Management options for the unfavorable nutrient balance of recreational fishing in Lake Balaton (Hungary)

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ABSTRACT
Various types of ground baits are loaded to lakes by anglers, but the ecological role of these materials is often overlooked. Thus, the aims of this study were to conduct a quantitative and qualitative assessment of the baits used by anglers in the largest lake of Central-Europe (Lake Balaton, Hungary), estimate the annual nutrient balance of recreational fishing, and relate the nutrient loading from this source to the total external load. Our study demonstrated that popular angler baits varied substantially in their nutrient contents and in their molar nitrogen to phosphorus (N:P) ratios. The net nutrient balance of recreational fishing was +19.3 t total N year⁻¹ and +5.2 t total P year⁻¹, equivalent to 0.7% and 3.2% of the estimated total annual N and P loads, respectively. The rate of nutrient loading may be doubled if the present trends continue: anglers will use 20% more bait with an even higher nutrient content and will also show higher propensity to release the fish after catching. In turn, sustainable nutrient balance of fisheries management could be achieved by limiting the anglers’ bait use to 1.5 kg day⁻¹ and restricting baits to those which have relatively low P (<0.3%) and N (<1.5%) contents.

Introduction

External, anthropogenic nutrient loading is one of the most concerning issues in many freshwater ecosystems, negatively affecting the health of these habitats (Carpenter and Lathrop 2008; Smith and Schindler 2009; Schindler 2012). Shallow lakes and rivers are especially vulnerable in this respect because they are preferred recreational sites but are sensitive to even small perturbations of their nutrient cycles. Elevated levels of limiting nutrients in the water column can result in planktonic eutrophication and concomitant biotic changes, such as the decline of submerged macrophytes, fish kills, and the loss of biodiversity (Carpenter et al. 1998; Søndergaard et al. 2010). Among the several biogenic elements that may serve as nutrients, nitrogen (N) and phosphorus (P) are of particular importance because their availability were shown to be highly correlated with ecosystem productivity and algal biomass (Vollenweider and Kerekes 1982; Schindler 2012). Accordingly, an essential target of freshwater restoration projects is to minimize or eliminate external N and P loads, and control internal nutrient cycling at the same time (Gulati et al. 1990; Kasprzak et al. 2003; Søndergaard et al. 2008).

In general, the most important sources of anthropogenic N and P loads are the urban-, industrial- and agricultural runoffs, the direct inflow of untreated sewage, and the atmospheric deposition (Carpenter et al. 1998; Tang and Xie 2000; Jeppesen et al. 2003; Camarero and Catalán 2012). Moreover, the recent adverse shift in the P balance of the global fish production – caused by the intensifying use of fertilizers and modern feeds with high nutrient contents – is now also seriously threatening natural aquatic ecosystems (Huang et al. 2020). In addition, there may be other fishery-related effects that are often not taken into account when assessing ecosystem-scale nutrient budgets. A good example for this could be the external nutrient loads deriving from anglers’ ground baits (materials thrown into the water in order to attract fish to a designated area), which occur in many freshwater ecosystems with significant recreational fishing activity (Wolos, Teodorowicz, and Grabowska 1992; Amaral et al. 2013; Grochowska et al. 2020; Imbert et al. 2022). This issue is of increasing importance since recreational fishing involves hundreds of millions of people worldwide (Lewin, Arlinghaus, and Mehner 2006; Arlinghaus, Tiller, and Bork 2015) and the popularity of ground baiting is increasing with economic development and as a result of its intensive propagation in fishing media and on electronic social platforms, especially among specialized carp anglers (Arlinghaus and Mehner 2003; Niesar et al. 2004; FAO 2010). It was shown that even a moderate ground bait use may influence food web processes and increase secondary production, as well as support primary producers and induce eutrophication (Arlinghaus and Niesar 2005; Lewin, Arlinghaus, and Mehner 2006;
Hlaváč et al. 2016; Mehner et al. 2019; Imbert et al. 2022). For example, Arlinghaus and Mehner (2003) showed that specialized carp angling may contribute significantly to anthropogenic eutrophication, and that the trophic state of naturally nutrient-poor waterbodies are more likely to be affected by ground baiting than nutrient-rich waters. In North-Eastern Poland, ground baits introduced into the water by anglers comprised more than 10% of the total external P load in 30% of the lakes studied, and in one case, it was assessed to be responsible for the 44.8% of the total P load (Grocwowska et al. 2020). Furthermore, the over-use of ground baits and the concomitant bacterial decomposition of uneaten organic matter can cause local hypoxia in the sediments (Turner and Ruhl 2007), which may trigger internal nutrient loading via the liberation of iron-bound P (Boström et al. 1988) and reduce the density of benthic invertebrates (Cryer and Edwards 1987). However, compared to the wide-scale popularity of recreational fishing, its consequences on nutrient cycling in aquatic ecosystems is yet largely undiscovered in most areas concerned.

