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Quantitative Estimates of Nutrient Inputs From Angling Baits in Lakes Supporting Different Recreational Fisheries

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ABSTRACT

Recreational anglers use ground baiting to attract fish and increase catch inputs organic matter that can have important effects on water quality by increasing eutrophication. However, nutrient inputs from angling bait by recreational fisheries have not yet been estimated. We quantified nutrient inputs from angling baits in small lakes supporting specialized carp, put-and-take, and specialized roach recreational fisheries with a 2-year field survey of angling activity and in-person angler questionnaires. Angling activity was highly variable among recreational fisheries and averaged 82 (±74 SD) angler-day/ha/year in lakes with specialized carp fisheries, 145 (±80) in lakes with put-and-take fisheries, and 36 (±18) in lakes with specialized roach fisheries. Angling activity also differed temporally among recreational fisheries, with high angling activity in spring and summer for specialized carp and specialized roach fisheries, and in autumn and winter for put-and-take fisheries. The type and amount of baits used by anglers strongly differed among recreational fisheries, with specialized carp anglers using boilies (2.5 ± 1.5 SD kg/angler/day) and seeds (2.1 ± 1.9 kg/angler/day), put-and-take anglers using exclusively pellets (0.39 ± 0.15 kg/angler/day), and specialized roach anglers using ground baits (0.72 ± 0.36 kg/angler/day). Nutrient inputs from angling baits were highly variable among recreational fisheries and ranged from 0.5 (±0.2 SD) kg/ha/year of nitrogen and 0.1 (±0.0) kg/ha/year of phosphorus in specialized roach fisheries to 10.2 (±9.3) kg/ha/year of nitrogen and 1.6 (±1.5) kg/ha/year of phosphorus in specialized carp fisheries. Our findings revealed that ecological consequences of ground baiting differed among recreational fisheries, which should be useful for developing fishery-specific regulations to efficiently manage ground baiting.

1 | Introduction

Recreational angling in inland waters is a popular hobby in many industrialized countries (Arlinghaus and Mehner 2003; Cooke and Cowx 2004; Lewin, Arlinghaus, and Mehner 2006) that provides a "myriad of social, cultural and economic benefits" (Arlinghaus, Mehner, and Cowx 2002). However, recreational angling can also cause important ecological impacts such as the decline of exploited fish stocks (Cooke and Cowx 2004; Arlinghaus and Cooke 2009). Recreational angling is also suspected to contribute to degradation of water quality and eutrophication in lakes through ground baiting (Cryer and Edwards 1987; Koel et al. 2019). Ground baiting is a common practice in many fisheries across the globe that introduces angling baits to attract fish and increase catch (Mehner et al. 2019). Angling baits primarily consist of a mixture of

cereals, plant, or animal flours that can have high-nitrogen (N) and -phosphorus (P) contents (Wolos, Teodorowicz, and Grabowska 1992; Imbert et al. 2022). In some cases, anglers use large quantities of angling baits (e.g., average of 14.1 kg/year; Arlinghaus 2004). However, studies quantifying the amount of baits used by anglers are rare. Daily inputs of baits by anglers averaged 3.6 kg/day in Hungary and 2.3 kg/day in Germany (Arlinghaus and Mehner 2003; Boros, Mozsár, and Specziár 2022). Consumption of angling baits by fish can also be an important proportion of their diet in some recreational fisheries that strongly differ among individuals within the same population (Bašić et al. 2015; Imbert et al. 2024; Gutmann et al. 2017).

Inputs of angling baits in freshwater ecosystems are a source of human subsidies (Oro et al. 2013), but knowledge of ecological impacts on ecosystems is limited. In Lake Balaton (Hungary), annual nutrient inputs from ground baiting (16.3 t of N and 5.2 t of P) were 0.7% of total annual N and 3.2% of total annual P loads of the lake (Boros, Mozsár, and Specziár 2022). When used in high quantities, angling baits can locally affect ecological conditions (Cryer and Edwards 1987). For instance, pellets are used to control invasive Lake trout (*Salvelinus namaycush*) in an oligotrophic lake in Yellowstone Park (USA) by deoxygenation that increases embryo mortality on spawning grounds (Koel et al. 2019). In a large reservoir (2000 ha) in Portugal, angling baits at high angling pressure could increase nutrient concentration and primary production to accelerate lake eutrophication (Amaral et al. 2013).

