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The Restoration of Aquatic Ecosystems in the Alps and Pyrenees: A Case Study from the LIFE RESQUE ALPYR Project

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Abstract

High mountain aquatic and semi-aquatic ecosystems of the alpine biogeographical region harbour specialized biota, yet they are increasingly being degraded by non-native fish introductions, livestock pressure, afforestation and the abandonment of traditional wet meadow management. The LIFE RESQUE ALPYR project (2022–26) implements coordinated restoration actions across four Natura 2000 sites in the Pyrenees and the Alps, targeting eleven habitat types and several threatened vertebrate species. Building on prior LIFE initiatives in both mountain ranges, LIFE RESQUE ALPYR develops and tests replicable protocols for invasive fish eradication in lakes of varying sizes, livestock exclusion from sensitive waters and mires, clear-cutting and revegetation on afforested mires and the re-establishment of mowing in wet meadows. Here we present the project's ecological rationale, study areas, objectives and methods, together with the expected outcomes and lessons learned to support transferability to other mountain protected areas. This approach integrates robust ecological monitoring and stakeholder engagement to ensure long-term biodiversity gains and to reconcile traditional land-use practices with modern conservation priorities. Evidence from comparable Alpine and Pyrenean systems shows that amphibian and aquatic invertebrate communities can recover rapidly following fish removal, while mire restoration and appropriate meadow management accelerate vegetation and trophic recovery, producing cascading benefits for riparian and semi-aquatic insectivores. Quantified outcomes include the complete removal of non-native fish from 22 lakes (55.4 ha); the reoligotrophication of 10 lakes; the restoration of ≥3 ha of wet meadows and ≥8–10 ha of mires by means of grazing-exclusion and afforestation-removal actions; and the development of operational protocols designed for replication in European mountain regions.

Introduction and conservation context

High-mountain aquatic and semi-aquatic ecosystems (glacial lakes, peat bogs and mires, wet grasslands and seasonally flooded meadows) are characterized by harsh climates, short growing seasons and high levels of specialization and endemism (Schmitt 2009; Pironon et al. 2022). Although limited in extent, these habitats include several priority habitat types listed under the EU Habitats Directive, together with specialized plant communities such as *Sphagnum*-dominated peatland flora and wet-meadow species of high conservation value. They support unique assemblages ranging from invertebrates and amphibians to semi-aquatic mammals and insectivorous bats, many of which are also protected under European legislation.

During recent decades, the ecological integrity of these systems has been increasingly compromised across Europe. Historically fishless alpine lakes have been widely stocked with predatory fish for recreational angling (Tiberti et al. 2014b; Ventura et al. 2017), while land-use changes have intensified nutrient inputs (Tiberti et al. 2014a) and disrupted natural hydrological regimes (Rossi et al. 2024). In both the Pyrenees and the Alps, introductions of trout (*Salmo trutta*, *Oncorhynchus mykiss*, *Salvelinus alpinus*, *Salvelinus fontinalis*) and minnows (*Phoxinus* spp.) have caused amphibian extirpations (Tiberti & von Hardenberg 2012; Miró et al. 2018); altered littoral (Buchaca et al. 2022; Osorio et al. 2022) and pelagic (Tiberti et al. 2014b; Sabás et al. 2019) food webs; and reduced insect emergence (Tiberti et al. 2016) and trophic subsidies from lakes to terrestrial ecosystems (Bello et al. 2024).

