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THE PEARL MUSSEL *MARGARITIFERA MARGARITIFERA* (LINNAEUS, 1758) (BIVALVIA: MARGARITIFERIDAE) IN POLAND – CURRENT SITUATION

KATARZYNA ZAJĄC, TADEUSZ ZAJĄC

Institute of Nature Conservation, Polish Academy of Sciences, Al. Mickiewicza 33, 31-120 Cracow, Poland (e-mail: kzajac@iop.krakow.pl)

ABSTRACT: The pearl mussel was abundant in the Sudety Mountains until the late 19th century. No live mussels were found within the present borders of Poland since the early 20th century. In 2006–2007 we did a detailed survey of 50 streams and rivers within the former range of the pearl mussel to verify its current status and assess the habitat conditions. No live mussels were found. On the whole, the rivers and streams were found to be degraded. Only four streams met the habitat requirements of the species. Well-preserved shells with a nacre layer were found at the site of the last known population in the Koci Potok stream. To determine whether the shells represented an extinct population or rather indicated the presence of the last survivors, we placed *Unio crassus* shells in the stream within the historical range of occurrence. Those shells dissolved at the rate of approximately 20% per year, indicating that empty shells would not have remained intact within the channel. Possibly the earlier-found shells had been preserved in the banks above the water level. The possibility that they represent the last survivors can not be excluded. Further search for the last survivors, extended to cover northern Poland, is recommended.

KEY WORDS: *Margaritifera margaritifera*, shell dissolution, stream survey, oligotrophic water, Allee effect

INTRODUCTION

The insufficiency of data on the distribution and population health of European freshwater mussels is one of the main obstacles to their conservation (LOPES-LIMA et al. 2014). One of the best-studied large-bodied freshwater mussels is the pearl mussel *Margaritifera margaritifera*. There are numerous studies on its genetics, distribution and biology (GEIST 2010). It occurs in cold upland oligotrophic streams and rivers with coarse substratum (e.g. BUDDENSIEK et al. 1990, 1993, SOUSA et al. 2013). Its range spans the northern part of the European continent from Spain and Portugal to Finland and the adjacent part of Russia, although its distribution range is disjunct in Poland and Lithuania where the species has gone extinct (LOPES-LIMA et al. 2014). This mussel has a very long lifespan (DUNCA et al. 2011). It is dioecious (ZIUGANOV et al. 1994) but the females switch to hermaphroditism when the density of males is low (BAUER 1987). Its reproductive strategy in Europe is based on releasing large numbers of small parasitic glochidia directly to the water where they infest salmonid fishes (*Salmo salar* and *S. trutta*; BAUER & VOGEL 1987). Pearl mussel populations have decreased dramatically since the beginning of the 19th century (up to 90%), and this trend is ongoing (e.g. BAUER 1983, 1986, YOUNG et al. 2001). Most of the remaining populations are highly fragmented and functionally extinct due to the lack of recent recruitment (GEIST 2010). The extinction process of the species has not been studied in Poland, and the information existing elsewhere is sparse and published in national languages.

From the 17th century on, the Sudety Mts were well known as an area where the pearl mussel was abundant (BENA 2003). It occurred mainly in the upper courses of the Bóbr and Nysa Łużycka upland rivers and above all the Kwisa river near the towns of Gryfów and Leśna (PAX 1932). The first indica-

tions of population decline are found in historical documents from the 18th century (BENA 2003). The evidence points to a dramatic decline probably continuing till the end of the 19th century (DYDUCH-FALNIOWSKA & ZAJĄC 2004, ZAJĄC 2009).

There are no data on direct causes of that decline but it coincides with intensification of agriculture, intensive human settlement of arable land, and development of local industry. These processes were accompanied by deforestation (wood industry, tanbark), river and stream regulation (mills), and an increase in water pollution due to agriculture, growth of towns and local industry (weaving). The regulation of rivers and even small stream channels in the Sudety region was done on a huge scale: they were usually formed into stone-lined U-shaped beds or at least sided with stone walls. These projects were related to the emergence of human settlements at the bottom of stream valleys and the construction of water mills as a power source. Other possible factors in the decline are the widespread introduction of the rainbow trout *Oncorhynchus mykiss*, which is not a host for pearl mussel larvae, and the invasion of the muskrat *Ondatra zibethicus* from the Czech territory, which was thought to prey on the species (DYK 1958), although the muskrat rather seldom occurs within the pearl mussel habitat.

