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NEXT STEP OF INVASION: THE ASIAN CLAM *CORBICULA FLUMINEA* (O. F. MÜLLER, 1774) (BIVALVIA: CYRENIDAE) COLONISES SMALLER SANDY RIVERS IN POLAND

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Abstract: This contribution presents a new observation of *Corbicula fluminea* (O. F. Müller) in Poland, found in 2021 in the Nida River, 40 km north of the nearest known locations. No species of the genus *Corbicula* has been previously recorded in the Nida, continuously explored for freshwater mussels since 2019. Live specimens were found in 20% of the collected sediment samples. The presence of young clams suggests that the population may be expanding rapidly through active movement or passive downstream drift. The clam was most likely introduced to the Nida by anglers as bait, but other possible pathways (e.g. transfer by kayaks or waterfowl, releases by aquarists) and the species' impact on invaded ecosystems and native bivalves are discussed.

Key words: invasive alien species; freshwater mussels; natural river; *Unio crassus*

INTRODUCTION

Corbicula fluminea (O. F. Müller, 1774) is considered to be one of the most invasive species of freshwater ecosystems (Minchin 2009, Sousa et al. 2014, Laverty et al. 2015), spreading very rapidly over the past century from its native East Asian range to all continents except Antarctica (Crespo et al. 2015). Genetic studies imply that expansive strains of *Corbicula* spp. are of hermaphroditic, androgenetic lineages with extremely low genetic diversity and originate from East Asian and South African populations (Park & Kim 2003, Pigneur et al. 2014, Gomes et al. 2016). The expansion of *C. fluminea* began on the North American West Coast, where in 1924 the species was first recorded outside of its native range, possibly brought there by immigrants from Asia as a food product (Counts 1981). In Europe, the species was first recorded at the mouth of Portuguese and French rivers in 1980 (Mouthon 1981) and is believed to have arrived with the ballast waters of trans-oceanic ships (Kinzelbach 1991, Karatayev et al. 2007). Since then, new records of this clam from increasing number of European rivers and lakes have been reported, showing its spread to the north and east of the continent (Crespo et al. 2015, Gomes et al. 2016). The place of origin of European populations is uncertain. Based on molecular evidence, it could be North or South America, but direct introduction from Asian populations into Europe has also been suggested, as well as introducing from Africa first into South America and then into Europe (Pigneur et al. 2014, Gomes et al. 2016).

The exceptional invasive success of *C. fluminea* is mainly related to its life cycle (rapid growth, early maturity, high fecundity, diverse reproductive strategies) and its high dispersal potential (McMahon 1999, Sousa et al. 2008, Crespo et al. 2015). Within its native range, *C. fluminea* reproduces both sexually and asexually. In the invaded range individuals are hermaphrodites, reproducing asexually through androgenesis and capable of self-fertilisation

(Kraemer 1978, Kraemer et al. 1986, Sousa et al. 2008, Pigneur et al. 2014). Adults incubate eggs and larvae within their inner demibranchs, and release completely formed juveniles (pediveliger larvae) into the water; these anchor to sediments, vegetation, or hard surfaces, and mature within 3–6 months. The lifespan of *C. fluminea* is 1–5 years, with typically two spawning periods, producing up to 70,000 juveniles per year (McMahon 1999, Sousa et al. 2008).

The passive dispersal of *C. fluminea* is usually attributed to human activities, mainly including transport in ballast/bilge water or by byssal attachment to boat hulls, transport with sand and gravel, use as food, ornament, tourist curiosity and fishing bait, fish stocking, aquaculture and aquarium trade/releases (McMahon 1999, Karatayev et al. 2007, Sousa et al. 2008, Lucy et al. 2012, Crespo et al. 2015). Its natural passive dispersal is associated with downstream drift of pediveligers and juveniles with water current or their transport by byssal attachment to floating objects, fish, birds, and mammals (Prezant & Chalermwat 1984, McMahon 1999, Sousa et al. 2008). Endozoochorous dispersal in the guts of fish or birds, although possible, is a rather rare occurrence (Gatlin et al. 2013, Coughlan et al. 2017). Also, an active pedal movement (both downstream and upstream) is likely of minor importance for the species' rapid spread over long distances (Voelz et al. 1998, Pernecker et al. 2021).