The “traditional” bait materials are grain seeds (e.g., corn, wheat), bread, and other bakery products, while in “modern” carp fishing selectivity and enhanced catching rates are achieved by the use of more complex baits, such as ground cereal-based mixes, pelleted fish foods, and so-called boilies ("boilies" are 1 to 3 cm diameter ball-shaped, flavored baits made from boiled paste fixed typically with egg white and usually containing ground cereals and fishmeal, milk protein, soy flour, and other ingredients). The different types of baits may contain nutrients in varying proportions and have a different digestibility as a function of their ingredients. For example, Amaral et al. (2013) found that the total N content in 10 popular complex baits varied between 12 and 31 g kg⁻¹, while this range was 1.5–6.3 g kg⁻¹ for total P. Arlinghaus and Mehner (2003) showed that self-made boilies may contain more than two times higher amounts of P than cereals, while Niesar et al. (2004) reported that commercial fish feed (also used commonly by anglers for baiting) contains 3.5 – 5-times more P than coarse ground baits or commercially prepared boilies. Imbert et al. (2022) also showed that the nutrient content of popular ground baits is highly diverse, with N contents varying by a factor three and P contents by a factor of five among different materials.

Nevertheless, not only the absolute nutrient content but the digestibility of these materials influences the effect of ground baiting on the water quality. Cyprinid fishes often consume considerable amounts of bait material in the littoral zone (up to 45.5% relative proportion in the gut contents; Specziář, Tölg, and Bíró 1997; Specziář and Rezsu 2009) and retain 20–50% of dietary N and 15–56% of P (Hlaváč et al. 2014, and references therein), while the remaining part is excreted or egested. Niesar et al. (2004) reported that P retention efficiency varied between 3.6% and 32.1% in common carp (Cyprinus carpio) fed by a range of diets, with the lowest efficiencies associated with low P content food types. Although the plant-based ground baits typically contain less P than those also including ingredients of animal origin, the nutrients in crude vegetable sources are mostly unavailable for stomachless fishes (e.g., cyprinids), which are unable to break down complex carbohydrates (Arlinghaus and Mehner 2005, and references therein). Thus, different types of angling baits may have notably different potentials to induce external nutrient loading and to promote anthropogenic eutrophication.

From the perspective of net nutrient load, the effect of recreational fishing should be considered complexly, where nutrient load by baiting (and stocking where relevant) is counterbalanced at least in part by the nutrient removal by fish harvest. This is important because the components of the nutrient balance are not independent; the amount of ground bait used and fish capture rates are generally correlated (Wolos, Teodorowicz, and Grabowska 1992; Arlinghaus and Mehner 2003; Czerniejeiwski and Brysiewicz 2018). In addition, the net nutrient load by recreational fishing depends on to what extent the captured fish are taken home or released back to the water (i.e., catch-and-release fishing practice) (Arlinghaus and Mehner 2003; Niesar et al. 2004). The effect of recreational fishing can vary between net nutrient removal and significant net nutrient load, as a function of the variability in anglers’ abundance; their ground bait usage, their propensity to keep or release their catches, and the composition of the popular ground baits (e.g., Edwards and Fouracre 1983; Wolos, Teodorowicz, and Grabowska 1992; Arlinghaus and Mehner 2003; Niesar et al. 2004; Amaral et al. 2013; Czerniejeiwski and Brysiewicz 2018). The above cited studies suggest that an adverse trend in the general nutrient balance of recreational fishing occurs mainly due to the increasing nutrient content of modern baits and popularity of catch-and-release fishing.

We conducted this study to discover how intensive angling activity could affect the nutrient balance of a large freshwater ecosystem, Lake Balaton (Hungary). The external nutrient load to Lake Balaton – a popular recreational area and valuable natural habitat – has been a long-standing problem. Its management required complex measures, including developments in sewage treatment, controlling the use of fertilizers on the watershed, and the (re)construction of the Kis-Balaton Water Reservoir. These interventions have led to the recovery of Lake Balaton from eutrophic to meso-oligotrophic state (Istvánovics et al. 2007). However, after a massive algal bloom in 2019 (Istvánovics et al. 2022), scientists and stakeholders were convinced that the established long-term water
quality targets required further exploration and monitoring of all potential sources of external nutrient load, as well as their conjugation with further management options. Accordingly, by considering that recreational fishing and the related activities (e.g., ground baiting) have the potential to affect the nutrient cycling of aquatic ecosystems, the aims of this study were: (1) to determine the types, quantity and nutrient (total N and P) contents of ground baits used by anglers in Lake Balaton, (2) to assess the annual nutrient balance of fisheries management and the related activities (fish stocking and removal, ground baiting) in the lake, (3) to compare the net nutrient loading from fisheries management with the total external load, and (4) to draw up scenarios on the potential positive or negative effects of recreational fishing in case of future changes in angling practices, and provide recommendations that could help to reduce or prevent the anthropogenic nutrient loading to the lake.

Materials and methods

Study site

Lake Balaton (Figure 1) is the largest (~600 km²), shallow (mean depth: 3.2–3.5 m) lake in Central Europe, situated in western Hungary. Besides its ecological value (the lake is a designated Natura 2000 site and is under the protection of Ramsar Convention), Lake Balaton is important to the Hungarian economy as a recreational area, visited by millions of tourists every year. Although the lake was subject to massive eutrophication between the 1960s and 1990s, water quality has since improved due to restoration efforts (Istvánovics et al. 2007; Bernát et al. 2020). Lake Balaton can be characterized with moderate productivity since the mid-1990s (usually around 5–20 μg L⁻¹ annual mean chlorophyll-a values in the lake water; Bernát et al. 2020), except for a case in the early autumn of 2019, when a massive phytoplankton bloom occurred in the western region of the lake (Istvánovics et al. 2022). During that period, chlorophyll-a levels exceeded 300 μg L⁻¹ in the Keszthely-Basin and 600 μg L⁻¹ close to the estuary of Zala-River (data from the Central-Transdanubian Water Management Directorate of Hungary).

