THESES

OF DOCTORAL (PHD.) DISSERTATION

Hungarian University of Agriculture and Life Sciences

Development of artificial spawning nests and study of their efficiency in natural waters

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1. RESEARCH BACKGROUND AND OBJECTIVES

Fish stocks of our freshwaters facing with numerous environmental and anthoropogenic challenges. As a result of the global climate change, the winter ice cover of waters in the temperate zone typically shrinks, their average temperature increases, and the water regimes become more extreme, different from average (absence or changing pattern of floods). These processes have a significant impact on the success of native fish spawning, mostly affecting it in a negative way. At the same time, the level of exploitation of fish stocks (through commercial and recreational fishing) remains high, which may lead to their further decline.

The fish stocks of Lake Balaton iis considerered to not be self-sustaining at the moment. This is mainly due to the significant angling pressure. The natural recruitment cannot fulfill the fish volumes removed by anglers, since the earlier water regulation measures (construction of the Sió floodgate in 1863-64, draining of the surrounding wetlands) eliminated a considerable part of the natural spawning grounds. The maintenance of the fish stock structure expected by anglers therefore mainly depends on fish stocking.

One of the most important apex predators of the lake's fish community is the pikeperch or zander (*Sander lucioperca*), whose population is subject to a constantly increasing angling pressure, which is almost comparable to that of common carp (*Cyprinus carpio*). Specziár, in his 2010 monograph, concludes that the current stock size will be difficult to sustain in the long term. The fisheries management body mostly stocks one-year-old pikeperch, whose acquisition is often limited by market constraints. Based on recapture data, the "turnover" of pikeperch (i.e. the expected time of recapture of the stocked fish) is short, similarly to that of common carp.

1.1 OBJECTIVES

In my thesis, focusing primarily on the Balaton stock of pikeperch, I set the following research and development objectives:

1. To design and test spawning nests that are easy to handle, can be mass-produced, are durable and can support the recruitment of – primarily – the stock of pikeperch for several years.
2. To study which shape, size and substrate cover of the spawning nests is the most efficient in terms of the quantity of laid eggs.
3. To examine the differences between the tested substrates in terms of hatching success.
4. To analyze the interannual variability of the efficiency data of the pikeperch nests in terms of the quantity of laid eggs.
5. To study the impact of different bottom substrate types on the efficiency of spawning nests.

2. MATERIAL AND METHODS

2.1. Deployment sites of benthic spawning nests

The studies were performed at four sites of the Eastern Basin and three sites of the Western Basin of Lake Balaton. Of these, the locations at Fonyód, Balatonvilágos and Tihany were well-known, "traditional" pikeperch spawning grounds with hard, rocky or marly bottom. At the Balatonberény, Balatonszemes, Balatonudvar and Siófok sites, the bottom consists of sandy silt, which itself, is not a suitable spawning substrate for pikeperch.

The precise location and some basic characteristics of the study sites are shown in Table 1.

Table 1: Characteristics of the deployment sites of the benthic spawning nests

Site code	Municipality	GPS (WGS84) coordinates	Distance from shore (m)	Depth (m)	Bottom substrate type
1	Balatonberény	46.71891, 17.2949	770	2.8	soft (silt)
2.	Fonyód	46.75038, 17.5399	540	3.6	hard (rock/marl)
3.	Balatonszemes	46.81374, 17.75693	570	3.2	soft (silt)
4.	Balatonudvari	46.89414, 17.81006	550	3	soft (silt)
5.	Tihany	46.9216, 17.8924	250	3	hard (rock/marl)
6.	Siófok	46.91524, 18.04744	460	3.8	soft (silt)
7.	Balatonvilágos	46.96544, 18.15019	520	4.2	hard (rock/marl)

The experimental benthic spawning nests were placed at different localities in the different study years (Table 2). They were always deployed in the period between 10 and 16 March, depending on when the weather conditions (wind and ice cover) made the work possible.

