



HAL
open science

Rehabilitation of whitefish fisheries in lakes Geneva and Bourget during the eutrophication period: assessing socio-economic impacts through large collaborative research

Hervé Rogissart, Chloé Goulon, Jean Guillard

► To cite this version:

Hervé Rogissart, Chloé Goulon, Jean Guillard. Rehabilitation of whitefish fisheries in lakes Geneva and Bourget during the eutrophication period: assessing socio-economic impacts through large collaborative research. *International Journal of Limnology*, 2024, OLA, 60, pp.13. <10.1051/limn/2024012>. <hal-04670416>

HAL Id: hal-04670416

<https://hal.science/hal-04670416v1>

Submitted on 12 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Special issue - Biology and Management of Coregonid Fishes - 2023
Guest editors: Orlane Anneville, Chloé Goulon, Juha Karjalainen, Jean Guillard, Jared T. Myers and Jason Stockwell

RESEARCH ARTICLE

OPEN ACCESS

Rehabilitation of whitefish fisheries in lakes Geneva and Bourget during the eutrophication period: assessing socio-economic impacts through large collaborative research

Hervé Rogissart¹, Chloé Goulon¹ and Jean Guillard^{1*}

Université Savoie Mont Blanc, INRAE, CARRETEL, 74200 Thonon-les-Bains, France

Received: 21 December 2023; Accepted: 20 June 2024

Abstract – Lakes provide ecosystem services such as water resources, tourism, biodiversity, and fishing, and therefore their management represents important societal challenges. Since the early 1960s, significant anthropogenic pressures (human population growth and industrial and agricultural development) have accelerated the degradation of lake ecosystems, leading to eutrophication and subsequent increased sedimentation on fish spawning grounds and decreased dissolved oxygen concentrations. This negatively affects the natural recruitment of whitefish (*Coregonus lavaretus*), an emblematic species of peri-alpine lakes. Over the years, such processes have resulted in a decline in the whitefish population stock, thereby leading to a drastic drop in catch and causing major economic losses. From the beginning of the 1980s, alongside the restoration of water quality, professional fishers, recreational anglers, state services, and researchers from INRA worked together to develop an applied research program called ‘Pacage Lacustre’ to improve and optimise salmonid stocking. The goal was to counterbalance the low juvenile natural recruitment and maintain whitefish populations. Here, we retrospectively retrace the key stages of this research program and its main impacts on society. Collaborative efforts played a key role in rehabilitating whitefish populations in lakes Geneva and Bourget, particularly when their abundances were the lowest. Therefore, these efforts had a substantial impact on preserving commercial and recreational fishery activities, in addition to favorable societal impacts, highlighting the importance of such collaborative work.

Keywords: Research impact / fishery management / stocking / salmonids / citizen science

1 Introduction

Lakes provide numerous ecosystem services worldwide, such as water resources, tourism, biodiversity, and fisheries; therefore, their preservation presents a major societal challenge (Reynaud and Lanzanova, 2017; Sterner *et al.*, 2020; Inácio *et al.*, 2022). In France, the management of peri-alpine lakes is not only a regional challenge, but also a national and international one. Peri-alpine lakes are the largest bodies of freshwater in France; moreover, water from Lake Geneva is shared with Switzerland (Bravard and Clémens, 2008; Pflieger and Bréthaut, 2012). These lakes have substantial fishing potential and represent a renewable resource that has long been used by professional fishers and recreational anglers (Loup, 1950; Bardel, 1956). Similar fish communities are found in these lakes and mainly comprise cyprinids, esocids, and the heavily fished percids and salmonids (Gerdeaux *et al.*, 2006).

Since the 1950s, lake ecosystem degradation has intensified due to an increase in anthropogenic pressure due to population growth, expanded tourism, and industrial and agricultural development (Jenny *et al.*, 2020). Between the early 1950s and late 1970s, lakes Geneva and Bourget underwent a period of pronounced eutrophication (Baulaz *et al.*, 2021) which considerably affected water quality and associated lake ecosystem services, similar to many lakes around the world at that time (Carpenter, 2005; Schindler, 2012, Schindler, 2016). The desirable threshold of total phosphorous is 15 µg/L to limit excessive algal production and impacts on ecosystem services (OCDE, 1982; Baulaz *et al.*, 2021). In 1979, total phosphorus values reached peak values of 90 µg/L in Lake Geneva and 172 µg/L in Lake Bourget (Rimet *et al.*, 2020).

Salmonids, especially whitefish (*Coregonus lavaretus*), receive special attention and undergo extensive scientific monitoring in these two lakes because they are heritage species with high economic value (Gerdeaux *et al.*, 2006; Anneville *et al.*, 2015). However, they are highly sensitive to environmental deterioration (Alexander *et al.*, 2017). During whitefish reproduction, eggs are deposited on lake substrates at

*Corresponding author: jean.guillard@inrae.fr

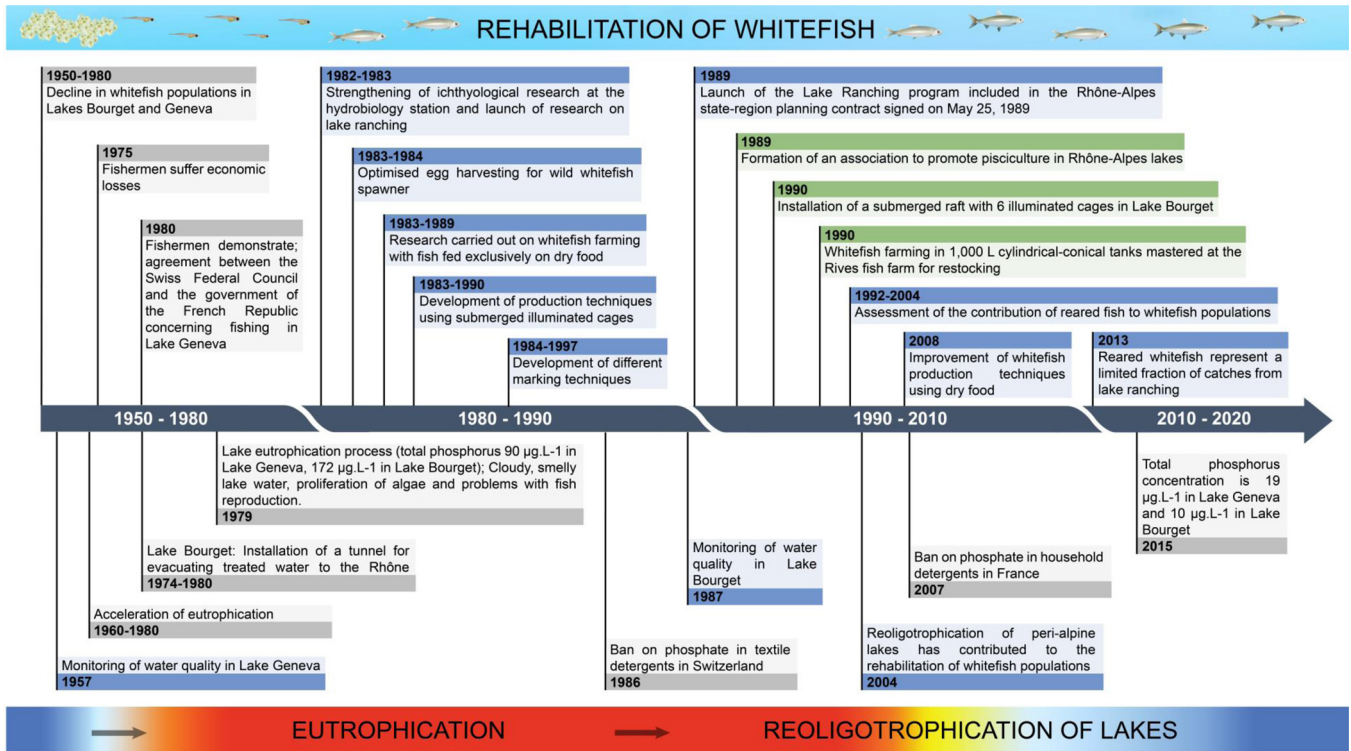


Fig. 1. Chronology of the key phases in the research program of whitefish rehabilitation and reoligotrophication in lakes Bourget and Geneva (1950–2015; adapted from Rogissart *et al.*, 2023).

specific temperatures and oxygen levels (Eckmann, 2013). Thus, eutrophication affects the survival of eggs and juveniles due to increased sedimentation rates on spawning grounds and decreased oxygen availability, particularly at the water-sediment interface (Muller and Stadelmann, 2004; Eckmann, 2013). Therefore, during the eutrophication period, recruitment was negatively affected and led to sharp declines in whitefish populations (Gerdeaux *et al.*, 2004) and, consequently, major economic losses for fishing companies and related professions such as fishers, fishmongers, and catering (Gagnaire, 1988). In addition, perch (*Perca fluviatilis*) recruitment in Lake Geneva was extremely poor in the early 1980s due to very poor weather conditions (Dubois *et al.*, 2008). During these years, perch catches were notably low and led to a social crisis because they represented another crucial source of income for professional fishers.

Supported by anglers and environmental organisations, professional fishers raised these issues with public authorities and elected officials. These protests led to the strengthening of the local fish research group at the Institut National de la Recherche Agronomique (INRA) laboratory in Thonon-les-bains, France, in 1983 (Olive, 1986). The group aimed to intensify research efforts on fish ecology and fishery management in lakes Geneva and Bourget. The works mainly focused on understanding fish reproduction (Gillet, 1989) and the effects of environmental factors on fish dynamics (Gerdeaux, 2004). Moreover, a fish stocking program called ‘Pacage lacustre’ (‘Lake Ranching’; Champigneulle, 1996)

was developed to restore lake salmonid populations (Champigneulle, 1989). The goal was to evaluate and refine methods for stocking whitefish populations across peri-alpine lakes using native breeding stock to rehabilitate populations (Aronson *et al.*, 1993) and prevent the disappearance of professional fishing, a vital component of local and regional economies (Champigneulle *et al.*, 2001). The purpose of this study was to retrospectively outline the key phases of the research program (Fig. 1) and examine its diverse impacts on society (Rogissart *et al.*, 2023), and was inspired by the research impact analysis method (Analyse de l’Impact Sociétal de la Recherche: ASIRPA; see Supplementary Information) developed by the National Research Institute for Agriculture, Food, and the Environment (INRAE), previously called INRA (Joly *et al.*, 2015; Smit and Hessels, 2021).