Discharge of heated water from power stations can greatly facilitate the establishment of this species in the invaded areas and its further spread, as such local 'heat islands' can serve as refuges during cold winters and as source populations for colonisation of unheated waters (Penk & Williams 2019). In Poland, discharges of heated water also appear to play a critical role in the invasion of *C. fluminea* (Łabęcka et al. 2018, Urbańska et al. 2018). It was first reported in heated waters discharged to the Odra River from the power plant in Nowe Czarnowo near Gryfino (Western Pomerania) in 2003 (Domagała et al. 2004). In the same place a year later, a related taxon was also recorded: the also invasive, triploid form of *C. fluminalis*, the taxonomic status of which is still unclear (Łabęcka et al. 2005, Skuza et al. 2009, Kołodziejczyk & Łabęcka 2011, Morhun et al. 2022).

Shortly thereafter, within a few years, *C. fluminea* spread throughout the lower and middle reaches of the Odra River (Müller et al. 2007, Wawrzyniak-Wydrowska 2007, Wilke 2007, Schmidlin et al. 2012, Piechocki & Szlauer-Łukaszewska 2013, Szlauer-Łukaszewska et al. 2017). Shells of *Corbicula* sp. were also found in 2014 in gull pellets during the foraging interaction studies between gulls and ducks in the Szczecin Lagoon (Marchowski et al. 2016). Recent records come from the upper course of the Odra River and the artificial Gliwice Canal (Cebulska & Krodkiewska 2019), as well as from the mouth of the Osobłoga (left tributary of the Upper Odra), where in 2015 the species was misidentified as *Sphaerium rivicola* (Spałek 2016). In 2016, a new population of *C. fluminea* was also recorded in central Poland, in the Warta-Gopło Canal in Konin, which is a part of a power plant lake cooling system (Urbańska et al. 2018) and a part of the international inland waterway E70 connecting the Vistula and Odra basins.

The first record of *C. fluminea* from the Vistula basin was described by Maćkiewicz (2013), who found it in Kraków in 2011 and suspected that the clams had been in the river at least since 2008, able to overwinter in the wild. In 2011–2016, twenty seven new sites of the species were recorded in the Upper Vistula between Opatowiec and Puławy (Bonk et al. 2018). Within the surveyed river section, the largest clam individuals and their highest population density were recorded up to 1 km downstream from the outflow of heated water discharged from the power plant in Połaniec (Bonk et al. 2018). In 2016, *C. fluminea* was collected in the Vistula and its two oxbows in Warsaw (Romanowski et al. 2016). In this and the following year, subsequent sites inhabited by this species were recorded from the middle course of the Vistula upstream from Warsaw. The southernmost of these sites were directly influenced by heated water discharged from the Kozienice Power Plant (Romanowski et al. 2017). Another population was found in 2017 at the mouth of the small Skawinka river upstream from Kraków (Dumnicka et al. 2018), approx. 3 km below the discharge of heated water from the power plant in Skawina. This paper reports a new locality of *C. fluminea* occurrence in Poland.

STUDY AREA AND METHODS

In the Nida, a left tributary of the Vistula in central Poland, the first specimens of *C. fluminea* were noticed on July 29–30, 2021, at the bridge in Antoniów near Stawy (50°34'41.8"N, 20°29'48.0"E; Fig. 1), on the Motkowice-Pińczów stretch of the river. This new site is located approximately 40 km north of the nearest previous records of the species (Vistula near Opatowiec; Bonk et al. 2018). The clams were located while sampling in search of juveniles of *Unio crassus*, regularly conducted in this site since 2019. They were found in a submerged sandy dune formed by the river near the middle part of the riverbed, cov-