Table 2: Spawning nest deployment sites in different study years

	Balatonberény	Fonyód	Balatonszemes	Balatonudvari	Tihany	Siófok	Balatonvilágos
2017	X	X	X		X		X
2018		X			X		X
2019		X			X		X
2020		X	X	X	X	X	X

2.1.2. Location of hatchery experiments

The hatching success of the pikeperch eggs laid on the nests was studied both under natural conditions, in Lake Balaton, and under hatchery conditions, excluding potential egg predators These studies took place partly in the harbour of the Siófok site of Balaton Fisheries Nonprofit Company (BHGNP), partly in 5 m^3 flow-through system, filled with fishpond water at the Buzsák site of BHGNP. All the nests used in the hatching experiment came from the study site in Fonyód.

2.2. Experimental spawning nest design

When designing the nests, several requirements had to be taken into account in addition to the needs of the target species. On the one hand, they had to be durable in underwater conditions so that they could remain usable for several years, if possible. On the other hand, the objective was to create a nest design that could be handled, transported and deployed easily, even by human force.

The operation of a total of ten different benthic spawning nest prototypes was studied during the tests.

1. Perforated aluminum (Al) sheet welded into a 50x50cm square Al frame covered by (A.) artificial grass with a 6 cm fibre length; (B.) a polyprolylene (PP) pine garland with a 3 cm fibre length fixed upon a metal wire.
2. Perforated Al sheet welded into a 70x70cm square Al frame covered by (A.) artificial grass with a 6 cm fibre length; (B.) a PP pine garland with a 3 cm fibre length fixed upon a metal wire.
3. Perforated Al sheet welded into a circular Al frame with a diameter of d=56 cm covered by (A.) artificial grass with a 6 cm fibre length; (B.) a PP pine garland with a 3 cm fibre length fixed on a metal wire.
4. Perforated Al sheet welded into a circular Al frame with a diameter of d=80 cm covered by (A.) artificial grass with a 6 cm fibre length; (B.) a PP pine garland with a 3 cm fibre length fixed on a metal wire.
5. Perforated Al sheet welded into a circular Al frame with a diameter of d=56 cm covered by (A.) artificial grass with a 6 cm fibre length; (B.) a PP pine garland with a 3 cm fibre length fixed on a metal wire; held afloat by a frame made of a 5-cm-diameter PVC tube.

2.4. Experiments

2.4.1. Preliminary testing of the prototypes – study of nest occupation

A preliminary study was carried out in 2017 with the purpose to check whether the designed nests would be accepted by the fish at all. The methodology for nest deployment, inspection and measurements was also developed at that time.

Nest rows were placed at five locations in the 2017 study year. An equal number of the ten prototypes (5 per location) were randomly tied one after the other, in one row, at a distance of 1.5 m from each other, and placed into Lake Balaton on 16 March.

The first inspection took place on 27 March 2017, during which, each nest was individually photodocumented recording the fact of occupancy or lack thereof, as well as the species of fish laying the eggs (pikeperch /roach/mixed).

2.4.2. Determining the quantity of eggs

In order to study the quanity of eggs attached to a unit surface in the individual substrate types, approximately 10x10 cm samples were first cut out of them in field conditions (3 samples per substrate type). Sampling took place at the Fonyód and Siófok sites in 2018 and 2020. Thereafter, three sub-samples of 2x2 cm were taken from each sample with the greatest possible precision. Eggs were carefully removed from these sub-samples, and the number of eggs per unit area (eggs/cm^2) was determined by simple counting under a Leica DMS-1000 type digital microscope. The number of eggs per nest was determined based on the size of egg-covered surface and the number of eggs per 1 cm^2 surface unit.

The number of eggs in the occupied nests was determined using the digital photos taken during field inspections (checking). The surface covered with eggs was determined as the number of pixels of the individual nest photos using the ImageJ software. Thereafter, the number of eggs per nest could be easily calculated by applying the previously defined egg/cm^2 ratio.