At the beginning of the 20th century the pearl mussel was regarded as extinct in the main areas of its prior occurrence in Poland: the Nysa Łużycka, Kwisa and Bóbr rivers (PAX 1932, TOMASZEWSKI 1932). In 1921 an impoverished population was found in the Koci Potok stream, a small tributary of the Nysa Łużycka (PAX 1932), with a large number of empty shells interpreted by researchers to be the result of high mortality (DYK 1957, DUTKIEWICZ 1958, 1960). The Koci Potok was regulated before World War II and the results are still visible today: the bed was sided with stone walls in the upper parts to meet the needs of the water mill, and the lower meandering course of the stream was regulated with fascine mattresses. The last field survey of this stream in search of the pearl mussel was done in the 1950s by DUTKIEWICZ (1958), who only found 67 empty shells. Other data on the occurrence of the pearl mussel in other areas of Poland, contained in Polish (SAMEK 1976) and French historical documents (DASZKIEWICZ 2008), are difficult to verify.

The 1960s saw an unsuccessful attempt to reintroduce the pearl mussel in Polish streams in the Sudety Mts. In June 1965, Prof. Vaclav Dyk from Brno supplied pearl mussels to his Polish colleague Dr. Tadeusz Kaźmierczak of the Department of Nature Conservation, Polish Academy of Sciences. Thirty of them were introduced in the Śnieżny Potok stream in the Karkonosze National Park (Fig. 1, site 50). Another 70 were introduced to the Kwisa river between Rozdroże Izerskie and Świeradów Zdrój (Fig. 1, site 26). Two weeks later there were no traces of the introduced mussels (KAŹMIERCZAK 1966).

There are no current published field studies properly documenting the status of the pearl mussel in the Sudety region. All available information comes from general assessments (PAX 1932), indirect information from historical documents (BENA 2003) or surveys after presumed extinctions (DUTKIEWICZ 1958, 1960). In this paper we describe the condition of pearl mussel habitats in the Sudety Mts and, in view of suggestions about its possible reintroduction, we discuss the prospects for survival of this species.

MATERIAL AND METHODS

STUDY AREA

A large-scale survey of mussels poses a methodological challenge; it requires a large effort to gather all the data needed to estimate population parameters (ANONYMOUS 2004, YOUNG et al. 2001). Our search for the pearl mussel was carried out in the Sudety Mts and its foothills during the summer and autumn of 2006 and 2007. Special attention was paid to rivers or streams known to harbour the species in the past or where it had been reintroduced. Information on the reintroduction effort in the 1960s (KAŹMIERCZAK 1966) was supplied by Prof. Zbigniew WITKOWSKI of the Department of Nature Conservation, Polish Academy of Sciences (pers. comm.), who was an eyewitness to the reintroduction. All watercourses that might suit the pearl mussel were inspected to determine its status in each one. After excluding streams with typical high mountain characteristics or those that were too small, completely regulated, severely polluted or otherwise disqualified, we chose 50 streams (Fig. 1). The whole course of these streams was inspected and identified as satisfactory or unsatisfactory habitat for the pearl mussel. First we paid special attention to the river morphology, under the assumption that the water chemistry could change due to ongoing implementation of water quality improvement programmes. We searched mainly for streams similar to the "A" river in Szumawa, Czech Republic, site of the nearest pearl mussel population; the landscape and habitat features there are similar to those in Łużyce, where the largest populations of *M. margaritifera* in the Sudety Mts were found in the past. Each stream was inspected by two researchers experienced in searching for freshwater mussels. They waded in the water along both banks, searching the stream bed and banks, and when nec-

