à disparaître. La propagation de l'écrevisse signal a commencé dans la seconde moitié du XX^{e} siècle, mais elle a fortement progressé ces dernières années. Les dernières études de la faune piscicole dans le système de la rivière Drwęca, un affluent de la basse Vistule, ont simultanément révélé de nouvelles informations sur l'occurrence des écrevisses. L'espèce la plus répandue était l'écrevisse américaine, présente sur dix sites dans tout le bassin fluvial. La deuxième espèce exotique, l'écrevisse signal, a été observée en quatre endroits dans la partie supérieure du système fluvial, mais aucune population mixte n'a été notée. Un résultat particulièrement précieux de l'étude a été la découverte d'un site inconnu d'écrevisses nobles dans un petit cours d'eau.

Mots clés : Écrevisse invasive / introduction d'espèces / écrevisse noble / exigences en matière d'habitat / rivière

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1 Introduction

Currently, at least five crayfish (*Crustacea, Decapoda*) species occur in the freshwaters of Central Europe, including Poland. Among them, only the noble crayfish *Astacus astacus* (Linnaeus, 1758) is a native species historically (Kossakowski, 1966). Originally, this species was widespread and was of great economic importance. Since the first half of twentieth century, large quantities of noble crayfish yields have been exported to western Europe (Leńkowa, 1962). Unfortunately, in the second half of the twentieth century a crayfish plague pathogen, *Aphanomyces astaci* spread throughout many regions of Europe causing the disappearance of indigenous crayfish populations. Actually, despite their relatively vast ranges in Europe, both the noble and also the narrow-clawed crayfish *Astacus leptodactylus* are in strong decline (Souty-Grosset *et al.*, 2006; Kouba *et al.*, 2014).

Alien crayfish species which occur in Central Europe, *i.e.*, the spiny-cheek crayfish Faxonius limosus (Rafinesque, 1817), the signal crayfish Pacifastacus leniusculus (Dana, 1852) and the red swamp crayfish Procambarus clarki (Girard, 1852) are of North American origin (Kozák *et al.*, 2015). The spiny-cheek crayfish was the first of the species introduced in an attempt to replace the noble crayfish (Leńkowa, 1962; Holdich and Black, 2007). The first individuals were released in the late nineteenth century into a tributary of the Warta River (Odra River system, Baltic basin), and from here the species expanded its range of occurrence. While the spiny-cheek crayfish is resistant to the crayfish plague, can be a carrier of it. Thus, the decline of the native crayfish species continued.

The signal crayfish was the second species to be introduced into many regions beyond its natural range of occurrence because of its advantageous culture parameters and functional values in comparison with other species, *e.g.*, large size, fast growth rates, environmental tolerance and resistance (Lewis, 2002; Holdich *et al.*, 2009). This animal was brought to Sweden (Europe) in the late 1950s, and in the nearly seventy years since then has either deliberately or accidentally spread over a substantial part of the continent (Henttonen and Huner, 1999). Currently the signal crayfish is considered to be the most widely-distributed alien crayfish, and it occurs in at least twenty European countries (Kouba *et al.*, 2014). Moreover, the species has a large environmental impact on native crayfish species (Gherardi, 2007; Holdich *et al.*, 2009; Savini *et al.*, 2010; Galib *et al.*, 2021).

The consequences that environmental changes, especially those related to the climate, have on living resources, including aquatic organisms, must be carefully recorded (Harrod, 2016; Rolls *et al.*, 2017). Research of fish fauna conducted in freshwaters can simultaneously provide new data on the occurrence of other taxa associated with aquatic environments, including crayfish (Skov *et al.*, 2011). Our most recent, detailed studies in the Drwęca River system (northern Poland, Baltic Sea basin), revealed the information on crayfish occurrence in this basin. The aim of this study was to present the latest data on the distribution of three crayfish species in the surveyed area.

2 Material and methods

The Drwęca is a medium-sized river, and the largest tributary of the lower Vistula River (below the dam at Włocławek). The river is 231 km long, and its catchment area is 5697 km^2. The upper part of the system is located in the Warmia and Masuria, whereas the lower section is included in Kuyavia and Pomerania regions. The area has a typical postglacial shape with numerous undulating expanses and lakelands. The highest altitude reaches 312 m.a.s.l. The Drwęca River has numerous tributaries, of which the longest is the Wel River (107 km). The Lake Jeziorak (3219 ha) is the largest of many lakes in the river basin. The region has been under human pressure for centuries, and agriculture areas cover 88% of the Drwęca catchment. In addition, numerous fish farms are located in the river system. The best preserved natural habitats are mainly in stream and river valleys that are covered by various forms of protection. In the Drwęca River and some inflows, nature reserve has been established in which migratory fish species, mainly salmonids, are protected.

Data on crayfish were collected together with fish in the Drwęca River system in the 2015–2018 period (Radtke *et al.*, 2019). Surveys were carried out using the standard electrofishing method in rivers and streams (Backiel and Penczak, 1989). This method is considered to be convenient and effective for catching crayfish, especially those in flowing waters (Price and Welch, 2009; Reid and Devlin, 2014, Larson and Olden, 2016). The shallow sites were sampled by wading upstream along a section of 150 m (115−250 V, DC), whereas in deeper stretches samples were collected from a boat drifting downstream at a distance of 500 m (200 V, smoothed AC). When crayfish appeared, the species and abundance were recorded (at higher numbers abundance was estimated as >20, >30, or >40 individuals). Additionally, one site (in the Struga Rychnowska, a small stream in the Drwęca River system) was repeated in 2019 and individuals were measured (total length, TL, mm). Altogether, 104 sites were examined throughout the Drwęca River system (Fig. 1). A list of fish species detected together with crayfish at individual sites are presented as supplementary data (Tab. S1).