The fish fauna of the lake consists of 36 species, among which the most abundant are bleak (Alburnus alburnus) and common bream (Abramis brama) (Specziár and Erős 2020). Common carp is the most typical species in anglers’ catches (50–60% of the total removed fish biomass), while the overall proportion of cyprinids in the total annual fish harvest is 70–80% (Boros 2022). The top predator in the lake, also important in anglers’ catches, is pikeperch (Sander lucioperca). Since 2013, commercial fishing has been almost completely banned, while it remains legal for recreational anglers to catch fish from Lake Balaton in accordance with strict daily limits. In present days, commercial fishing includes only the occasional eel (Anguilla anguilla) trappings at the estuary of Sió Canal. Angling has been more and more popular in Lake Balaton during the last two decades, highlighted by the substantial increase in issued annual angling licenses (from 20000 to about 30 000) over this period, as well as the number of short-term licenses (daily, three days, and ten days), which increased from 30000 to 60000(data obtained from the Balaton Fishery Management Nonprofit Ltd.). The total fishing activity is estimated to be more than 1.3 million fishing days per year. Although there are no exact data on the distribution

Figure 1. Lake Balaton (46°51'00"N 17°43'12"E) and its 5775 km² catchment area. The lake has several smaller and larger inflowing watercourses, whereas the only outflow is the Sió Canal located in the eastern basin. Anglers are fishing and using ground bait across the entire littoral zone.
of recreational fishing effort along the shoreline, it is evident that anglers occur everywhere in the littoral zone of Lake Balaton utilizing all the accessible shore sections and using small boats to reach reedy areas. Recreational fishing typically occurs at the littoral zone (0–200 m distance from the shore) and thus bait material load is the most significant in this region across the whole lake. A smaller part of the anglers fish offshore for pikeperch, but this method is not accompanied with ground baiting. Beside the traditional cyprinid and pikeperch fishing, specialized common carp fishing, targeting trophy specimens and practicing catch-and-release approach are becoming even more popular. There is no daily bait limit for anglers at the present.

Surveying the baiting habits of anglers in Lake Balaton

In 2020, in collaboration with the Balaton Fishery Management Nonprofit Ltd., an online survey was conducted among anglers to gather information on their general fishing habits and the usage of ground baits in Lake Balaton. The survey included the following questions:

- What type of license(s) (annual, daily, three or ten days) do you own?
- How many days do you spend with angling in Lake Balaton a year?
- Do you use any bait material to attract the fish to the fishing site or to the hook?
- If you use bait material, how many days a year?
- If you use bait material, how much of it per day (kg) and what bait types (e.g., corn and other grains or nuts, bread, ground cereal-based mixes, pellets and boilies)?

The survey was accessible through the website of the Balaton Fishery Management Nonprofit Ltd. and it was propagated in the relevant online media and social platforms. The questionnaire was completed and submitted correctly by 1959 anglers, which represents ca. 5% of the angler community visiting Lake Balaton. The information obtained after summarizing the surveys was used to calculate the amount of ground baits loaded to the lake, by extrapolating the data to the total number of days spent by fishing at Lake Balaton on an annual basis (data on the number of anglers and the tickets sold was provided by the Balaton Fishery Management Nonprofit Ltd.).

In addition, we had direct information on the amount and type of ground baits used by specialized carp anglers during the two, 6–8 days long fishing tournaments (IBCC – https://ibcc.hu/english/, NBBH – https://nbbh.bbv.hu/) in 2020, because participants were requested by the representatives of the Balaton Fishery Management Nonprofit Ltd. to provide these data in a questionnaire.

Composition of angling baits

Altogether, 17 different types of angling baits were included in the chemical (total N and P content) analyses. The “traditional” bait materials were represented by corn and bread, because these two were proven to be preferred by Hungarian anglers. The 15 most popular commercial baits (ground cereal-based mixes, pellets, boilies; 5 types from each category) were selected according to the selling statistics of a large local distributor company.

As the first step of sample preparation, all selected types of bait materials were freeze-dried (lyophilized) for 48 h in order to determine their moisture content and prepare them for homogenization. After this procedure, samples were ground to a fine powder with a Retsch ZM-200 ultra-centrifugal mill (Retsch GmbH, Germany). Subsamples (three replicates per type) of the powders were combusted at 550°C for 8 h and the produced ashes were dissolved in hot 0.3 N HCl solution (Boros and Mozsár 2015). Phosphorus contents of aliquots were measured colorimetrically with a Hitachi U-2900 spectrophotometer (Hitachi High Technologies Ltd., Japan), using the molybdenum-blue method (for more details about the P measurement methodology see Boros and Mozsár 2015). The size of subsamples for the analysis was selected according to the expected P content range of the bait materials examined and the calibrated measurement range of the colorimetry. Total N content of samples (also three replicates per type) was assayed with a Flash EA 1112 elemental analyzer (Thermo-Fischer Scientific Inc., USA), calibrated as to cover the expectable range of N content in standard bait subsamples based on literature data. When the N level of a sample fell outside the calibrated range, the size of the subsample was adjusted so as to fit its N level to the calibrated interval and the measurement was repeated. Accuracy of the measurements was checked regularly against a sulfanilamide analytical standard during the analysis.