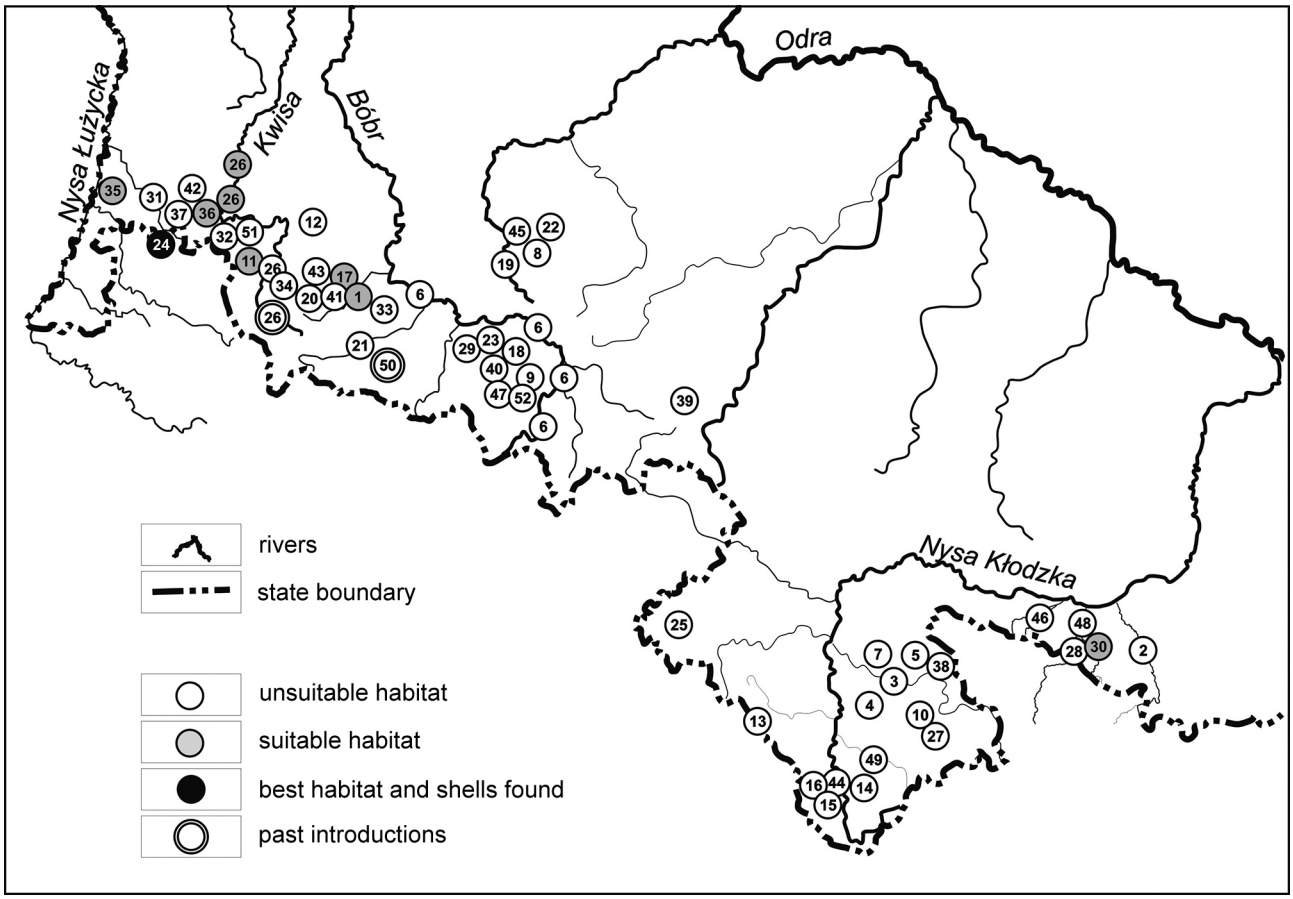

Fig. 1. Distribution of streams inspected for the presence of pearl mussel or for habitat suitability. Hollow circles represent the inspected watercourses that do not suit the habitat requirements of the pearl mussel; gray circles indicate streams with suitable habitat; black dot indicates Koci Potok as the best habitat with remnants of shells, and double circled dots indicate the former introductions to Śnieżny Potok and Kwisa (KAŹMIERCZAK 1966). Numbers indicate the respective river given in the following list: 1 – Kamienica, 2 – Biała Głuchołaska, 3 – Biała Lądecka, 4 – Biała Woda, 5 – Borówkowy Potok, 6 – Bóbr, 7 – Brodek, 8 – Bukownica, 9 – Bystrek, 10 – Czarna Woda, 11 – Czarny Potok, 12 – Długi Potok, 13 – Dzika Orlica, 14 – Gogorówka, 15 – Gołodlnik, 16 – Górski Potok, 17 – Grudzki Potok, 18 – Gruszówka, 19 – Kaczawa, 20 – Kamieniczka, 21 – Kamienna, 22 – Kamiennik, 23 – Karpnicki Potok, 24 – Koci Potok, 25 – Kudowski Potok, 26 – Kwisa, 27 – Leśnica, 28 – Łąka, 29 – Łupia, 30 – Łuża, 31 – Miedziński Potok, 32 – Miłoszowski Potok, 33 – Młynówka, 34 – Mrożynka, 35 – Nysa Łużycka, 36 – Ciek od Grabiszyc, 37 – Ciek od Zalipia, 38 – Orliczka, 39 – Pełcznica, 40 – Pijawnik, 41 – Piniowy Potok, 42 – Platerówka, 43 – Raczyna, 44 – Różana, 45 – Sarnka, 46 – Świbna, 47 – Świdnik, 48 – Widna, 49 – Wilczka, 50 – Wrzosówka (Śnieżny Potok), 51 – Ciek od Zacisza, 52 – Żywica