We organized the manuscript into five sections. The first section describes the study sites, whitefish catch, and main research actions conducted by the researchers in this project. The second section highlights the stocking techniques and key outcomes of the whitefish population rehabilitation in lakes Geneva and Bourget. The third section describes and highlights the numerous and important impacts on society of the ‘Pacage lacustre’ program, including the knowledge acquired through collaborative research among fishers, anglers, stakeholders, authorities, and scientists. The fourth section presents the limitations and threats of stocking practices on fish communities and ecosystems, and the fifth details future challenges of whitefish rehabilitation in lakes.

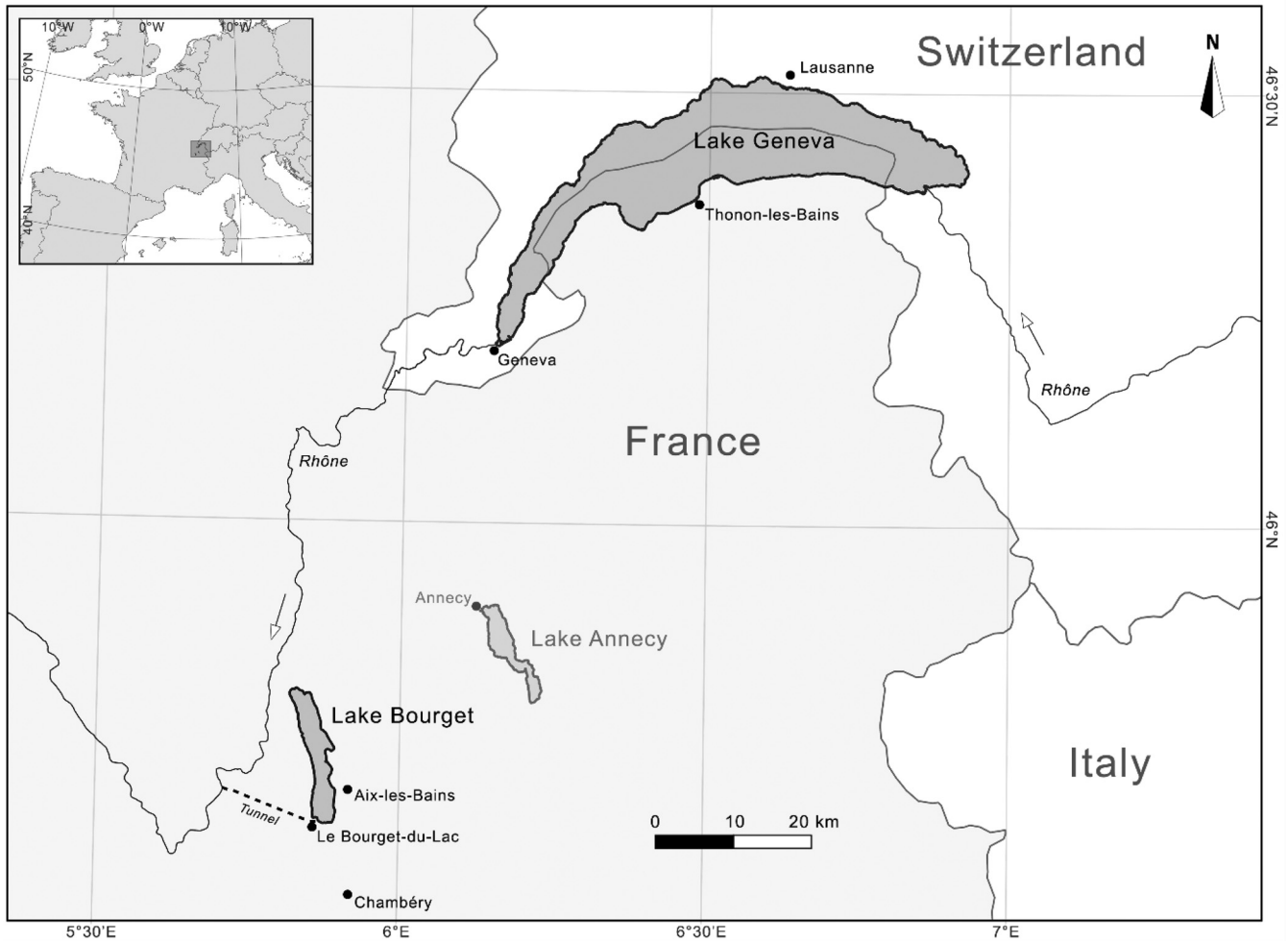


Fig. 2. Location of the two peri-Alpine lakes studied (lakes Bourget and Geneva). Dashed lines indicate the tunnel excavated through the Chat Mountain range to divert the treated sewage from the Chambéry, Aix-les-Bains, and le Bourget-du-Lac drainage stations into the river Rhône.

2 Study sites, whitefish catch data, and key research activities

2.1 Study sites

Lake Geneva is the largest natural alpine lake of Western Europe (surface area = 582 km² 46°27'N – 6°32'E), located on the border between France and Switzerland (Fig. 2), with a maximum depth of up to 309 meters (mean depth = 157 m; Rimet *et al.*, 2020) and is considered as a warm monomictic lake (Anneville *et al.*, 2017). Lake Bourget is the largest natural French lake entirely within France (Fig. 2), located on the western edge of the Alps (surface area = 44.5 km²; 45°44'N – 5°52'E) and is a deep monomictic lake (maximum depth = 145 m; mean depth = 85 m).

In the context of pronounced eutrophication (Anneville *et al.*, 2017; Baulaz *et al.*, 2021), measures were implemented in Lake Geneva in the early 1970s to decrease phosphorus levels and preserve the water quality (Fig. 3). These measures involved constructing sewage plants on the whole watershed, reducing external phosphorus loading via improving water treatment, and reducing the use of phosphorus to fertilize soils.

Furthermore, in 1986, Switzerland prohibited polyphosphates in laundry detergent (Rapin and Gerdeaux, 2013). In France, phosphates have only been banned in domestic laundry detergents since 2007 (National Decree no. 2007-491).

In the same period, between 1974 and 1980, sewage plants around Lake Bourget (Chambéry, Aix-les-Bains and Bourget-du-Lac; France) were also improved to reduce eutrophication. To reduce the discharge of wastewater into the lake (Fig. 3), a tunnel of 12.2 km was dug in a nearby mountain (Massif de l'Épine) to transport it toward the river Rhône. This system is more adequately equipped to sustain the discharge levels evaluated at 40 g/m²/year of total inorganic nitrogen and 6.72 g/m²/year of total phosphorus. These levels represent respectively four and nearly ten times the dangerous load (Balland *et al.*, 1977). This engineering action significantly reduced eutrophication in Lake Bourget and helped improve the poor water quality (Jacquet *et al.*, 2014).

The fight against phosphorus inputs included reducing polluting discharges from anthropogenic activities and appropriate management of each lake and its watershed (Loizeau and Dominik, 2005). Physicochemical and biological data (phosphorus, phyto- and zooplankton levels, water