Assessment of the nutrient balance of fisheries management in Lake Balaton

The net nutrient balance of angling-oriented fisheries was calculated based on the total amount of nutrients removed from and loaded into the lake by all related activities. Specifically, the fish catch taken by the anglers (including the commercial catch of non-native fishes, which is also part of the recreational fisheries management in Lake Balaton) and fish
carcasses collected and removed by the fisheries management company represent nutrient removal (with negative values in the nutrient balance), whereas fish stocking and ground baiting (both recreational and tournament) represent nutrient load (with positive values in the nutrient balance): net nutrient load$_{NP} = -$ catch$_{NP} -$ carcass removal$_{NP} +$ stocking$_{NP} +$ recreational baiting$_{NP} +$ tournament baiting$_{NP}$. Note that catch-and-release is strictly applied in tournaments, and thus, the nutrient balance of these events is confined to the effect of baiting. Data on the mass of nutrients removed in the form of fish biomass, as well as the nutrient inputs by fish stockings are available from Boros (2022) for the period 2017–2019, while nutrient input by ground baits was estimated in the present study. Since anglers were asked about their general fishing activity and baiting habits, representativeness of nutrient load data by ground baiting probably best overlap with the considered interval of fish stocking and harvesting data.

To relate the net nutrient loading attributed to recreational fishing to the total annual external nutrient loads received by Lake Balaton, total N and P load data were obtained from the Central-Transdanubian Water Management Directorate of Hungary (http://www.kdttvzigh.hu). For the period 2017–2019, the total average annual external load was assessed to be 2628 t of N (range: 2342–3088 t) and 165 t of P (146–194 t), including loads carried by inflowing watercourses, direct inflow of untreated sewage, the urban-, industrial- and agricultural runoffs and the atmospheric deposition.

**Results**

**Anglers’ bait use**

The average bait input per angler was 1.5 kg (95% CI: 0.0–8.0 kg) a fishing day, while related only to the days when baiting actually occurred, this amount was 2.3 kg (95% CI: 0.2–10.0 kg). The intensity of ground baiting varied considerably among anglers; 6% of anglers declared not using ground baits at all, 65% reported using less than 2 kg day$^{-1}$ and 11% reported using more than 5 kg day$^{-1}$ (Figure 2(a)). The distribution of different types of bait materials used during recreational fishing was: 46.8% “traditional” bait (e.g., corn, bread), 37.9% ground cereal-based mix, and 15.3% pellet or boilie (Figure 3(a)). Note that coarse anglers not always evidently differentiate between pellets and boilies, and therefore, these bait types were evaluated together.

![Figure 2](image-url)  
Figure 2. Ground baiting intensity distribution of recreational (a) and multi-day tournament (b) anglers in Lake Balaton. IBCC: International Balaton Carp Cup in 2020; NBBH: International Balaton Boilie Fishing Competition in 2020.
Intensity of ground baiting varied considerably among tournament anglers, too; 45% of IBCC and 66% of NBBH teams reported using not more than 100 kg bait materials during the events, whereas 3% and 2% of teams acknowledged using more than 500 kg bait during the eight- and six days long events, respectively (Figure 2(b)). Although ground bait usage intensity was much higher during fishing tournaments (mean: 19.1 kg day⁻¹ team⁻¹, 95% CI: 2.7–82.8 kg day⁻¹ team⁻¹) than during recreational fishing, the total amount of ground baits thrown into the lake by sport anglers (about 45 t year⁻¹; 52.8% grain seeds and 47.2% pellet or boilie) is of minor importance in the total annual load (Figure 3(b)).

In sum, the total bait input (recreational fishing + carp fishing tournaments) to the lake was estimated to be 2084 t year⁻¹, which is equivalent to a load of 35 kg ha⁻¹ year⁻¹.

**Nitrogen and phosphorus contents of ground baits**

The most popular baits were highly variable in dry matter content, ash content, but even more importantly, in N and P content (Table 1). Pellet type of baits had the highest N and P contents (mean ± SD: 3.9 ± 1.7% N and 0.9 ± 0.4% P), followed by the boilies (1.8 ± 0.3% and 0.5 ± 0.2%), and ground cereal-based mixes were lowest in their nutrient content (1.4 ± 0.3% and 0.4 ± 0.2%). Regarding the traditional baits, both corn and bread had lower N and P contents than the complex commercial ground baits. The difference between the lowest (0.1% in bread) and highest measured P contents (1.5%; Pellet 1 in Table 1) was 15-fold. The lowest N contents were found in corn and in one of the cereal-based mixes (0.9% in both), while “Pellet 1” had the highest N content (5.8%). Thus, there was a 6.4-fold difference between the lowest and highest N contents. Bread had the highest N:P ratio (20.5, in molar units), while “Ground cereal-based mix 2” had the lowest ratio (5.2). The average N:P ratio in all examined bait materials was 9.5 ± 3.4.

**Nutrient load by baiting and the nutrient balance of fisheries management**

Annual amount of angler bait contained 29.5 t of N and 8.4 t of P. However, the net nutrient loading to the lake (i.e., the nutrient balance) – as a result of recreational and tournament fishing – has to be evaluated with the consideration of other factors too, such as fish stocking and removal. Given that the N and P load to the lake with fish stockings (in the form of fish biomass) was on average 9.0 and 2.8 t during the last years, while the removal was 19.2 t N and 5.9 t P (Boros 2022), the net nutrient balance of recreational fishing and the related activities was + 19.3 t total N year⁻¹ and + 5.2 t total P year⁻¹ (Figure 4). These values were equivalent to the 0.7% of the estimated total annual external N load to the lake, and to the 3.2% of the total P load (Figure 4).