essary using aquascopes or else hand-checking poorly visible places (e.g. tree roots, areas under grass cover, spaces eroded under banks). Soft sediments were also sampled with a rake with netting and sieved in search of mussels.

The Koci Potok stream (also called Gajnik or Żrenica in Polish, Kočičí Potok in Czech, Catzenenfluss and Katzbach in German), the last known site of the pearl mussel occurrence, is a small creek located near Łowin village and Zawidów town. It is also a boundary stream between the Czech Republic and Poland; access to it was forbidden in the past. The stream is small, shallow (<0.6 m deep), and narrow (channel width 0.8 m) in the upper course, flows in a V-shaped valley, and then comes to a wider floodplain where it begins to meander, channel, and increase (<3 m wide, <1.5 m deep). At the edge of the V-shaped valley the channel bottom is covered with fine gravel (<1 cm) and is incised into the valley bottom (<1 m). Along its course are short sections of accumulated large stones from previous channel regulation, and woody debris is frequent. Then the stream proceeds through a saddle between hills, forming a breakthrough, and there is a short section of steep channel with rapid flow and large boulders (<0.3 m diameter) in the channel bottom. Then the stream reaches another flat, wide floodplain where it meanders again. In this section the water erodes clay layers from the bank. The bottom is covered with fine gravel mixed with coarse sands. There are remnants of stone lining and fascine mattresses on some sections of the bank. The current velocity is variable, ranging from 0.6 to 1.2 m/s, and the depth reaches 1.5 m in meander pools.

The catchment area of the upper course of the Koci Potok is covered with deciduous forest (Miedziański Las forest) on the hill slope on the right bank; the left bank is flatter and overgrown with riverine alder forest of natural character. Further on it flows through a flat valley covered with natural riverine forest. In the breakthrough the catchment is overgrown with deciduous forest on both banks. In the lower course the river is adjacent to deciduous forest on the Polish side; on the Czech side is a narrow strip of alder trees screening a pasture and a large cultivated field. Then the river flows through narrow strips of scrub willow and degraded alder woods surrounded by arable land on both sides. Near Zawidów the river is regulated with stone lining.

We paid special attention to the Koci Potok. During four seasons (2006, 2007, 2009, 2010) it was inspected intensively by two independent teams. The stream was found to be inhabited by fishes including bullhead *Cottus* sp. and trout *Salmo trutta* morpha *fario*.

SHELL DISSOLUTION

To determine whether the shells that were found in the Koci Potok (DUTKIEWICZ 1958, 1960, this study) could have been preserved within the channel, we enclosed three groups of seven well-preserved *Unio crassus* shells in plastic net-bags (2 × 5 mm mesh) and on 2 April 2009 attached them to tree roots at the bank under slow laminar water flow at sites where the occurrence of pearl mussel shells had been recorded (Fig. 1). We used shells of *Unio crassus*, because shells of *M. margaritifera* are not available in Poland, their import from abroad needs special permission from the Ministry of Environment, and, last but not least, in case of accidental net-bag opening during the experiment foreign shells would be introduced into the Koci Potok, and it would be impossible to determine whether or not they were of local origin. Before that, any sediments were washed off of the shells which were then dried to constant dry weight and weighed to 0.001 g accuracy. The water conductivity in the stream section where the experiment was set up was 169 μS/cm at the upper end (9.8°C, pH 7.5, oxygen 0.64–0.67 mg/l) and 177 μS at the lower end (9.2°C, pH 7.48, oxygen 0.68–0.74 mg/l). The nets were inspected again on 26 April 2010 and the shells were collected; they were clean, so they were not washed but only dried to constant dry weight and weighed again.