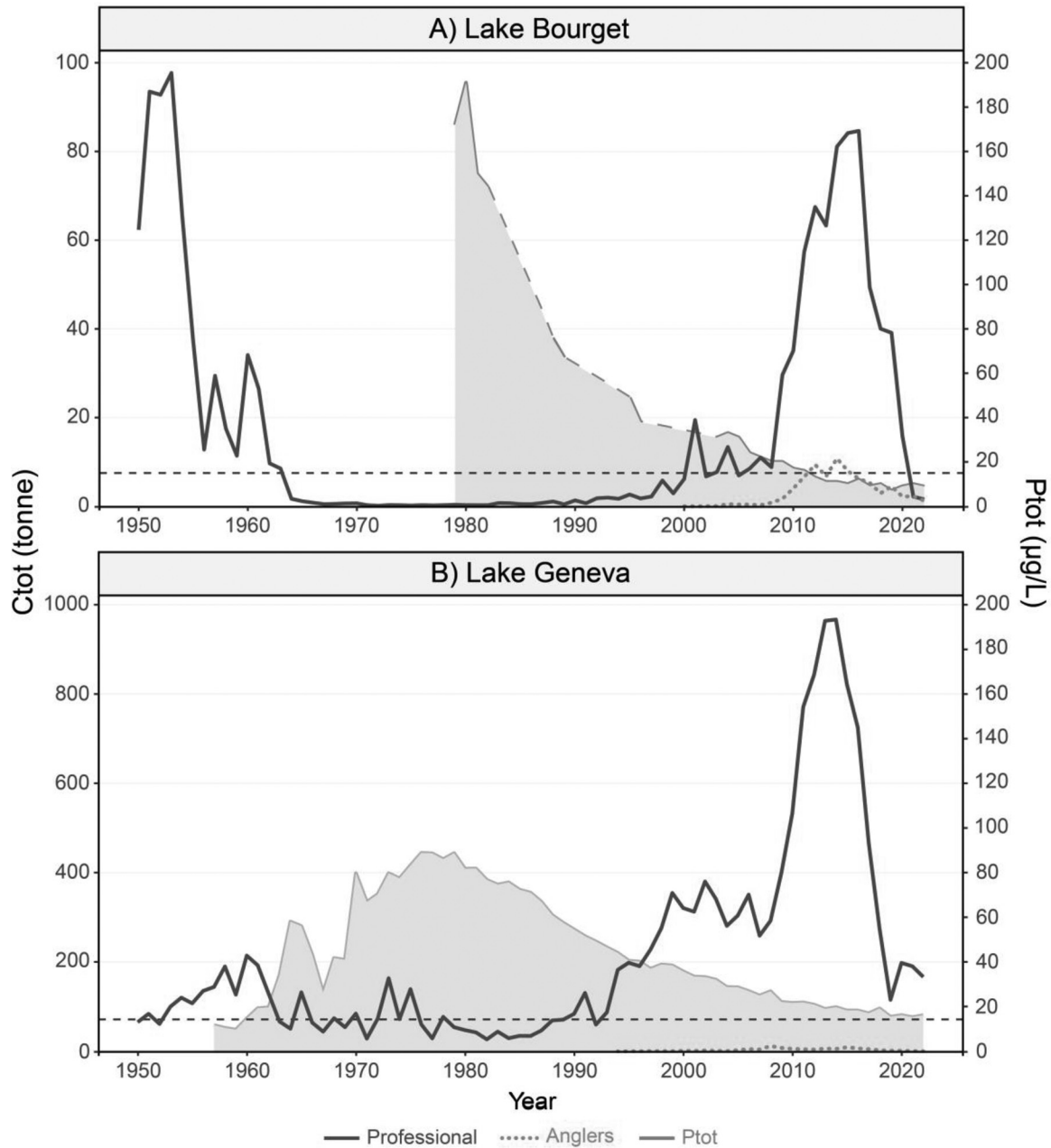


Fig. 3. Change in total whitefish (*Coregonus spp.*) catches (Ctot) by professional fishers (solid blue curve) and recreational anglers (dotted orange curve) in tons (Jacquet *et al.*, 2022; Goulon *et al.*, 2023), along with weighted mean annual concentrations of total phosphorus (Ptot; data from SOERE SI-OLA; Rimet *et al.*, 2020) from 1950 to 2022 in Lake Bourget (A) and Lake Geneva (B). The dashed grey line indicates extrapolated data. The dashed horizontal black line highlights the 15 µg/L Ptot threshold recommended by OCDE (1982).

transparency, oxygen, *etc.*) have been collected since 1957 and 1987 from lakes Geneva and Bourget, respectively (Rimet *et al.*, 2020). The phosphorus concentrations decreased in both lakes beginning in the 1980s, initiating a process of reoligotrophication, leading to the status of Lake Geneva as a meso-eutrophic lake. While phosphorous levels dropped below 20 µg/L in 2013, the current level remains above the 15 µg/L threshold (Fig. 3). Lake Bourget is much smaller than Lake Geneva, with a volume about 30 times smaller and a mean depth 2 times shallower. Lake Bourget became oligotrophic in 2012, with phosphorus concentrations falling

below the 15 µg/L threshold. In 2021, total phosphorus concentrations were 16 µg/L in Lake Geneva and 9.5 µg/L in Lake Bourget (Fig. 3). Natural recruitment of whitefish was enhanced by improving water quality (Gerdeaux, 2004).

2.2 Whitefish catches in the two lakes

The European whitefish is a mainly lake-dwelling stenothermic fish belonging to the Salmonidae family and Coregoninae (Bonaparte, 1845) subfamily. Genetic studies (Bernatchez and Dodson, 1994) proposed that populations in

the alpine region should be considered as a single species complex, defined as the *C. lavaretus* (L.) species complex (Østbye *et al.*, 2005). This species is mainly found in cold environments such as lakes, reservoirs, and ponds, and has a zooplanktivorous diet (Anneville and Hamelet, 2018). Whitefish fisheries have a high socioeconomic value in peri-alpine lakes (Gagnaire, 1988). In Lake Geneva, whitefish catches fell from 100–200 t/year in the 1950s to 30–50 t/year from 1974 to 1984 (Fig. 3) and in Lake Bourget, whitefish catches collapsed from 100 t/year before 1950 to approximately 0.1 t/year from 1970 to 1980 (Fig. 3; Jacquet *et al.*, 2022; Goulon *et al.*, 2023).

2.3 Important research actions conducted by the scientific team

Scientific collaborations, bibliographic syntheses and numerous missions to countries such as Czechoslovakia, Poland, East Germany, and Finland have been undertaken to examine the different methodologies applied to whitefish population rehabilitation and to better understand whitefish ecology (Champigneulle, 1983, 1985; Gillet, 1989). The factors limiting the natural reproduction of whitefish were thoroughly analysed, focusing on their habitats, bioecological requirements, and stock dynamics. Eutrophication has emerged as the main force influencing trophic resources, while hindering natural recruitment (Champigneulle, 1985; Champigneulle *et al.*, 2001). Significant changes in whitefish growth have been observed in Lake Geneva, where a sharp increase in size-at-age between 1953 and 1982 (Fig. S3 A) meant whitefish reached 30 cm during the third year compared their fifth year in the 1950s (Champigneulle *et al.*, 1983). This change was attributed to the ~4X increase in zooplankton biomass between the early 1960s and early 1980s (Fig. S3 B). Consequently, fish reached the legal capture size (30 cm) prematurely, potentially before they reproduced, thereby affecting the number of spawners and recruitment. These conclusions, supported by a bibliographical synthesis (Champigneulle, 1985), confirm that the release of whitefish juveniles in peri-alpine lakes could help rehabilitate and/or sustain whitefish populations. Therefore, the ‘Pacage Lacustre’ strategy was implemented to optimise the rearing production of juvenile fish in terms of quantity and quality. This strategy was also cost-effective because it controlled the supply of fish eggs to the natural environment.

Monitoring whitefish release and assessing the relevance of this stocking strategy was essential throughout this process. Assessing the effectiveness of whitefish stockings was challenging, particularly because of extremely low recruitment. Therefore, marking and control surveys on captured whitefish were essential to accurately determine the proportion of fish originating from supportive breeding versus those originating from natural recruitment (Champigneulle and Escomel, 1984; Rojas-Beltran *et al.*, 1995). This integrated approach, which combines in-depth knowledge of whitefish ecology, monitoring of releases, well-defined management objectives, and rigorous evaluation of stocking, has been key to the rehabilitation and sustainable management of whitefish populations in lakes Geneva and Bourget.

3 Stocking techniques, methodology development, and results

3.1 Controlling the supply of eggs from wild spawners

From 1983 onwards, stocking was carried out in lakes Geneva and Bourget using only eggs collected from their respective wild spawners, to avoid the introduction of non-native stocks as was previously done using juveniles from different countries (Büttiker, 2005). Professional fishers catch spawners during the reproductive period (from November to January). Prior to 1983, during spawner harvests, a large percentage of gillnet catch was males (>60%) and a majority of captured females were non-ovulated (>55%). These catches resulted in a substantial loss of potential eggs (Champigneulle *et al.*, 1983) and a poor balance between the number of females and males. To optimise egg harvesting while reducing costs, the usual practices were changed. First, gillnet meshes were optimised (square or diamond-shaped, 40 mm at Bourget and 44 mm at Lake Geneva) to catch spawners and limit the capture of younger males, who tend to mature earlier than females (Champigneulle *et al.*, 2001). Non-ovulated females were kept on fish farms until ovulation, contributing to improved egg harvests (Champigneulle *et al.*, 1983). Experimental studies assessed variations in the rate of ovulation in females over time and space to identify the most favourable time and location for spawning (Champigneulle *et al.*, 1994, 2001). Second, to ensure the survival of fertilised eggs, artificial fertilisation was conducted promptly, as the proportion of fertilisable eggs declined rapidly beyond a 2 h window following death (Champigneulle *et al.*, 1983). Furthermore, fertilisation was carried out using milts from a larger number of males to promote spawner diversity (C. Gillet, pers. com.). Subsequently, the eggs were rinsed several times with clean water to mitigate aggregation before being transported to fish farms for incubation (Champigneulle *et al.*, 2001). The survival rate during the first week post-hatching exceeded 70% compared to that in the natural environment, where, according to Viljanen (1988), survival rates could drop below 10% (Champigneulle, 1996).

3.2 Fish rearing production techniques

From the beginning of the 1980s, whitefish production was solely based on living plankton, which had a highly limited production capacity. The goal of the project was to develop techniques for the mass production of juveniles and reduce costs. The Rives fish farm in Thonon-les-Bains (France) was renovated and expanded between 1990 and 1993 thanks to the commitment of the partners (Champigneulle *et al.*, 1991, 2001). Furthermore, because whitefish larvae are vulnerable when released into the natural environment (Eckmann, 2013), research focused on production techniques to pre-grow fish to the fingerling stage. A nutritional program was developed that included physiological research. In 1983, tests were conducted using live and frozen zooplankton and pellets typically used for trout. Zooplankton (mainly *Bosmina spp.*, *Daphnia spp.*, and Cyclops) were collected once a day from a boat on Lake Geneva using a net (300- μ m mesh) and then either used

directly or frozen (Dewaele, 1983; Champigneulle *et al.*, 1986). Live zooplankton appeared optimal, providing a better larval survival rate (approximately 20% at two months) and growth comparable to that in the natural environment. Frozen plankton also showed good results, but with lower survival rates (6.5% at 2 months) (Champigneulle *et al.*, 1986).

However, zooplankton supply was difficult, uncertain, and expensive. The annual cost of stocking 100,000 fingerlings was estimated at 69,100 francs (€10,519), a significant proportion of which was related to labour costs for harvesting zooplankton (Dewaele, 1983). Trout pellets proved to be unsuitable, resulting in a high percentage of malformed fingerlings (Champigneulle *et al.*, 1986). Therefore, to reduce costs and overcome these problems, a major research effort was made to design dry food to facilitate mass fish farming in tanks (Bergot *et al.*, 1986). Meanwhile, pending the development of exclusively dry food, illuminated cages inspired by Polish cages (Boutry, 1983) were used to directly rear juveniles in the lake. This method involved placing whitefish larvae within a cage with a fine mesh (0.5–5 mm depending on the size of the fry) to prevent predation (Champigneulle *et al.*, 2001). A nocturnal lighting system in the centre of the cage attracted zooplankton through phototaxis (Champigneulle *et al.*, 1986).

