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Brief Report

One Year Monitoring of Ecological Interaction of *Silurus glanis* in a Novel Invaded Oligotrophic Deep Lake (Lake Maggiore)

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Abstract: The European catfish (*Silurus glanis*) was introduced in Italy during the last century for aquaculture purposes, and now it is well-established. *S. glanis* is an invasive species and a top predator that can deplete prey supply in the surrounding habitat, leading to changes in the aquatic food web. Consequently, its presence is considered a threat to native fish populations. Its presence in the Lake Maggiore (Northern Italy) is recent and there is a lack of knowledge about its ability to completely exploit this new ecosystem throughout the year. This study corroborated the ability of European catfish to exploit both pelagic and littoral habitats, promoting trophic interactions in both habitats. Over 2019, multiple sampling approaches have been applied by collecting *S. glanis* and analysing its stomach contents with the aim of inferring interactions with the freshwater community. Its diet was mainly based on crayfish (*Orconectes limosus*), followed by six prey fish and the genus *Corbicula*; two fish species (*Padogobius bonelli* and *Salaria fluviatilis*) were added to the list of known prey fish. Notably and alarmingly for the early potential top-down pressure towards all trophic levels, young individuals were proved to also feed on fish and crayfish. *S. glanis* showed the ability to hunt at deep depths (>60 m) and a high growth rate, despite Lake Maggiore being oligotrophic.

Keywords: *Silurus glanis*; invasive species; trophic interaction; Lake Maggiore; prey selection; pelagic habitat; littoral habitat

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1. Introduction

The introduction of non-native fish into the freshwater system has a long history across Europe [1], the successful introduction of the European catfish (*Silurus glanis*, L., 1758) being one of the most widespread [2]. Its introduction in Italy was for aquaculture purposes in the early 20th century, but was also introduced in ponds of private fishing reserves, and subsequently reported in rivers since the 1930s onward [3,4]. The first certain catch of an individual *S. glanis* was reported in the late 1960s in the River Po basin [3], of which catches became more frequent from the following decades. From the 1980s, the presence of *S. glanis* can be considered common and continuous in the Po valley, artificial channels included [5], and nowadays it is well-established in the eutrophic sub-alpine lakes, such as Lake Varese, Lake Comabbio, and Lake Monate [6,7]. The first reports of its presence in the oligotrophic and deep Lake Maggiore dated back to the early 1990s [8], which is now successfully colonised by *S. glanis*, demonstrating its remarkable ecological plasticity.

S. glanis is considered an opportunistic predator [2], and the most important factor affecting its diet is the spatial and temporal availability of prey, thus reflecting the most abundant prey available [2,9]. It is a top predator with a wide trophic niche [10–12], which makes its diet unpredictable. Furthermore, *S. glanis* can adapt its diet to novel and available resources, including developing new feeding behaviour [13]; thus, its presence in a newly invaded habitat is considered a potential threat. Across a range of dietary studies on *S. glanis*, almost 60 fish species have been reported [2,9]. However, its diet can also include benthic or mid-water column organisms [2,14,15], such as Chironomidae, Hemiptera, and Diptera, with macrobenthos being the main food for juveniles [2,16]. Adults are mainly ichthyophages, even though they can occasionally eat birds, insects, reptiles, and small mammals [17]. Cannibalism phenomena has been observed in *S. glanis* aquaculture since the juvenile stage [18]. Moreover, its diet can vary with season [9] and from the earliest to the latest stage of invasion [19]. However, proper knowledge on *S. glanis* trophic ecology in its invasive range is scarce, mainly restricted to riverine or reservoir populations where the fish is more easily captured [20].