RESULTS

Only seven of the 50 watercourses examined showed hydrological and morphological structure deemed suitable (similar to sites of *M. margaritifera* in Szumawa, Czech Republic), and the remaining 43 were deemed unsuitable (high mountain streams, too small, too shallow, or regulated). Two of the seven selected watercourses were polluted (Ciek od Grabiszyc stream and the Kwisa river between Mirów and Gryfów towns: $NO_3 > 3$ mg/l, $PO_4 > 0.1$ mg/l). The Stara Kamienica stream (conductivity: 62 μS/cm, 8.3°C, pH 7.0, flow 0.9–1.1 m/s) was found to have very good water quality but it appeared to be too dynamic to sustain mussels, and the most suitable channel section is short. The Grudzki Potok stream (125 μS/cm, 8.8°C, pH 6.83, flow 0.4–0.7 m/s) seemed too small for the mussel's requirements. Very good habitat conditions were found in the Łuża stream (116 μS/cm, 8.5°C, pH 7.1, flow < 0.8 m/s,) and the Czarny Potok stream (93 μS/cm, 5.9°C, pH 6.78, flow < 0.64 m/s). Some rivers were found to be very natural in character but were too dynamic, with high transport of big cobbles and boulders and no areas of stabilised bottom (e.g. upper course of Kwisa river, Mrożynka stream). The best habitat was found in the Koci Potok stream, described below.

We also carefully checked the sites of the attempted reintroduction of the pearl mussel in the 1960s. The Śnieżny Potok creek was found to be a typical mountain stream with a rocky bed and very steep channel slope, a poor habitat for mussel survival. The upper course of the Kwisa river was also found to be far too dynamic for the species, and we found large cobbles (10–20 cm) dispersed 50–80 m from the channel in the forest, transported by the river during floods. There were no traces of mussels.

The survey in the Koci Potok in 2006 turned up three well-preserved pearl mussel shells: (1) aged 28 years plus, eroded umbo, length 91 mm, width 44 mm; (2) aged 19 years plus, eroded umbo, length 109.5 mm, width 53 mm, height 33 mm; (3) aged 25 years plus, eroded umbo, length 91 mm, width 42 mm, height 30.5 mm (this shell was closed and contained very fine sand). We also found seven periostracum fragments from the part near the siphons (Fig. 2). The survey in 2007 revealed one well-preserved pearl mussel shell (aged 11 years plus, eroded umbo, length 93 mm, width 50 mm) and two near-siphon periostracum fragments. The 2009 survey revealed one pearl mussel shell (aged 18 years plus, very damaged hind and umbo parts) and one near-siphon periostracum fragment. Their locations are shown in Fig. 3; one shell was found in the upper meandering part of the stream (up to the breakthrough) and the rest in the lower part. All shells were found on flat channel bottom except

for the 2009 shell, which was found fixed in the bank: half-buried in the clay and perpendicular to the bank wall, with the siphon edge directed against the current. The part of the shell that was lodged in the clay was poorly preserved, consisting almost solely of periostracum, unlike the part in the water, which contained nacre.

The shells of *U. crassus* exposed for one year lost significant amounts of mass (Fig. 4). On average they lost 21% of their weight (25% loss at upper site, from 13.2 ± 4.93 g to 9.91 ± 4.52 g; 23% loss at middle site, from 11.3 ± 2.57 g to 8.6 ± 2.59 g; 16% loss at lower site, from 12.0 ± 3.94 g to 10.1 ± 3.60 g). Multivariate analysis (MANOVA) with repeated measures and controlled order of sites along the stream flow, revealed significant differences (estimate = 10.7, F = 192.9, NDF = 1, DDF = 18, $p < 0.0001$). The difference in shell weight between subsequent years interacted significantly with the order of samples along the flow (estimate = 1.01, F = 9.12, NDF = 2, DDF = 18, p = 0.002).

The difference in weight between years for a given shell was correlated with initial shell mass at low statistical significance (r = 0.43, n = 21, p = 0.054; Fig. 5): the lighter the shell, the larger the difference. After excluding the outlier (shell weighing > 22 g) the difference was significant (r = 0.45, n = 20, p = 0.046).