**Nutrient balance models for alternative scenarios in fishing practices**

The scenarios (Figure 5) on the potential effects of recreational fishing in case of alternative future trends in angling practices and bait material formulation but at relatively constant catching and stocking rates show that: (1) If anglers use less than 1.5 kg of bait material a day, and the N and P contents of baits are limited to 1.5% and 0.3% then the nutrient balance could have been negative (i.e., recreational fishing would lead to a net nutrient removal from the lake) or neutral; (2) Considerable improvement could be achieved in the nutrient balance even if the upper limit of the daily useable bait material is in the range 2–5 kg and at the same time the maximal N and P contents of
Table 1. Compositions of different types of bait materials (ground cereal-based mixes, pellets, boilies, corn, bread) used commonly by anglers in Lake Balaton.

| Sample type and No. | Dry matter content, % | Ash content, % | N % in dry matter | N % in the bait (in wet matter) | P % in dry matter | P % in the bait (in wet matter) | Molar N:P ratio | Available information |
|---------------------|------------------------|----------------|-------------------|---------------------------------|------------------|---------------------------------|----------------|-----------------------|
| Ground cereal-based mix 1 | 93.0 | 11.3 | 1.5 | 1.4 | 0.3 | 0.3 | 11.8 | Ingredients: corn, bread, sweet industry by-products, gains, flavorings |
| Ground cereal-based mix 2 | 95.2 | 9.8 | 1.8 | 1.7 | 0.8 | 0.7 | 5.2 | Composition is not specified by manufacturer |
| Ground cereal-based mix 3 | 77.7 | 17.2 | 1.2 | 0.9 | 0.2 | 0.2 | 10.9 | Ingredients: cereals, sweet industry by-products, flavorings |
| Ground cereal-based mix 4 | 92.5 | 1.1 | 1.8 | 1.6 | 0.5 | 0.5 | 7.2 | Ingredients: cereals, bread crumb, oily seeds, flavorings |
| Ground cereal-based mix 5 | 92.3 | 0.9 | 1.6 | 1.5 | 0.3 | 0.3 | 10.7 | Ingredients: cereals, bread, flavorings |
| Pellet 1 | 98.3 | 5.9 | 5.9 | 5.8 | 1.5 | 1.5 | 8.8 | Small (1–2 mm) granulate. Ingredients: wheat, animal protein, fish oil, rapeseed, fish meal, calcium phosphate, sunflower seed. P content: 1–1.3% |
| Pellet 2 | 97.9 | 2.8 | 4.9 | 4.8 | 1.1 | 1.0 | 10.3 | Large (15 mm) granulate. Ingredients: wheat, fish meal, soy bean, fish oil, palm oil, animal fat. P content: 1.1% |
| Pellet 3 | 96.1 | 1.2 | 1.4 | 1.3 | 0.3 | 0.3 | 11.5 | Small (1–2 mm) granulate. Contains ingredients of plant and animal origin (not further specified) |
| Pellet 4 | 98.2 | 3.8 | 4.0 | 4.0 | 1.0 | 1.0 | 8.6 | Small (1–2 mm) granulate. Contains ingredients of plant and animal origin (not further specified) |
| Pellet 5 | 96.6 | 2.9 | 3.5 | 3.4 | 0.9 | 0.9 | 8.9 | Large (20 mm) granulate; Composition is not specified |
| Boilie 1 | 73.2 | 6.0 | 2.2 | 1.6 | 0.5 | 0.4 | 10.0 | Ingredients: plant-based flour, seeds, eggs, flavorings, fish oil |
| Boilie 2 | 71.6 | 0.8 | 1.8 | 1.3 | 0.6 | 0.4 | 6.9 | Ingredients: corn, wheat, soy bean, eggs, flavorings |

(Continued)
| Sample type and No. | Dry matter content, % | Ash content, % | N % in dry matter | N % in the bait (in wet matter) | P % in dry matter | P % in the bait (in wet matter) | Molar N:P ratio | Available information |
|--------------------|-----------------------|----------------|-------------------|---------------------------------|------------------|---------------------------------|----------------|----------------------|
| Boilie 3           | 86.2                  | 2.9            | 2.4               | 2.1                             | 0.9              | 0.8                             | 5.9            | Contains ingredients of plant and animal origin (not further specified) |
| Boilie 4           | 74.8                  | 7.1            | 2.4               | 1.8                             | 0.6              | 0.5                             | 8.2            | Ingredients: plant-based flour, animal protein, eggs, sweet industry by-products, flavorings |
| Boilie 5           | 83.5                  | 4.4            | 2.4               | 2.0                             | 0.6              | 0.5                             | 9.5            | Contains ingredients of plant and animal origin (not further specified) |
| Corn               | 95.6                  | 0.8            | 1.0               | 0.9                             | 0.3              | 0.3                             | 7.0            | Dried corn grains |
| Bread              | 68.9                  | 1.7            | 1.9               | 1.3                             | 0.2              | 0.1                             | 20.5           | Coarse white bread |
Conversely, the net balance of recreational fishing could worsen (i.e., result in about 20–30% higher nutrient load) either if the extent of “catch-and-release” fishing increases by 20%, if the nutrient content of baits increase by 20%, or if anglers use 20% more bait materials than presently. If all these unfavorable trends occur together then the net nutrient input – as a result of recreational fishing – would be almost two times higher than today.