Mires in these mountain regions are also affected by livestock overgrazing, which increases nutrient load, disturbs peat soils (both by compaction and pugging) and alters diatom and bryophyte assemblages, driving systems toward hydrological instability (Rossi et al. 2024). Studies from European mountains show clear compositional shifts in grazed mires, with resilience determined by pH and bryophyte cover, and increases in eutraphentic taxa under intense pressure (Gonzalez-Saldias et al. 2025). At the same time, afforestation of subalpine mires lowers water tables and increases shading, promoting transitions to more generalist vegetation. To mitigate this problem, targeted tree removal combined with active revegetation accelerates the recovery of peat-forming plant communities (Hedberg et al. 2012); meta-analyses show that enhanced restoration consistently outperforms passive approaches (Allan et al. 2024). Abandonment of traditional mowing adds another layer of pressure on wet meadows, where lack of management favours competitive dominant graminoids and reduces species richness. Long-term experiments and synthesis studies indicate that well-timed, low-intensity mowing can counteract successional homogenization, although responses vary depending on hydrological conditions (Hajková et al. 2022).

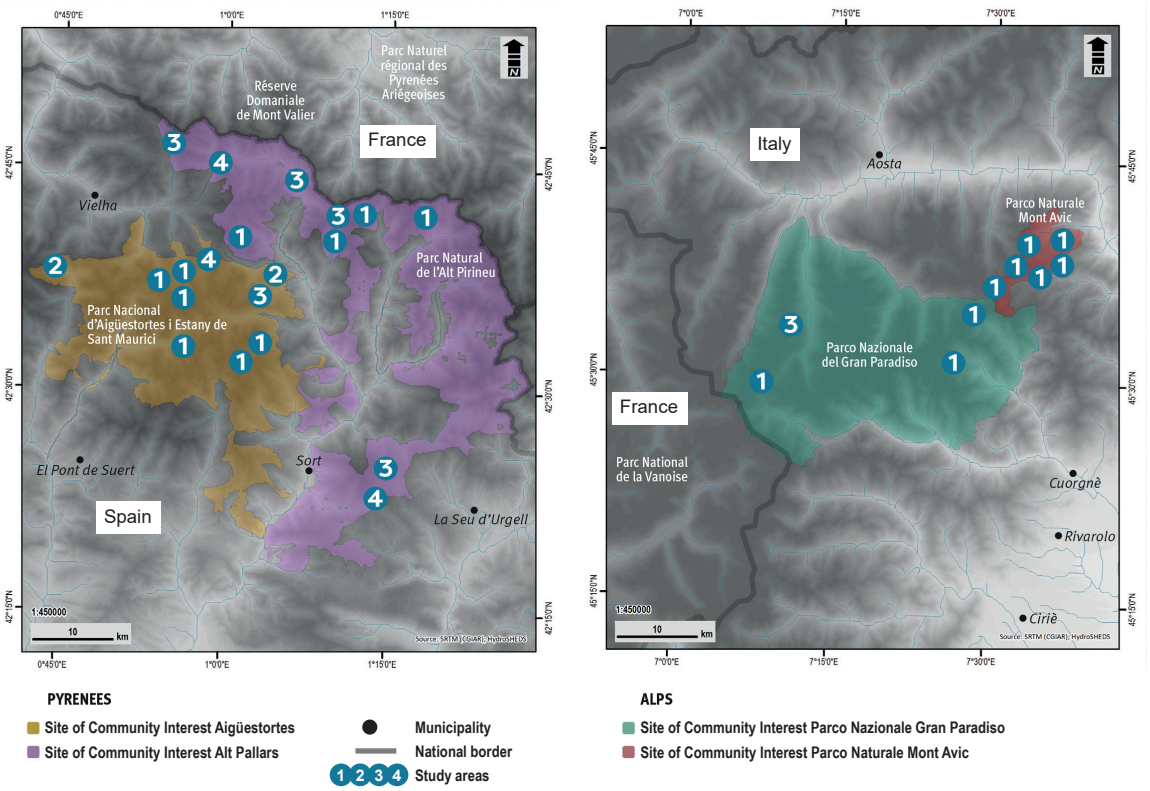


Figure 1 – Map of the study area with conservation actions indicated by numbers: 1) Restoring the natural state of some lakes through the elimination of non-native fish species; 2) Selective mowing of meadows and neighbouring mires; 3) Livestock grazing management; 4) Conservation improvement of mires by selective tree clearcutting. Source: SRTM (CGIAR); HydroSHEDS