3 Results

Except fish and lampreys, three species of crayfish have been found at 15 sites in the entire Drwęca River system (Fig. 1). There were two alien species, *i.e.*, the spiny-cheek and the signal crayfish. Also the noble crayfish, the one native species was noted. The spiny-cheek was the most widespread in the river system as it was found at ten locations (Tab. 1). In most positions just a few individuals, both juveniles and adults, were observed. The habitats of these species were located mainly downstream from lakes, and they were clearly differentiated in terms of morphometry and substrate. The number of spiny-cheek crayfish was the highest in the small stream Iłga, between relatively large lakes, *i.e.* the Gil Lake and the Drwęckie Lake (Tab. 1, Fig. 1).

New sites of signal crayfish were found in the upper part of the Drwęca system. Among four stretches, this species was most abundant in the small, rapid stream Grabiczek (Tab. 1). The presence of numerous individuals, both adults and juveniles, indicated that habitat and breeding conditions were good for *P. leniusculus*; however, in the remaining streams, this species was not abundant.

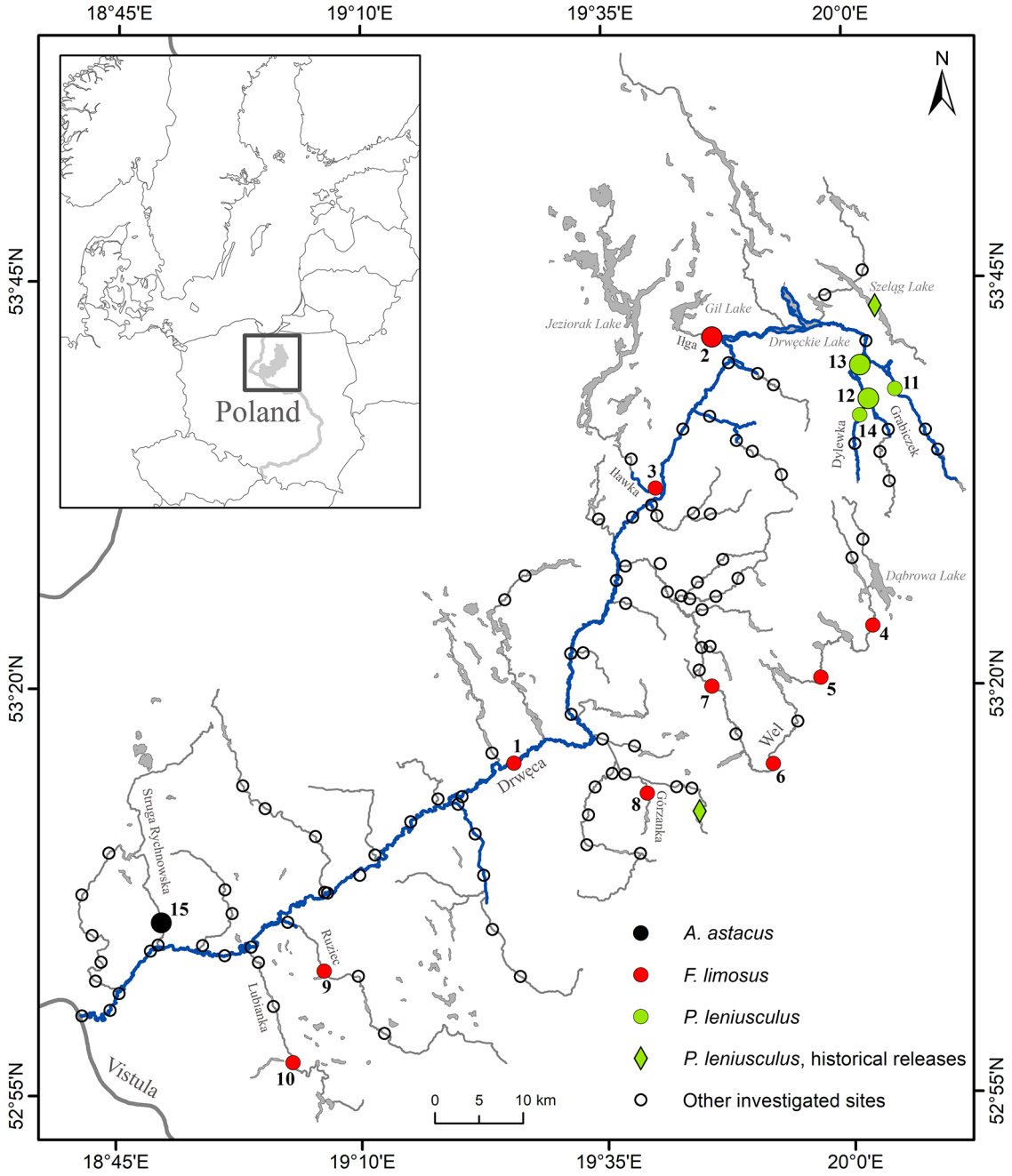

Fig. 1. Distribution of investigated sites in the Drwęca River system. Colour circles: sites where the crayfish species were detected (numeration as in Tab. 1, small circles: <20 specimens, big circles: >20 specimens); empty circles: sites where crayfish were not detected; diamonds: sites of historical release of *P. leniusculus*. Stream sections of the nature reserve in the Drwęca River system are marked in blue.