Fig. 2. Pearl mussel shells found in the Koci Potok stream in 2006–2007

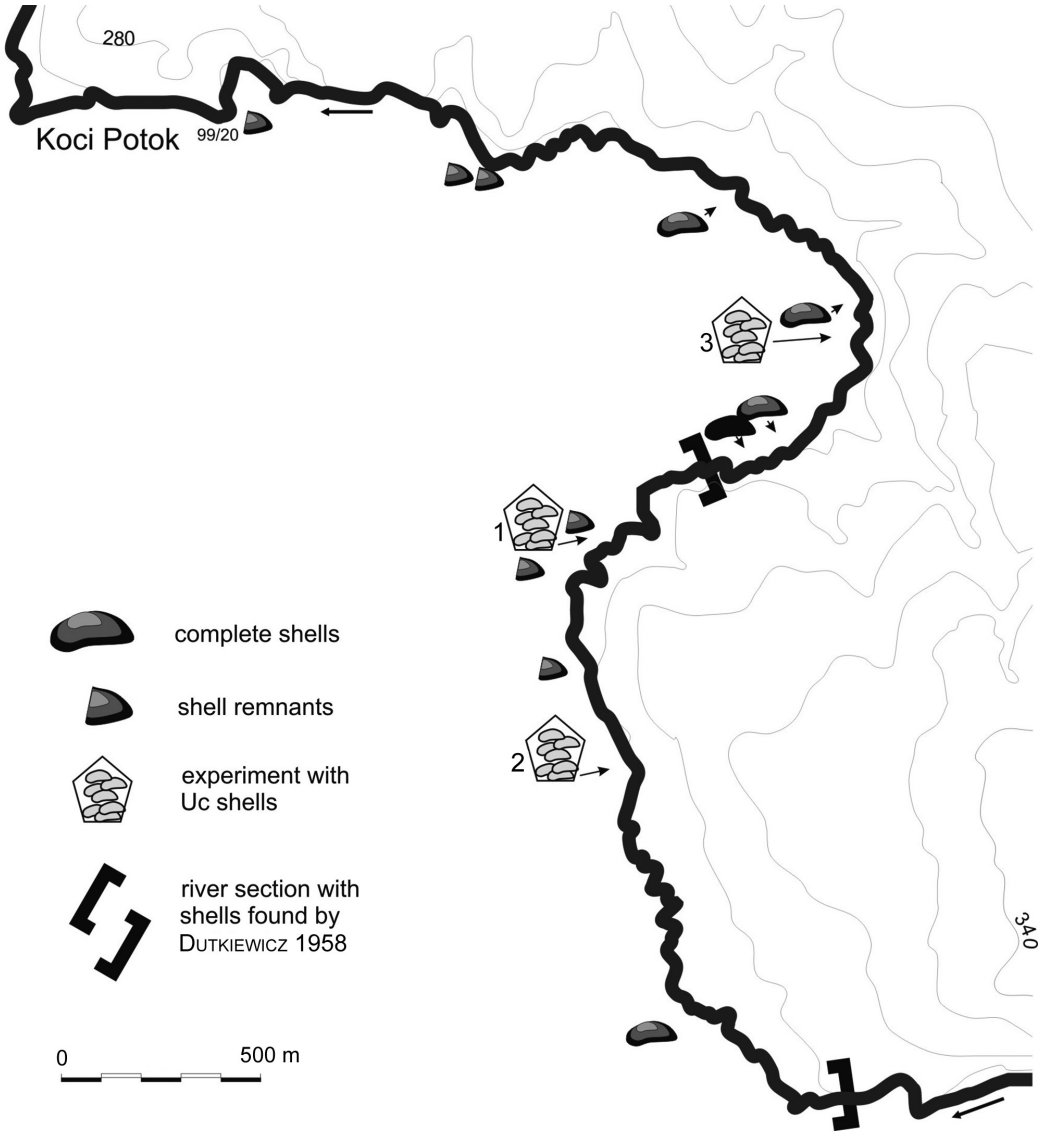

Fig. 3. Distribution of pearl mussel shells and shell periostracum remnants (main places), and experiment dissolving *U. crassus* shells in the middle course of Koci Potok stream. Black shell indicates shell found in river bank (see text for details)