Discussion

Sustainability is now an ultimate objective in utilization and management of natural resources such as freshwater ecosystems. Our study demonstrated, however, that the nutrient balance of angling-oriented fisheries management showed a surplus in Lake Balaton (i.e., it represented a net addition to the lake’s nutrient pool). The most significant component of the nutrient balance was the ground...
bait use of anglers that was not fully compensated by the fish harvest. It was also found that ground baits vary significantly in their nutrient contents, and thus, different bait types contribute to nutrient load of the lake to a different degree. Although the nutrient load from the recreational fishing (and the related activities) is low compared to the total external load received by Lake Balaton, these results indicate that rules of recreational fishing and bait manufacturing should be reconsidered to minimize the risk of a positive nutrient balance and concomitant environmental impacts.

**Ground baits are used extensively in recreational and tournament fishing**

As an accompaniment of carp-oriented fishing strategy, angler’s ground bait use is remarkable in Lake Balaton. Most anglers use ground baits at least occasionally, and in total, they put more than 2000 t of bait material into the lake annually. Picturing the order of magnitude, this bulk of organic matter is nearly threefold more than the annually harvested fish biomass (Boros 2022) and even amounts to one-third of the mean annual production of chironomids (ca. 5700 tons in wet weight, based on data of Specziár and Vörös 2001), organisms which constitute a considerable proportion of the secondary production and represent an important natural food resource for fish in Lake Balaton (Specziár and Rezsó 2009). Bait material may constitute a notable portion in the diet of fish, mainly in common carp, roach (*Rutilus rutilus*), white bream (*Blicca bjoerkna*) and common bream in Lake Balaton (Specziár, Tölg, and Bíró 1997). Therefore, it is likely that ground baiting substantially influences nutrient and energy fluxes though the lake’s food web as well (c.f., Mehrer et al. 2019).

Mean daily ground bait use (2.3 kg) of anglers in Lake Balaton does not differ considerably from that reported from other waterbodies characterized by carp- or in more general, cyprinid-oriented fishing in Europe. For example, anglers used on average about 1 kg day⁻¹ (Wołos, Teodorowicz, and Grabowska 1992) to 2.2 kg day⁻¹ (Czerniejewski and Brysiewicz 2018) ground bait in Polish lakes, whereas specialized carp anglers reported using on average about 3 kg day⁻¹ bait in Germany (Arlinghaus and Mehrer 2003). On the other hand, the present results point out that carp tournament anglers can use (much) more bait during a few days long event than most coarse angler does during the entire fishing season. Therefore, specific research is needed to explore the differences in the environmental impacts of dispersed regular ground baiting typical for coarse recreational angling and occasional, local mass bait inputs during angling competitions.

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**Figure 5. Examples on the possible influences of an expansion of the “catch and release” (C&R) practice and use of bait materials with increasing nitrogen and phosphorus contents, as well as expectable effects of some feasible restrictions in bait use on the nitrogen (a) and phosphorus (b) balances of angling-oriented fisheries management in Lake Balaton.**
Modern baits contain more nitrogen and phosphorus than traditional ones

In contrast to the erstwhile practice, when mainly corn, other cereals and nuts were used for ground baiting (Wolos, Teodorowicz, and Grabowska 1992), our survey revealed that sophisticatedly made up baits – pellets, boilies, and complex ground cereal-based mixes – with substantial amount of animal-based ingredients are now widely used in Lake Balaton. The same trend is typical globally (Arlinghaus and Mehter 2003; Niesar et al. 2004; Amaral et al. 2013). The shift in bait composition however significantly increased their nutrient content as well. While purely plant-based baits typically contain < 2% N and < 0.4% P (Wolos, Teodorowicz, and Grabowska 1992; Hlaváč et al. 2014; and this study), we found that the most popular commercial baits contain substantially more N (up to six times more compared to the corn) and P (up to five times more compared to the corn). Higher nutrient concentration in modern baits is a consequence of the increasing use of fish meal and other animal-based ingredients (Niesar et al. 2004). For example, dried fish meal contains 9–12% N (10 to 13 times more than in the corn) and 1.4–4.8% P (5 to 16 times more than in the corn) (Hendrixson, Sterner, and Kay 2007; Tacon, Metian, and Hassan 2009). Moreover, fish feeds (mainly pellets) with high nutritional value and N and P concentrations, developed specifically for aquaculture usage are also included to some fish baits or even distributed directly as ground bait (e.g., Pellet 1 in this study; see also Niesar et al. 2004).

Ground baits predominate the nutrient balance of recreational fishery

At present, the predominant component of the nutrient balance of fisheries management is the load caused by ground baiting in Lake Balaton. From this source more than 28.7 t N year\(^{-1}\) and 8.2 t P year\(^{-1}\) is introduced to the lake and this load is not fully counterbalanced by the harvested fish biomass. The present net nutrient input by recreational fishery was equivalent to only a small fraction of the total external nutrient load received by the lake on an annual basis (to < 1% of N and about 3% of P loads). These data indicate that the nutrient surplus deriving from recreational fishing could have only a minor effect on ecological functioning of Lake Balaton yet. Nevertheless, this seemingly minor source is also worth consideration because reduction of the nutrient load is a management priority in Lake Balaton, especially because recovering the ecosystem from the eutrophic state has required a huge effort and the risk of the re-occurrence of phytoplankton blooms is still high.