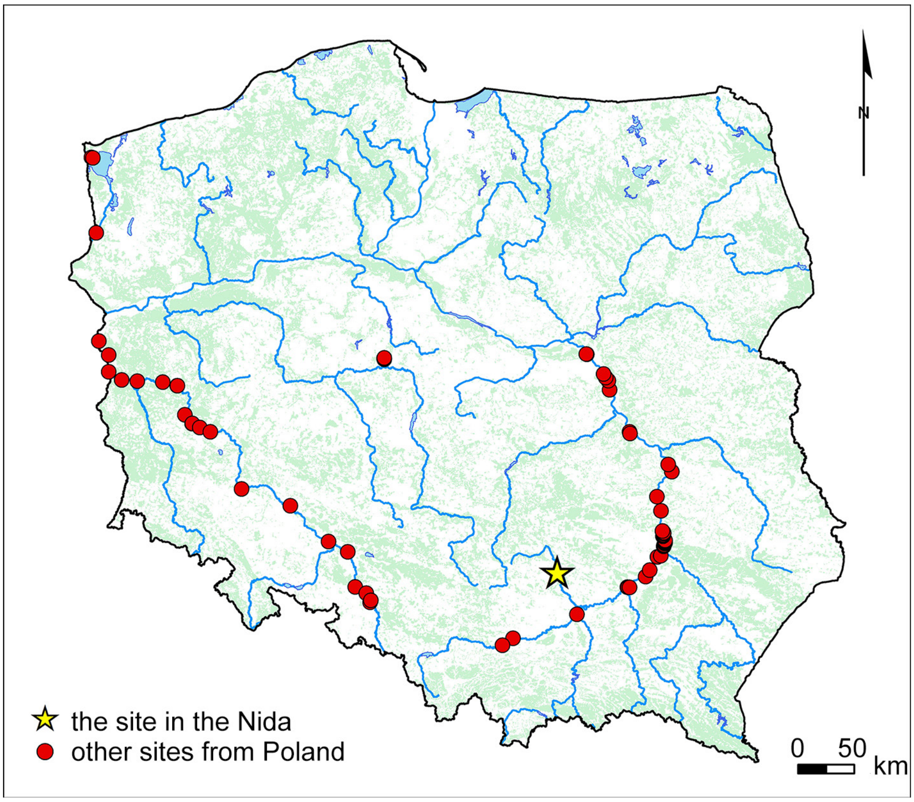


Fig. 1. Distribution map of all known records of *Corbicula fluminea* from Poland, highlighting the new locality in the Nida River. Based on the map in the invasiveness assessment survey of *C. fluminea* in Poland (Łabęcka et al. 2018), supplemented with later published data, i.e. Romanowski et al. (2017), Dumnicka et al. (2018), Urbańska et al. (2018), and Cebulska & Krodkiewska (2019). In view of the paper by Morhun et al. (2022) *C. fluminea* localities in Poland must be verified as some of them may refer to *Corbicula leana* [editor's remark].

Fig. 2. Habitat of *C. fluminea* in the middle Nida River valley

Table 1. Shell dimensions of live *C. fluminea* individuals from the Nida River and of other *Corbicula* sp. individuals from the sites inhabited by them in Poland. The mean, standard deviation (SD), and the range are given; na – not available

Site no.	River/site	N	Length (mm)			Height (mm)			Width (mm)			Reference
			mean	SD	range	mean	SD	range	mean	SD	range	
1	Lower Odra (53°12'43.38"N, 14°28'03.79"E)	69	28.6	3.2	20.1–34.8	26.7	2.8	18.3–32.2	18.8	2.2	13.5–28.9	Domagała et al. 2004
2	Upper Odra (50°24'42.48"N, 18°06'26.10"E)	66	7.68	5.23	na	6.55	4.66	na	4.54	3.46	na	Cebulska & Krodkiewska 2019
3	Gliwice Canal (50°21'33.73"N, 18°09'36.14"E)	3	8.67	3.06	na	7.5	2.94	na	5.27	2.04	na	Cebulska & Krodkiewska 2019
4	Vistula near Połaniec (50°26'35.34"N, 21°22'03.79"E)	34	17.0	7.08	na–32.9	na	na	na	na	na	na	Bonk et al. 2018
5	Vistula near Niekurza (50°26'23.24"N, 21°23'41.75"E)	232	10.9	3.11	na–29.0	na	na	na	na	na	na	Bonk et al. 2018
6	Vistula near Annopol (50°51'36.72"N, 21°50'57.88"E)	288	8.7	2.91	na–21.0	na	na	na	na	na	na	Bonk et al. 2018
7	Nida (50°34'41.99"N, 20°29'48.01"E)	12	13.67	5.22	7.7–27.2	10.66	2.76	7.0–16.5	8.23	1.81	5.2–11.6	this study