Unexpectedly, a new noble crayfish location was noted in the central course of the Struga Rychnowska stream (Fig. 1). Individuals measured from 3.9 to 10.6 cm and the length-frequency distribution indicated the presence of at least three age groups (Fig. 2). The species was quite numerous, and its relative density (0.2 ind. m^{-2}, one pass) revealed suitable. habitat conditions for *A. astacus*. (Tab. 1). This stream segment is isolated from the main river in its lower course by the old mill weir. No mixed populations of crayfish species were found in particularly sites in the whole Drwęca River system. Moreover, at the sites with crayfish, the structure of fish species was highly diversified and no simple interdependencies could be observed (see Appendix).

4 Discussion

The spiny-cheek crayfish was introduced into the lower Vistula River system before 1911 (Kulmatycki, 1935). At the time, crayfish were noted in a few lakes located in the basins of the Wda and Brda rivers, which are left-bank tributaries of the Vistula. In Masurian lakes the spiny-cheek crayfish was

Table 1. Description of crayfish sites in the Drwęca River system and the number of captured specimens.

Species / Stream name	Site number	Sampling date	Latitude (N)	Longitude (E)	Mean width (m)	Mean depth (m)	Dominating substrate	Number of specimens
Faxonius limosus								
Drwęca	1	03.10.2018	53.25761	19.42744	20.0	2.0	Sand	1 (adult)
Iłga	2	06.09.2018	53.69066	19.77679	4.5	0.2	Sand	>20 (adults + juveniles)
Iławka	3	24.09.2015	53.53731	19.67278	6.0	0.4	Sand	6 (adults + juveniles)
Wel	4	30.08.2017	53.39369	20.04155	6.0	0.3	Pebbles	2 (adults)
Wel	5	30.08.2017	53.34255	19.95244	6.5	0.4	Pebbles	8 (adults + juveniles)
Wel	6	31.08.2017	53.25507	19.86876	7.0	0.6	Sand	7 (adults + juveniles)
Wel	7	30.08.2017	53.33415	19.76514	10.0	0.4	Gravel	1 (adult)
Górzanka	8	26.09.2018	53.2256	19.65296	5.0	0.3	Sand	6 (adults + juveniles)
Ruziec	9	24.10.2018	53.04432	19.10226	3.2	0.2	Sand	4 (adults + juveniles)
Lubianka	10	24.10.2018	52.95106	19.05091	2.5	0.2	Sand	1 (adult)
Pacifastacus leniusculus								
Drwęca	11	05.09.2018	53.63633	20.08522	6.0	1.0	Sand	4 (adults + juveniles)
Grabiczek	12	05.09.2018	53.62589	20.04071	4.0	0.4	Gravel	>40 (adults + juveniles)
Grabiczek	13	06.09.2018	53.66331	20.02811	6.5	0.3	Gravel	>30 (adults + juveniles)
Dylewka	14	05.09.2018	53.62317	20.0375	3.5	0.1	Pebbles	2 (adults)
Astacus astacus								
Struga Rychnowska	15	06.08.2019	53.09508	18.82638	2.5	0.2	Gravel	>40 (adults + juveniles)