In Lake Bourget, this method improved the acclimatisation of fry in the lake and increased their survival when stocked in March and early April under optimal temperature and zooplankton density conditions (40–56% survival rate; Champigneulle and Rojas-Beltran, 1996). Rafts of lighted cages, mainly managed by professional fishers, helped sustain wild whitefish populations at critical times when the stock was at its lowest (approximately 100 kg/year from 1966 to 1990). However, since 2004, the cage technique has been gradually abandoned, not only because of the excessive workload in conducting maintenance operations, but also because of the effectiveness of lower-cost mass rearing techniques using dry feed (0,006 € to 0,05 €/unit compared to 0,06 €/unit in cages).

Substantial progress has been made in the composition and size of low-cost dry food using yeast and/or freeze-dried beef or pork liver (Champigneulle *et al.*, 1994) leading to successful whitefish raising in fish farm tanks (50–200 francs/kg, around current 8–30 €/kg). Dabrowski *et al.* (1984), Bergot *et al.* (1986), and Champigneulle (1988) have defined the optimal parameters for rearing: temperature (14–15°C), light (09 am to 5 pm), density (100–200 larvae/L), and feeding rate (every 5 min, 2–4 g/tank/8 h by automatic feeders). Specific cylindrical-conical tanks (5, 60, and 250 L), have been tested (Champigneulle *et al.*, 1989) and later modified into 1,000 L adapted to mass rearing (200–400 larvae/L at 6–11°C; Champigneulle *et al.*, 1994) to reduce global costs. This study focusing on egg and larval production allowed better management of the entire fish rearing cycle in large-scale production (Rojas Beltran and Champigneulle, 1991; Rojas Beltran *et al.*, 1991, 1992).

3.3 Development of fish marking techniques

To assess stocking efficiency, fish-marking techniques must be developed. Indeed, interannual fluctuations in population dynamics can be caused by various factors such

as fishing, environmental conditions, and stock-recruitment relationships, which can completely mask the fish contribution from supportive breeding to those from natural recruitment. External techniques (Sandford *et al.*, 2019) were developed for the fingerlings by cauterising the adipose fin or removing the pelvic fin on individuals with an overall length of 28 mm or more (Champigneulle and Escomel, 1984). Based on a study by Meng *et al.* (1986), marking techniques using the injection of encoded magnetised micromarks into the nasal cartilage were conducted. Champigneulle *et al.* (1987) successfully tested the possibility of using these marks in smaller individuals (30–50 mm in whitefish, Champigneulle and Rojas Beltran, 2001). The application of these techniques has allowed for an operator to mark approximately 1,500–2,000 fish per day. However, given the size of the lakes and the large number of fish to be raised, this marking technique has not facilitated marking on a larger scale, as the stocking of the two peri-alpine lakes requires the release of millions of fish annually.

Therefore, research has focused on mass techniques for internal marking using fluoro-marking which binds to calcified structures, such as bones and otoliths. The first marking technique on the otolith involved the rapid bathing of individuals at the egg or larval stage in a hyperosmotic solution of sodium chloride with tetracycline (Rojas-Beltran *et al.*, 1995a, 1995b). These methods facilitated the identification and quantification of fingerlings released during fishery rehabilitation. Since the late 1990s, the use of tetracycline hydrochloride as a marker has been regulated in many countries due to its antibiotic potency (Wright *et al.*, 2002). Therefore, alternatives are required. Alizarin Red S (ARS) was tested as a new marker and then selected (Cachera, 1997; Caudron and Champigneulle, 2006, 2009). The adaptation of mark, release, and recapture techniques allowed for accurate quantification of the effects of releases on the scale of lakes Geneva and Bourget (Tab. S2).

3.4 Efficacy of rearing and quantification of catches

To recapture whitefish, compulsory fishing logbooks were set up for recreational anglers and professional fishers targeting whitefish in Lake Geneva in 1986 and Lake Bourget in 1988. This data collection included recording details of the fishing techniques employed, duration of the fishing trip, fish size, and the number of fish with external marks. The efficacy of stocking was evaluated based on the total catch and results from the recapture logbooks. Catch data over the periods of potentially marked cohorts helped assess the performance of mark, release, and recapture by extrapolation (the weight of the catches of marked fish in catch samples representative of the main fishing periods). Marking experiments demonstrated that the 'Pacage Lacustre' Project played a major role in the rehabilitation and maintenance of whitefish populations in lakes Geneva (Champigneulle and Gerdeaux, 1992) and Bourget (Champigneulle and Cachera, 2003). Indeed, at the end of the 1980s, recaptured fish were estimated to weigh 20–27 kg per 1,000 fingerlings in Lake Geneva (3–4.5 cm; Champigneulle and Gerdeaux, 1992). In the early 2010s, total phosphorus dropped below 20 µg/L in Lake Geneva and 15 µg/L in Lake Bourget, thereby improving the ecological

quality of the water (Jacquet *et al.*, 2014) via a reduction in nutrient inputs; whitefish catches were primarily from natural fish recruitment (Gerdeaux, 2004; Champigneulle and Caudron, 2013). In Lake Bourget, the efficacy of stocking was 10.8%, 9.1%, and 7.1% for the 2004, 2005, and 2006 cohorts, respectively (Champigneulle and Cachera, 2008). The stocking yield was evaluated at 2.3 and 7.8 kg/1000 fingerlings, for the 2004 and 2003 cohorts respectively (Tab. S2). Based on the literature and data from other lakes, the fishing tonnage from stocking in 2010 was estimated to be between 1% and 4% of whitefish catches, with the remainder originating from natural reproduction (Champigneulle and Caudron, 2013).

4 Global impacts on society

These management practices had major impacts at different scales and on different targets. They influenced not only the local and regional economy, but also the environment, regulation laws, lake management, human health, and local political actions with social and territorial consequences, as defined in the ASIRPA method (see supplementary; Joly *et al.*, 2015; Smit and Hessels, 2021).

Supportive breeding enabled the rehabilitation and maintenance of the whitefish populations in lakes Geneva and Bourget (Gerdeaux, 2004; Fig. 3). In supportive breeding, eggs from spawners in the same lakes should be preserved, at least in part, by the genetic heritage of the populations. This approach was based on significant differentiation in the enzyme genes of whitefish in Lake Bourget (Vuorinen *et al.*, 1986). The use of eggs from Bourget spawners could potentially improve the conservation of this population, which is probably better adapted to the environmental conditions of Lake Bourget, especially given its location at the southern limit of its original range in Europe. The rehabilitation of whitefish was the combined effect of reoligotrophication, reinforced by supportive breeding and appropriate environmental conditions (Anneville *et al.*, 2009). Increased temperatures had a positive effect as higher water temperatures in spring improved larval survival by better matching the hatching date of the larvae with the appearance of prey resulting in favorable larval growth. Consequently, whitefish catches rapidly increased for both professional fishers and recreational anglers (Fig. 3). Improvements in water quality have led to drinking water at a lower cost, and the absence of olfactory disturbances and better lake transparency have improved the living environment, reduced stress, and boosted human well-being (Baulaz *et al.*, 2021).

4.1 Socio-economic impact

Since the 1990s, the success of supportive breeding programs in the two peri-alpine lakes, in parallel with the restoration of the aquatic environment, has stabilised the incomes of professional fishers and maintained their livelihood. During the eutrophication period, concerns were prevalent over the potential disappearance of the fishing profession, which could have direct repercussions on catering, tourism, and the overall quality of the area (Gagnaire, 1995). Developing and optimising large-scale production techniques and reducing costs have lowered the total cost of fish stocking.

An economic assessment of the program estimated that in 1993, due to dry feed production techniques, pre-summer whitefish production in a tank cost of 10 francs (around current 2.53 €) could generate 70–75 francs in predictable recapture, as opposed to 29–36 francs in a lighted cage in 1990 (based on the purchase price from the fishers, *i.e.*, 30 francs per kg in 1989; Gagnaire, 1995). For anglers, the number of licences has sharply increased over the years and spending is higher on supplies and services (boat rental, purchase of fishing equipment, boat maintenance, hotels, and catering). The economic benefits linked to recreational angling in France's Lake Geneva were estimated around 12 M€ annually (Mauger, 2016). The benefits for Lake Bourget were estimated around 2 M€ annually, excluding boats, purchases, maintenance, mooring, and launching (Versant Sud Développement, 2014). In peri-alpine lakes, salmonid fishing represents an important interest and attracts a large number of anglers compared to other fish families (Cachera and Hofmann, 2015).

4.2 Political impacts

The management of these two peri-alpine lakes involves two major institutions that played key roles in coordinating policies, communicating results to the public, and addressing key political implications. These management institutions had direct political impacts, particularly through cross-border agreements, fishing commissions, and regulatory adjustments, which affected various stakeholders, including fishers.

For Lake Geneva, a Franco-Swiss cross-border commission, the Commission Internationale pour la Protection des Eaux du Léman (CIPEL), has coordinated the water policy between the two countries since 1962. Furthermore, an international agreement between the Swiss Federal Council and the Government of the French Republic created a Fishery Commission to regulate fishing in Lake Geneva, which came into force in 1982 to harmonise fishing regulations and ensure the protection of fish resources and their environments. The key aspects of this agreement focused on stocking measures including the operation of incubation and breeding establishments in both countries. For Lake Bourget, since 1974, the management is carried out by Comité Intercommunautaire pour l'Assainissement du Lac du Bourget (CISALB), an intercommunity committee. The results of studies on the quality of aquatic environments and biological resources were presented to the working group of the advisory commission, and the synthesised findings were disseminated to the public. For both lakes, the scientific committee provided advice on water quality management, and scientists from the same research group are still part of these commissions. Moreover, scientific studies related to fish ecology, physiology of reproduction, and population dynamics have been crucial for drawing up fishing regulations.