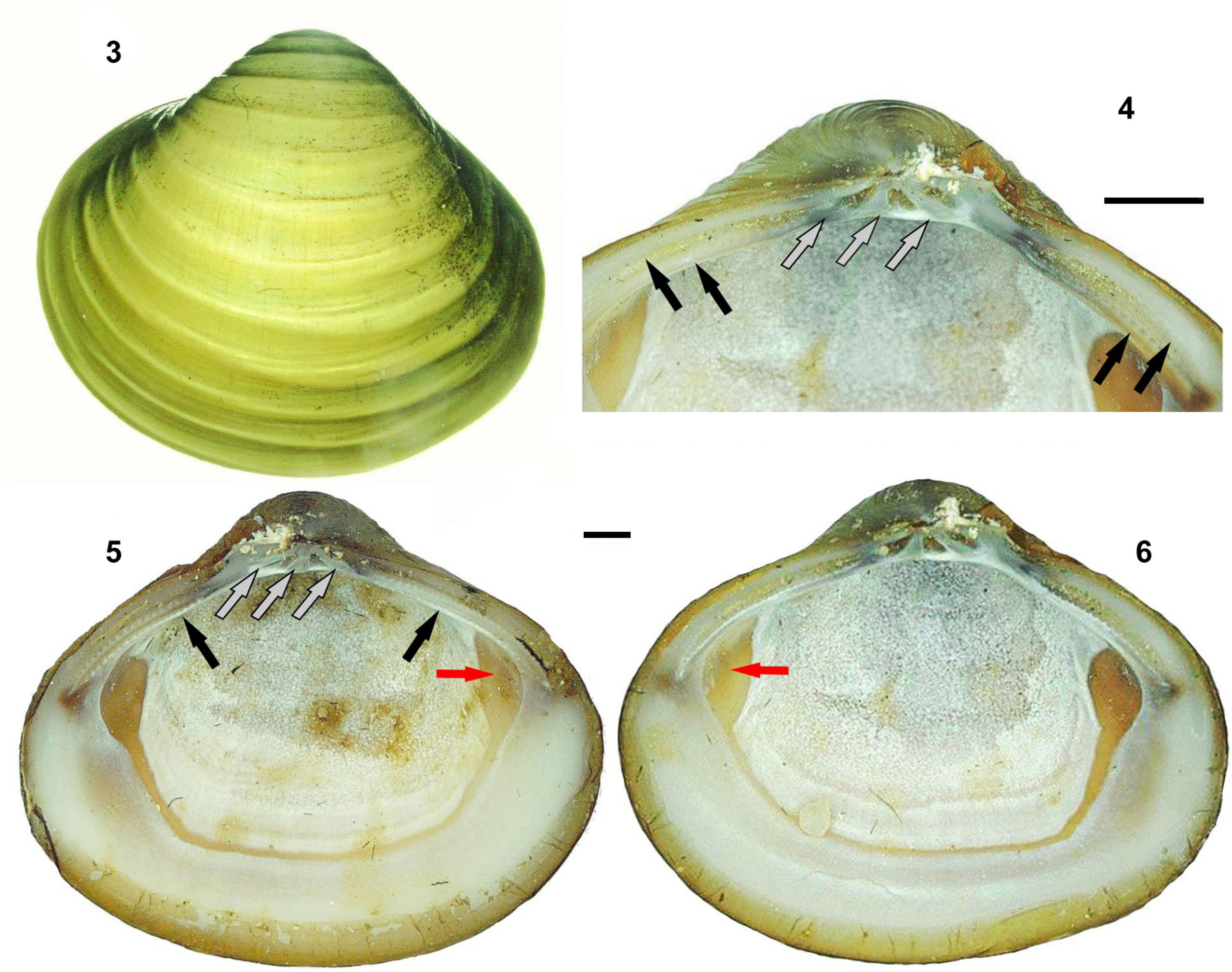
ered with sparse stems of *Sparganium* sp. (Fig. 2). On September 14, 2021, regular sampling of the dune was carried out. Using a rake with a net (0.5 mm mesh), 50 samples of bottom sediments were taken. Each sample covered 0.33 m² (rake 0.33 m wide collected bottom sediment from 1 m). Each sample was washed on the netting and the retained bivalves were collected and assigned to species (Piechocki & Wawrzyniak-Wydrowska 2016). Detailed identification of *C. fluminea* (see Figs 3–6) was done according to Araujo et al. (1993), López-Soriano et al. (2018) and Morhun et al. (2022). The length, height and width of each individual were measured with a vernier calliper with an accuracy of 0.1 mm. Table 1 summarises the average shell dimensions of live individuals from this site and compares them with those from other sites of the species in Poland.