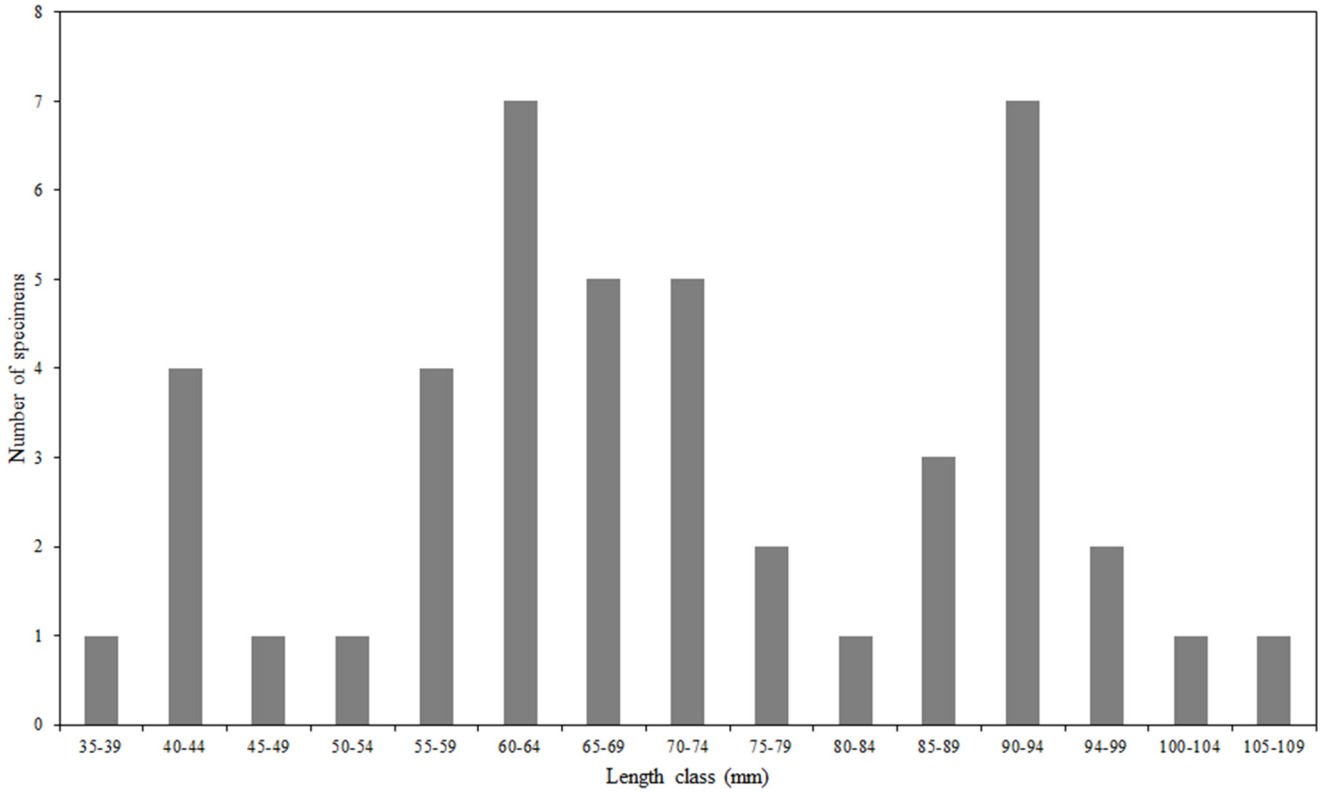

Fig. 2. Length distribution of noble crayfish (*A. astacus)* in the Struga Rychnowska.

observed as early as the 1950s; however, it was not noted in the lakes and rivers of the Drwęca River basin until the 1970s (Leńkowa, 1962; Kossakowski and Orzechowski, 1975). The species appeared in this system most likely at the end of twentieth century, when it gradually overtook the river basin and associated lakes. Currently, *F. limosus* is considered to be the most common species in the region (Śmietana, 2011a).

The signal crayfish was first released into Polish waters in the early 1970s (Kossakowski *et al.*, 1978) and subsequent attempts were continued into the 1990s through introductions

Table 2. Temperature requirements (°C) and basic reproductive characteristics of three crayfish species inhabiting the Drwęca River system.

Parameters	*Astacus astacus*	*Pacifastacus leniusculus*	*Faxonius limosus*	References
Temperature preference	16.0–21.0			Kozák *et al.*, 2015
Optimum growth temperature	19.0–20.0	19.0–23.0	24.0–25.0	Firkins and Holdich, 1993; Kouba *et al.*, 2010; Simčič *et al.*, 2014
Upper temperature tolerance limit[1]	23.0–25.0	25.0–28.0	30.0	Kivivuori, 1994; Simčič *et al.*, 2014; Kozák *et al.*, 2015
Upper lethal temperature[2]	30.0–33.0	32.0–35.0		Becker *et al.*, 1975; Kozák *et al.*, 2015
Age of sexual maturity	3–5	2–3	1–2	Kozák *et al.*, 2015
Average ovarian fecundity (eggs per female)	149–242	361–371	447	Stypińska, 1978; Chybowski, 2013
Average pleopodal fecundity (eggs per female)	80–200	200–400	200–300	Skurdal *et al.*, 2011; Kozák *et al.*, 2015

[1] – threshold above which the species reveals avoidance or physiological disturbance.
[2] – temperatures determined by different methods.

into several Mazurian lakes and fish farms (Krzywosz, 1994). As a result, an abundant signal crayfish population has been established in a small tributary of the Pasłęka River, which neighbors the Drwęca catchment (Krzywosz, 2006b). Moreover, in the second half of the last century the species was also stocked into two facilities located in the Drwęca River system, which led to its escape into open waters (Fig. 1). However, there was no confirmation on the persistence of this crayfish species in the longterm following the first attempts to culture them (Krzywosz *et al.*, 1995; Śmietana, 2011b). Until recently, the signal crayfish occurred in at least 18 natural sites in Poland (Śmietana, 2011b), although the last reports have indicated that it is much more widely distributed. Lately, this species has expanded strongly in the Wieprza River drainage (Pomerania coast, southern Baltic Sea basin) following its introduction to fish farms near Kępice and Miastko in the late 1990s (Dobrzycka-Krahel *et al.*, 2017). Additionally, a fairly large number of signal crayfish have been recorded in a few Masurian lakes (Ulikowski and Chybowski, 2018). Recent new sightings of this species in the upper part of the Drwęca River system are probably the result of the crayfish escaping from breeding farms.

In the light of contemporary changes occurring in aquatic environments, determining the presence both native and invasive species is increasingly important (Capinha *et al.*, 2013; Harrod, 2016; Rolls *et al.*, 2017). Currently, with increased temperatures and other environmental changes, high tolerance determines the possibilities for species to expand. The spiny-cheek crayfish in particular has a high thermal optimum and the highest fecundity rate, including early sexual maturation (Tab. 2). It is an ubiquitous species that can even survive polluted and saline waters (Jaszczołt and Szaniawska, 2011). The signal crayfish is also characterized by a similarly high reproduction rate and thermal tolerance (Tab. 2). Certainly, these attributes are the cause of the rapid expansion of signal crayfish in the Wieprza River basin (Dobrzycka-Krahel *et al.*, 2017). The noble crayfish prefers cool/cold water, and its fecundity index is the lowest among the species occurring in the Drwęca River system (Tab. 2). Additionally, the species is susceptible to crayfish plague, thus, it is also being supplanted by invasive, resistant species as a result of direct pressure and inter-specific competition (Söderbäck, 1991; Gherardi *et al.*, 2002; Schulz *et al.*, 2006; Holdich and Pöckl, 2007). In this context, finding new noble crayfish location in the stream Struga Rychnowska was exceptionally valuable. Examples of native crayfish population recovers following crayfish plague has been observed in several countries (Fürst, 1995; Kokko *et al.*, 2012; Kozubiková-Balcarová *et al.*, 2014).

