Minnow introductions in mountain lakes result in lower salmonid densities

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Abstract Small fish species such as minnows (Phoxinus sp.) are introduced into mountain lakes by anglers that use them as live bait for fishing salmonids that were previously introduced in these naturally fishless habitats. Introduced fish severely impact native biota but minnows are nevertheless released believing to provide forage for game fish, i.e., salmonids. However, our results indicate that minnows negatively interact with game fish, reducing their relative densities. On some occasions, minnows can remain the only present fish following trout extinction. We believe that this information should be urgently disseminated among anglers as a pragmatic argument to also convince anglers less sensitive to conservation issues that carrying minnows to the mountains is not a good idea whatever the main interest is, e.g., nature conservation or outdoor recreation.

Keywords Ecological interactions · Salmonidae · Cyprinidae · Fish introduction · Fishery management · Conservation measures

though fish introductions severely impact native biota of originally fishless mountain lakes (Knapp et al. 2001; Ventura et al. 2017; Miró et al. 2018), salmonids are commonly introduced to sustain or promote recreational angling. Such game fish are mainly introduced via institutional stocking programmes, but their presence facilitates the collateral introductions of some small fish such as minnows Phoxinus sp. (Fam. Cyprinidae) which are used as live baits by anglers (Museth et al. 2007; Miró and Ventura 2015).

As the case has been in northern Europe (Museth et al. 2007), such illegal introductions are spreading minnows in the Pyrenees (Miró and Ventura 2015), Alps (Tiberti et al. 2020; De Santis et al. 2021), and -likely- in other mountain ranges across Europe.

The release of minnows can be either accidental or conscious. In the latter case, the release can be due either to carelessness, or to the common belief that small cyprinids can become food for trout improving
their populations, namely “forage fish” (Miró and Ventura 2015). However, the alleged positive effects of minnows on trout are generally not supported by empirical data and neither by food-web theory. On the contrary, scientific literature shows some examples of their negative ecological interactions, mainly from some boreal mountain lakes, where minnows negatively affect trout populations by competition for food and predation on eggs (Lien 1981; Museth et al. 2007, 2010; Borgstrøm et al. 1996, 2010; Global Invasive Species Database 2021). Similar studies are however missing from the lakes of the southern European mountains, where minnow introductions are also widespread (Miró and Ventura 2015; Tiberti et al. 2020).

The aim of the present study was to assess if minnows negatively affect the densities of salmonids inhabiting the mountain lakes in a new geographic area, i.e., southern European mountain ranges (Alps and Pyrenees). Our main study hypothesis is that minnows negatively interact with salmonids, as already observed in northern regions (Museth et al. 2007). Our study hypothesis is verified if the densities of salmonids are lower when coexisting with cyprinids.

To test our hypothesis, between 2012 and 2019, we sampled 43 originally fishless mountain lakes, 30 with introduced salmonids only and 13 with both introduced salmonids and cyprinids (Fig. 1) in four Sites of Community Importance (SCI) from the Catalan Pyrenees and the Western Italian Alps: the SCIs Aigüestortes (ES0000022), Alt Pallars (ES5130003), Parco Nazionale del Gran Paradiso (IT1201000), and Parco Naturale Mont Avic (IT1202000) (Fig. 1). All study lakes are typical mountain lakes between 0.3 and 24.2 ha (mean ± sd: 4.75 ± 4.72 ha) and 3.0–73.0 m deep (mean ± sd: 15.3 ± 13.6 m), cold and ice-covered for 6–9 months per year, placed close or above the local timberline between 1618 and 2747 m a.s.l. (mean ± sd: 2321 ± 230 m a.s.l.). Introduced fish include several salmonid species and some populations of European minnow species complex, Phoxinus sp. (Fig. 1). Periodic fish stocking could artificially increase the density of salmonids, but, at the time of fish sampling, introductions were already prohibited or suspended since at least 4 years (from 4 to > 40 years) in all lakes.

We sampled salmonids with multi-mesh gillnets and cyprinids with fyke-nets. In lakes with salmonids, we estimated their relative densities as Captures Per Unit Effort (CPUE; No. of salmonids × m−2 of gillnet × Day−1), deploying 1–4 multi-mesh gillnets in the central part of the lakes depending on the lake size. To this end, we used two kinds of gillnets: standard nets in the Pyrenean lakes (30 m long × 1.5 m high, divided into 12 panels with variable mesh size; CEN 2015) and some different nets in the Alpine

![Fig. 1 Study area and lakes with presence of salmonids and minnows: a SCIs Aigüestortes and Alt Pallars in the Pyrenees (20 km grid); b SCIs Parco Nazionale Gran Paradiso and Parco Naturale Mont Avic in the Alps (20 km grid); c position of the SCIs in Europe (1000 km grid)](image-url)
Minnow introductions in mountain lakes result in lower salmonid densities in lakes (36 m long × 1.8 m high, divided into six panels with increasing mesh sizes: 10.0, 12.5, 18.5, 25.0, 33.0, 38.0 mm). In lakes with cyprinids, their CPUE was estimated as No. of cyprinids × trap−1 × day−1 deploying 2–6 fish traps (i.e., fyke nets; 0.5 m wide × 0.4 m high D-shaped mouth, 4 mm mesh size with a 2 m long central wing or lead) in the littoral area of the lakes (with their mouths facing the shoreline). Because gillnetting and fyke netting sessions were sometimes repeated in the same lakes, in such cases we calculated an average CPUE weighting by the duration of the fishing sessions.