Taken together, these interacting threats underscore the need for integrated, site-specific restoration strategies that simultaneously address trophic disruption, hydrological alteration and land-use change. This need has been progressively tackled through successive LIFE projects. The LIFE+ BIOAQUAE project (LIFE11 BIO/IT/000020) marked a major milestone by carrying out the first successful eradication of salmonids from high-mountain lakes in Europe. Building on this achievement, LIFE+ LimnoPirineus (LIFE13 NAT/ES/001210) (Carrillo et al. 2020) accomplished the first complete removal of non-native minnows from small lakes in the Pyrenees. In addition to developing and validating effective protocols for eliminating invasive fish in small alpine lakes, LIFE+ LimnoPirineus implemented a broad suite of habitat restoration actions, including peatland and wet-meadow improvements, recovery of priority habitats and targeted measures for specialist flora. Together, these actions provided a solid proof of concept for integrated restoration approaches in the Pyrenees. As a result of this coordinated work, native amphibian communities showed rapid recovery, and the ecological structure and functioning of high-mountain mires were substantially enhanced. Building upon these advances, LIFE RESQUE ALPYR (LIFE20 NAT/ES/000369) (Centre d'Estudis Avançats de Blanes 2022) constitutes the crucial phase of scaling and validating these methods at a broader biogeographical scale. The project extends this approach across both the Pyrenees and the Alps and tackles more complex challenges, particularly the eradication of invasive fish from larger lakes, thereby demonstrating its wider applicability across Europe.

Study areas and target taxa

LIFE RESQUE ALPYR operates across four Natura 2000 sites from the Pyrenees and the Alps: the Aigüestortes i Estany de Sant Maurici National Park (PNAESM) with SCI Aigüestortes (ES0000022), the Alt Pirineu Natural Park (PNAP) with SCI Alt Pallars (ES5130003), the Gran Paradiso National Park (IT1201000) and the Mont Avic Natural Park (IT1202000) (Figure 1). Baseline surveys across these areas revealed high incidences of invasive fish in high mountain lakes and widespread grazing impacts in mires, alongside accelerating forest encroachment threatening subalpine mires.

In the Pyrenees, introduced fish are now present in approximately 70% of lakes within Aigüestortes and 35% within Alt Pallars (Miró & Ventura 2013, 2015). In the Alps, 89% of lakes in Mont Avic and 29% in Gran Paradiso are affected. These introductions have caused local extirpations of amphibians and declines in aquatic invertebrate communities, with cascading effects on semi-aquatic mammals that depend on emergent aquatic insects for foraging (Figure 2).

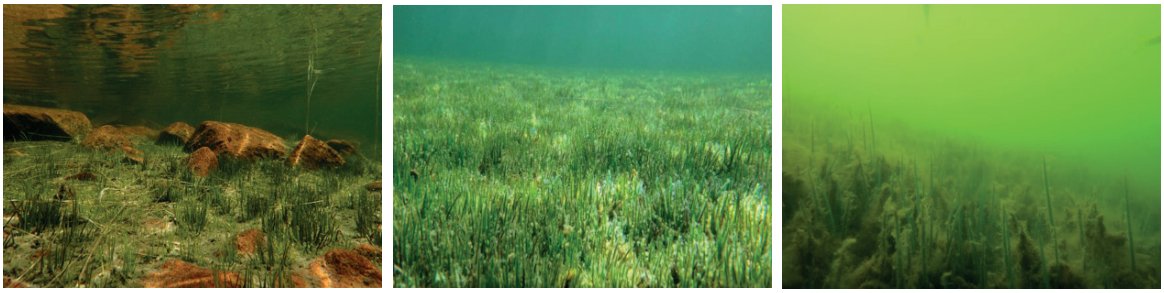


Figure 2 – Photographs showing the effects of fish presence on water transparency and the presence of microalgae. From left to right: natural Lake without fish; lake with trout and minnow; lake with minnow. © Kike Ballesteros