Since the mid twentieth century, few noble crayfish sites have been recorded in northeastern Poland (Leńkowa, 1962; Kossakowski and Orzechowski, 1975). In the Drwęca River system this species formerly occurred in two isolated lakes: Grodzieńskie and Okonin, located about 10 km from the newly detected site in the Struga Rychnowska, but there is no direct connection among them, thus, to date the presence of the noble crayfish in the Drwęca River system has not been confirmed in the literature. Whereas, after the current research, it turned out that there is a small fish farm above the site in Struga Rychnowska where an attempt to culture a noble crayfish was done since the end of the 20th century. It is therefore the likely source of origin for this population. According to a local fish breeder, this species was previously present in the Struga Rychnowska and became extinct in the mid-1970s due to pollution. The current persistence of the noble crayfish population there indicates that the stream is free from crayfish plague and pollution, which are the basic requirements in successful restitution (Śmietana *et al.*, 2004).

Alien crayfish species can have a strong impact on entire ecosystems, including on fish (Reynolds 2011). Specifically, because of vigorous activity the signal crayfish can transform riverbeds, vegetation, and the species structures of invertebrates and fish in areas in which they settled (Crawford *et al.*, 2006; Peay *et al.*, 2009; Mathers *et al.*, 2016). In locations inhabited by salmonids, crayfish species can cause significant losses of fish eggs, larvae, and fry through predation and competition for sheltering places (Griffiths *et al.*, 2004; Edmonds *et al.*, 2011; Setzer *et al.*, 2011; Findlay *et al.*, 2015). Moreover, the signal crayfish can modify spawning substrate for gravel-breeding fish and limit food resources through its strong tendency to dig burrows (Guan, 1994; Harvey *et al.*, 2011; Johnson *et al.*, 2011). Studies before and after *P. leniusculus* invasion in some upland streams indicate a decline in the abundance of benthic fish and juvenile salmonids

(Galib *et al.*, 2021). Consequently, considering that the Drwęca River catchment is a nature reserve, signal crayfish expansion poses a threat to protected salmonid fishes inhabiting this area. Simultaneously, invasive species such as the spiny-cheek crayfish, can be an important component of predatory fish diet (Czarnecki *et al.*, 2003; Haertel-Borer *et al.*, 2005).

In the mid twentieth century there were pronounced changes in the distribution of crayfish in the waters of central Europe, and the disappearance of the noble crayfish was particularly acute. The wide range of occurrence of spiny-cheek crayfish and the increasing numbers of signal crayfish sites are evidence of high adaptability of these species to growing changes because of greater reproductive potential, faster growth rates and higher environmental tolerance in comparison to native European species (Gherardi, 2007; Holdich *et al.*, 2014). Hence, they can displace indigenous inhabitants, such as the noble crayfish, that are less resistant to environmental change. The signal crayfish is also capable of dominating the spiny-cheek crayfish in mixed populations (Krzywosz, 2006a; Hudina *et al.*, 2011; Ulikowski and Chybowski, 2018). These species-specific interactions, divergent requirements, and spatial isolation (barriers) could explain the separation of the individual crayfish taxa in the Drwęca River system.

Certainly, progressing changes in freshwater environments will affect the future state of all astacofauna (Capinha *et al.*, 2013; Kouba *et al.*, 2014). Increased water temperatures and decreased water flow are anticipated in the rivers in the region studied (Kundzewicz *et al.*, 2018, Pniewski *et al.*, 2018). Furthermore, crayfish are increasingly being viewed as suitable animals for aquaculture and also for aquarium breeding. Quite recently a new invasive species, the red swamp crayfish Procambarus clarki (Girard, 1852), has been recorded at several sites in the upper and middle segments of the Vistula River basin, which are the potential sites for specie's spread to the lower catchment (Maciaszek *et al.*, 2019). Globally, this animal is one of the worst invasive crayfish species (Gherardi, 2007; Chucholl, 2011; Capinha *et al.*, 2013; Twardochleb *et al.*, 2013). Accordingly, the actual state of the crayfish populations in the Drwęca River system seems to be unstable, therefore, further changes can be anticipated in the distribution and expansion of existing and new alien species. It can be also assumed that in the Drwęca River system there are other localities of crayfish occurrence that were not detected by the methods used, especially in deep sections of the rivers. Nevertheless, the new site of noble crayfish occurrence identified in this study requires special maintenance.

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Conflicts of interest. The authors declare that they have no conflicts of interest.

Ethics and permits

All research pertaining to this article did not require any research permit(s).

Supplementary Material

Table S1. Appendix list of co-occurring fish species in sites where the crayfish specimens were detected (the dominant fish species are in bold). Numeration of sites as in Table 1.

The Supplementary Material is available at https://www.kmae-journal.org/10.1051/kmae/2021025/olm.

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References

Backiel T, Penczak T. 1989. The fish and fisheries in the Vistula River and its tributary, the Pilica River. In: Dodge DP, ed. Proceedings of the International Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences, 106: 488–503.