Angling baits are a form of "intentional pollution" (Arlinghaus and Cooke 2009) that should be explicitly managed and regulated in recreational fisheries. However, regulation of ground baiting is lacking in most recreational fisheries because managing ground baiting is complex (Lewin, Arlinghaus, and Mehner 2006; Cowx 2015), notably because of knowledge gaps about seasonal dynamics of use and type of angling baits. Indeed, inputs of subsidies in different seasons can strongly modulate effects on freshwater ecosystems (Nakano and Murakami 2001) and nutrient contents strongly differ among angling baits used in recreational fisheries (Imbert et al. 2022). Therefore, quantitative estimates of ground-baiting seasonal dynamics and nutrient inputs in recreational fisheries are urgently needed to improve management of freshwater ecosystems.

Our objective was to quantify the nutrient inputs from ground baiting by recreational fisheries to determine if they were large enough to alter nutrient dynamics in small lakes in southwestern France. First, we used a 2-year field survey in seven lakes to quantify seasonal variability of angling activity by specialized carp, put-and-take, and specialized roach recreational fisheries. Second, we used an in-person angler questionnaire to quantify the type and amounts of baits used by anglers in the three recreational fisheries. Finally, we estimated seasonal dynamics and total amount of N and P nutrients introduced by anglers in the three recreational fisheries. Our findings would hopefully be useful for determining which ground-baiting activity should be regulated for angling fisheries in small lakes.

2 | Materials and Methods

2.1 | Study Area

The study area included recreational fisheries in seven gravel pit lakes (average surface area ± SD = 13.0 ± 6.7 ha; Figure 1, Table 1) located along the River Garonne, in southwestern France (Alp et al. 2016; Zhao et al. 2016). In five lakes, angling was managed by public angling clubs and accessible to anyone with a national fishing license. In two lakes, fishing rights were owned by municipalities or private owners who required a specific fishing license (Zhao et al. 2016). These lakes were not interconnected, so were ecologically independent. Three lakes supported carp fisheries (SpC1 = 6.7 ha, SpC2 = 18.8 ha, and SpC3 = 18.2 ha), where anglers usually spend several days and nights (usually from 24 to 72 h) to catch and release common carp (*Cyprinus carpio*). Three lakes supported put-and-take fisheries (Cowx 2015) (PaT1 = 9.1 ha, PaT2 = 10.4 ha, and PaT3 = 2.8 ha), where anglers usually spend short sessions (1 day maximum) to capture stocked rainbow trout (*Oncorhynchus mykiss*) (Cucherousset et al. 2021). One lake supported a roach fishery (SpR1 = 15.2 ha), where anglers spend short sessions (1 day maximum) to capture small-bodied cyprinids such as roach (*Rutilus rutilus*), rudd (*Scardinius erythrophthalmus*), bream (*Abramis brama*), and tench (*Tinca tinca*) that are mostly released.

2.2 | Angling Activity

From January 2021 to December 2022 (24 months), angling activity was assessed by counting the number of anglers in each lake during regular surveys in all lakes. Surveys were performed at different times of day (8:00 am to 5:00 pm) on different days of the week, including weekend days and public holidays, to sample the entire temporal variability of angling activity. During each survey, the entire perimeter of all lakes was monitored and the number of anglers and type of recreational angling were recorded. The 112 surveys represented

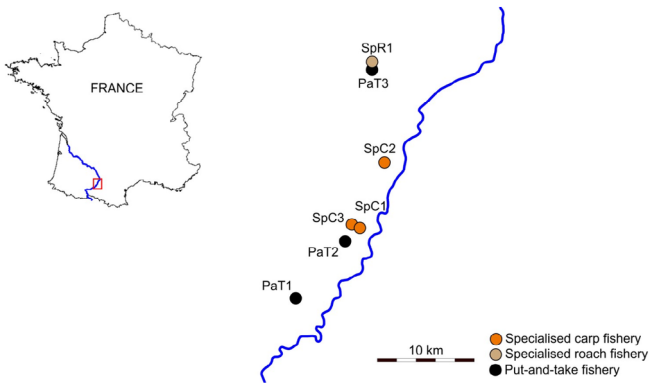

FIGURE 1 | Locations of seven study lakes in the floodplain of the Garonne River, southwestern France, where inputs of ground baiting by specialized carp (bright-orange circles), put-and-take (tan circles), and specialized roach (black circles) angling fisheries were estimated between August 2021 and May 2022. Lakes are not interconnected.