RESULTS AND DISCUSSION

Individuals of *C. fluminea* were present in 20% of the collected samples. In total, 12 individuals were found, only the young of the year (shells without annual rings; Figs 3–6). The average density was 0.73 ind./m². The Asian clam co-occurred at this site with native bivalves. Among them, Sphaeriidae dominated (33%; with two identified species: *Sphaerium rivicola* and *Pisidium amnicum*), followed by *C. fluminea* (17%) and Unionidae: *Unio pictorum* (26%), *U. tumidus* (9%), *Anodonta anatina* (7%), *Pseudanodonta complanata* (6%) and *U. crassus* (3%).

In the Nida, the clams were found in waters of natural thermal regime, in the sandy shallows of underwater sandbars near the bank with lower water velocity, where the bottom is overgrown by immersed vegetation with dominance of *Batrachium* sp. combined with the emerged *Sparganium* sp. vegetation (Fig. 2). The species can occur on a variety of substrates, but prefers sandy sediments mixed with silt and clay (Sousa et al. 2008, Lucy et al. 2012). Areas of large sandy deposits are also inhabited by this species in other rivers in Poland: the Upper Vistula (Bonk et al. 2018) and the Upper Odra (Cebulska & Krodkiewska 2019).

Compared to other populations of *C. fluminea* in Poland, the average shell length of live individuals from the Nida is in the middle, with the smallest clams recorded in the Upper Odra and the largest in the Lower Odra (Table 1; see also Maćkiewicz 2013, Romanowski et al. 2016, 2017, Urbańska et al. 2018). There were no large individuals, nor fresh or old empty shells, and the density was very low



Figs 3–6. Identification characters of *Corbicula fluminea* from the Nida River. Diagnostic features according to ARAUJO et al. (1993), LÓPEZ-SORIANO et al. (2018), MORHUN et al. (2022); photographs were taken using a Keyence VHX-950F microscope (Keyence International, Mechelen, Belgium), equipped with the digital analysis software; shell features of *C. fluminalis* are given in brackets for comparison: 3 – right valve: outer yellowish surface of shell has well marked concentric and regular sulcations (ribs), which are coarse and sparse – specimens with 5 or 6 ribs per 0.5 cm being most frequent in Nida (*C. fluminalis*: 6 to 14 ribs per 0.5 cm); rounded posterior margin of shell (*C. fluminalis*: more oval); umbo more or less centrally located – moderate umbo extension (*C. fluminalis*: much more extended); 4 – hinge (inner surface of right valve) with three cardinal teeth (gray arrows) and two pairs of long, finely serrated lateral teeth – one pair per side of hinge (black arrows); 5 – inner surface of left valve: hinge with three cardinal teeth (gray arrows) and two single long lateral serrate teeth (black arrows), red arrow – subequal adductor muscle scar (*C. fluminalis*: anterior adductor muscle scar closer to shell margin than posterior scar; 6 – inner surface of right valve: red arrow – subequal adductor muscle scar. Scale bars 1 mm

(cf. BONK et al. 2018). Additionally, finding only this year's young in the samples collected proves that such individuals predominated in this site. This is characteristic of a young population that is unlikely to have been established in this habitat for more than one generation (cf. CEBULSKA & KRODKIEWSKA 2019). This could also indicate a high potential for population growth and thus for the development of an invasion (WAWRZYNIAK-WYDROWSKA 2007).