2.4.3. Study of the efficiency of different spawning nest types based on egg numbers

From year 2018, after the exclusion of floating nests, we examined the efficiency of all other nest types based on the quantities of laid eggs. The distance between individual nests was two meters. The rows were anchored on the bottom with two 10-kg weights. The rows were marked by 2 small buoys at each end, and the entire experimental area was delimited by 4 buoys made of 200-l yellow barrels. Each row consisted of 6 nests, which followed each other randomly, both in terms of size, shape and substrate.

The above experimental arrangement was deployed in the same layout each year between 2018 and 2020 at the Fonyód, Tihany and Balatonvilágos sites. The deployment of the nests was carried out by a crew of three persons from an ORCA 540 type workboat.

The nest inspections took place on a weekly basis. During the inspections, each nest was individually photodocumented (Nikon D500 camera, AF-Nikkor DX 35mm f/1.8G fixed lens), regardless of the presence or absence of eggs.

2.4.4. Testing the impact of bottom substrate

The efficiency of benthic spawning nests under different bottom substrate conditions was examined in the 2020 study year. In addition to the three hard-bottom (stony, marly) study sites (Fonyód, Tihany, Balatonvilágos), three sites (Balatonszemes, Balatonudvari, Siófok) were also selected where the bottom substrate consisted of silt or silty sand. The nest deployment was carried out on 10–11 March 2020, using the same methodology as before, at a water temperature of 4.3 °C (at the Siófok site, measured at the water surface). Inspections were carried out weekly. Spawning took place within no more than 5 days before 27 March, at a water temperature of 6.8 °C (Siófok, water surface).

2.4.5. Egg hatching experiments

The study took place between 28 March and 1 April 2019. For the hatching experiment, the nests removed from the Fonyód site were transferred without delay to the Siófok and Buzsák sites, keeping them wet and taking care to avoid any damage to them during the transportation. For the experiment, the fertilized eggs were removed together with the substrate from a part of the nests placed in Lake Balaton. Equal 3 x 3 cm pieces were cut from the substrates containing the eggs, which were then hung, by weighed-down thin fishing lines, from a rope stretched near the water surface, at a distance of 30 cm from the surface.

The water temperature was 8.5±1 °C in Lake Balaton and 10.2±2 °C at the pond farm during the experiment. The egg development was checked under a Leica DMC-1000 digital microscope, first every 12 hours, then every 4 hours. All eggs in which intensively moving, developed and distortion-free embryos were visible 1–2 hours before hatching were regarded as "viable".

2.5. Data analysis

All original, field collected data were transformed using the log(x+1) function. Normal distribution was tested with the Kolmogorov-Smirnov test, always with a 95 % confidence interval. If the normality condition was met, parametric tests (Student's t-test, one-way analysis of variance - ANOVA) were used. If parametric tests could not be applied, the Kruskal-Wallis (KW) test was used. The widely used Tukey's post-hoc test was applied for pairwise comparisons upon evaluation of the ANOVA results, while Dunn's test was used following the KW test.

To examine the potential impact of the different bottom substrate types, multi-way factorial ANOVA was used, in which the "number of eggs" was regarded as the dependent variable, while "shape", "size", "substrate" and „site” were considered factors. All analyses were performed in the R statistical environment.

3. RESULTS

3.1. Preliminary testing of the prototypes

Of the 250 benthic spawning nests deployed during the 2017 study, 148 (59.2%) were occupied by fish. However, if the "floating" nest prototypes (5.A and 5.B) are excluded from the dataset, this share increases (66%).

The "floating" prototypes were simply not working, the fish did not occupy them, presumably because of the disturbing effect of local currents. These nests were also regularly found tangled during inspection. For this reason, they were excluded from subsequent testing.

Nest occupancy varied considerably between the five study sites (52-72%).

In addition to pikeperch eggs, the share of roach eggs was also found to be significant in the nests: pikeperch spawned on 68% of all occupied nests, roach on 20%, while the sexual products of both species were found on 12%.