Becker CD, Genoway RG, Merrill JA. 1975. Resistance of a northwestern crayfish *Pacifastacus leniusculus* (Dana), to elevated temperatures. *Trans Am Fish Soc* 104: 374–387.

Capinha C, Larson ER, Tricarico E, Olden JD, Gherardi F. 2013. Effects of climate change, invasive species, and disease on the distribution of native European crayfishes. *Conserv Biol* 27: 731–740.

Chucholl C. 2011 Population ecology of alien "warm water" crayfish (*Procambarus clarki*) in a new cold habitat. *Knowl Manag Aquat Ecosyst* 401: 29.

Chybowski Ł. 2013. Absolute fecundity of two populations of signal crayfish, *Pacifastacus leniusculus* (Dana). *Arch Pol Fish* 21: 357–362.

Crawford L, Yeomans WE, Adams CE. 2006. The impact of introduced signal crayfish *Pacifastacus leniusculus* on stream invertebrate communities. *Aquat Conserv Mar Freshw Ecosyst* 16: 611–621.

Czarnecki M, Andrzejewski W, Mastyński J. 2003. The feeding selectivity of Wels (*Silurus glanis* L.) in Lake Góreckie. *Arch Pol Fish* 11: 141–147.

Dobrzycka-Krahel A, Skóra ME, Raczyński M, Szaniawska A. 2017. The signal crayfish *Pacifastacus leniusculus* – distribution and invasion in the southern Baltic coastal river. *Pol J Ecol* 65: 445–452.

Edmonds NJ, Riley WD, Maxwell DL. 2011. Predation by *Pacifastacus leniusculus* on the intra-gravel embryos and emerging fry of *Salmo salar*. *Fisheries Manag Ecol* 18: 521–524.

Findlay JD, Riley WD, Lucas MC. 2015. Signal crayfish (*Pacifastacus leniusculus*) predation upon Atlantic salmon (*Salmo salar*) eggs. *Aquat Conserv Mar Freshw Ecosyst* 25: 250–258.

Firkins I, Holdich DM. 1993. Thermal studies with three species of freshwater crayfish. *Freshw Crayfish* 9: 241–248.

Fürst M. 1995. On the recovery of *Astacus astacus* L. populations after an epizootic of the crayfish plague (*Aphanomyces astaci* Shikora). *Freshw Crayfish* 8: 565–576.

Galib SM, Findlay JS, Lucas MC. 2021. Strong impacts of signal crayfish invasion on upland stream fish and invertebrate communities. *Freshw Biol* 66: 223–240.

Gherardi F. 2007. Understanding the impact of invasive crayfish. In: Gherardi F, ed. Biological invaders in inland waters: profiles, distribution and threats. Invading Nature: Springer Series In Invasion Ecology 2, Springer, Dordrecht, The Netherlands, 507–542.

Gherardi F, Smietana P, Laurent P. 2002. Interactions between non-indigenous and indigenous crayfish species. *Bull Fr Pêche Piscic* 367: 899–907.

Griffiths SW, Collen P, Armstrong JD. 2004. Competition for shelter among over-wintering signal crayfish and juvenile Atlantic salmon. *J Fish Biol* 65: 436–447.

Guan R-Z. 1994. Burrowing behaviour of signal crayfish, *Pacifastacus leniusculus* (Dana), in the River Great Ouse, England. *Freshw Forum* 4: 155–168.

Haertel-Borer SS, Zak D, Eckmann R, Baade U, Hölker F. 2005. Population density of the crayfish, *Orconectes limosus*, in relation to fish and macroinvertebrate densities in a small mesotrophic lake – implications for the lake's food web. *Int Rev Hydrobiol* 90: 523–533.

Harrod C. 2016. Climate change and freshwater fisheries. In: Craig JF, ed. Freshwater Fisheries Ecology. John Willey & Sons, Ltd., Chichester, UK, 641–694.

Harvey GL, Moorhouse TP, Clifford NJ, Henshaw AJ, Johnson MF, Macdonald DW, Reid I, Rice SP. 2011. Evaluating the role of invasive aquatic species as drivers of fine sediment-related river management problems: The case of the signal crayfish (*Pacifastacus leniusculus*). *Prog Phys Geogr* 35: 517–533.

Henttonen P, Huner JV. 1999. The introduction of alien species of crayfish in Europe: A historical introduction. In: Gherardi F, Holdich DM, ed. Crayfish in Europe as alien species: How to make the best of the bad situation? A.A. Balkema, Rotterdam, The Netherlands, 13–22.

Holdich DM, Black J. 2007. The spiny-cheek crayfish, *Orconectes limosus* (Rafinesque, 1817) [Crustacea: Decapoda: Cambaridae], digs into the UK. *Aquat Invasions* 2: 1–15.

Holdich DM, James J, Jackson C, Peay S. 2014. The North American signal crayfish, with particular reference to its success as an invasive species in Great Britain. *Ethol Ecol Evol* 26: 232–262.

Holdich DM, Pöckl M. 2007. Invasive crustaceans in European inland waters. In: Gherardi F, ed. Biological invaders in inland waters: profiles, distribution and threats. Invading Nature: Springer SeriesInInvasion Ecology 2, Springer, Dordrecht, The Netherlands, 29–75.

Holdich DM, Reynolds JD, Souty-Grosset C, Sibley PJ. 2009. A review of the ever increasing threat to European crayfish from non-indigenous crayfish species. *Knowl Manag Aquat Ecosyst* 11: 394–395.