Mires in the project area face additional pressures from livestock overgrazing. In Aigüestortes and Alt Pallars, 80% of mires are grazed and 20% are overgrazed, leading to plant mechanical disturbance, soil alterations through trampling and increased nutrient inputs that, taken together, compromise habitat quality. Simultaneously, afforestation by *Pinus uncinata* and other tree species lowers water tables, increases shading and shifts peatland communities toward generalist species. Approximately 30% of subalpine mires in the Spanish sites are currently affected by forest encroachment. The parallel decline in traditional mowing practices further contributes to the homogenization of wet meadows, favouring dominant graminoids and facilitating additional encroachment.

The project targets eleven Annex I habitat types, including priority HCIs 4020*, 6230*, 7110*, 91D0* and 7220*, covering alpine lakes (3110, 3130), wet grasslands and meadows (6410, 6520) and minerotrophic and ombrotrophic mires (7140, 7230). Focal vertebrates include amphibians such as *Rana temporaria*, *Calotriton asper*, *Alytes obstetricans* and *Alytes almogavarii*; the semi-aquatic mammal *Galemys pyrenaicus*; and seven species of insectivorous bats, including *Rhinolophus hipposideros*, *Plecotus macrobullaris* and *Barbastella barbastellus*. Their foraging behaviour can depend heavily on aquatic insect emergence, with evidence from European lakes and riparian systems showing that bat activity peaks coincide with emergence dynamics and aerial insect flux from water bodies (Salvarina et al. 2018).



Figure 3 – Main methods used for non-native fish eradication in high mountain lakes. Clockwise from top left: fykenetting, with nets deployed along littoral zones to capture minnows larger than ~30 mm; electrofishing, allowing active capture of both minnows and salmonids of all sizes in littoral areas and in associated inlet and outlet stream sections; gillnetting, deployed all over the lake for both minnows and salmonids; intensive rod-angling: complementary fish removal method to reduce the initial density of adult salmonids. © Fykenetting and Electrofishing by Sorelló Estudis al Medi Aquàtic. Rodangling and Gillnetting by Stefano Brighenti.



Figure 4 – Rotenone application in Lake Manhèra (SCI Aigüestortes, Val d'Aran). © Marc Ventura



Figure 5 – Temporary fence (August to October) at Estanyeres de Son (PNAESM, within the park). Livestock exclusion fences promote the recovery of vegetation and flowering of plants, allowing them to recolonize degraded areas. © Eulàlia Pladevall

Objectives and working hypotheses

The overarching objective is to restore the ecological function of high mountain lakes and mires, re-establish amphibian metapopulation connectivity and improve the conservation status of semi-aquatic mammals and insectivorous bats by removing alien fish, reducing nutrient and trampling pressures, reinstating wet meadow management and reversing afforestation in mires. The project also aims to generate replicable protocols for mechanical and chemical fish eradication, livestock management and mowing and mire forest control, and to upscale results via a European expert network and practitioner guidelines.

Conservation actions and methods

Invasive fish eradication in High Mountain Lakes

We designed eradication campaigns tailored to lake size, bathymetry and habitat complexity. Following pre-treatment baseline surveys of amphibians, macroinvertebrates, zooplankton and key physico-chemical indicators, fish removal was carried out through intensive, multi-year, site-specific operations combining gill-netting across depth strata, fykenetting, electrofishing and targeted rod angling, with effort scaled to bathymetry and structural complexity (Figure 3). In total, 22 lakes across both mountain ranges (Figure 1) are undergoing treatment. Field effort will be adjusted adaptively, increasing if fish reduction is below 90% after the second year, applying criteria established in previous LIFE projects. This approach maximizes cost-efficiency, extends eradication feasibility to medium and large lakes and generates transferable decision rules and effort–response curves to guide future replication.

Where mechanical methods are infeasible, the project tests a rigorously controlled eradication protocol using rotenone, a biodegradable piscicide. This approach was used in three Pyrenean lakes with minimal outflow and severe minnow impacts: Tres Estanys del Mig (3.7 ha), Tres Estanys de Baix (2.8 ha) and Manhèra (1.5 ha) (Figure 4). Treatments use CFT Legumine® (3.3% rotenone) under the supervision of the Norwegian Veterinary Institute and are timed to minimize side effects on non-target taxa; rotenone decay is tracked via GC-MS (Prats et al. 2024) to confirm rapid dissipation. The objectives are the permanent removal of *Phoxinus* spp. and the rapid recovery of native communities, while establishing an EU relevant safety blueprint for piscicide use in sensitive mountain contexts.

Selective mowing of wet meadows

Traditional mowing has been reinstated in the two subalpine sites of Aigüestortes and Pleta de Molières i Planes de Son, on a combined 3 ha, with ~80% of the area mown each summer and ~20% retained as controls. The action targets recovery of HCIs 6410 and 6520 and also benefits associated mires and wet heaths (4020*, 7230) through increased structural heterogeneity and reduced graminoid dominance (locally, tree and shrub encroachment is also reduced).

Livestock management and assisted plant migration

In six mire systems across Spain (Rubió, Sartari, Font de la Tosca, Plan deth Horn, Estanyeres) and Italy (the Djouan area), the project deploys permanent and seasonal fencing (typically 0.2–1.0 ha per enclosure) to halt trampling and eutrophication, supplements this with assisted transplants of mire specialists in Spanish sites (0.5–2% of area, 3–10 species) and installs minor trail rerouting to maintain pastoral activity while protecting sensitive zones (Figure 5).

Selective tree removal in mires

At Locampo, Parros and Pla Muntaner, ~6 ha of mire systems have been cleared of encroaching *Pinus uncinata* following baseline hydrology and vegetation assessments, with partial retention at Locampo and Parros and near total removal in Pla Muntaner to re-





Figure 6 – Training course for professionals specializing in the knowledge and dissemination of the Alt Pirineu Natural Park's values (SCI Alt Pallars). © Top: Alt Pirineu Natural Park; bottom Marta Mora



Figure 7 – Project presentation and educational activity in the Forum of Green Schools (Centre de Fauna Pont de Suert, Alta Ribagorça). © Associació la Sorellona



Figure 8 – Intensive angling sessions (Lake Miserino, SCI Gran Paradiso National Park) have been used to engage anglers as key stakeholders and promote ecological awareness. Angling in mountain lakes is both a primary pathway for fish invasions and a popular recreational activity outside protected areas. Addressing this potentially conflicting context probably represents the most challenging communication objective of the entire project. © Stefano Brighenti

store water tables and light regimes that favour peat forming communities. Citizen participation complements professional staff to strengthen social acceptance and awareness.

Community engagement and dissemination

Stakeholder workshops, field days and materials shared with protected-area managers and schools frame restoration as a partnership. This social process is essential where fish eradication or livestock exclusion could raise concerns; communicating robust ecological evidence and demonstrating rapid recovery helps sustain local support. Documented links between fish removal, increased amphibian and macroinvertebrate presence and improved foraging resources for terrestrial insectivores provide compelling narratives for broader biodiversity benefits (Figures 6, 7 and 8).

Monitoring, evaluation and expected outcomes

A comprehensive monitoring and evaluation framework sustains the project's ecological restoration goals while quantifying outcomes at biological, environmental and socio-economic scales (Figure 9). Nine dedicated monitoring actions assess rotenone decay until concentrations fall below analytical detection, and model fish-removal success in near real time using open-population removal models. Lake recovery is evaluated through standard surveys tracking amphibians, macroinvertebrates, macrophytes, phytoplankton and zooplankton and water transparency. Cross-ecosystem effects of fish removal are measured with automated bat acoustic recorders and non-invasive monitoring (e.g., environmental DNA) of semi-aquatic insectivores including *G. pyrenaicus*. Vegetation, bryophytes, butterflies, water-table levels and cryptic soil and moss-dwelling biodiversity are recorded in permanent plots in hay meadows, fenced mires and peatland areas following clear-cutting.