Long-term trends of the nutrient balance however show a marked shift with an indication of potential alteration in the ecological status of Lake Balaton. Namely, before recreational fishing became such a popular pastime and the use of modern ground baits became rife, fishery management generated a significant nutrient removal from the lake. From 1900 to the early 1960s, when commercial fishery was dominant in Lake Balaton and recreational fishing had only marginal importance, the nutrient balance was negative at an assessed mean removal rate of 27.1 ± 10.7 t N year\(^{-1}\) and 8.4 ± 3.3 t P year\(^{-1}\) (based on catch data presented in Biró 1997; Specziár 2010, and using conversion factor of 2.6% N and 0.8% P per unit wet mass of fish according to; Boros 2022). Compared to this, the present net loads of 19.3 t N year\(^{-1}\) and 5.2 t P year\(^{-1}\) represent a marked deterioration in the nutrient balance of fisheries management. Moreover, if our forecasted “worst case scenario” occurs, the long-term change (from the 1960s) of the P balance of fisheries management would amount to more than 10% of the present total non-fishing related external load, an order very likely to influence the nutrient dynamics within the aquatic ecosystem and the likelihood of bloom events in primary production. Unfortunately, similar unfavorable trends were reported for other freshwater ecosystems with high recreational fishing activity (Arlinghaus and Mehter 2003; FAO 2010) and for the entire fishery and aquaculture industry at the global scale (Huang et al. 2020).

For effective management, the components of the nutrient balance and their relationship should be understood. Nutrient balance of recreational fishing is typically comprised of three main and closely interrelated components. Probably the most optimized of these is the stocking, because it has a direct economic constraint motivating fishery managers to conduct effective fish breeding protocols and stocking strategies. For example, stocking practice has benefited much from consecutive studies evaluating natural recruitment and bottlenecks in diet ontogeny of fish, and the efficiency of alternative stocking strategies in Lake Balaton (e.g., Specziár 2010, 2011; Specziár and Turcsányi 2014, 2017). In contrast, optimizing between the harvest rate and ground bait use is less supported by scientific models. As discussed above, the probability of surplus in the nutrient balance of recreational fishing tends to increase with economic development; more bait materials with higher nutrient contents are used on the one hand, and an increasing proportion of the captured fish are released back to the waters, and therewith, the nutrient removal by fish harvest is narrowing on the other hand.

In consequence of the above described trends and their potential impact on aquatic ecosystems, there is a definite need for controlling the nutrient balance of recreational fishing, and especially, the nutrient load from ground baiting.
Implications for the management of recreational fishing

By considering the social and economic importance of recreational fishing, the management strategy should prioritize regulations that have less of an effect on the catching success of anglers, but yet favor sustainability of the nutrient balance. Our survey shows that most coarse anglers already use only a moderate amount of ground bait (less than 2–3 kg day\(^{-1}\), Figure 2a), and thus limiting the usage of ground baits would concern only a smaller group of the angler community. Similar patterns were observed in the tournament fishing (Figure 2b) as 40% of the total baits were loaded by the 12–14% of teams at the IBCC and NBBH in 2020. The other obvious factor that could be regulated more strictly is the nutrient content of ground baits. Since there is a wide range of traditional and modern baits with low N and P contents that are proven to attract fish efficiently, such limitation may also affect angling success to a lesser extent. Model scenarios suggest that at the actual level of fish catches and stockings, the potential unfavorable impacts of recreational fishing on lake-scale nutrient balance could be completely eliminated if anglers restricted their bait material usage to 1.5 kg a day, and used products with low nutrient content (< 1.5% N and < 0.3% P). Under these circumstances, the nutrient balance of fisheries management could turn to neutral or even negative (i.e., result in nutrient removal). Moreover, significant improvement could be achieved if the nutrient content of bait materials is limited at a relatively moderate level (e.g., at 2–3% N and 0.4–0.5% P content) and at the same time, anglers would slightly reduce their bait material usage.

Based on the above mentioned considerations, to reduce or prevent further anthropogenic nutrient loading to the Lake Balaton, we propose the following management actions:

1. – Definitely, the most important and effective step could be the regulation of ground bait manufacturing. The production of new generation angler ground baits with minimal nutrient (especially P) content and high digestibility would be important to address the issue of water pollution and eutrophication. Our recommendation is that N and P content of commercial ground baits should be limited at a level typical for the traditional plant-based baits (i.e., corn and other cereals, bread), 1.5–2% and 0.3–0.5%, respectively. The molar N:P ratio in the baits is also important, since this parameter determines to what extent these materials support algal growth. In Lake Balaton, where the productivity of phytoplankton is typically regulated by P availability (Istvánovics, Osztics, and Horti 2004), baits with higher N:P ratio, but still low nutrient content should be preferred. The optimal development of algae needs N and P to be supplied in a ratio of about 10 to 1 (Moss, Madgwick, and Phillips 1996), so the target N:P ratio in the baits should be higher than that to reduce the chance of eutrophication. Vegetable sources should be favored during bait formulation, and the digestibility of these products could be improved, for example by thermal and mechanical pre-treatments (as shown, for example, by Hlaváč et al. 2014), so that fish can utilize more nutrients from the consumed bait. For example, bread is a traditional baiting material that can be recommended for anglers because it has low P content (0.1%), a favorable N:P ratio (20.5), and is probably well digestible by fish, given that it contains thermally- and mechanically treated wheat. In turn, P-rich pellet-type baits and other bait types containing fish meal and other animal-based ingredients in high proportion should be avoided preferably because these may have the highest environmental impact.