Although the Nida has a natural thermal regime, undisturbed by discharges of heated water, in the last few decades this river has also experienced a noticeable increase in water temperature, which is strongly correlated with an increase in air temperature (MARSZELEWSKI & PIUS 2021). The long-term average water temperature in the coldest months (December–February) in the Nida is between 2.7 and 3.5 °C (MARSZELEWSKI & PIUS 2021), being above the assumed lower lethal limit of *C. fluminea* (0–2 °C; LUCY et al. 2012). Also in summer, the average river temperature (18.3–19.7 °C; MARSZELEWSKI & PIUS 2021) far exceeds the temperature required for the reproduction of this species (approx. 10–15 °C; MCMAHON 1999, CRESPO et al. 2015). *C. fluminea* exhibits high phenotypic plasticity and can survive in winter near-freezing conditions (MÜLLER & BAUR

2011, Cvetanovska et al. 2021). Climate warming, with milder winters, may additionally favour the species' establishment even in rivers with a cooler thermal regime (Weitere et al. 2009, Crespo et al. 2015, Gama et al. 2017, Łabęcka et al. 2018). Data from other populations in Poland show that *C. fluminea* is capable of overwintering in Polish unheated waters (Maćkiewicz 2013, Łabęcka et al. 2018), although their thermal conditions are far from optimal for the species. Therefore, it is not expected that *C. fluminea* will rapidly reach high abundance in the Nida comparable to that in heated waters (Bonk et al. 2018, Urbańska et al. 2018, Penk & Williams 2019), but the rate of its invasion in this river is unpredictable and must be constantly monitored.

The new record of the species reported here is important as it indicates that *C. fluminea* has invaded the natural river, with intact hydrology and natural fluvial habitats, until recently rather devoid of invasive species. Such conditions are in sharp contrast to those of the Odra and Vistula, which are strongly modified rivers, with changed hydrology and inflows of warm waters, inhabited by extremely large, probably source populations of the invader (Bonk et al. 2018). It should be emphasised that in 2019, the 48-kilometre long stretch of the Nida (from Rębów to Jurków, downstream) was intensively searched for the presence of unionids and no signs of *C. fluminea*, even empty shells, were found (unpubl. data). It is worth noting, however, that a variety of invasive species have recently been recorded there, including the alien striped crayfish *Orconectes limosus* (Śmietana et al. 2018), which may show predation on juvenile bivalves (Klocker & Strayer 2004). The co-occurrence of invasive crayfish with invasive bivalves could potentially intensify the decline in populations of endangered native mussels (Dobler & Geist 2022).

The introduction pathway of *C. fluminea* into the Nida is unknown. The reported site is far from larger human settlements and even individual houses. Hence, releases by aquarists, which are considered to play an important role in the invasion of the species in Poland (Bonk et al. 2018, Łabęcka et al. 2018) and other countries (Lucy et al. 2012), are an unlikely introduction route to the Nida. This river section has not been modified recently, and no construction work has been carried out near the river to which sand or gravel 'contaminated' by *C. fluminea* may have been brought in from elsewhere. However, both in the described site and in the longer section above and below, the Nida is popular among anglers. Therefore, the introduction of *C. fluminea* by anglers using it as a natural fishing bait appears to be one of the most likely vectors (cf. Sousa et al. 2007, Lucy et al. 2012, Ferreira-Rodríguez et al. 2021). Another possible mode of transmission by anglers is when young clams adhere to damp angling gear, such as keep nets, which are often immersed in a river for long periods and then transported to another angling site (Minchin 2014). The clams could also be brought by waterfowl (cf. Prezant & Chalermwat 1984, McMahon 1999, Coughlan et al. 2017), mainly including swans and mallards, which often rest and forage in this place. Foraging in the sandy shallows, covered with submerged and raised vegetation, could facilitate the release of young clams attached to bird legs or feathers. Another possibility is transfer by kayaks. The Nida is very popular for kayaking, and what more, the kayak harbour is just above the site. Since the kayaks are not regularly cleaned and dried after each trip (cf. Anderson et al. 2014), *C. fluminea* larvae and juveniles, attached to the hulls or in the water inside the kayaks, may have been transported from other places invaded by the species (cf. McMahon 1999, Lucy et al. 2012). The presence of only young specimens among those caught in the Nida suggests that the population found there may reproduce there from a small number of individuals or may expand from the upper part of the river through active movement or passive downstream drift of early developmental stages (Prezant & Chalermwat 1984, McMahon 1999) or within sediment transported by the spates. For this species, introducing even one self-fertilising 'founder' individual may be sufficient to initiate a new, rapidly growing population (McMahon 1999).

C. fluminea can adversely affect both individual species and entire freshwater ecosystems (Sousa et al. 2008, 2014). Due to its high productivity and filtration rate, it disrupts the trophic web, transforming natural rich benthic communities into large patches of monoculture, reducing habitat availability for other species, and promoting prolific macrophyte growth. At higher abundances, *C. fluminea* competes with native sphaeriids and unionids for space and food resources, causing their displacement and reduced growth. Filter- and deposit-feeding clams can also affect recruitment of unionid juveniles and ingest unionid sperm, glochidia and small juveniles. High bioturbation activity, production of faeces and pseudofaeces, and massive die-offs of *C. fluminea* can significantly alter the microhabitat and sediment and water biochemistry, causing mortality of unionids and other species of benthic fauna (reviewed in Sousa et al. 2008, 2014, Crespo et al. 2015, Ferreira-Rodríguez et al. 2018a, b, Haag et al. 2021).

Due to its invasiveness and potential harmful effects on native fauna and freshwater ecosystems, *C. fluminea*, along with three other species of bivalves (*Crassostrea gigas*, *Sinanodonta woodiana*, *C. fluminalis*), is included in the Polish list of plants and animals of alien species which, if released into the natural environment, may threaten native species or natural habitats (Rozporządzenie 2011). Additionally, *C.*

fluminea is subject to the provisions of the recently introduced Alien Species Act (Ustawa 2021), focused on the prevention and management of the introduction, and spread of invasive alien species.

Species of the genus *Corbicula* have never been found in the Nida catchment before. Research on benthic fauna has been carried out in the river since the 1970s and revealed the presence of 20 species of freshwater bivalves (Piechocki 1981, Zając & Zając 1999, Korzeniak et al. 2004, Barga-Więcławska 2012, Cieplok & Strzelec 2018), including species protected in accordance with the Polish Regulation of the Minister of the Environment (Rozporządzenie 2016) on species protection of animals (P), and listed in the Red List of Threatened Animals in Poland (Dyduch-Falniowska & Zając 2002) as vulnerable (VU) or endangered (EN), based on IUCN criteria (IUCN 2012), such as *Pseudanodonta complanata* (P, EN), *Anodonta cygnea* (P, EN), *Sphaerium rivicola* (P, VU), *Pisidium obtusale* (VU), *P. moitessierianum* (VU), *P. tenuilineatum* (VU) and *P. liljeborgii* (VU), as well as *Unio crassus* (P, EN) – a very common species in the Nida in the 1970s, but disappeared in the 1980s, likely because of water pollution. There is ongoing programme of its restitution in the Nida, founded by EU Life+ programme (https://life4delta.pl). The species was rediscovered in 2019 and since then, the introduction of juveniles from breeding has also taken place in the Nida. The expected invasion of *C. fluminea* poses a new and serious threat to *U. crassus* and other native species, mainly due to competition for food and space, which at higher densities may displace native mussels and reduce their growth (Ferreira-Rodríguez et al. 2018a, b, Haag et al. 2021). Thus, the newly reported population of *C. fluminea* poses a risk to the success of reintroduction programme.

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