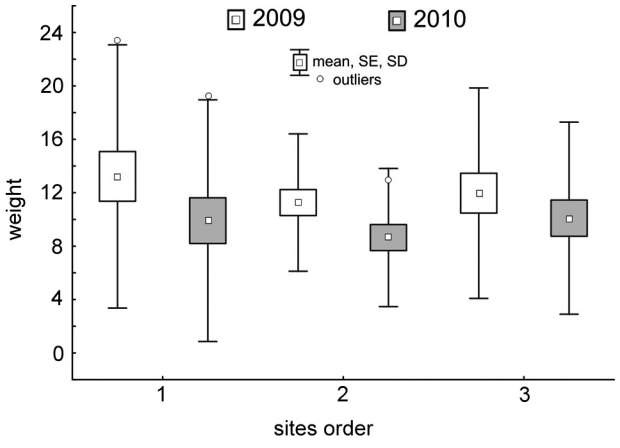

Fig. 4. Differences in *U. crassus* shell weight between April 2009 (light boxes) and April 2010 (gray boxes) at sites along the flow (Site 1 is in upper course of river – see Fig. 3)

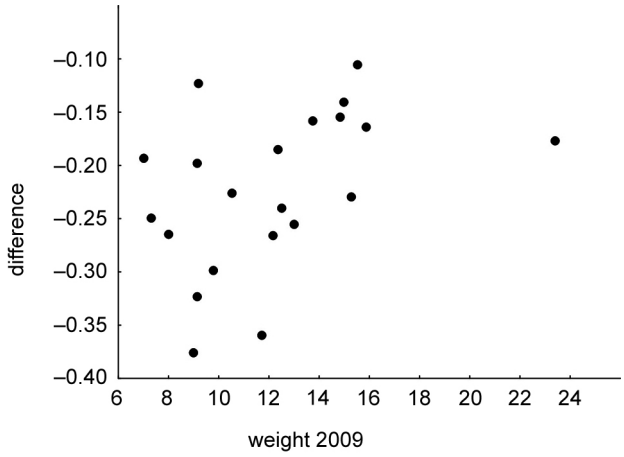

Fig. 5. Shell weight loss between 2009 and 2010 due to dissolving of calcium in soft waters of the Koci Potok, versus initial shell weight

DISCUSSION

This large-scale survey of streams and rivers in the Sudety yielded no traces of pearl mussels within the present borders of Poland, except in the Koci Potok stream. Our surveys of watercourses known to have harboured abundant pearl mussel populations (PAX 1932) strongly suggest that a principal cause of their disappearance was chemical pollution of the water by industry and/or sewage from towns. For example, according to information from local authorities the Kwisa river was almost devoid of fish. Most of the upper sections of the streams and rivers that formerly had viable pearl mussel populations are now completely regulated, running along geometric beds sided with stone walls (e.g. Potok Miłoszowski stream). We do not know the level of fine sediment transport in the past, but as a rule the present-day rivers of this area transport large quantities of sand and have silt deposition.

Unfortunately, few streams have retained their natural character. Any future reintroduction of the species would have to be limited because few streams offer a suitable habitat. Only the Łuża stream habitats probably have not been subjected to any drastic alteration (except for fine sediment supply). Before the study the Widna river appeared very promising, with its natural channel and remnant population of pearl mussels which existed in the upper course of the river in the Czech Republic until the mid 20th century (PAX 1932, O. SPISAR pers. comm.). However, after heavy rains in 1997 which caused catastrophic floods in Poland, the Widna channel was regulated and is now a completely artificial structure.

In contrast, the Czarny Potok stream, which has the same type of habitat as the upper Kwisa, was completely regulated in the past (on maps from the 1980s its channel is straight, with many straight-draining ditches) but now is becoming increasingly naturalized. Its good water quality is no doubt due in part to cessation of farming.

We found no signs of the pearl mussel introduced in the Sudety Mts in the 1960s. Most likely this project was a complete failure, attributable mainly to poor knowledge of the habitat requirements of the species. The localities for introduction were selected to avoid the widespread water acidification that was occurring in the Sudety Mts at that time (Z. WITKOWSKI pers. comm.). No attention was paid to microhabitat selection or to channel hydrology and morphology. The Śnieżny Potok stream is a completely hostile habitat due to its stony bed, and the upper Kwisa is very dynamic and has no suitably stable habitat: cobbles approximately 20 cm in diameter have been thrown out of the channel during high water incidents (see also HASTIE et al. 2003).