Further, it is problematic that commercial ground bait distributors rarely indicate the exact composition of their products, especially their nutrient content. In fact, the labels in only 2 out of the 15 examined commercial products contained information about the P content. Thus, distributors should provide more detailed information on the composition of their baits (including their N and P content), so that anglers could differentiate between materials posing higher or lower environmental risk.

2. – Policy makers and lake managers should consider setting up daily bait usage limits for anglers. Currently, there are no such recommendations or restrictions in place at Lake Balaton, although these could contribute substantially to the improvement of the nutrient balance of recreational fishing. Daily bait limit set at a level of 1–3 kg would affect only the minority of anglers in Lake Balaton, and according to other studies, could still support an effective catching of cyprinid fishes. For example, Wolos, Teodorowicz, and Grabowska (1992) found that catching rates were maximal at a ground baiting intensity of 1.5–2 kg day\(^{-1}\), and Czerniejewski and Brysiewicz (2018) showed that catch rate reached a plateau at a ground baiting intensity of ca. 3 kg day\(^{-1}\) in Polish lakes.

3. – The amount of harvested fish represents the contra (nutrient removal) side of the nutrient balance. Thus, too low of a harvest rate could be unfavorable for the nutrient balance of recreational fishery. Although it is one of the main causes of the unsustainable nutrient balance, catch-and-release fishing practice is also a sensitive issue both from social (mainly ethical and emotional) and ecological aspects (Arlinghaus et al. 2007). It is evident though that catch-and-release fishing should be associated with stricter regulations of ground baiting.

4. – Although it is responsible to only a small fraction of the net nutrient load, tournament fishing can be considered as the least sustainable component of recreational fishing. At fishing competitions, contenders apply considerable amount of ground baits (exceptions are events targeting piscivorous species), and at the same time, catch-and-release is strictly applied. It should be
emphasized, however, that some progressive changes have been initiated, and organizers have commenced to introduce some bait usage limits for future events (e.g., at IBCC 2022 ground bait use will be limited at 100 kg per team).

5. – Prioritization of measures supporting natural recruitment of fish stocks and stocking of the smallest appropriate size classes of fish would also favor sustainability of the nutrient balance in recreational fishing. Therefore, research projects aimed at exploring and managing constraints of natural recruitment, and elaborating of optimized stocking strategies, should be implemented.

6. – Finally, anglers should be informed about the possibilities of environmentally conscious fishing practices (e.g., in short brochures, advertisements in fishing magazines) and they should be alerted to the potential water quality deterioration effects arising from heavy ground- and pre-baiting.

Although eutrophication is one of the most concerning consequences of anthropogenic nutrient load to freshwater ecosystems, the significance of ground bait use by recreational fishermen still seems to be unrecognized and/or not taken into account in nutrient dynamics models, even where it likely should be (but see Grochowska et al. 2020). The effect of ground baiting presumably could vary considerably among waterbodies of different ecological characteristics, but this topic is largely disentangled yet. Large waterbodies with relatively low shore line-to-water surface area ratio supposedly could be less concerned by the nutrient load from recreational fishing. Nevertheless, this study revealed that ground baiting could contribute to the nutrient balance of large lakes, too. In turn, smaller waterbodies with high shore line-to-water surface area ratio might be much more sensitive to intensive ground baiting. A majority of the few studies which have investigated the effect of recreational fishing on nutrient cycling identified a clear potential of water quality concern (e.g., Arlinghaus and Niesar 2005; Lewin, Arlinghaus, and Mehner 2006; Hlaváč et al. 2016; Mehner et al. 2019). Therefore, this issue should be addressed more seriously by future research as well as considered by fishery managers and stakeholders. We suggest that the approach presented here could serve as a general framework for such attempts. Although the herein defined daily bait limits are specific to Lake Balaton, similar management actions could be elaborated world-wide for waterbodies with intensive ground baiting.

Conclusions

In conclusion, popular angler baits vary substantially in their chemical composition and thus each type of these materials may exert different effects on the nutrient dynamics and productivity of lakes. However, as Niesar et al. (2004) noted, the nutrient composition or nutritive value of baits is presumably of minor importance for most anglers, as long as these materials attract the fish to the hook. Nevertheless, because the quantity of ground baits introduced to waters is increasing tendentiously, and because this food resource gets into the aquatic food web and may represent a considerable nutrient surplus, the ecological role of bait materials should gain more attention both among anglers and policymakers. The recent N and P balance of fisheries management shows that angling-aimed recreational use results in a net nutrient addition to the lake’s nutrient pool, although this source may be of minor importance in the overall nutrient budget of Lake Balaton. However, with the increasing global concern about water pollution, it is becoming necessary that recreational fishing also reduces its negative impacts on the environment and operates according to the rules of sustainability. The suggested revisions of fishing regulations and bait formulation could contribute to achieving an optimal balance between the social, economic, and environmental benefits of recreational fishing not only in Lake Balaton, but also in other concerned freshwater ecosystems.

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