For Lake Geneva, the Fishery Commission still exists today and serves the dual purpose of ensuring the exchange of knowledge between the two countries, addressing challenges and regulatory amendments to protect fish resources and their habitats, and harmonising fishing regulations. Members of the fishing services of Swiss cantons, professional and recreational fishers from both countries, and scientists, including those from INRAE, engaged in discussions on fishery regulations,

which are then proposed to the Fishery Commission. A scientific research group was established to advise the working group based on scientific findings. The 1982 Lake Geneva Agreement specifies the number of fish to be released for the stocking program and maintains whitefish fry production knowledge mainly at the Rives Fish Farm. This development has triggered a series of substantial implications, particularly regarding the organisation of fishing for harvesting whitefish broodstock eggs. On 29 March 1990 a senator from Haute-Savoie drew the attention of the French government, proposing a change in regulations to authorise the sale of spawners caught during egg harvesting fisheries. After several attempts to call this into question, in 2002, the government modified the environmental code and authorised the sale of spawners by professional fishers, ensuring a source of income for fishers during the closure period and their involvement.

4.3 Social and territorial outcomes

The ‘Pacage lacustre’ project led to the creation of the ‘Association pour la mise en valeur Piscicole des Plans d’Eau en Rhône-Alpes’ (APERAs), which structures and strengthens the collaboration between professional fisher and angler associations. The creation of this association resulted from a partnership among all local stakeholders and was made possible only through the strong involvement of INRA scientists (Champigneulle *et al.*, 1991). Today, APERA continues to spearhead stocking operations under the ‘Pacage lacustre’ program, producing several million of whitefish larvae (Richard *et al.*, 2023).

Support for fish populations has facilitated the preservation of fishing heritage activities in lakes Geneva and Bourget, especially for professional fishers.

An increase in salmonid catches has boosted local economies. Owing to the quality of fishing, recreational fishing has become an important tourist activity, with 5,000 anglers from France and abroad visiting lake Bourget every year for fishing or holidays. The direct economic spin-off for the region was estimated to be more than €1.56 million in 2012. In 2010, nine local jobs depended on recreational fishing (Versant Sud Développement, 2014). Thonon’s Fishing and Lake Ecomuseum (Eco-musée de la pêche et du lac at Thonon-les-Bains, France) was built in 1987 and hosts > 5,000 visitors on average each year (Fig. S4, data from 1997 to 2023 from the Thonon-les-Bains town hall), helping preserve the memory and historical heritage of fishing.

The promotion of locally produced fish has given an additional advantage to regional gastronomy, with the development of different preparations that have established themselves on restaurant menus for more than 20 yr (Montuelle and Clemens, 2015), including raw or smoked fish. This last preparation enables fishers to sell their produce over longer periods with a high labour cost to resale the price ratio.

4.4 Scientific and management impacts

4.4.1 Collaboration of scientists, managers, and fishers

Significant scientific and management progress resulted from the ‘Pacage lacustre’ project, thanks to a collaborative and multidisciplinary approach. This endeavour, initiated in

the early 1980s, marked a pivotal moment with the increased involvement of ichthyologists, fostering partnerships with administrations and fishers, both professional and recreational, and the formation of APERA. Sustained exchanges between scientists and managers on experimental techniques and protocols have enabled the implementation of optimised stocking, moving from laboratory experimentation to large-scale production for peri-alpine lakes. One main impact was the renovation of the state-owned fish farm at Rives in Thonon-les-Bains, due to the France’s Ministry of Agriculture and the Rhône-Alpes regional council. This facility is one of the most prominent European fish farms for producing juvenile lake salmonids for stocking (Guillard, 1988; Champigneulle *et al.*, 1991), today managed by APERA. The Institute’s scientific expertise in fishing commissions and its participation in formulating fishery management plans for lakes Geneva and Bourget exemplify the integration of research into fishery regulations. Scientific engagement extends beyond traditional actions, with INRA scientists actively participating in symposiums, national meetings with professional fishers, and international conferences. This collaborative exchange facilitated discussions about the management and development of fish resources, thereby reinforcing the broader impact of the project. This knowledge has been disseminated through various channels, including press releases, weekly reviews, books, and scientific articles; over 72 articles in the general press, specialised journals, and books attest to the widespread awareness generated by the project (Rogissart *et al.*, 2023). Furthermore, fishery data have been used in schoolbooks to explain the link between biodiversity and human activities (Bordi *et al.*, 2019; Boucher *et al.*, 2021). The first European Congress on whitefish management was organized in Thonon in 1984 by A. Champigneulle (Dabrowski and Champigneulle, 1986). In 2023, INRAE scientists organised the 15th congress (<https://coregonid2023.symposium.inrae.fr/>).

4.4.2 Successes of cooperation between scientists, managers, and fishers

Collaboration between scientists, managers, and fishers in the whitefish rehabilitation project demonstrated the power of participatory research. The exchange of traditional knowledge and scientific expertise created a synergy in which the real-life experiences of managers and fishers complement the rigorous data-driven approaches of scientists. Environmental restoration was prioritised, which is essential for conserving natural fishery resources. Extensive research was conducted to optimise breeding and develop marking techniques. Managers implemented restocking measures, fishing regulations, and water quality improvements. Fishers actively contributed to the data collection and monitoring of fish populations while supporting the project. Collaboration has been a great success, directly benefiting fishers through significant increases in catch (Fig. 3; Gerdeaux, 2004), preservation of traditional fishing activities, and provision of ecosystem services to local communities (Baulaz *et al.*, 2021).

Learning from this experience, other fishery management initiatives can benefit from community involvement, stakeholder participation, and the application of appropriate regulations to ensure the sustainability of fishery resources and protection of the ecosystem. To make a rehabilitation

program more effective, the dialogue among stakeholders must be strengthened. Managers must be informed about what science can and cannot offer to address the problems they face, whereas scientists must work together to provide the necessary information and tools.

5 Limitations and threats

Supportive breeding helped support whitefish populations when their abundances were at their lowest and in parallel with the reoligotrophication of the lakes, facilitating their rehabilitation (Gerdeaux, 2004; Anneville *et al.*, 2009). Restoration of water quality has significantly reduced sedimentation on spawning grounds, improving oxygenation and promoting natural reproductive success (Gerdeaux, 2004). However, many questions remain regarding intra- and inter-specific relationships (*e.g.*, competition, predation, habitat, and genetics), carrying capacity, spawning habitat quality and long-term management methods.

5.1 Potential negative impacts of stocking

5.1.1 Inter-specific relationships

Whitefish population dynamic and the reoligotrophication of the environment have led to changes in interspecific fish relationships and the entire food web. The increase in whitefish population have led to stronger trophic competition for zooplankton with species such as roach (*Rutilus rutilus*, Anneville *et al.*, 2017). It could have also amplified their competition with larval and young-of-the-year perch in the pelagic zone (Gerdeaux *et al.*, 2006; Anneville *et al.*, 2017). In addition, reoligotrophication has benefitted macrophyte areas favourable for the natural spawning of pike (*Esox lucius*; Gillet, 1989; Lods-Crozet *et al.*, 2013), allowing for the development of their populations and, ultimately, increasing predation on salmonids.

5.1.2 Selectivity from fish sampling

Stocking methods, even those using native broodstock, could potentially induce artificial selection: indeed, the methodology for harvesting whitefish eggs increases this risk by using nets with a specific mesh size, which influences the selection of spawner size and therefore, selects neither the largest nor the smallest individuals. Fishing was conducted over short periods, and thus selected only a small part of the broodstock. Early (mid-November) or late (mid-January) spawners were under-selected. Late spawners are potentially more important for adaptation to changing climatic conditions and, ultimately, for the survival of populations (Stewart *et al.*, 2021).

5.1.3 Fish farm domestication

The effects of domesticated whitefish, particularly when fish are kept for long periods on fish farms, could lead to the selection of individuals which are not necessarily those best able to survive in the natural environment (Eckmann, 2012). In addition, the mixing of gametes during artificial fertilisation, with competition between spermatozoa from different genitors (Wedekind *et al.*, 2007; Perroud *et al.*, 2021), and the absence of choice of partner (Auld *et al.*, 2019), can lead to artificial

selection which is not necessarily in favour of the individuals most suitable for survival in the natural environment. This could result in a significant decrease in genetic variability, compromising the adaptive capacity of populations in response to environmental changes. Furthermore, the early life stages of fish farms (incubation, resorption, and first feeding) are not subject to the natural selection that occurs in the lake environment (temperature, pressure, light, feeding, olfactory memorisation, *etc.*).

5.1.4 Genetic diversity

Management practices and fishing contribute to the decline in the genetic diversity of salmonids (McMillan *et al.*, 2023), including whitefish (Anneville *et al.*, 2015) and genetic diversity remains an important driver for ensuring evolutionary changes and the adaptation of species to environmental changes, such as global warming (Meffe, 1995). Therefore, scientific studies on stocking methods and species ecology must continue to ensure the conservation of heritage fish populations.

5.1.5 Habitat and carrying capacity

Stocking can alter habitat by influencing the use of lacustrine zones and modifying ecological interactions among sympatric forms of whitefish (Heikineheimo *et al.*, 2000). In addition, stocking can affect carrying capacity and, therefore, have negative impacts on wild populations and stocked individuals, including increased dispersal, predation and reduced growth and survival rates (Cox, 1994). Assessing the effects of stocking on habitat and carrying capacity is essential for mitigating ecosystem disturbance and effectively improving stocking practices (Taylor *et al.*, 2013; Wang *et al.*, 2022).

5.2 Spawning habitat and natural recruitment

Spawning habitats, crucial to natural recruitment, can be affected by several anthropogenic stressors, which could compromise rehabilitation efforts. For example, shoreline development can lead to hydrological changes and increased sedimentation, causing the degradation of spawning habitats (Meadows *et al.*, 2005; Sundblad and Bergström, 2014). In addition, pollutants and contaminants can negatively affect phenotype, metabolism, and embryonic and larval development (Wedekind *et al.*, 2010; Yaripour *et al.*, 2021, 2022). Elevated water temperatures can disrupt embryo development and survival (Eckmann, 2013; Stewart *et al.*, 2021), which poses an increasing threat, especially in the context of climate change (Desgué-Itier *et al.*, 2023). The restoration, protection and monitoring of these spawning habitats are essential to ensure long-term rehabilitation success and hence, the resilience and sustainability of whitefish populations.