Significant difference could be detected between study sites with silty and rocky bottom substrates in terms of the occupancy rate of the nests (Student's t-test, $t=3.6$, $df=3$, $p=0.034$).

The higher nest occupancy values registered over hard, rocky bottom conditions can have several reasons. On the one hand, it could be assumed (and was also confirmed in practice during inspections) that the easily mobilized soft sediment was just more likely to cover or, in extreme cases, bury the nests. In such cases, the fish simply did not notice the nests, so they did not have the opportunity to clean them, either. But it may also happen that pikeperch tend to use silty habitats less during the spawning period.

For pikeperch, there are no preliminar study data available on the bottom substrates of the spawning grounds. In the case of walleye (*Sander vitreus*), radiotelemetric studies showed that it avoided habitats with a silty bottom or a dense vegetation cover during the spawning season. We also know about this closely related species that its deposited eggs almost never hatch in experimental systems characterized by silt or soft sediment. However, it should be noted that, unlike pikeperch, walleye does not guard its nest, i.e. there is no sediment removal by males. For this reason, eggs are more likely to find themselves in anaerobic conditions.

Occupancy data were also examined by nest type. In this case, no significant difference could be detected (ANOVA: $F= 0.85$; $df=7$; $p=0.55$). Despite the fact that two nest types (small, round ones with artificial grass, and large, square ones with garland cover) were characterized by higher average occupancy values, the high standard deviation at all cases suggests that this is only a random result. Based on our results, no nest type preference could be determined.

The preliminary prototype testing proved that the spawning nest designs – with the exception of the floating nests – provided an adequate spawning surface for pikeperch and roach and therefore, were suitable for further testing under operating conditions.

3.2. Determining the quantity of eggs per unit surface

3.2.1. The 2018 study

Based on the experience of the 2017 studies, the nests were deployed earlier, on 12–13 March. For the counting, samples of egg-covered substrate were collected on 28 March 2018. Eggs were removed from the surface of the unit-size (1x2 cm) substrate and thus, could be counted.

According to the results of the counts carried out under a digital microscope, a unit surface of the artificial grass substrate contained, on average, more eggs (350±158) than in the pine garland substrate (305±88). However, the difference between the two substrates was not significant (Student's t -test: t=0.55; df=8; p=0.29), presumably because of the large standard deviation. Consequently, there was no significant difference – neither substantially, nor in practical terms – between the two types of substrate in the amount of eggs attached to a unit surface.

5.2.2. The 2020 study

In year 2020, the calculation of the amount of eggs per surface unit was repeated, since I decidedly wanted to use fresh data for the study of the impact of the substrate. On this occasion, the amount of eggs per 1 cm^2 turned out to be 107.4±74 on the artificial grass, and 78.3±51 on the pine garland. The t-test used for the statistical comparison of the two values not revealed significant difference this time either (Student's t-test: t=0.913, df=4, p=0.18).

It could also be concluded that the pairwise mean values (artificial grass-artificial grass – garland-garland) measured in the two study years also proved not be significant (Student's t-tests: p>0.05; Table 6). The reason for the recorded high standard deviation values may be that the fish do not necessarily deposit their reproductive products evenly, so there can be a considerably variable numberof eggs on the randomly sampled surfaces.

Table 3: Egg counts on unit surface (1 cm^2) of the substrate in the 2018 and 2020 studies

	artificial grass		pine garland	
	average	SD	average	SD
2018	175	79	107.4	74
2020	152.5	42.5	78.3	51

Of the results of the two studies, those of 2020 were used in the further analyses.

3.3. Testing the impact of bottom substrate conditions

In the 2020 study year, a total of 89% of the deployed spawning nests were occupied by pikeperch. The occupancy rate was slightly lower in soft (silt, sandy silt) bottom conditions (84.9%) than in the case of hard (rock, marl) substrate (95.8%). However, the difference between the two values was not significant(Student's t-test: t=1.067, df=2, p=0.19).