Notably, very little is known about oligotrophic and deep lakes (such as the Lake Maggiore), an ecosystem very different from its original (big rivers), and only about a limited period (wintertime) [7]. Difficulties of sampling lentic ecosystems, especially big lakes, has led to a scarcity of data, with only one recent study which started to fill the gap on the ecology of *S. glanis* in this novel environment [7]. Taking advantage of support by professional fishermen, and the experimental usage of large mesh gillnets suitable for catching *S. glanis*, the authors provided a first glimpse into the trophic interaction of *S. glanis* with the lake community, but only over a limited period of time (wintertime) [7]. Thus, for setting management plans, it is essential to understand how the species is able to exploit the new ecosystem in its entirety with regard to both the pelagic and littoral habitat throughout the year. The aim of this study is to contribute additional knowledge about habitat exploitation of *S. glanis* in a novel environment, as well as its interactions with the inhabiting freshwater community. Over a year of sampling in 2019, multiple sampling approaches were put in place to (i) establish the ability of *S. glanis* to exploit the entire lake ecosystem by collecting individuals from littoral and pelagic habitats, and (ii) establish interactions with the freshwater community by stomach content analysis. Considering the recent invasion of this species in the Lake Maggiore, this data will provide essential baseline information to promote further in-depth investigations on *S. glanis* ecology in the Lake Maggiore and improve strategies for biodiversity management.

2. Materials and Methods

A total of 59 sampling efforts regularly took place between the end of January 2019 and mid-November 2019 in the Lake Maggiore at Golfo della Quassa (Ispra, Va, Italy) (Figure 1), divided in two macro categories: (i) pelagic and (ii) littoral sampling. Sampling was not performed in the littoral environment between 15th March and 1st June, and between 15 November to 24 January, due to fishing law restrictions. Thus, the former period corresponds to the breeding time of *Esox* sp., *S. lucioperca* and *P. fluviatilis*; the latter corresponds to *Coregonus* sp. spawning time. Technical equipment adopted for professional fishing in inland waters were used, mainly the bottom and flying nets for littoral and pelagic sampling, respectively (Supplementary Material S1). A 5.85 long and 2 m wide boat approved for professional fishing in inland waters was used for lowering and withdrawal of the nets. All nets adopted in this study were certified by the "Italian–Swiss Commission for Fisheries (C.I.S.P.P.)" in the "regulation implementing the convention for fishing in Italian–Swiss waters between the Italian Republic and Swiss Confederation".

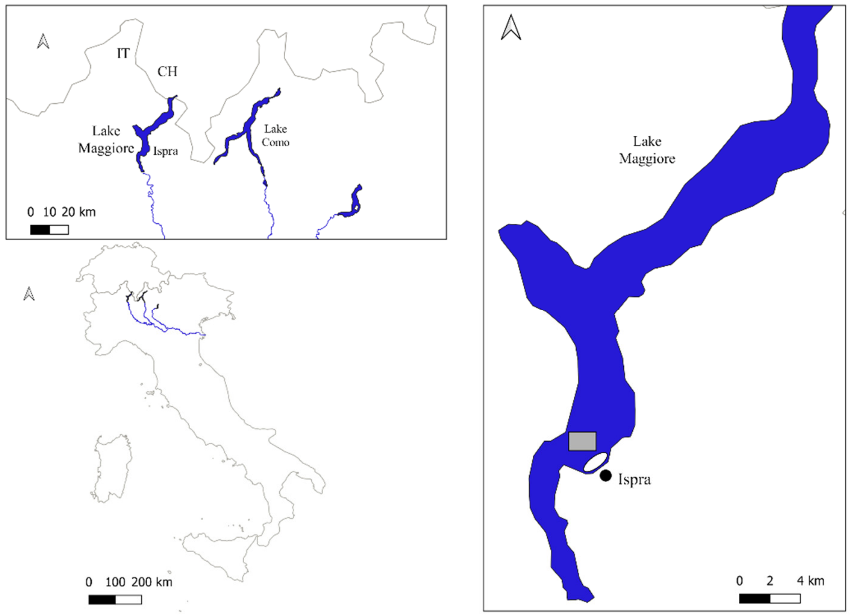

Figure 1. Sampling location in the Lake Maggiore near the town Ispra. The grey rectangle indicates the area where littoral sampling took place, whilst the white ellipse indicates the area of pelagic sampling.