Cyprinids were found coexisting with Salmo trutta in 11 out of the 13 lakes with both salmonids and cyprinids, and they were never found in the eleven lakes with Salvelinus fontinalis. Their CPUE varied considerably among lakes (mean ± sd: 137.08 ± 202.14 minnows trap⁻¹ day⁻¹), up to 690.17 minnows trap⁻¹ day⁻¹. Also, the CPUE of salmonids varied a lot (mean ± sd: 0.41 ± 0.68 fish m⁻² day⁻¹) depending on the sampled lake and species, being Salvelinus fontinalis the species with the highest average and maximum CPUEs (Fig. 2a). Where salmonid and cyprinid coexist, the relationship between their CPUEs suggest that salmonids can reach higher densities only where minnow density was low and vice-versa (Fig. 3).

To cope with non-normal distribution of CPUE data and small sample sizes, we tested the study hypothesis with a non-parametric one-tailed Wilcoxon rank sum tests (or Mann Whitney U Tests). The median CPUE of salmonids was significantly higher when cyprinids were not present (W = 322, p < 0.001), and when cyprinids were present (W = 181, p < 0.05).

Fig. 2 Panel a Boxplot comparing the relative densities (Capture Per Unit Effort-CPUE) of different salmonid species (OM: rainbow trout Oncorhynchus mykiss; ST: brown trout Salmo trutta; SA: arctic char Salvelinus alpinus; SF: brook trout Salvelinus fontinalis) in 43 mountain lakes from the Pyrenees and Alps; panel b salmonid CPUE when cyprinids are absent (S) or present (S + C); panel c salmonid CPUE when cyprinids are absent (S) or present (S + C), excluding lakes with brook trout Salvelinus fontinalis; panel d brown trout CPUE when cyprinids are absent (S) or present (S + C).

Fig. 3 Relationship between salmonid and cyprinid Capture Per Unit Efforts (CPUEs) in the 13 mountain lakes with both fish families
n_1 = 30, n_2 = 13, p < 0.001; Fig. 2a). The same result could be observed also when we excluded the lakes with *S. fontinalis* (W = 181, n_1 = 19, n_2 = 13, p < 0.05; Fig. 2c) and when we considered only the lakes with *S. trutta* (W = 121, n_1 = 15, n_2 = 11, p < 0.05; Fig. 2d), to avoid possible bias related to the likely existence of different species-specific interactions between salmonid species and minnows.

The initial results obtained show a negative interaction between minnows and salmonids. Where minnows coexist with salmonids, the observed density patterns (Fig. 3) could be the result of a progressive replacement of trout by minnows in some lakes. This could be due to predation (e.g., on trout eggs) and competition, which -in a few lakes where fishing is permitted- sum up to the effects of trout removal by anglers. In this regard it is also interesting to note that there are mountain lakes where salmonid populations -including self-sustaining populations- disappeared after the introduction of cyprinids (Miró and Ventura 2015; Tiberti et al. 2020), which should be considered a further and extreme consequence of minnow introductions on salmonids. In addition, the fact that minnows were not found in any lake with *S. fontinalis*, suggest that also salmonid populations may exclude/ control minnow populations, e.g., preventing their establishment by predation or competition for food resources (see Museth et al. 2003). Better understanding the mechanisms of mutual exclusion between minnows and salmonids could have potential management and conservation implication, for example in the field of biological control (Koenig et al. 2015). We however aim to address such mechanisms of exclusion in a better detail, when a more representative sample of lakes will be available.

In conclusion, our results confirm our study hypothesis showing that releasing minnows generally has negative consequences for salmonids, as already observed in some mountain and lowland lakes from the boreal region (Museth et al. 2007). While the exact nature of the ecological interaction between minnows and salmonids in southern mountain lakes systems deserves further studies, we believe that our results are sufficient to support the idea that minnow introductions should be avoided. The same indication stems from conservation instances, from several studies on the huge ecological impact that minnows generate in mountain lakes, through predation on native amphibians and invertebrates, and trophic cascades (Gacia et al. 2018; Miró et al. 2018; Tiberti et al. 2021). However, providing evidence of the impact of minnows on salmonids could be a highly effective argument for ensuring the collaboration of anglers (i.e., the main vectors of minnow invasion; Miró and Ventura 2015) and their compliance with some necessary restrictions about the use of minnows as live baits.

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**Data availability** All data are summarized in the paper.

**Declarations**

**Conflict of interest** None of the authors declares a conflict of interest.

**Consent to participate** All authors expressed their consent to participate in the paper.

**Consent for publication** All authors agree with the paper contents and with its publication in biological invasions.

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