Regarding the mean number of eggs per nest, factorial ANOVA confirmed a significant impact of the size, nest substrate type and bottom substrate. On average, significantly more eggs were found in larger nests, regardless of their shape or nest substrate type. At the same time, the artificial grass substrate proved to be verifiably more effective than the pine garland, while the spawning nests placed on soft substrate clearly contained less eggs. Beside these, no combined effects were detected.

Artificial benthic spawning nests have proven to be an extremely effective tool for assisting pikeperch spawning under natural conditions in the largest shallow lake of Central Europe. While different types of artificial nests can be considered widespread in pond farming conditions, no data are available on their use in natural waters.

Based on our results, the size of the artificial nest is a key determining factor of its efficiency expressed in terms of egg quantity. According to available literature data, male pikeperch build nests of approximately 50 cm in diameter on the bottom in natural waters. Accordingly, most experimental devices had a size of 50x50 cm, while their shape was mostly square to make manufacturing easier. Only some authors mention having used larger spawning nests of 65 x 65 cm or 89 x 89 cm.

The use of larger spawning nests can be beneficial in natural water conditions, because the mating couples of pikeperch are not of the size that could be handled in pond farms. It is likely that pikeperch prefer the offered spawning nests to natural spawning sites available in Lake Balaton, so these are primarily occupied by larger fish. In addition, they also seem to be a better choice because eggs are less scattered over the substrate in a larger nest, so the pikeperch male can protect them more effectively. The flat design of the manufactured nests also contributes to this behaviour. Although we did not examine the impact of egg-predating species in this series of experiments, it is worth mentioning that, in walleye, egg predation was found to be significant. However, it should also be noted that males of *S. vitreus* do not guard the nest or the fry.

The efficiency of experimental spawning nests – in terms of eggs quantity – was clearly higher on hard substrate than in soft, silty bottom conditions, while the number of occupied nests did not differ significantly. Even though reproduction of pikeperch on silty bottoms was previously recorded, the results of this study lead to an assumption that such bottom conditions are suboptimal for the species. If we assume that larger individuals occupy the spawning sites first, then smaller-size fish, which lay fewer eggs, could find only spawning sites that provide less optimal conditions. However, our experience on Lake Balaton can lead to revising this assumption, at least to some extent. The fact that the number of occupied nests did not differ in the case of the two bottom substrate types, only the amount of deposited eggs was less, suggests that, on a whole, there are few good-quality spawning sites available for pikeperch in Lake Balaton. This, along with the lack of food in the early (plankton-consuming) life stage, as well as the cannibalism indicated by previous studies, can negatively affect the stability of the pikeperch stock, heavily exploited by anglers.

3.4. Hatching experiment

In the experiment performed in the flow-through tanks of a hatchery, the share of viable embryos (i.e. those intensively moving before hatching) was 88.10±10% on artificial grass, and minimally lower, 85.9±13%, on pine garlands. In the experiment carried out in Siófok Harbour, similar, but slightly higher values were registered (91.2±16 %, 90.9±14 %, respectively). There was no statistically verifiable difference between the tested substrates or between the two study sites (ANOVA F=1.0061, df=3, P=0.394).

The share of viable embryos was rather high in both cases, and differed only very slightly. The dense, fibrous structure of the artificial grass did not result in increased egg mortality caused by lack of oxygen or infection. This result confirms the previous hypothesis, according to which, the hatching rate of pikeperch should be higher on artificial (plastic, non-biodegradable) substrates. This can be explained by the fact that saprophytic fungi, which are mostly facultative pathogens, are present in lower density on these surfaces. However, this explanation is put into some doubt by the recent confirmation of the colonization of a plastic substrate placed into a Hungarian water reservoir by numerous pathogenic microbes.

It should also be mentioned that significant egg predation was recorded on the substrate pieces placed in Siófok Harbour. This definitely reduced the egg density, even though the extent of this decrease is not known. At the same time, however, the share of viable embryos was not significantly higher, despite the fact that, in the flow-through system, part of the suspended solids of the intake water settled on the surface of the eggs.