Fish retrieved in the nets with *S. glanis* individuals were recorded and released. All *S. glanis* individuals caught were measured and underwent laparotomy (Table 1). For sexually mature specimens, the sex was recorded, and in the case of female individuals, the degree of maturation of the gonads was specified. Stomach content was analysed for each individual, and the names of the species found in the stomachs were reported only in the absence of taxonomic doubts assignment; otherwise, if digestion was too advanced, it was just recorded that the stomach was full. Stomachs were weighed both when full and after content removal.

Table 1. Description of Siluro glanis individuals caught in this study. Name of the individual (ID), habitat of sampling, depth of sampling (metres) specimen weight (grams), specimen length (millimetres), water temperature (T), sex and stomach status, and species identified in the stomachs are indicated.

ID	Habitat	Depth (m)	Weight (g)	Length (mm)	T (°C)	Sex	Stomach	*Alosa agone*	*Alburnus alburnus*	*Padogobius bonelli*	*Perca fluviatilis*	*Salaria fluviatilis*	*Rutilus rutilus*	*Corbicula* sp.	*Orconectes limosus*
L1	Littoral	3	7650	1050	7.2	Male	Empty								
L2	Littoral	>60	3580	800	8.7	Immature	Empty								
L3	Littoral	Na	501	435	Na	Immature	Full					✓			
L4	Littoral	Na	509	435	22.5	Immature	Full								✓
L5	Littoral	3–6	2795	757	17	Male	Full								✓
L6	Littoral	3–6	2215	705	17	Male	Full								✓
L7	Littoral	3–6	3200	810	18.3	Male	Full								
L8	Littoral	3–6	3300	840	18.3	Male	Full								✓
L9	Littoral	4–6	148	270	17.9	Immature	Empty								
L10	Littoral	4–6	219	330	17.9	Immature	Empty								
L11	Littoral	4–6	718	478	17.9	Immature	Full								✓

L12	Littoral	5–8	7200	1015	19.8	Female	Full	✓							
L13	Littoral	5–8	8925	1120	19.8	Male	Full	✓							
L14	Littoral	5–8	11,150	1160	19.8	Female	Empty								
L15	Littoral	6–8	7020	985	19.6	Female	Empty								
L16	Littoral	4–6	143	270	22.2	Immature	Empty								
L17	Littoral	4–6	318	355	22.2	Immature	Full								✓
L18	Littoral	3–6	6500	990	23	Female	Full								✓
L19	Littoral	3–6	5200	870	23	Female	Full								✓
L20	Littoral	4–7	921	505	23.4	Immature	Full								✓
L21	Littoral	8	24,800	1490	Na	Male	Empty								
L22	Littoral	5–7	8400	1090	25.5	Male	Full							✓	✓
L23	Littoral	3–5	810	505	25.5	Immature	Full							✓	✓
L24	Littoral	3–5	345	382	25.5	Immature	Full								✓
L25	Littoral	3–5	197	300	25.5	Immature	Full			✓		✓			
L26	Littoral	3–5	790	480	23.7	Immature	Full		✓				✓		✓
L27	Littoral	3–5	325	380	Na	Immature	Empty								
L28	Littoral	3–5	880	510	Na	Immature	Empty								
L29	Littoral	3	270	365	Na	Immature	Empty								
L30	Littoral	3–5	835	530	22.7	Immature	Full				✓				
L31	Littoral	3–5	535	472	22.7	Immature	Full				✓				
L32	Littoral	3	830	485	23.2	Immature	Full								
L33	Littoral	3	320	390	23.2	Immature	Full								
L34	Littoral	3–5	738	500	22.8	Immature	Full								✓
L35	Littoral	3–5	397	395	22.8	Immature	Full				✓				✓
L36	Littoral	3–5	198	312	22.8	Immature	Empty								
L37	Littoral	3–5	1085	540	Na	Immature	Full								✓
L38	Littoral	3–5	624	465	Na	Immature	Empty								
L39	Littoral	5–10	829	500	22.5	Immature	Full								✓
L40	Littoral	5–10	845	500	21.5	Immature	Full								✓
L42	Littoral	0.1–1	15.3	118	Na	Juvenile	Full								
L43	Littoral	0.1–1	21.85	134	Na	Juvenile	-								
L44	Littoral	0.1–1	8.87	106	Na	Juvenile	-								
L45	Littoral	0.1–1	12.78	117	Na	Juvenile	-								
L46	Littoral	0.1–1	17.86	128	Na	Juvenile	-								
L47	Littoral	5–10	2190	705	18.5	Male	Full								
L48	Littoral	5–10	1700	640	18.5	Male	Full				✓				✓
L49	Littoral	5–15	346	378	18	Immature	Empty								
L50	Littoral	5–15	851	510	18	Immature	Empty								
P1	Pelagic	35	13,200	1220	8.1	Female	Full	✓							
P2	Pelagic	35	4800	830	8.1	Female	Full								
P3	Pelagic	35	1800	670	8.1	Male	Full								
P4	Pelagic	35	2200	740	8.1	Male	Empty								
P5	Pelagic	30	13,600	1210	9	Female	Empty								
P6	Pelagic	30	11,300	1210	9	Male	Empty								
P7	Pelagic	30	5840	930	9	Female	Full								
P8	Pelagic	30	3510	800	9	Female	Empty								
P9	Pelagic	30	3350	780	9	Male	Empty								
P10	Pelagic	30	4850	900	9	Female	Full								
P11	Pelagic	30	3420	825	9.1	Male	Empty								
P12	Pelagic	30	4950	880	9.1	Male	Empty								
P13	Pelagic	30	6370	970	9.1	Female	Empty								