Hudina S, Galić N, Roessink I, Hock K. 2011. Competitive interactions between co-occurring invaders: identifying asymmetries between two invasive crayfish species. *Biol Invasions* 13: 1791–1803.

Jaszczołt J, Szaniawska A. 2011. The spiny-cheek crayfish *Orconectes limosus* (Rafinesque, 1817) as an inhabitant of the Baltic Sea – experimental evidences for its invasion of brackish waters. *Oceanol Hydrobiol Stud* 40: 52–60.

Johnson MF, Rice SP, Reid I. 2011. Increase in coarse sediment transport associated with disturbance of gravel river beds by signal crayfish (*Pacifastacus leniusculus*). *Earth Surf Process Landf* 36: 1680–1692.

Kivivuori LA. 1994. Temperature selection behaviour of cold- and warm-acclimated crayfish [*Astacus astacus* (L.)]. *J Therm Biol* 19: 291–297.

Kokko H, Koistinen L, Harlioğlu MM, Makonen J, Aydin H, Jussila J. 2012. Recovering Turkish narrow clawed crayfish (*Astacus leptodactylus*) populations carry Aphanomyces astaci. *Knowl Manag Aquat Ecosyst* 404: 12.

Kossakowski J. (1966) Raki. [Crayfish]. PWRiL, Warszawa.

Kossakowski J, Mnich M, Kossakowski G. 1978. The first introduction of the crayfish, *Pacifastacus leniusculus* Dana into Polish waters. *Freshw Crayfish* 4: 195–196.

Kossakowski J, Orzechowski B. 1975. Crayfish *Orconectes limosus* in Poland. *Freshw Crayfish* 2: 31–47.

Kouba A, Kanta J, Buřič M, Policar T, Kozák P. 2010. The effect of water temperature on the number of moults and growth of juvenile Noble Crayfish, *Astacus astacus* (Linnaeus). *Freshw Crayfish* 17: 37–41.

Kouba A, Petrusek A, Kozák P. 2014. Continental-wide distribution of crayfish species in Europe: update and maps. *Knowl Manag Aquat Ecosyst* 413: 05.

Kozák P, Ďuriš Z, Petrusek A, Buřič M, Horká I, Kouba A, Kozubiková-Balcarová E, Policar T. 2015. Crayfish biology and culture. University of South Bohemia in České Budějovice, Vodňany.

Kozubiková-Balcarová E, Beren L, Ďuriš Z, Fischer D, Horká I, Svobodá J, Petrusek A. 2014. Status and recovery of indigenous crayfish populations after recent crayfish plague outbreaks in the Czech Republic. *Ethol Ecol Evol* 26: 299–319.

Krzywosz T. 1994. Introdukcja raka sygnałowego, *Pacifastacus leniusculus* Dana, do wód Polski (Introduction of the signal crayfish, *Pacifastacus leniusculus* Dana, to Polish waters). *Rocz Nauk PZW* 7: 81–93.

Krzywosz T. 2006a. Co-occurrence of the signal crayfish (*Pacifastacus leniusculus* (Dana)) and the spiny-cheek crayfish (Orconectes limosus (Raf.)) in a foothill-like river (northern Poland). *Arch Pol Fish* 14: 309–316.

Krzywosz T. 2006b. Evaluation of changes in the abundance of three catchable crayfish species in Lake Pobłędzkie (northern Poland). *Arch Pol Fish* 14: 131–140.

Krzywosz T, Chybowski Ł, Ulikowski D. 1995. Rak sygnałowy w Poland – historia, stan obecny, perspektywy (Signal crayfish in Poland–history, current status, perspectives). *Komun Ryb* 1: 5–8.

Kulmatycki W. 1935. *Cambarus affinis* Say – rak amerykański, nowy mieszkaniec wód Pomorza i Wielkopolski (*Cambarus affinis* Say – American crayfish, a new inhabitant of waters of Pomerania and Greater Poland). *Przeg Ryb* 8: 367–374.

Kundzewicz ZW, Pniewski M, Mezghani A, Okruszko T, Pińskwar I, Kardel I, Hov O, Szczesniak M, Szwed M, Benestad RE, Marcinkowski P, Graczyk D, Dobler A, Forland EJ, O'Keefe J, Choryński A, Parding KM, Haugen JE. 2018. Assessment of climate change and associated impact on selected sectors in Poland. *Acta Geophys* 66: 1509–1523.

Larson ER, Olden JD. 2016. Field sampling techniques for crayfish. In: Longshaw M, Stebbing P (eds) Biology and ecology of crayfish, CRC Press, Boca Raton, Florida, 287–323

Leńkowa A. 1962. Badania nad przyczynami zaniku, sposobami ochrony i restytucją raka szlachetnego *Astacus astacus* (L.) w związku z rozprzestrzenianiem się raka amerykańskiego *Cambarus affinis* Say (Research on the crayfish, *Astacus astacus* L., the causes of its disappearance, and the measures for its preservation and restitution in connection with the spreading of the American species *Cambarus affinis* Say). *Ochrona Przyr* 28: 1–38.

Lewis SD. 2002. Pacifastacus. In: Holdich DM, ed. Biology of freshwater crayfish, Blackwell Science, Oxford, 511–540.