To conclude, it can therefore be concluded that the hatching success is not significantly influenced by the type of artificial substrate. In practice, the use of the latter can be primarily determined by its availability, value for money and durability.

3.5. Long-term (3-year) study of the efficiency of different spawning nest types

The long-term studies were conducted at the study site known from the 2018 and 2020 spawning periods, which was characterized by a hard (marly, rocky) bottom. The study sites (Balatonvilágos, Tihany, Fonyód) and the layout of the deployed nests was the same in all three study years.

3.5.1. Changes in egg quantities by nest type in the different study years

Significant differences were found between the egg quantities recorded in the individual nest types in all three sites, (Kruskal-Wallis tests: $H_{Balatonvilágos}=70.79$; $H_{Tihany}=68.93$; $H_{Fonyód}=66.89$; $P<0.00001$ in all three cases). However, pairwise comparisons using Dunn’s post-hoc test confirmed a significant difference only based on the size of the spawning nests.

In the Balatonvilágos sampling site, low variance was typically found in relation to both the individual nest types and the quantity of eggs between the years within the same nest type.

In the Tihany study site, a pattern similar to the previous one was recorded. In the case of square nests covered with artificial grass, higher standard deviations were registered in 2018 and 2020 compared to the other values, but there was no statistically verifiable difference between the averages within the same type in this case either.

This phenomenon might be explained by the uneven bottom substrate conditions at the study site. The hard-bottom spawning ground at Tihany has significant faults, cracks, and rocky outcrops. It is possible that, because of these, some nests lay in a non-ideal position on the bottom, so the pikeperch could only partly use them as a spawning substrate.

In the Fonyód study site, more significant differences were found compared to the Tihany and Balatonvilágos sites.

Low egg quantities – comparable to those found in small nests – with relatively high standard deviations were recorded on the large, round, pine garland-covered nest type in 2018 and 2020, and on the large, square, pine garland-covered nest type in 2020. The possible reason for this is that pikeperch individuals of smaller average body size gathered at this spawning site. At the same time, it is also possible that, due to the large extent of the Fonyód spawning ground, significantly more and better-quality natural spawning sites were available in this place, which were preferred by large pikeperch over artificial substrates. However, this latter assumption is put into doubt by the high egg coverage values on nests covered with artificial grass.

3.5.2 Study of spawning nest efficiency based on the cumulative impact of the site and the year

Based on the results of factorial ANOVA, it can be concluded that differences between the study years (weather, water temperature, water level) had no verifiable effect on the egg quantities laid onto the experimental benthic spawning nests.

On the other hand, the deployment location did have a verifiable effect, despite the fact that only data from habitats characterized by a hard (marly, rocky) bottom were taken into account in this analysis. The different abiotic environmental characteristics of the sites, however slight, may play a role in this. Since neither tagging studies nor population genetic studies succeeded in proving any real, population-level separation between the pikeperch stocks of the individual parts (basins) of Lake Balaton, different life cycle characteristics of the individuals spawning in the different places can be virtually ruled out as a cause.

The differences related to the size of the spawning nest and the quality of the substrate were confirmed by studies taking into account time series data.

4. CONCLUSIONS AND RECOMMENDATIONS

The developed benthic spawning nests can be used with great efficiency in Lake Balaton and other fishing waters. They can be used particularly well in waters with limited natural spawning grounds. In the case of pikeperch, the spawning nests proved to be efficient even in muddy bottom conditions because of the characteristics of the reproductive behavior of the species, i.e. the spawning-site-cleaning activity of the males. This is particularly noteworthy with regard to Lake Balaton, since the sediment, which is easily mobilized by wind and wave action in the large shallow lake, is very likely to bury the deployed spawning nests. In smaller angling ponds or reservoirs, this phenomenon is improbable or, if it occurs, its extent should be negligible.

A sufficiently early deployment of the spawning nests can ensure that they are used only by pikeperch. Still, the presence of roach eggs proves that the developed artificial structures can provide suitable spawning sites for other fish species as well.