P14	Pelagic	30	10,400	1160	9.1	Male	Empty
P15	Pelagic	30	7740	1008	9.1	Female	Full
P16	Pelagic	14	7210	1020	12.2	Male	Empty
P17[¥]	Pelagic	25	-	-	15.7	-	-
P18	Pelagic	15	7450	1040	Na	Male	Empty
P19	Pelagic	9	1100	545	16	Immature	Empty
P20	Pelagic	20	6350	970	Na	Female	Empty
P21	Pelagic	20	6980	1005	Na	Female	Empty
P22	Pelagic	20	2265	688	13	Male	Empty
P23	Pelagic	20	9750	1150	13	Male	Empty

3. Results

In total, 59 sampling efforts took place, and *S. glanis* was caught in 23 of them (Table 2; Supplementary Tables S1–S4). A total of 72 individuals—23 pelagic and 49 littorals—were collected for analysis (except one pelagic individual who escaped from the net, Table 1). The number of littoral individuals was higher than pelagic ones, but the biomass of littoral individuals was less than the pelagic ones, being 121 kg and 138 kg, respectively. Pelagic individuals were mainly bigger than 60 cm in body length, except individual P19 that was caught during summertime (54.5 cm), and the maximum body length measured was 122 cm. On the contrary, the majority of littoral *S. glanis* (28 individuals) measured less than 60 cm in body length, mainly caught during summertime. The longest *S. glanis*, 149 cm in body length, was caught using a fishing rod (Table 1). Five individuals were juvenile, 30 immature, 21 male, and 15 female; all but one pelagic individuals were sexually mature. Female individuals caught at the end of June showed highly developed gonads, suggesting the individuals were close to spawning, whilst individuals caught in mid-July had empty gonads, indicating the end of the spawning season. Biometric data of all specimens allowed to investigate the growing rate, which showed a high rate, also considering the littoral and pelagic habitats separately (Figure 2a–c).