Maciaszek R, Bonk M, Strużyński W. 2019. New records of the invasive red swamp crayfish *Procambarus clarki* (Girard, 1852) (Decapoda: Cambaridae) from Poland. *Knowl Manag Aquat Ecosyst* 420: 39.

Mathers KL, Chadd RP, Dunbar MJ, Extence CA, Reeds J, Rice SP, Wood PJ. 2016. The long-term effects of invasive signal crayfish

(*Pacifastacus leniusculus*) on instream macroinvertebrate communities. *Sci Total Environ* 556: 207–218.

Peay S, Guthrie N, Spees J, Nilsson E, Bradley P. 2009. The impact of signal crayfish (*Pacifastacus leniusculus*) on the recruitment of salmonid fish in a headwater stream in Yorkshire, England. *Knowl Manag Aquat Ecosyst* 395: 12.

Pniewski M, Marcinkowski P, Kundzewicz ZW. 2018. Trend detection in river flow indices in Poland. *Acta Geophys* 66: 347–360.

Price JE, Welch SM. 2009. Semi-quantitative methods for crayfish sampling: sex, size, and habitat bias. *J Crustac Biol* 29: 208–216.

Radtke G, Bernas R, Dębowski P, Morzuch J, Skóra M. 2019. Ichtiofauna systemu rzeki Drwęcy (Fish fauna of the Drwęca river system). *Rocz Nauk PZW* 32: 5–56.

Reid SM, Devlin J. 2014. Effectiveness of stream sampling methods in capturing non-native Rusty Crayfish (*Orconectes rusticus*) in Ontario. *Can Field-Nat* 128: 111–118.

Reynolds JD. 2011. A review of ecological interactions between crayfish and fish, indigenous and introduced. *Knowl Manag Aquat Ecosyst* 401: 10.

Rolls RJ, Hayden B, Kahilainen KK. 2017. Conceptualising the interactive effects of climate change and biological invasions on subarctic freshwater fish. *Ecol Evol* 7: 4109–4128.

Savini D, Occhipinti-Ambrogi A, Marchini A, Tricarico E, Gherardi F, Olenin S, Gollasch S. 2010. The top 27 animal alien species introduced into Europe for aquaculture and related activities. *J Appl Ichthyol* 26: 1–7.

Schulz HK, Śmietana P, Maiwald T, Oidtmann B, Schulz R. 2006. Case studies on the co-occurrence of Astacus astacus (L.) and Orconectes limosus (Raf.): snapshots of a slow displacement. *Freshw Crayfish* 15: 212–219.

Setzer M, Norrgard JR, Jonsson T. 2011. An invasive crayfish affects egg survival and the potential recovery of an endangered population of Arctic charr. *Freshw Biol* 56: 2543–2553.

Simčič T, Pajk F, Jaklič M, Brancelj A, Vrezec A. 2014. The thermal tolerance of crayfish could be estimated from respiratory electron transport system activity. *J Therm Biol* 41: 21–30.

Skov C, Aarestrup K, Sivebæk F, Pedersen S, Vrålstad T, Berg S. 2011. Non-indigenous signal crayfish *Pacifastacus leniusculus* are now common in Danish streams: preliminary status for national distribution and protective actions. *Biol Invasions* 13: 1269–1274.

Skurdal J, Hessen DO, Garnås E, Vøllestad LA. 2011. Fluctuating fecundity parameters and reproductive investment in crayfish: driven by climate or chaos? *Freshw Biol* 56: 335–341.

Śmietana P. 2011a. *Orconectes limosus* (Raf. 1817). In: Głowaciński Z, Okarma H, Pawłowski J, Solarz W. ed. Gatunki obce w faunie Polski. I. Przegląd i ocena stanu, (Alien species in the fauna of Poland. I. An overview of the status). Instytut Ochrony Przyrody PAN, Kraków, 206–210.

Śmietana P. 2011. *Pacifastacus leniusculus* (Dana, 1852). In: Głowaciński Z, Okarma H, Pawłowski J, Solarz W, ed. Gatunki obce w faunie Polski. I. Przegląd i ocena stanu (Alien species in the fauna of Poland. I. An overview of the status). Instytut Ochrony Przyrody PAN, Kraków, 201–205.

Śmietana P, Krzywosz T, Strużyński W. 2004. Review of the national restocking programme Active protection of native crayfish in Poland 1999–2001. *Bull Fr Pêche Piscic* 372–373: 289–299.

Söderbäck B. 1991. Interspecific dominance relationship and aggressive interactions in the freshwater crayfishes *Astacus astacus* (L.) and *Pacifastacus leniusculus* (Dana). *Can J Zool* 69: 1321–1325.

Souty-Grosset C, Holdich DM, Noël PY, Reynolds JD, Haffner P. 2006. Atlas of Crayfish in Europe. Museum national d'Histoire naturelle, Paris, France.

Stypińska M. 1978. Zmienność indywidualnej płodności absolutnej raków występujących w wodach Pojezierza Mazurskiego. (Individual variabilities in absolute fertility of crayfish occurring in the waters of the Masurian Lake District). *Rocz Nauk Rol* H, 98: 177–203.

Twardochleb LA, Olden JD, Larson ER. 2013. A global meta-analysis of the ecological impacts of nonnative crayfish. *Freshw Sci* 32: 1367–1382.

Ulikowski D, Chybowski Ł. 2018. Lake Hańcza – a new site for signal crayfish (*Pacifastacus leniusculus* Dana) occurrence in Poland. *Fish Aquat Life* 26: 141–147.

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