TABLE 1 | Surface area, volume, depth, total phosphorus concentration, and total nitrogen concentration in seven study lakes in southwestern France where effects of ground baiting by specialized carp ($n=3$), put-and-take ($n=3$), and specialized roach ($n=1$) angling fisheries were estimated between August 2021 and May 2022.

Lake	Surface (ha)	Volume (m^3)	Depth (m)	Total phosphorus concentration (μg/L)[a]	Total nitrogen concentration (mg/L)[a]
SpC1	6.7	121,300	2.0	17.1 ± 12.0	0.5 ± 0.05
SpC2	18.8	270,000	2.0	34.1 ± 16.2	0.9 ± 0.25
SpC3	18.2	422,500	3.7	21.0 ± 23.2	0.6 ± 0.03
PaT1	9.1	250,000	4.4	27.7 ± 6.7	0.7 ± 0.04
PaT2	10.4	306,300	4.3	14.7 ± 15.3	1.2 ± 0.34
PaT3	2.8	n.a.	2.9	n.a.	n.a.
SpR1	15.2	307,000	2.9	58.9 ± 13.7	0.5 ± 0.03

[a]Average values based on measurements performed in September 2021 and 2022 in each lake.

more than one survey per week during 2 years (4.66 surveys per month).

2.3 | Questionnaire Survey

Between August 2021 and May 2022, in-person questionnaires of 110 anglers were used to determine types and quantities of baits used in each recreational fishery. In study lakes, anglers were usually specialized, so anglers from each fishery were selected to account for potential variability in angling practices, including 40 carp anglers, 40 put-and-take anglers, and 30 roach anglers. Total numbers of individual anglers using the seven lakes could not be estimated, but we assumed that the total number of anglers surveyed represented all anglers who fished in study lakes. Most anglers encountered in study lakes at the end of the study had already participated in the study. The questionnaire included questions about types of bait used (seeds, ground baits, boilies, pellets, and others) and the quantity used for each bait type during each angling session. In all fishery types, baits were primarily used to attract fish. In carp and put-and-take fisheries, a very small amount of bait was used on hooks. Responses to questionnaires were used to estimate the amount of angling baits used by each angler on each angling day in each recreational fishery (kg/angler/day). Previously analyzed elemental composition of each angling bait revealed that pellets were highest in nutrient content ($N=5.5\%\pm1.5\%$; $p=1.24\%\pm0.46\%$), followed by boilies ($N=2.9\%\pm1.6\%$; $p=0.57\%\pm0.17\%$), ground baits ($N=1.8\%\pm0.3\%$; $p=0.36\%\pm0.15\%$), and seeds ($N=2.5\%\pm1.9\%$; $p=0.25\%\pm0.14\%$) (Imbert et al. 2022). Based on these estimated N and P contents, estimated daily angling activity, and the amount of angling baits used by individual anglers, daily inputs of N and P from angling baits (kg/ha/day) were estimated in each study lake in 2021 and 2022. Daily inputs were summed to estimate annual input of N and P (kg/ha/year) in each lake for each recreational fishery. Finally, the amount of N and P (kg) in the water of each lake was estimated from lake volume and nutrient concentration (Table 1), for comparison to estimated inputs of N and P (kg) from angling baits introduced each year.

2.4 | Statistical Analyses

Daily angling activity (angler-day/ha/year) was estimated for each recreational fishery by multiplying lake size by the average number of anglers who fished each day in 2021 and 2022. Weekdays and weekends were estimated separately because angling activity was higher on weekends than weekdays. The temporal pattern of angling effort for each fishery was estimated using temporal regression with a 6-week interval and "geom_smooth" function from the ggplot2 R package (Wickham 2011; R Core Team and contributors worldwide 2018). Next, seasonal dynamics of angling activity were compared among fisheries using a linear mixed effects model ("lme4" package, Bates et al. 2015), with fishery type, date, and their interaction as fixed factors and lake as a random effect. Finally, the quantity of angling bait used by anglers was compared among recreational fisheries using a nonparametric Kruskal–Wallis test, followed by pairwise post hoc comparisons (Dunn's test).