5.3 Long-term horizon for stocking as a management method

Whitefish populations in lakes Geneva and Bourget are at the southern limit of their range, and in the context of climate change, these populations are threatened (Stewart *et al.*, 2021; Eckmann, 2013). Notably, the contribution of supportive whitefish breeding represented a limited fraction of catches

over the 2003-2013 decade (Champigneulle and Caudron, 2013), during lake reoligotrophication. Stocking success depends on environmental conditions and lake status (Baer *et al.*, 2023). New marking surveys in lakes Bourget (2018-2020) and Geneva (2023) will update the estimates of the current contribution of stocking to whitefish populations, especially in the context of climate change. Supportive breeding can be an option to support future whitefish populations if natural recruitment returns close to zero, which is linked to reproductive issues. This remains an open question, requiring a better understanding of the impacts on the diversity of stocking and the way in which the exploitation of this species should be approached, going beyond simple scientific work but becoming a societal question of lake use.

6 Conclusion and future challenges

Collaboration among scientists, managers, and fishers led to whitefish population rehabilitation in lakes Geneva and Bourget, safeguarding professional fishing companies and their sectors, and also created a model for inclusive, participatory research. The project achieved its primary objective and also generated substantial scientific, economic, and managerial impacts. The circulation of knowledge, facilitated by collaborative efforts and multidisciplinary approaches, has become integral to the sustained success of the project in parallel with similar approaches in other peri-alpine lakes. The lessons learned and established practices serve as a model for future endeavours in the ecological restoration and sustainable management of fish resources. However, project limitations highlight the need for ongoing scientific enquiry, adaptive management, and a holistic approach to preserve the delicate balance of peri-alpine lake ecosystems. Threats and limitations (especially harm to intraspecific diversity) are not fully absent from this project, and as these lakes face potential new threats from global change. Further research is required on the adaptive potential of whitefish and the ecophysiology of their reproduction.

Acknowledgements

This project was a part of the ASIRPA INRAE research program, and received funding from INRAE. The authors thank DipSo (Direction pour la Science Ouverte) and AQUA department (INRAE) for their support. We thank the ASIRPA team: Sylvie Colleu, Sami Bouarfa, and Delphine Mézière for their valuable contributions and discussions during the project. Many thanks to Christian Gillet, a contributor to the ‘Pacage Lacustre’ project, for sharing valuable information with us. The authors are grateful to APERA organisation, Luce Arnold-Gagnaire, Sébastien Cachera, Michaël Dumaz, Alain Gagnaire, Roger Plassat, and Alexis Tite for generously sharing a wealth of information on the historical aspects of environmental restoration and salmonid rehabilitation. We extend our gratitude to the late Max Michoud for his generous contributions to this project, particularly for sharing historical insights and expertise related to the work at Rives Fish Farm. We are also grateful to Jason D. Stockwell, Ellen George Karboski and an anonymous reviewer for their valuable comments and suggestions, which improved the manuscript. Finally, we express our appreciation to Alexis Champigneulle for his

extensive research contributions to the ecology and biology of coregonids, as well as his dedicated efforts in fishery management in lakes Geneva and Bourget.

Conflicts of interest

The authors have not disclosed any competing interests.

Supplementary material

Figure S1. Impact pathway adapted from Rogissart *et al.* (2023).

Figure S2. Radar of impacts adapted from Rogissart *et al.* (2023).

Figure S3. A) Total size-at-age (cm; year) of whitefish from Lake Geneva in 1950 and 1982 (Dottrens, 1950; Champigneulle *et al.*, 1983). B) Evolution of zooplankton biovolume (ml/m²) in Lake Geneva (adapted from Champigneulle and Caudron, 2013; data from SOERE SI-OLA; Rimet *et al.*, 2020).

Figure S4. A) Number of annual and monthly visitors to Thonon’s Fishing and Lake Ecomuseum (Eco-musée de la pêche et du lac) in Thonon-les-Bains, France, dedicated to preserving the memory and historical heritage of fishing. The dashed line represents the annual average from 1997 to 2023. B) Boxplot shows the number of visitors from 1997 to 2023 (data from Thonon-les-Bains, France, town hall). The museum welcomes both individual visitors and groups with limited individual access during the summer season, from June to the end of September.

Table S1. Vector of impacts adapted from Rogissart *et al.* (2023).

Table S2. Whitefish stocking and assessment of ‘Pacage lacustre’ contributions in Lake Geneva and Lake Bourget using marking methods by cauterising the adipose fin (ad. fin.) and fluoromarking with Alizarin Red S (ARS) (Champigneulle and Gerdeaux, 1992; Champigneulle and Cachera, 2003, 2008).

The Supplementary Material is available at <https://www.limnology-journal.org/10.1051/limn/2024012/olm>.

References

- Alexander TJ, Vonlanthen P, Seehausen O. 2017. Does eutrophication-driven evolution change aquatic ecosystems? *Phil Trans R Soc B: Biol Sci* 372: 20160041.
- Anneville O, Lasne E, Guillard J, Eckmann R, Stockwell JD, Gillet C, Yule DL. 2015. Impact of fishing and stocking practices on coregonid diversity. *Food Sci Nutr* 6: 1045–1055.
- Anneville O, Hamelet V. 2018. Whitefish diet in the pelagic zone of Lake Geneva, Campagne 2017. Commission Internationale pour la Protection des Eaux du Léman (CIPEL), *Thonon-les-bains, France*.
- Anneville O, Vogel C, Lobry J, Guillard J. 2017. Fish communities in the Anthropocene: detecting drivers of changes in the deep peri-alpine Lake Geneva. *Inland Waters* 7: 65–76.
- Anneville O, Souissi S, Molinero JC, Gerdeaux D. 2009. Influences of human activity and climate on the stock-recruitment dynamics of whitefish, *Coregonus lavaretus*, in Lake Geneva. *Fish Manag Ecol* 16: 492–500.
- Aronson J, Floret C, Le Floc’h E, Ovalle C, Pontanier R. 1993. Restoration and rehabilitation of degraded ecosystems in arid and semi-arid lands. I. A view from the south. *Restor Ecol* 1: 8–17.