In parallel with ecological monitoring, surveys are conducted with citizens (400), university students (200) and key stakeholders (50–100, including natural area managers, scientific community, anglers, farmers, NGOs, etc.) to assess perceptions and potential conflicts regarding the conservation actions. All indicators feed into a dynamic LIFE KPI database updated until 2026 and maintained thereafter under the After-LIFE plan.

Expected outcomes include the complete eradication of alien fish from 22 lakes (55.4 ha) across the four SCIs, three treated with rotenone and 19 through mechanical control, reducing the proportion of invaded lakes. Reoligotrophication towards reference conditions is targeted in at least 10 lakes impacted by livestock or minnow-driven trophic shifts, with transparency, nutrients and chlorophyll monitored against pristine benchmarks. Habitat restoration totals ~3 ha of wet meadows at Aigüestortes, ~4 ha of fenced

peatlands in Spain and Italy, ~6 ha of selective deforestation in mires and ~150 m² of recovery in the petrifying spring at Font de la Tosca.

Rapid recolonization of treated lakes by amphibians is expected where nearby source populations persist, alongside the re-establishment of macroinvertebrate and zooplankton communities typical of fishless conditions. Increased insect emergence is anticipated to enhance foraging for bats and other insectivores. Project deliverables include technical guidelines for mechanical and chemical fish eradication, for grazing and mowing management and for mire forest control, as well as a monograph synthesizing all monitoring evidence to support replication in other regions.

Risk management and mitigation

Use of rotenone is restricted to three closed-basin lakes selected for minimal outflow and maximal ecological benefit; permissions were obtained from the competent authorities, and application is supervised by Europe's most experienced rotenone team to assure compliance and safety. Seasonal timing avoids sensitive life stages of non-target taxa, and degradation is chemically verified. Mechanical eradications adapt effort if reductions are <90% by year two. Fence maintenance is planned throughout the alpine season to address weather damage, and participatory engagement is used to limit the risk of sabotage. The budget includes a 5% buffer for inflation, with protected areas prepared to extend eradication for up to two years post-project if needed.

Replicability, innovation and socio-economic impact

RESQUE ALPYR's two major demonstration fronts are the first rigorous, monitored application of rotenone in EU high mountain lakes and the scaling of mechanical eradication to medium and large structurally complex lakes with explicit effort rules and eradication probability modelling. The project also pilots assisted plant migration in overgrazed mires and integrates molecular tools into routine monitoring to make biodiversity surveillance cost effective and transferable. With more than 1.5 million visitors a year across the four protected areas, open exhibitions, citizen science via the iNaturalist platform and a specialist network under action E.5 are expected to accelerate the diffusion of methods and policies such as fishing and live bait bans, which the partner parks already enforce as a precondition for durable outcomes. Job creation amounts to ~12 FTEs (full-time equivalent) during the project, with additional indirect benefits through local services and eco-tourism.



Figure 9 – Standard surveys of vegetation and macroinvertebrates in the areas under study. © Top: Eulàlia Pladevall; bottom: Marta Mora

Conclusions

LIFE RESQUE ALPYR illustrates how integrated restoration, combining non-native fish removal, hydrology-based peatland recovery and reinstatement of traditional wet-meadow management, can rebuild trophic structure and biodiversity in high-mountain aquatic systems. Evidence from the Pyrenees and the Alps demonstrates that these actions are feasible, ecologically effective and replicable, with rapid amphibian and invertebrate recovery after fish eradication and accelerated vegetation recovery under enhanced peatland practices. By coupling robust monitoring with stakeholder engagement, protected mountain areas across Europe can adopt and adapt this model to reverse degradation and secure long-term ecological integrity.

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