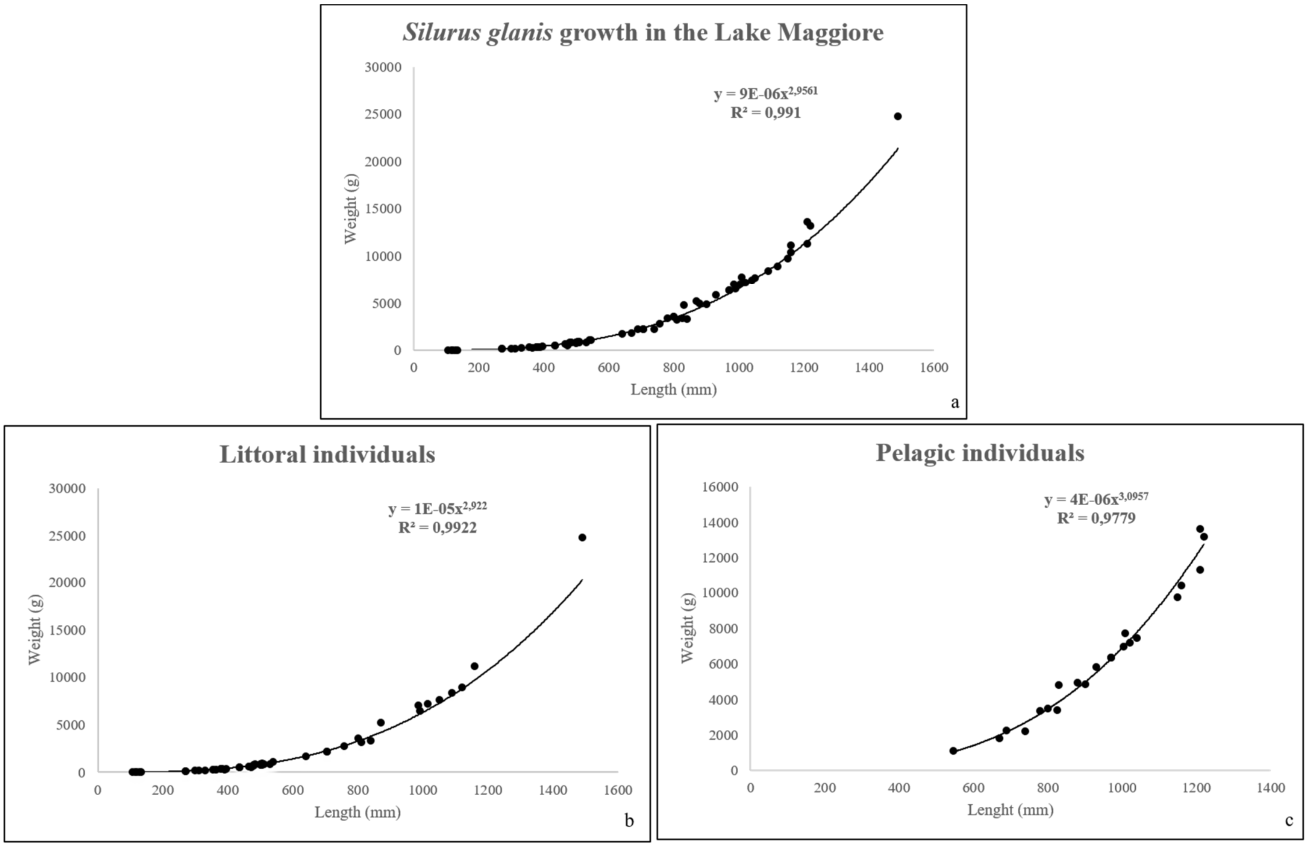

Figure 2. Growing rate of (**a**) Silurus glanis in the Lake Maggiore based on weight and length of all individuals. (**b**) only for individuals caught in the littoral habitat. and (**c**) only in the pelagic habitat.

Table 2. Littoral and pelagic fish community description. Species found during sampling, its native or invasive status, and number of sampling occasions the species were retrieved in each environment (cf. Supplementary Tables S1–S4).

Species	Status	Littoral	Pelagic
Alosa agone	Native	2	28
Carassius carassius	Invasive	3	-
Coregonus sp.	Invasive	2	46
Esox sp.	Native	6	-
Gymnocephalus cernuus	Invasive	4	-
Lepominus gibbosus	Invasive	5	-
Lota lota	Native	2	-
Perca fluviatilis	Native	20	-
Rutilus rutilus	Invasive	24	2
Salmo trutta complex	Native	-	4
Sander lucioperca	Invasive	21	4
Scardinius erythrophthalmus	Native	7	-
Siluro glanis	Invasive	23	12
Squalius cephalus	Native	3	-
Tinca tinca	Native	5	-

The minority of littoral individuals (16 in total) had empty stomachs, whilst the majority (30 individuals) presented with content in their stomachs at different stages of digestion (Table 1), of which the contents retrieved varied between 0.27 g up to 326 g. As most of the stomach content did not allow species identification, the investigation is mainly descriptive. The invasive American crayfish *Orconectes limosus* (Rafinesque, 1871) was found to be the predominant prey, found in 19 specimens (63%), and for 12 specimens, it was the only content in the stomach. In two samples, some freshwater clams belonging to the invasive genus *Corbicula* were retrieved, whilst the other components of the stomach content were fish. Specifically, *S. glanis* inhabiting the littoral area of the Lake Maggiore resulted to prey on *S. fluviatilis*, *P. bonelli*, *A. alburnus*, *R. rutilus*, *A. agone* and *P. fluviatilis*, mainly present as a single component of the stomach. For six specimens, it was impossible to determine the stomach content composition due to the high digestion stage. Most pelagic individuals (16 specimens) had an empty stomach, and a full stomach only for six individuals. Stomach content was exclusively composed of fish, but it was possible to identify the species in only two individuals (both cases *A. agone*), because of the high digestion stage. However, it seemed plausible to think that some of the preys were *Coregonus* sp., since, whilst catching *S. glanis*, *Coregonus* sp. individuals often were found either in the mouth of some individuals of *S. glanis*, or in the nets presenting obvious wounds caused by *S. glanis*, suggesting predation of this genus. The wounds indeed displayed the imprint of a dental arch of *S. glanis*, recognizable by the characteristic abrasions causing scale removal, instead of lacerations typical of other predators present in the Lake Maggiore, such as *Esox* sp. In two individuals with empty stomachs, it was possible to notice the presence of decapod crustaceans in their faeces.

Whilst sampling for *S. glanis*, a total of 14 species were found in the littoral habitat, of which seven were native, whilst only six were in the pelagic habitat, of which two were native (Table 2). In the pelagic habitat, observations of *Coregonus* sp. were predominant, as the nets available for sampling were specific to that genus. There was no opportunity to catch *A. alburnus*, *S. fluviatilis* and *P. bonelli* due to their small size, although their presence was confirmed by stomach content analysis. Interestingly, two invasive species that are not considered pelagic species, *R. rutilus* and *S. lucioperca*, were caught by flying nets (pelagic environment) during summertime (Supplementary Table S4).

4. Discussion

This study corroborated the ability of *S. glanis* to exploit both pelagic and littoral habitats in the Lake Maggiore, and its capability to hunt in the deep area of the lake. Indeed, an individual (L2) was caught at more than 60 m depth, supporting its ecological plasticity [9]. Although due to fishing law restrictions, it was not possible to catch *S. glanis* in the littoral habitat during springtime, the presence of *S. glanis* in the pelagic habitat was preponderant towards that time (Supplementary Table S4), and the presence of *A. agone* in the stomach confirmed its interaction at the pelagic trophic level. All pelagic individuals except one were found sexually mature, suggesting the presence of *S. glanis* in the pelagic habitat before spawning season, usually when the temperature reaches at least 18–19 °C around June, possibly due to the higher trophic contribution this habitat can provide. In the pelagic habitats, individuals bigger than the littoral ones retrieved, where a lack of individuals under 60 cm body length could suggest the absence of *S. glanis* in the pelagic habitat of younger individuals.

A total of 60 fish species, of which cyprinids are predominant, were identified in the diet of *S. glanis* [2,7,9], and this study added two more fish species, *P. bonelli* and *S. fluviatilis*, as well as *Corbicula* sp. The diet of *S. glanis* in the Lake Maggiore described here was based on six fish species (*A. agone*, *A. alburnus*, *P. bonelli*, *P. fluviatilis*, *S. fluviatilis* and *R. rutilus*), and *Coregonus* sp. was suspected. However, the invasive crayfish *O. limosus* was predominant in the stomach content, suggesting its relevant importance in the *S. glanis* diet. This might be due to the high abundance of this species in the Lake Maggiore and the ease of its capture compared to other prey [2,9,19]. *O. limosus* is an invasive species whose presence in Italy has been recorded since 1991 when it was accidentally introduced from Poland [21], and which is proliferating well in lakes of Northern Italy; its presence is considered a major threat to biodiversity and considered of Union Concern [22]. Another invasive crayfish considered of Union Concern [22], and thus a threat for biodiversity, is *Procambarus clarkii* (Girard, 1985), regularly found in Lake Maggiore since 2001. Unexpectedly, it was not found in any *S. glanis* individuals analysed in this study. This finding may be justified by the fact that its occurrence seemed to be more restricted to the southern part of the Lake [21], and further investigations are required to infer the pressure *S. glanis* may have on this invasive species. Another invasive species of the Lake Maggiore retrieved in stomach content is *Corbicula* spp., first recorded in 2010, and well-established in the southern basin [23]. *P. bonelli* and *S. fluviatilis* were mainly retrieved in smaller individuals, probably because small *S. glanis* tend to spend much of their time hiding among stones and rocks, which is the habitat of *P. bonelli* and *S. fluviatilis*.

Previous studies reported the diet of *S. glanis* being mainly based on macrobenthos before shifting to preying upon cyprinids at a larger size, that is, until reaching 30–35 cm body length [6,16,17], as well as crayfish [19]. On the contrary, in this study, the minimum size of *S. glanis* with a full stomach was 11.8 cm in body length (individual L42), and it was possible to recognise its presence in the stomach of a *S. fluviatilis* which was 4 cm in length, as well as for individual L43 (13.4 cm body length) in which it was possible to find a *S. fluviatilis* and individual L46 (12.8 cm body length) which had stomach content composed of *S. fluviatilis* and *P. bonelli*, revealing the ability of young *S. glanis* to eat not just macrobenthos. Notably, it is thus the absence of macrobenthos in the stomach content of *S. glanis*, especially for younger individuals, which represents the main diet component of young *S. glanis* individuals inhabiting the nearby Lake Varese and Ticino River [16]. This feeding ability of young individuals poses the need for a better understanding of the trophic ecology of *S. glanis*. Furthermore, the growing rate of *S. glanis* individuals was high, comparable to one of the nearby, but eutrophic, Varese and Comabbio Lakes [16]. Growth in *S. glanis* is highly variable, depending on their habitat [2]; individuals from both pelagic and littoral habitats in this study showed a high growth rate, which is interesting considering that Lake Maggiore is oligotrophic, demanding an in-depth focus of this species in this novel invaded environment.

Despite the limited number of individuals caught and number of sites investigated, due to sampling difficulties in lentic environments without widespread support from commercial and professional fishermen, this study stresses the need to further investigate the potential pressure of this species, with special attention on the population growth trend in the pelagic habitat. Although there are many difficulties in gathering more information due to limited logistic support (i.e., difficulties in catching samples from both habitats covering the whole ecosystem), the involvement of fishermen, citizen scientists, and more refined analysis (i.e., DNA barcoding of stomach content, stable isotope analysis, environmental DNA) could offer focal tools to further study biological invasions [24,25]. Considering the recent invasion of this species, this study added important baseline information to justify the collection of more refined quantitative data over a long period, to better investigate how *S. glanis* could affect native fauna, and aim to plan proper strategies for biodiversity management.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w14010105/s1, "Sampling methods for littoral environment" and "Sampling methods for pelagic environment", supported by Table S1: Details of littoral sampling through "voltana" nets. date of net lowering (d1) and time (t1), date of net withdrawal (d2) and time (t2), water depth and water temperature (T) are detailed, Table S2: Details of littoral sampling through "Reet de pes bianc" nets. Date of net lowering (d1) and time (t1), date of net withdrawal (d2) and time (t2), water depth and water temperature (T) are detailed. Table S3: Details of littoral sampling through "Reet de bundela" nets. Date of net lowering (d1) and time (t1), date of net withdrawal (d2) and time (t2), water depth and water temperature (T) are detailed, and Table S4: Details of pelagic sampling through "Reet de bundela volante" nets. Date of net lowering (d1) and time (t1), date of net withdrawal (d2) and time (t2), water depth and water temperature (T) are detailed.

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