We found very well preserved shells only in the Koci Potok stream (Fig. 2). The shells were concentrated in the same area where DUTKIEWICZ (1958) found his shells (Fig. 1; site 24). Probably this area represents the habitat of the very last survivors in the Sudety region. Using the same survey methods we found no shells or (sub-)fossils in any other surveyed streams and rivers, including the Kwisa and its tributaries, known to have had very large pearl mussel populations in the past (PAX 1932). Shells from the 19th century are rather unlikely to be found. The number of shells found in a river is proportional to the live population (HASTIE 2006), which may suggest some survivals.

The experiment with shell dissolution in the Koci Potok showed that shells preserved in such good condition are unlikely to be a remnant of a living population from the 19th or early 20th century preserved within reach of the stream's soft water. The shells lost one-fourth of their weight during the first year. Probably the pearl mussel shells found in the Koci Potok were exposed to the stream water for not longer than four years, especially since the dissolution rate for smaller remnants is faster than for large shells. HASTIE (2006) gave a generally similar duration of shell dissolution (ca 5 years) for *M. margaritifera*.

There are two possible explanations for the presence of shells in the Koci Potok: survival of a small sample of mussels hidden at inaccessible sites, which are very frequent in the stream; or storage of some shells in conditions of isolation from soft water, possibly above the water table in sediments excavated during river regulation, or else buried in anoxic conditions after a river bank collapse in the past. These shells may have emerged to the surface through slow erosion, to be found near open water.

The possibility remains that the finding of shells in such good condition is due to survival of a small group of mussels hidden at inaccessible sites (K. OTTO-NAGEL, B. BRENNER – pers. comm.). Specialists warn that it is very difficult to find this species when very few individuals remain. The Koci Potok stream is very difficult to penetrate. It has very deep horizontal cuts eroded in the banks and many bank sections are covered with tree roots, woody debris and other material, making them practically impossible to examine.

More likely the shells were eroded from the bank. DUTKIEWICZ (1958) stated that many shells he found had been washed from sediments, probably from remnants of earlier mussel beds. The shells may have been preserved in sediments above the water level if they were excavated during stream regulation, and left above the water table. One of the shells found

was immersed in the water at a depth of ca 20 cm, and lodged in the clay bank. This suggests that it had been buried in the clay layer during a bank collapse. The Koci Potok has very deep horizontally eroded cuts in the banks. If such a clay bank collapsed it would bury even a large bed of mussels, and such a buried bed would be excavated gradually by horizontal erosion. Our experiment demonstrated that a shell of this type could not persist in flowing water. If the watercourse surveys are continued it should be determined conclusively whether the shells were eroded from the bank, live mussels survived, or there were no more shells to be found. DUTKIEWICZ (1958) reported 67 shells during one survey in the 1950s but we only found shells, and only during the first two years of the survey.

The age of the shells we found sheds some light on the question of extinction. The age estimation is only approximate due to the umbo damage, but the youngest individual was not older than 20 years and the oldest one not older than 40 years. If they were shells of surviving mussels, they started their lives not earlier than the 1970s, after the visits by DUTKIEWICZ (1958, 1960), when the pearl mussel was in decline throughout the Sudety region. It is highly unlikely that the pearl mussel was reproducing successfully and recruiting in the Koci Potok during that time, because that was when acidification (SO_x) and nitrification (NO_x) of the environment was at their most intense in the Sudety Mts, on the scale of an ecological disaster (1970–1980; FABISZEWSKI & BREJ 2000).

A small remnant population would have had little chance of escaping extinction in the absence of active conservation measures. Although the pearl mussel is believed to be hermaphroditic and thus able to fertilise successfully even in an extremely small population (BAUER 1987), the remaining living mussels would have suffered from Allee effects of low population numbers and also a genetic bottleneck. Also, in a small population even a minor event (e.g. a bank collapse) can lead to extinction.

Whether the pearl mussel occurs in other areas of Poland is an open question. The historical record is insufficient but an analysis of the pearl mussel's European range (LOPES-LIMA et al. 2014) indicates that it may also occur in northern Poland. Its occurrence in southeast Germany and in Latvia to the northeast suggests that the area inbetween, northern Poland, should be inhabited. If there are rivers with soft enough water in the postglacial uplands of northern Poland, they should be examined as a matter of urgency. The data suggest that a reasonably large pearl mussel population was present in the Sudety Mts more recently than previously thought, and there are grounds for cautious optimism that living individuals remain. Most of the pearl mussel's habitat in Poland has been examined insufficiently or not at all (northern Poland), and potential habitats are steadily improving due to proper water quality management. All this means that the river surveys should be continued and expanded.

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