- Auld HL, Noakes DL, Banks MA. 2019. Advancing mate choice studies in salmonids. *Rev Fish Biol Fish* 29: 249–276.
- Baer J, Kugler M, Schubert M, Schotzko N, Rösch R, Vonlanthen P, DeWeber JT. 2023. A matter of time—Efficacy of whitefish stocking in a large pre-alpine lake. *Fish Manag Ecol* 30: 615–626.
- Balland P, Dutruy S, Jost J. 1977. Rapport III-12. Assainissement du bassin versant du lac du Bourget : mesure et élimination des apports. *Journées de l'hydraulique* 14: 1–13.
- Bardel M, 1956. La pêche professionnelle des corégones dans les eaux françaises du lac Léman. *Bull Fr Piscic* 182: 26–36.
- Baulaz Y, Dorioz JM, Peyrache-Gadeau V. 2021. Exploration fonctionnelle du territoire des grands lacs alpins par le prisme des services écosystémiques, in: Université de Savoie (Ed.), *Lacs et sociétés : éclairages alpins, pyrénéens et andins. Collection EDYTEM n° 21, France*, pp. 103–126.
- Bergot P, Charlon N, Alami-Durante H. 1986. The effects of compound diets feeding on growth and survival of coregonid larvae. *Arch Hydrobiol Beih Ergeb Limnol* 22: 265–272.
- Bernatchez L, Dodson JJ. 1994. Phylogenetic relationships among Palearctic and Nearctic whitefish (*Coregonus sp.*) populations as revealed by mitochondrial DNA variation. *Can J Fish Aquat Sci* 51: 240–251.
- Bordi C, Capelli B, Lapaquette P, Pellenard P, Venner M-C., Wojcik M. 2019. Des intrants parfois problématiques. In: *SVT Sciences de la Vie et de la Terre 2de*. France: Lelivrescolaire.fr Éditions, pp. 125
- Boucher B, Boudjemai R, Châtelain A, Fouquet C, Laborie A-L., Lafond L, Le Goff R, Michel-Lauret N. 2021. Des actions humaines qui modifient la biodiversité. In: *Cahier de SVT 5e, France, Nathan*, pp. 66.
- Boutry E. 1983. Les corégones du Léman: pêche, repeuplement et essais d'élevage de juvéniles en cages immergées. *Rapp Inst Limnol Thonon* 10: 32.
- Bravard JP, Clémens A. 2008. Le Rhône en 100 Questions. Villeurbanne: ZABR, GRAIE, 295 p.
- Büttiker B. 2005. Evolution de la faune piscicole et astacicole, ainsi que de la pêche dans le lac Léman. *Arch des Sci* 58: 183–191.
- Cachera S. 1997. Contribution à la mise au point et l'utilisation du fluoromarquage des otolithes de Salmonidés (*Coregonus lavaretus* et *Salmo trutta*). Rapport de Maitrise de Biologie des Populations et des Ecosystèmes, Université des Sciences et Technologies, Lille, France, 28 p.
- Cachera S, Hofmann F. 2015. Comment est organisée la pêche sur les lacs ? Comment est-elle réglementée ? In: Montuelle, B., Clémens, A. (dir.), *Le tour des grands lacs alpins naturels en 80 questions*, GRAIE, Villeurbanne, France, pp. 80–81.
- Carpenter SR. 2005. Eutrophication of aquatic ecosystems: Bistability and soil phosphorus. *Proc Natl Acad Sci USA* 102: 10002–10005.
- Caudron A, Champigneulle A. 2006. Technique de fluoromarquage en masse à grande échelle des otolithes d'alevins vésiculés de truite commune (*Salmo trutta*) à l'aide de l'alizarine red S. *Cybiuim* 30: 65–72.
- Caudron A, Champigneulle A. 2009. Multiple marking of otoliths of brown trout, *Salmo trutta* L., with alizarin redS to compare efficiency of stocking of three early life stages. *Fish Manag Ecol* 16: 219–224.
- Champigneulle A. 1985. Analyse bibliographique des problèmes de repeuplement en omble chevalier (*Salvelinus alpinus*), truite fario (*Salmo trutta*) et coregones (*Coregonus sp.*) dans les grands plans d'eau. In: Gerdeaux D, Billard R. (eds.), *Gestion Piscicole des Lacs et Retenues Artificielles*, INRA Editions Paris, France, pp. 187–217.
- Champigneulle A. 1988. A first experiment in mass-rearing of coregonid larvae in tanks with a dry food. *Aquaculture* 74: 249–261.
- Champigneulle A. 1996. Lake ranching of salmonids in french pre-alps: scientific, technic and socioeconomic aspects, perspectives of expansion. *CR Acad Agric France* 82: 101–112.
- Champigneulle A, Boutry E, Dewaele P, Maufof C. 1986. Rearing of larvae of Lake Lemman coregonids in France. Preliminary data on the production in small ponds, illuminated cages and tanks. *Arch Hydrobiol Beih Ergebn Limnol* 22: 241–264.
- Champigneulle A, Cachera S. 2003. Suivi des populations de salmonidés soumises à pacage lacustre. A. Lac du Bourget: Omble et corégone et relai avec le Contrat Lac. B. Nouvelles recherches sur la truite en système lac-affluents. *Rapp. S.H.L. INRA, Thonon* 75 p.
- Champigneulle A, Cachera S. 2008. Evaluation de la stratégie de pacage lacustre (repeuplement en lac) pour le corégone (*Coregonus lavaretus*) au lac du Bourget. *Rapp. S. H. L. INRA, Thonon*, 284-2008, 45 p
- Champigneulle A, Caudron A. 2013. Projet franco-suisse “Truite-Omble-Corégone” au Léman. *Rapport final. [Franco-Swiss project “Trout-Omble-Whitefish” in Lake Geneva. Final Report.]*. Available: https://www.pechehautesavoie.com/wp-content/uploads/2016/04/Rapport_Final_Salmonides_Leman.pdf (march 2024).
- Champigneulle A, Escomel J. 1984. Technical note: marking small salmonids by removal of the adipose or the tow pelvic fins. *Bull Fr Pêche Piscic* 293-294: 52–58.
- Champigneulle A, Escomel J, Laurent P. 1987. Marking small arctic chars (*Salvelinus alpinus*) by injection of magnetized microtags. *Bull Fr Pêche Piscic* 304: 22–31.
- Champigneulle A, Gerdeaux D. 1992. Survey of experimental stockings (1983-85) of Lake Geneva with spring-prefed *Coregonus lavaretus* Fry (3-4,5 cm). *Pol Arch Hydrobiol* 39: 721–729.
- Champigneulle A, Gerdeaux D, Gillet C. 1983. Les pêches de géniteurs de corégone dans le Léman français en 1982. *Bull Fr Pêche Piscic* 290: 149–157.
- Champigneulle A, Guillard J, Rojas-Beltran R. 1991. Programme pilote et recherches appliquées au pacage lacustre de salmonidés (octobre 1991). *Rapp Inst Limnol Thonon* 61-91: 78.
- Champigneulle A, Michoud M, Brun JC. 1989. Projet pacage lacustre ou optimisation des repeuplements de salmonidés lacustres en région Rhône-Alpes. Avant-projet technique et premier chiffrage d'une opération pilote. *Rapp Inst Limnol Thonon* 89: 45.
- Champigneulle A, Rojas-Beltran R. 2001. Le marquage des poissons. In: Gerdeaux (ed.), *Gestion piscicole des grands plans d'eau*, INRA Editions, Paris, France pp. 349–421.
- Champigneulle A, Michoud M, Brun JC. 2001. Pacage lacustre de salmonidés (omble chevalier, corégone et truite) dans le lac Léman et le lac du Bourget. In: Gerdeaux (ed.), *Gestion piscicole des grands plans d'eau INRA Editions Paris, France* pp. 349–421.
- Champigneulle A, Rojas-Beltran R, Gillet C, Michoud M. 1994. Maîtrise de l'élevage en bassins avec un aliment sec des corégones (*Coregonus lavaretus*) pour le repeuplement. *Piscic Fr Eau Vive Etang Saumatre Mar* 116: 4–26.
- Champigneulle A, Rojas-Beltran R. 1996. Elevage des larves et juvéniles de corégone (*Coregonus lavaretus* sp.) en cages lacustres éclairées pour l'attraction du zooplankton. *Hydro Appl* 8: 155–172.
- Cowx IG. 1994. Stocking strategies. *Fish Manag Ecol* 1: 15–30.
- Dabrowski K, Champigneulle A. 1986. Advances in fishery biology: biology, exploitation, rearing and propagation of coregonid fishes.

- Proceedings of the symposium on coregonid fishes, held 2nd to 4th Oct. 1984 at Thonon (France). *Adv Limnol* 22: 386.
- Dabrowski K, Charlon N, Bergot P, Sadasivam K. 1984. Rearing of coregonid (*Coregonus schinzi palea*, Cuv. et Val.) larvae using dry and live food I. Preliminary data. *Aquaculture* 41: 11–20.
- Desgué-Itier O, Melo Vieira S Soares L, Anneville O, Bouffard D, Chanudet V, Danis PA, Domaizon I, Guillard J, Mazure T, Sharaf N, Soullignac F, Tran-Khac V, Vinçon-Leite B, Jenny JP. 2023. Past and future climate change effects on the thermal regime and oxygen solubility of four peri-alpine lakes. *Hydrol Earth Sci Syst* 27: 837–859.
- Dewaele P. 1983. Progressissement en bassin des alevins de corégones. *Rapp Inst Limnol Thonon* 11: 29.
- Dubois JP, Gillet C, Hilgert N, Balvay G. 2008. The impact of trophic changes over 45 years on the Eurasian perch, *Perca fluviatilis*, population of Lake Geneva. *Aquat Living Resour* 21: 401–410.
- Eckmann R. 2012. Massive stocking with hatchery larvae may constrain natural recruitment of whitefish stocks and induce unwanted evolutionary changes. *Adv Limnol* 63: 325–336.
- Eckmann R. 2013. A review of the population dynamics of coregonids in European alpine lakes. *Adv Limnol* 64: 3–24.
- Gagnaire L. 1988. Rôle de la pêche française au Léman dans l'économie locale du Chablais. *Rapp Inst Limnol Thonon* 88: 93.
- Gagnaire L. 1995. Bilan du programme de pacage lacustre (1989–1993). L'agriculture en agriculture. *Journées d'information, Lyon, 5-6/10/94. DERF-ADA*, 47: 43–49.
- Gerdeaux D. 2004. The recent restoration of the whitefish fisheries in Lake Geneva: the roles of stocking, reoligotrophication, and climate change. *Ann Zool Fenn* 41: 181–189.
- Gerdeaux D, Anneville O, Hefti D. 2006. Fishery changes during reoligotrophication in 11 peri-alpine Swiss and French lakes over the past 30 years. *Acta Oecol* 30: 161–167.
- Gillet C. 1989. Le déroulement de la fraie des principaux poissons lacustres. *Hydroecologie Appl* 1: 117–143.
- Guillard J. 1988. Aménagement des pêcheries lacustres en Rhône-Alpes. Développement du pacage lacustre de salmonidés. Problématique de l'étude. *Rapp Inst Limnol Thonon* 39-88: 10.
- Heikineheimo O, Miinalainen M, Peltonen H., 2000. Diet, growth and competitive abilities of sympatric whitefish forms in a dense introduced population: results of a stocking experiment. *J Fish Biol* 57: 808–827.
- Inácio M, Barceló D, Zhao W, Pereira P. 2022. Mapping lake ecosystem services: A systematic review. *Sci Total Environ* 847: 157561.
- Jacquet S, Domaizon I, Anneville O. 2014. The need for ecological monitoring of freshwaters in a changing world: a case study of Lakes Annecy, Bourget, and Geneva. *Environ Monit Assess* 186: 3455–3476.
- Jacquet S, Avrillier J-N., Cachera S, Costel C, Crépin L, Frossard V, Goulon C, Guillard J, Hamelet V, Hustache JC, Laine L, Perney P, Quéting P, Raphy J, Rimet F, Rasconi S, Tran-Khac V. 2023. Suivi environnemental des eaux du lac du Bourget pour l'année 2022. *Rapport INRAE-CISALB*, pp. 29.
- Jenny JP, Anneville O, Arnaud F, Baulaz Y, Bouffard D!!, !! Domaizon I!, !Bocaniov SA!, !Chèvre N, Dittrich M, Dorioz JM, Dunlop ES, Dur G, Guillard J, Guinaldo T, Jacquet S, Jamoneau A, Jawed Z, Jeppesen E, Krantzberg G, Lenters J, Leoni B, Meybeck M, Nava V, Nöges T, Nöges P, Patelli M, Pebbles V, Perga ME, Rasconi S, Ruetz CR., III., Rudstam L, Salmaso N, Sapna S, Straile D, Tammeorg O, Twiss MR, Uzarski DG, Ventelä AM, Vincent WF, Wilhelm SW, Wängberg SA, Weyhenmeyer GA . 2020. Scientists' warning to humanity: rapid degradation of the world's large lakes. *J Great Lakes Res* 46: 686–702.
- Joly PB, Gaunand A, Colinet L, Larédo P, Lemarié S, Matt M. 2015. ASIRPA: A comprehensive theory-based approach to assessing the societal impacts of a research organization. *Res Eval* 24: 440–453.
- Lods-Crozet B, Gerdeaux D, Perfetta J. 2013. Changements des communautés biologiques littorales et piscicoles dans le Léman. *Arch Sci* 66: 137–156.
- Loizeau JL, Dominik J. 2005. The history of eutrophication and restoration of Lake Geneva. *Terre Env* 50: 43–56.
- Loup J. 1950. La pêche dans le lac du Bourget. *Rev Geogr Alp* 38: 157–175.
- Mauger JP. 2016. Impact économique, pêcheurs amateurs, lac Léman français. In: APALLF (ed.), *Les voix du Léman*, pp. 32–37.
- McMillan JR, Morrison B, Chambers N, Ruggerone G, Bernatchez L, Stanford J, Neville H. 2023. A global synthesis of peer-reviewed research on the effects of hatchery salmonids on wild salmonids. *Fish Manag Ecol* 30: 446–463.
- Meadows GA, Mackey SD, Goforth RR, Mickelson DM, Edil TB, Fuller J, Guy DE, Jr., Meadows LA, Brown E, Carman SM, Liebenthal DL. 2005. Cumulative habitat impacts of nearshore engineering. *J Great Lakes Res* 31: 90–112.
- Meffe GK. 1995. Genetic and ecological guidelines for species reintroduction programs: application to Great Lakes fishes. *J Great Lakes Res* 21: 3–9.
- Meng HJ, Muller R, Geiger W. 1986. Growth, mortality and yield of stocked coregonid fingerlings identified by microtags. *Arch Hydrobiol Beih Ergebn Limnol* 22: 319–325.
- Montuelle B, Clémens A. 2015. Le tour des grands lacs alpins naturels en 80 questions. *Zone Atelier Bassin du Rhône et Observatoire des Lacs Alpains, GRAIE, Villeurbanne, France*, 205 p.
- Müller R, Stadelmann P. 2004. Fish habitat requirements as the basis for rehabilitation of eutrophic lakes by oxygenation. *Fish Manag Ecol* 11: 251–260.
- OCDE. 1982. Eutrophisation des eaux : Méthodes de surveillance, d'évaluation et de lutte. *Organisation de Coopération et de Développement Economiques, Paris, France*, 164 p.
- Olive P. 1986. Etudes conduites sur les poissons du Léman par les ichtyologues de l'Institut de limnologie de Thonon. In: Ménaché M. (ed.), *Léman : expressions sans rivages, La Manufacture, France* pp. 69–71.
- Østbye K, Bernatchez L, Næsje TF, Himberg KJ, Hindar K. 2005. Evolutionary history of the European whitefish *Coregonus lavaretus* (L.) species complex as inferred from mtDNA phylogeography and gill-raker numbers. *Mol Ecol* 14: 4371–4387.
- Perroud G, Nusbaumer D, de Guttry C, Wedekind C. 2021. Male sexual signaling and expected effects of hatchery-induced sperm competition vary with water depth at which whitefish are caught. *Curr Zool* 67: 337–340.
- Pflieger G, Brethaut C. 2012. GOUVRHONE : Gouvernance transfrontalière du Rhône, du Léman à Lyon. *Genève : OFEV, DREAL Rhône Alpes, Agence de l'eau RMC, SIG, Canton de Genève, Canton de Vaud, EDF*, 218 p.
- Pomeroy PP. 1991. A comparative assessment of temporal variation in diet of powan, *Coregonus lavaretus* (L.), from Loch Lomond and Loch Eck, Scotland, UK. *J Fish Biol* 38: 457–478.
- Rapin F, Gerdeaux D. 2013. La protection du Léman, priorité à la lutte contre l'eutrophisation. *Arch Sci* 60: 103–116.
- Reynaud A, Lanzanova D. 2017. A global meta-analysis of the value of ecosystem services provided by lakes. *Ecol Econ* 137: 184–194.