In contrast to previous studies, the deployment of larger spawning nests is clearly advisable. Even though it was not examined in this study, it is generally known in fish that the amount of eggs deposited – and, in the case of pikeperch, the surface of the substrate covered with eggs – depends on the body size of the female. For this reason, knowledge of the body length distribution of the pikeperch living in a given waterbody can provide an additional clue for optimizing the size of spawning nests. In practice, obviously, this can only be assessed with adequate efficiency in smaller angling ponds.

The relatively high occupancy of spawning nests placed on soft sediment (silt) -covered bottoms does not only draw attention to the significantly limited amount of spawning sites available in Lake Balaton, but also to the phenomenon of "nesting fidelity", known in several fishes. It was also observed in a close relative of pikeperch, the North American walleye, but, in the case of our local species, few related data are available, and even those rather provide information on the phenomenon of „homing", characteristic of sexually mature individuals. In the case of Lake Balaton, the abundantly available habitats characterized with silty bottom presumably do not, by themselves, make it possible for pikeperch to reproduce successfully. Still, in the study years 2017 and 2020, we experienced spawning on nests deployed in such places, too, which makes it advisable to study the spawning-site-searching behavior of pikeperch in the future.

During the standardized studies done between 2018 and 2020, spawning took place at the end of March, well in line with the literature data. As a result of two major cold waves in the second half of March 2020, the water temperature (Siófok, at water surface) was only 5.5°C. This is significantly lower than values mentioned in the literature for Hungarian water bodies (around 10°C). Studies on walleye showed that, in this closely related species, the photoperiod, i.e. the length of the days, which greatly influences the circadian rhythm, plays an extremely important role in triggering spawning and the hormonal processes preceding it. Based on the experience of the present study, a further examination of this issue in pikeperch would be definitely justified.

Based on the study results of my thesis work, BHGNP has manufactured 2250 round spawning nests with a diameter of 80 cm, covered with artificial grass substrate. Ever since, these have been annually deployed according to the developed protocol, then collected for maintenance after the pikeperch spawning season (May-June).

On the one hand, the developed benthic spawning nests are quite effective tools assisting the spawning of pikeperch in natural waters and in fish farming facilities but, at the same time, obviously, they cannot solve alone the problems of natural recruitment of fish in habitats affected by varying degrees of anthropogenic pressure. In theory, a total of approximately 1 billion eggs are laid annually on all the nests placed into Lake Balaton. Based on our experiments, 90% of this amount hatches out, but since there is no suitable food (zooplankton) available for the larvae in the lake, only a small part, approximately 0.001–0.005%, survive the first summer. In practice, this means that the deployed nests can yield 1.5 to 7.5 pikeperch of the 0+ age group per hectare, calculated for the entire surface area of Lake Balaton. Comparing this value with Bíró's (1997) estimate (2.4–7.5 individuals of pikeperch/ha), the nests can still significantly contribute to a sustainable long-term exploitation of the stock. However, it should be noted that the handling of this large number of spawning nests means a significant annual burden for the fisheries management body, as the deployment, collection and maintenance (washing, repairing) of the devices all involve significant personnel and fuel costs.

As mentioned before, the use of artificial spawning sites, as well as the fishing rules set by BHGNP in the local fishing regulations, which are significantly stricter than the national ones (lower and upper size limits, quota system), are an important step to a sustainable – in the case of Lake Balaton, angling-oriented – fisheries management of pikeperch or any other target species. In the longer term, however, this would require more complex, catchment-level habitat restoration and habitat development actions. In the catchment area of Lake Balaton, there are still some quasi-natural habitats (e.g. Nagyberek, Pogányvölgyi stream, Lesence-Nádasmező) whose reconnection to the lake in a way that allows free movement of the fish, at least during the spawning season, would achieve significant results with a one-time investment, not only for pikeperch, but also for the entire fish fauna of the Balaton. These habitats – former bays of Lake Balaton – would not only provide a significant number of natural spawning grounds but could also have a positive impact on the survival of the fry because of their character (shallow habitats with rich vegetation).

Summarizing the above, the most important result of my doctoral work is the development of a new tool, whose applicability in fisheries practice was confirmed by scientific studies and commercial-scale experiments.

5. NEW SCIENTIFIC RESULTS

1. It was proven that completely artificial benthic structures (i.e. placed on the bottom) are an adequate spawning substrate for pikeperch, while floating nests are not suitable for individuals of that species.

2. It was found that, in the case of pikeperch, no difference could be detected between the studied eight types of spawning nest prototypes in terms of their occupancy (egg-containing nests), i.e. there was no size, shape or substrate preference.

3. It was demonstrated that there was no verifiable difference in the efficiency (eggs/cm^2) of two commercially available artificial nest cover (substrate) types (pine garland and artificial grass), so both of them can be used depending on economic aspects (availability, price, durability).

4. It was demonstrated – in contrast to previous literature data – that it was advisable to provide larger artificial spawning nests (round ones with 80 cm diameter or square ones with 70 cm side length) to the pikeperch in order to ensure that as many eggs as possible remain on the artificial substrate.

5. It was found that, in terms of average egg quantities (number of eggs/nest), the highest values could be registered on round nests of 80 cm in diameter covered with artificial grass. For this reason, as well as because of the durability of the artificial grass, this type can be recommended for serial production.

6. It was demonstrated that, even in the soft-substrate bottom conditions suboptimal for pikeperch (silt, soft sediment), the developed benthic

spawning nests were as efficient in terms of occupancy as in hard bottom conditions. On the other hand, as concerns the amount of eggs laid, significantly less eggs were registered on the nests placed on soft bottom substrate.

7. It was demonstrated that both tested substrate types (artificial grass and pine garland) resulted in similarly high efficiencies (over 85%) of pikeperch egg hatching.

6. SCIENTIFIC PAPERS PUBLISHED ON THE SUBJECT OF THE DISSERTATION

1. **Sziráki, B**., Staszny, Á., Juhász, V., Weiperth, A., Nagy, G., Fodor, F., Havranek, M., Koltai, T., Szári, Zs., Urbányi, B., Ferincz, Á. (2021): Testing the efficiency of artificial spawning nests for pikeperch (Sander lucioperca L.) under natural conditions (Lake Balaton, Hungary). *Fisheries Research*, 243 p. Paper 106070. (Q1, IF=2,42)

2. Staszny, Á., Paulovits, G., Takács, P., Juhász, V., Prigl, S., **Sziráki, B**., Urbányi, B.**,** Ferincz, Á. (2019): The role of ontogenetic development in fish scale shape changes, Applied Ecology And Environmental Research 17: 2 pp. 3535-3544. (IF=0,74) Q3

3. Juhász, V., Staszny, Á., **Sziráki, B.**, Szári, Zs., Nagy, G., Havranek, M., Németh, F., Jankovics, Z., Urbányi, B., Ferincz, Á. (2020): Különböző mesterséges süllőfészkek tesztelése a Balatonban, Halászat 113 (1): 24-32.

4. **Sziráki,** B., Staszny, Á., Urbányi, B., Szári, Zs., Fodor, F. , Nagy, G., Tulipán, T., Németh, F., Havranek, M., Ferincz, Á. (2018): Development of artificial spawning nests for pikeperch (Sander lucioperca L.) in a highly modified shallow lake (Lake Balaton, Hungary) In: Proceedings of the 5th European Congress of Conservation Biology, Jyvaskula, Finland

5. **Sziráki,** B., Staszny, Á., Juhász, V., Fodor, F., Urbányi, B., Szári, Zs., Nagy, G. , Havranek, M. , Ferincz, Á. (2019): Testing various artificial spawning nests of pikeperch (Sander lucioperca L.) in Lake Balaton, In: Fresh Blood for Freshwater 2019: Book of abstracts, 102-103.