3 | Results

3.1 | Angling Activity

Angling activity was highly variable among lakes. In specialized carp fisheries, angling activity averaged 82 (±74 SD) angler-day/ha/year and was 177 angler-day/ha/year in SpC1, 41 angler-day/ha/year in SpC2, and 28 angler-day/ha/year in SpC3. In put-and-take fisheries, angling activity averaged 145 (±80) angler-day/ha/year and was 68 angler-day/ha/year in PaT1, 164 angler-day/ha/year in PaT2, and 202 angler-day/ha/year in PaT3. In the specialized roach fishery (SpR1), angling activity was 35 angler-day/ha/year.

Seasonal dynamics of angling activity differed significantly among recreational fisheries (interaction between date and fishery type, $\chi^2=11.1$, $df=1$, $p<0.001$). In specialized carp fisheries, angling activity was highest in spring and summer (Figure 2a), with an increase from January to July–August, followed by a decrease until the end of December. In put-and-take fisheries,

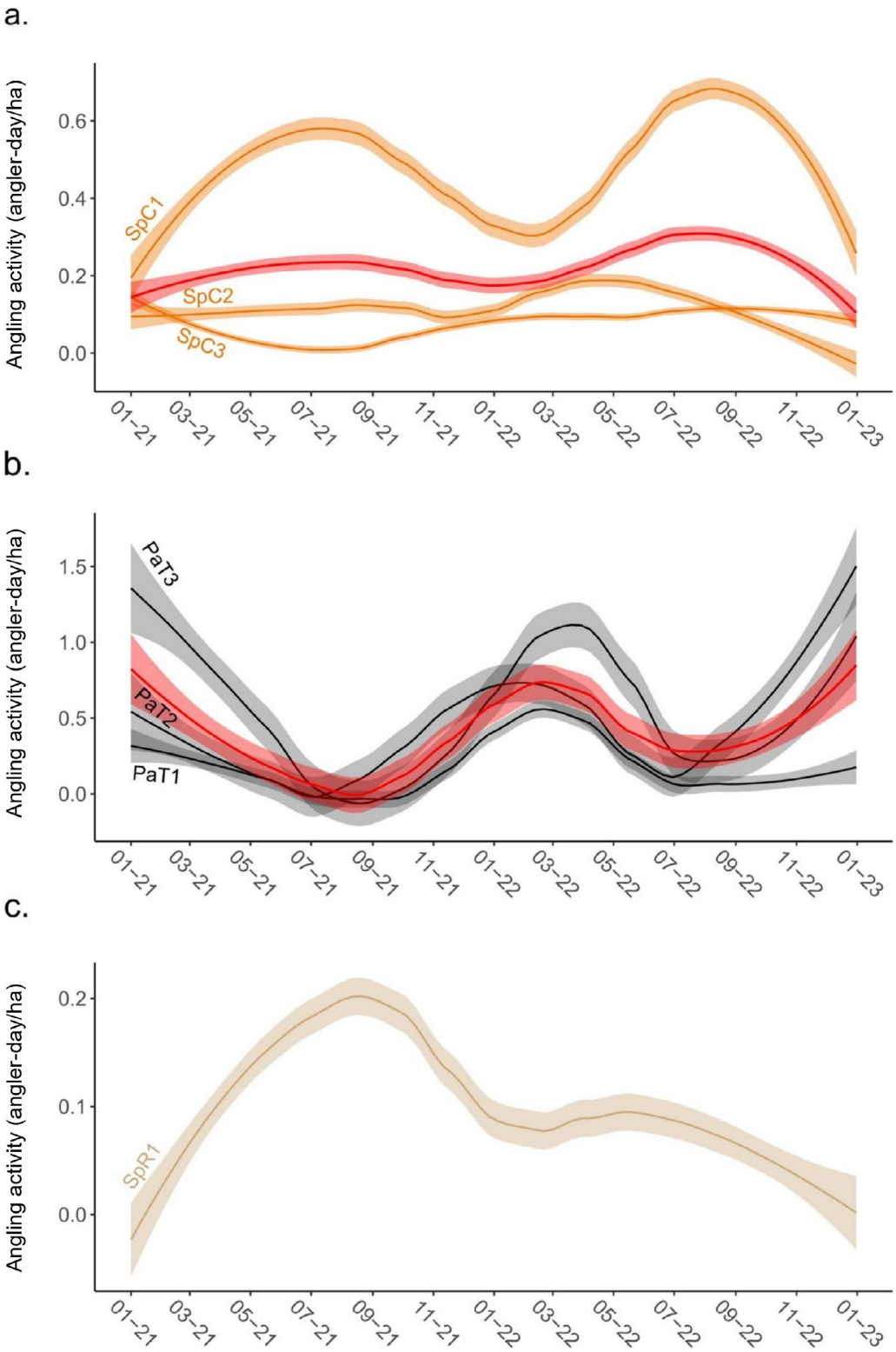

FIGURE 2 | Estimated angling activity (angler-day/ha) in (a) specialized carp fisheries ($n = 3$ lakes), (b) put-and-take fisheries ($n = 3$), and (c) specialized roach fisheries ($n = 1$) in southwestern France between August 2021 and May 2022. Colored areas are 95% confidence intervals of regressions and average trends are in red.

nearly no angling activity was in summer, but increased in autumn, and peaked from December to February (Figure 2b). In the specialized roach fishery, angling activity increased in summer 2021 (Figure 2c).

3.2 | Nutrient Inputs From Angling Baits

Anglers used similar angling baits in each recreational fishery that differed greatly among fisheries. In specialized carp

fisheries, all anglers used boilies, 78% used seeds, 5% used pellets, and 2.5% used ground bait, with higher mean quantities (±SD kg/angler/day) of boilies (2.5 ± 1.5) and seeds (2.1 ± 1.9) used than ground baits (0.02 ± 0.1) and pellets (0.05 ± 0.2) used ($\chi^2 = 111.44$, df = 3, $p < 0.001$; Figure 3a). In put-and-take fisheries, 98% of anglers used pellets, at a quantity (0.39 ± 0.15) that was significantly higher than other angling baits ($\chi^2 = 143.93$, df = 3, $p < 0.001$; Figure 3b). In specialized roach fisheries, anglers almost exclusively used ground baits (only 6.7% using seeds or pellets), at a rate (0.72 ± 0.36) that was significantly higher than seeds (0.02 ± 0.06) or pellets (0.03 ± 0.10; $\chi^2 = 100.41$, df = 3, $p < 0.001$; Figure 3c).

Annual nutrient inputs and seasonal variability of ground baiting were highly variable among recreational fisheries (Table 2, Figure 4). In specialized carp fisheries, nutrient inputs from ground baiting (kg/ha/year) were higher than other fisheries, and averaged (±SD) 10.2 (±9.3) of N and 1.6 (±1.5) of P (Table 2). Seasonality of nutrient inputs by specialized carp fisheries was highest in August 2022 (40 g N/ha/day, 6 g P/ha/day; Figure 4). In put-and-take fisheries, nutrient inputs from baits (±SD) was 3.1 (±1.7) of N and 0.7 (±0.4) of P (Table 2). Seasonal variability of nutrient inputs by put-and-take fisheries was opposite of specialized carp fisheries, with maximum inputs in winter (17 g N/ha/day, 4 g P/ha/day; Figure 4). In the specialized roach fishery, nutrient inputs from ground baiting were relatively low for N (0.5 ± 0.2) and P (0.1 ± 0.0; Table 2), varied little seasonally (Figure 4), and were quite limited (< 5 g N/ha/day, and 1 g P/ha/day). The amount of P introduced annually by anglers using angling baits averaged 2.7 times (±4.2) higher than the amount of P in study lakes, and was highest in specialized carp fisheries (4.59 times [±5.65] higher). The amount of N introduced annually by anglers was 52% (±88) of the N in study lakes, and was highest in specialized carp fisheries (97% ± 115%).

4 | Discussion

Recreational angling is a global practice and ground baiting is commonly used by recreational anglers. Ground baiting is a form of artificial subsidies that can impact recipient freshwater ecosystems, including water quality (Bašić et al. 2015; Britton, Cucherousset, and Dominguez 2022). Our study is a novel empirical assessment of nutrient inputs from angling baits in specialized carp, put-and-take, and specialized roach recreational fisheries in small lakes. In put-and-take fisheries, daily angling activity was highest in winter, where anglers used relatively small quantities of nutrient-rich pellets that represented limited nutrient inputs. In roach specialized fisheries, angling activity was relatively low and nutrient inputs from angling baits were very limited. In specialized carp fisheries, nutrient inputs were highest because anglers used large quantities of boilies and seeds, and nutrient inputs peaked in summer when primary production was highest. The amount of phosphorus and nitrogen from angling baits was a high proportion of nutrients available in study lakes. Altogether, our findings demonstrated that nutrient inputs from ground baiting were highly seasonal and strongly differed in quantity and quality among recreational fisheries due to differences in angling baits and seasons with highest levels of angling activity. Accounting for seasonal variability of bait inputs is important, to modulate effects on functioning of recipient ecosystems.

Although we found that amounts of baits used by anglers in study lakes were in the range of other studies (Arlinghaus and Mehner 2003; Boros, Mozsár, and Specziár 2022), our results highlighted differences between angling and natural subsidies. First, we found that seasonality of ground-baiting inputs differed strongly from natural inputs. In temperate lakes, natural particulate allochthonous subsidies are mainly tree leaves (Bartels et al. 2012), with inputs of leaves occurring mainly at the end of the year from October to December (Hanlon 1981). This seasonal pattern of natural particulate allochthonous subsidies is opposite to nutrient inputs of angling baits in specialized carp fisheries, with highest inputs in spring and summer. The difference between natural subsidies and angling baits may have important consequences for consumers and recipient ecosystems, as in forested streams for terrestrial and aquatic subsidies (Nakano and Murakami 2001; Baxter, Fausch, and Carl 2005). Second, N and P concentrations in tree leaves are much lower than in angling baits used by specialized carp anglers (Imbert et al. 2022), so nutrient-rich inputs from anglers could affect lake nutrient balance. Third, we found that angling bait inputs were pulsed and predictable, because angling pressure was much higher on weekends than weekdays, unlike natural subsidies (Weber and Brown 2013). This difference in timing of nutrient inputs could alter ecological effects, so future studies are needed to determine the relative importance of angling baits and natural subsidies on functioning of lake ecosystems. This is also particularly true for specialized carp fisheries when considering endurance events that concentrate a high density of anglers and high level of nutrient inputs from baits.

Unlike our study in small lakes, most previous studies investigating consequences of ground baiting on lake nutrient balance have been in large lakes (Boros, Mozsár, and Specziár 2022). For example, in Lake Balaton, Hungary, annual input of phosphorus from angling bait 0.09 kg/ha/year (Boros, Mozsár, and Specziár 2022) were 40 times lower than we estimated for a specialized carp fishery, whose inputs were 4 times higher than from put-and-take fisheries. Therefore, specialized carp fisheries likely have the strongest impacts on water quality because most of the nutrient inputs occur in summer when water temperature is high. Although put-and-take anglers exclusively used pellets, the most P-enriched bait type (Imbert et al. 2022), their impact was likely limited because inputs were mainly in winter, thereby limiting risk of eutrophication that is positively related to water temperature (Genkai-Kato and Carpenter 2005). We could not assess direct consequences of ground baiting on water quality because other confounding factors (e.g., biological invasions, agricultural pollution) could have affected nutrient dynamics in study lakes. We recommend experimental studies (e.g., Mehner et al. 2019) to test independent and interacting effects of nutrient inputs from ground baiting (i.e., type of angling bait, quantity of inputs, seasonality, and regularity) on water quality and ecosystem functioning. Such investigations would notably require quantitative estimates of the fate of angling baits after introduction, such as consumption by fish or unused. In addition, while our results revealed that the amount of phosphorus and nitrogen originating from

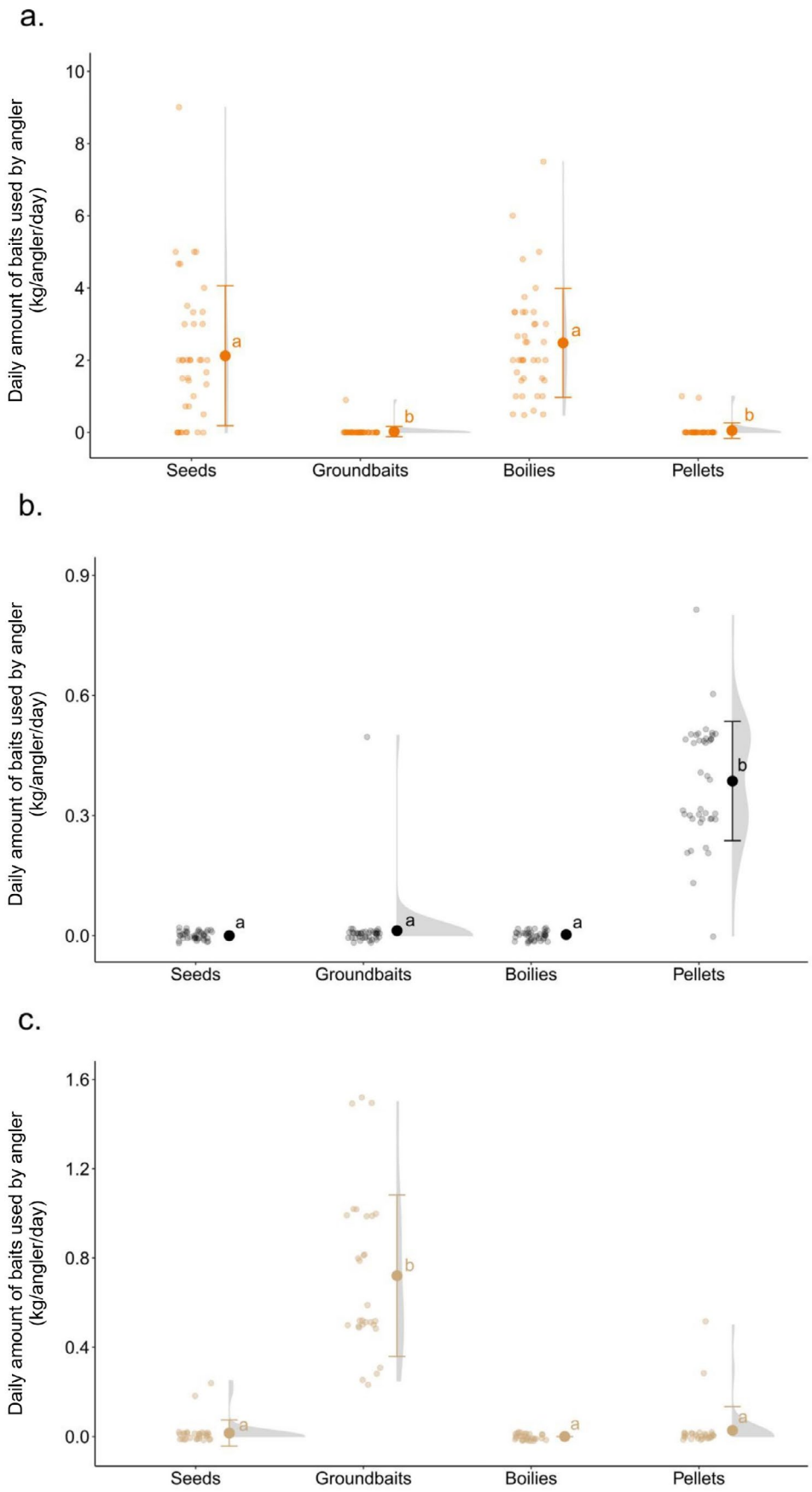

FIGURE 3 | Daily amount (kg/anglers/day) of angling baits (seeds, ground baits, boilies, and pellets) used by (a) specialized carp ($n = 40$), (b) put-and-take ($n = 40$), and (c) specialized roach ($n = 30$) anglers in southwestern France between August 2021 and May 2022. Letters indicate significant differences among angling bait types. Large colored circles are means and standard deviations and small circles are individual data points.

TABLE 2 | Estimated inputs of nitrogen (N) and phosphorus (P) from angling baits (kg/ha/year) used in specialized carp, put-and-take, and specialized roach recreational fisheries in seven study lakes in southwestern France between August 2021 and May 2022.

	N inputs (kg/ha/year)		P inputs (kg/ha/year)	
Recreational fishery	**2021**	**2022**	**2021**	**2022**
Specialized carp ($n = 3$)	9.3 ± 10.0	11.0 ± 10.5	1.5 ± 1.6	1.7 ± 1.6
Put-and-take ($n = 3$)	2.1 ± 1.4	4.0 ± 1.6	0.5 ± 0.3	0.9 ± 0.3
Specialized roach ($n = 1$)	0.6	0.3	0.1	0.1

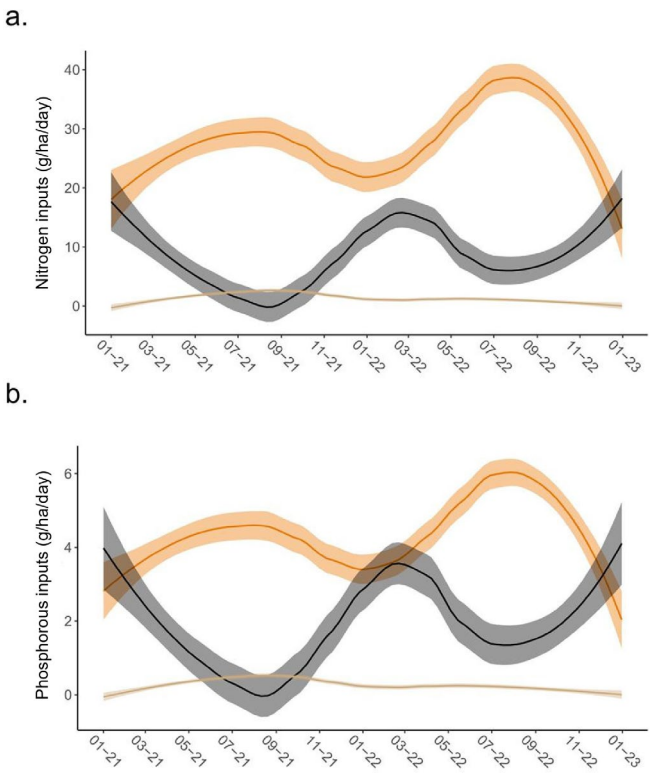

FIGURE 4 | Estimated nitrogen (a) and phosphorus (b) inputs in specialized carp fisheries (orange), put-and-take fisheries (black), and specialized roach fishery (brown) in southwestern France between August 2021 and May 2022. Shaded areas are 95% confidence intervals.

angling baits was a high proportion of nutrients available in lake water, nutrients are also stored in lake sediment and organisms, including fish. Therefore, fishing practices (catch-and release versus put-and-take) will likely affect nutrient dynamics differently (Arlinghaus and Mehner 2003). Consequently, we encourage further research to account for effects of angling bait on nutrient dynamic of lakes.

In summary, we found that nutrient inputs from ground baiting strongly differed from natural subsidies and among recreational fisheries. Although implementation of management measures could be difficult (Pereira and Hansen 2003), our findings provide robust, science-based bases to implement management measures to limit the risk of eutrophication and subsequent effects on water quality from ground baiting. The efficiency and acceptability of such management measures (e.g., limiting angling pressure, limiting the amount of angling baits, restricting use of certain nutrient-rich angling baits) should be determined to adapt management strategies to each fishery. Further research is needed to understand consequences of angling bait inputs on dynamics of nutrients and primary production of ecosystems. Effects are likely to be complex and not instantaneous, due to multiple organisms and processes involved in nutrient cycling that range from consumption by fish to degradation by microorganisms. Use of remote sensing can provide a unique opportunity to investigate these effects on dynamics of primary production.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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