- Richard A, Lecointre T, Goulon C. 2023. Evaluation de l'efficacité du repeuplement en corégones dans le Léman. Rapport d'Etape: Marquages à l'alizarine. *France: Thonon-les-Bains*, 2023, 13 p.
- Rimet F, Anneville O, Barbet D, Chardon C, Crepin L, Domaizon I, Dorioz JM, Espinat L, Frossard V, Guillard J, Goulon C, Hamelet V, Hustache JC, Jacquet S, Lainé L, Montuelle B, Perney P, Quetin P, Schellenberger A, Tran-Khak V, Monet G. 2020. The Observatory on LAkes (OLA) database: Sixty years of environmental data accessible to the public. *J Limnol* 79: 164–178.
- Rogissart H, Goulon C, Guillard J. 2023. Réhabilitation des salmonidés des lacs péri-alpins : Pacage lacustre. Une recherche participative impliquant des scientifiques et des pêcheurs. *INRAE* 2023, pp. 35 (hal-03918344)
- Rojas-Beltran R, Champigneulle A. 1991. New hope of reducing the cost of mass rearing whitefish, *Coregonus lavaretus* L., larvae on dry diet? *Aquac Fish Manag* 22: 369–372.
- Rojas-Beltran R, Champigneulle A. 1992. Studies on the improvement of the first feeding on a dry diet for *Coregonus lavaretus* L. larvae. *Aquaculture* 102: 319–331.
- Rojas-Beltran R, Champigneulle A, Chapuis G. 1991. The mass-rearing of *Coregonus lavaretus* larvae at high densities and two rearing scales with two dry diets. *Spec Publ Eur Aquac Soc* 15: 145–147.
- Rojas-Beltran R, Champigneulle A, Gillet C, Le Rouilly N. 1992. Influence of egg source, initial characteristics, and rearing conditions on the growth, survival, and development of *Coregonus lavaretus* L. larvae initially fed on a dry diet. *Pol Arch Hydrobiol* 39: 683–691.
- Rojas-Beltran R, Champigneulle A, Vincent G. 1995a. Mass-marking of bone tissue of *Coregonus lavaretus* L. and its potential application to monitoring the spatio-temporal distribution of larvae, fry and juveniles of lacustrine fishes. *Hydrobiologia* 300: 399–407.
- Rojas-Beltran R, Gillet C, Champigneulle A. 1995b. Immersion mass-marking of otoliths and bone tissue of embryos, yolk-sac fry and fingerlings of Arctic charr *Salvelinus alpinus* (L.). *Nord J Freshw Res* 71: 411–418.
- Sandford M, Castillo G, Hung T. 2019. A review of fish identification methods applied on small fish. *Rev Aquac* 12: 542–554.
- Schindler DW, Carpenter SR, Chapra SC, Hecky RE, Orihel DM. 2016. Reducing phosphorus to curb lake eutrophication is a success. *Environ Sci Technol* 50: 8923–8929.
- Schindler DW. 2012. The dilemma of controlling cultural eutrophication of lakes. *Proc Biol Sci* 279: 4322–4333.
- Smit JP, Hessels LK. 2021. The production of scientific and societal value in research evaluation: a review of societal impact assessment methods. *Res Eval* 30: 323–335.
- Sterner RW, Keeler B, Polasky S, Poudel R, Rhude K, Rogers M. 2020. Ecosystem services of Earth's largest freshwater lakes. *Ecosyst Serv* 41: 101046.
- Stewart TR, Mäkinen M, Goulon C, Guillard J, Marjomäki TJ, Lasne E, Karjalainen J, Stockwell JD. 2021. Influence of warming temperatures on coregonine embryogenesis within and among species. *Hydrobiologia* 848: 4363–4385.
- Sundblad G, Bergström U. 2014. Shoreline development and degradation of coastal fish reproduction habitats. *Ambio* 43: 1020–1028.
- Taylor MD, Brennan NP, Lorenzen K, Leber KM. 2013. Generalized predatory impact model: a numerical approach for assessing trophic limits to hatchery releases and controlling related ecological risks. *Rev Fish Sci* 21: 341–353.
- Versant Sud Développement. 2014. Les retombées économiques directes de la pêche de loisirs dans le secteur du lac du Bourget. *Communication, 13 oct. 2014, Fédération de Savoie pour la Pêche et la Protection du Milieu Aquatique, France.*
- Viljanen M. 1988. Relations between egg and larval abundance, spawning stock and recruitment in vendace (*Coregonus albula* L.). *Finn Fish Res* 9: 271–289.
- Vuorinen J, Champigneulle A, Dabrowski K, Eckmann R, Rosch R. 1986. Electrophoretic variation in Central European Coregonid populations. *Arch Hydrobiol Beih Ergebn Limnol* 22: 291–298.
- Wang Z, Feng J, Lozano-Montes HM, Loneragan NR, Zhang X, Tian T, Wu Z. 2022. Estimating ecological carrying capacity for stock enhancement in marine ranching ecosystems of Northern China. *Front Mar Sci* 9: 936028.
- Wedekind C, Rudolfson G, Jacob A, Urbach D, Müller R. 2007. The genetic consequences of hatchery-induced sperm competition in a salmonid. *Biol Conserv* 137: 180–188.
- Wedekind C, Gessner MO, Vazquez F, Maerki M, Steiner D. 2010. Elevated resource availability sufficient to turn opportunistic into virulent fish pathogens. *Ecology* 91: 1251–1256.
- Wright PJ, Panfili J, Morales-Nin B, Folkvord A, Mosegaard H, Meunier F. 2002. Validation and verification methods: direct validation. In: Panfili J, Pontual HD, Troadec H, Wright PJ. (eds.), *Manual of fish sclerochronology*, Ifremer-IRD coedition, Brest, France, pp. 114–128.
- Yaripour S, Huuskonen H, Rahman T, Kekäläinen J, Akkanen J, Magris M, Kipriianov PV, Kortet R. 2021. Pre-fertilization exposure of sperm to nano-sized plastic particles decreases offspring size and swimming performance in the European whitefish (*Coregonus lavaretus*). *Environ Pollut* 291: 118196.
- Yaripour S, Huuskonen H, Kipriianov PV, Kekäläinen J, Herz L, Akkanen J, Vainikka A, Janhunen M, Kortet R. 2022. Exposure of gametes to aged nano-sized plastic particles during fertilization can influence early larval development in the European whitefish (*Coregonus lavaretus*). *Aquat Toxicol* 250: 106264.

Cite this article as: Rogissart H, Goulon C, Guillard J. 2024. Rehabilitation of whitefish fisheries in lakes Geneva and Bourget during the eutrophication period: assessing socio-economic impacts through large collaborative research. *Int. J. Lim.* 60: 13: