

Monographic 50 years of limnological research in Sierra Nevada
















Emerging frontiers and future research in the mountain water tower of Sierra Nevada, Spain: concluding remarks

Guest Editors

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## Emerging frontiers and future research in the mountain water tower of Sierra Nevada, Spain: concluding remarks

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### MOUNTAIN WATER TOWERS

Mountains, covering about 27% of Earth's surface, provide more than 50% of the world's freshwater resources (Immerzeel et al., 2020). For this reason, they are commonly referred to as Mountain Water-Towers (MWTs), as their high-altitude regions function as natural reservoirs of freshwater (Messerli et al., 2004). They capture precipitation in the form of rain and snow, store it in glaciers, snowpacks, and groundwater systems, and gradually release it to feed rivers, lakes, and aquifers downstream. By regulating seasonal water flow, MWTs play a crucial role in sustaining delicate ecosystems like forest and wetlands, agriculture, hydropower, and human populations downstream (Viviroli et al., 2020).

However, mountains are among the most sensitive terrestrial environments, often described as “early warning systems” for climate change because they experience its effects more quickly and intensely than many lowland areas (Pepin et al., 2015). MWTs are increasingly threatened by both climate change and human activities (Reid et al., 2019, Vörösmarty et al., 2010). Factors such as rising temperatures, shifting precipitation patterns, deforestation, and excessive water extraction undermine natural water storage processes, while pollution further deteriorates water quality. These combined stressors threaten the reliability of freshwater supplies for nearly 1.9 billion people. Ultimately, the functioning of MWTs is closely linked to the concept of planetary boundaries, which define safe limits for key Earth system processes (Richardson et al., 2023, Rockström et al., 2014). Their degradation can push freshwater systems beyond the safe thresholds, threatening water security, food production, biodiversity, and ecological stability at regional and global scales (Knight, 2022). Protecting MWTs is essential to stay within the planetary boundary for freshwater use and to maintain the resilience of Earth's life-support systems.

The importance of MWTs is particularly pronounced in arid or semiarid regions such as the Mediterranean (Viviroli et al., 2007), which is considered a climate change hotspot, experiencing rising temperatures at rates about 20% higher than the global averages, along with altered precipitation regimes, and more frequent droughts, heatwaves, and extreme weather events (Lazoglou et al., 2024, Lionello & Scarascia, 2018, UNESCO, 2025). The Sierra Nevada, the southernmost high mountain range in Spain, hosts some of the continent's highest ice-free glacial lakes, located near the peaks at around 3000 meters above sea level—an altitude attributed to its low latitude relative to other European mountain ranges. Many small streams and tributaries originate from these glacial lakes and the surrounding green

meadows, locally known as *borreguiles*. After 50 years of intensive research, both lakes and rivers are now recognized as sentinel ecosystems for tracking global change, given their sensitivity to environmental stressors and unique biogeochemical dynamics (López-Rodríguez et al., 2022, Medina-Sánchez et al., 2022). Sierra Nevada's water resources are also increasingly threatened by climate change, pollution, and unsustainable land use, which deplete vital supplies and degrade downstream ecosystems. In response, the region has implemented educational, conservation, and research initiatives, including community science projects that involve students and residents in monitoring and restoring rivers and lakes (Biddanda et al., 2022), as well as the Sierra Nevada Global Change Observatory (OBSNEV), that positions Sierra Nevada at the forefront of global change research.

## ADVANCING FRONTIERS IN SIERRA NEVADA FRESHWATER RESEARCH

Despite fifty years of scientific research in Sierra Nevada, substantial knowledge gaps persist regarding the functioning, biodiversity, long-term resilience and vulnerability of its ecosystems (Fig. 1). Key emerging challenges, research frontiers, and necessary methodological innovations to enhance understanding and management of the Sierra Nevada's sensitive ecosystems include the following:

**Uncovering hidden biodiversity.** Despite their ecological value, the biodiversity of these high mountain lake and stream ecosystems remains poorly understood, particularly regarding understudied groups like bacteria, archaea, heterotrophic protists, fungi or viruses. In both lakes and streams, heterotrophic protists and fungi—particularly parasitic forms—have been historically overlooked but are now seen as vital to ecosystem function. Likewise, in lakes, benthic and littoral communities, despite their ecological importance, are far less explored than planktonic ones. Traditional microscopy often misses soft-bodied, colorless, or cryptic species, leading to underestimations of biodiversity. On the other hand, most streams and river studies have focused on macroinvertebrates, largely neglecting mesofaunal invertebrates, and other microscopic organisms. Advanced molecular tools such as sedimentary DNA (sedDNA), environmental DNA (eDNA), and high-throughput sequencing technologies are revealing new dimensions of biodiversity (Castellano-Hinojosa et al., 2017, 2023, 2024), yet fundamental questions about the diversity, ecological roles, evolutionary history, and conservation needs of these hidden communities remain unanswered.

**Culture collections as microbial biodiversity arks.** Given our previously mentioned limited understanding of microbial diversity in these ecosystems, there is a considerable risk of losing both known and undiscovered species before they get properly studied. To minimize this risk, culture collections arrive as an important resource by providing authentic biological material for high quality research, education and conservation in the form of long-term stored referenced cultured strains. The first aim of a culture collection is to catalog cultured strains of microorganisms, identified through 16S/18S SSU rRNA gene sequencing, microscopy, or a combination of both. These strains are cryopreserved in liquid nitrogen containers for years, serving as biodiversity arks that safeguard valuable genetic resources for future use. Just like an ark, preserved cultures can be revived when needed to restore key species that are extinct in their original environments but essential for maintaining ecosystem functions or properties (e.g., carbon sink capacity). Beyond conservation, culture collection enables a wide range of research applications: discovering new species of ecological, taxonomic, or evolutionary interest; exploring biotechnological and biomedical potential; acting as a link between eDNA studies and the actual cultured organisms; and providing means to study the effect of environmental stressors and contaminants under controlled environments. Most importantly, they offer the time needed to study, understand, and preserve microbial life. Establishing a dedicated microbial culture collection in the Sierra Nevada is urgently needed to preserve its threatened freshwater ecosystems and to support their long-term conservation and restoration.



**Figure 1.** Watercolor illustration of microscopic aquatic life from Sierra Nevada high-mountain lakes. Key ecological questions in ecology remain regarding where, why, how, and when these organisms occur, interact to form trophic webs, and respond to global environmental change in these fragile lake ecosystems (Image credit: C. Otero-Sabio, licensed under CC BY). *Ilustración en acuarela de organismos acuáticos microscópicos característicos de los lagos de alta montaña de Sierra Nevada. Todavía existen muchos interrogantes en ecología relacionados con dónde, por qué, cómo y cuándo estos organismos aparecen, interactúan para formar redes tróficas y responden al cambio ambiental global en estos ecosistemas vulnerables de alta montaña. (Crédito de la imagen: C. Otero-Sabio, bajo licencia CC BY).*

**Remote Sensing Applications.** Human activities have increasingly impacted aquatic ecosystems worldwide, underscoring the urgent need for effective water resource conservation. In response, national and international frameworks have emphasized the implementation of comprehensive water quality monitoring programs. Modern management of inland waters requires methods that are rapid, systematic, reliable, and cost-effective. However, long-term datasets describing the biological and physicochemical properties of most water bodies remain scarce, as traditional *in situ* sampling is both labour-intensive and costly, and many sites are logistically difficult to access (Filazzola et al., 2020, Gholizadeh et al., 2016). Recent advances in satellite remote sensing offer a promising pathway to overcome these challenges. Enhanced temporal, spatial, and spectral resolutions of modern sensors now allow for more detailed observation of inland waters. Yet, small water bodies (area < 0.1 km<sup>2</sup>)—which make up over 90% of global lakes—remain largely understudied using remote sensing techniques.

This emerging line of research explores the potential of remote sensing for monitoring small, high-mountain lakes in the Sierra Nevada (Llodrà-Llabrés, 2025). The study evaluates how variations in spectral and spatial resolution affect the estimation of chlorophyll-a concentrations, with particular attention to the adjacency effect—an often-overlooked factor that is especially relevant in small aquatic systems. Using one hundred field samples collected over a three-year period, the performance of Sentinel-2, Planet, and WorldView-3 imagery was compared across five Sierra Nevada lakes. Results

indicate that Planet imagery provides the most accurate chlorophyll-a retrievals, owing to its high spatial resolution and consistent performance under varying sampling conditions (Llodrà-Llabrés, 2025, 2026). Future work will expand on these findings by increasing the sample dataset to refine predictive models and by extending remote sensing applications to additional water quality parameters such as total suspended solids (TSS) and dissolved organic carbon. This research represents a key step toward establishing cost-efficient, scalable monitoring strategies for sensitive mountain lake ecosystems.

**Ensuring the continuity and integrity of long-term ecological research.** Long-term ecological research is vital for predicting species' responses to global change (Harold & Blanc, 2025). By capturing microevolution and phenotypic plasticity, real time and high-frequency observations can identify early indicators of adaptation or stress overlooked by short-term assessments. Such monitoring uncovers the mechanisms driving ecological shifts and provides the evidence needed for effective, science-based conservation and sustainability policies. Embedding long-term programs within institutional frameworks ensures data integrity and resilience against future threats (Zamora et al., 2025). Far from expendable, long-term monitoring represents essential scientific infrastructure and society's most reliable early-warning system for environmental change. For example, long-term data from Lake La Caldera (since 1980) reveal rising chlorophyll a levels linked to warming and Saharan dust inputs, accompanied by an increase in microzooplankton—but not mesozooplankton—indicating a disrupted food web at the producer–consumer interface and potential water quality decline (Bullejos et al., 2010, Villar-Argaiz et al., 2022).

The deployment of continuous multiparametric probes marks a major advance in long-term ecosystem research, providing high-frequency data that uncover subtle dynamics, enhance model calibration, and support meaningful temporal comparisons. In lakes and rivers, these automated sensors now allow continuous tracking of physicochemical parameters (e.g., temperature, dissolved oxygen, pH, nitrogen) and biological responses (e.g., photosynthetic pigments) to episodic events driven by human activity and climate, such as dust storms. An ongoing monitoring program in Sierra Nevada lakes reveals spatial patterns in prokaryotic alpha and beta diversity and how changes in physicochemical conditions affect key pivotal functional groups involved in biogeochemical processes such as phosphate solubilization, nitrogen fixation, nitrification or denitrification, among others (Castellano-Hinojosa et al., 2017). Despite the absence of clear signs of eutrophication, rising algal biomass and blooms—including toxin-producing cyanobacteria—have been observed in Sierra Nevada, the Pyrenees and globally (Jiménez et al., 2018a, Hou et al., 2022, Villar-Argaiz et al., 2022). Their presence in lake-edges is known, but their broader impact remains uncertain. Identifying the drivers of cyanobacterial composition and proliferation is essential for effective monitoring and conservation of these sentinel ecosystems. High-frequency data also highlight the impacts of human activities—such as tourism, cattle grazing, irrigation, and artificial snow production—that disrupt hydrological cycles and degrade water quality in lakes and rivers, driving eutrophication, pollution, and biodiversity loss (Godoy et al., 2022).

**Paleolimnology.** The analysis of sediment cores offers critical millennial- and centennial-scale context for interpreting recent environmental changes. These long-term records reveal that the Industrial Era—marked by phenomena like “hot droughts”—has been a major driver of ecological transformations. Shifts in biological communities and ecological indicators preserved in lake sediments reveal how Sierra Nevada lakes have responded to past climate variability and offer insights into the combined effects of ongoing warming, atmospheric aerosol deposition, and human activity (Jiménez et al., 2017, Jiménez et al., 2018b, García-Alix et al., 2020, Jiménez-Moreno et al., 2023). Emerging tools like sedDNA hold promise for reconstructing past communities and deepening our understanding of ecosystem change.

**Invasive and range-expanding species.** Invasions and the establishment of new species in high mountain streams and lakes pose a serious threat to native biodiversity and ecosystem integrity. While exotic species such as rainbow trout (*Oncorhynchus mykiss* (Walbaum, 1792)), North American

largemouth bass (*Micropterus salmoides* (Lacepède, 1802)), northern pike (*Esox lucius* Linnaeus, 1758), and common carp (*Cyprinus carpio* Linnaeus, 1758), among others, have been reported in the mid and low reaches of Sierra Nevada streams, no exotic fish species have been detected in Sierra Nevada lakes. Additionally, concerns exist over the spread of species like *Sparganium angustifolium* Michx. (1803), currently confined to Juntillas Lake, to other shallow lakes in the region such as Río Seco and Aguas Verdes (Sánchez-Martínez, 2024). If *S. angustifolium* were to expand its range, it could alter habitat structure and compete with native aquatic vegetation. However, there is currently no evidence that its presence poses a major threat to high mountain lakes. More pressing is the presence of the cladoceran North American *Daphnia* cf. *pulicaria* (sensu Hebert, 1995) in Borreguil Lake, which could spread and threaten the native European *D.* cf. *pulicaria* (sensu Alonso, 1996) in danger, highlighting the need to evaluate colonization risks. Protecting these unique and fragile ecosystems calls for coordinated, science-based management and restoration strategies.

**Integrating ecological theory to understand ecological impact of global change.** In the Anthropocene, human activities have sharply disrupted Earth’s biogeochemical cycles, boosting carbon, nitrogen, and phosphorus fluxes. The Mediterranean, a climate “hotspot,” experiences temperatures rising 20% faster than the global average, while increased Saharan dust alters key consumer–resource dynamics, threatening ecosystem function (IPCC, 2023). We now know that rising aerosol deposition and increasing temperatures are leading to shifts in zooplankton communities from copepod dominance to dominance by cladocerans and rotifers (Vila-Duplá, 2025). However, the mechanisms driving these changes remain poorly understood. Key gaps in our understanding include the limited availability of multifactorial and long-term studies, the scarcity of research conducted in natural multitrophic systems and, notably, the absence of a unified ecological framework to investigate these complex responses. Future research aims to integrate Ecological Stoichiometry (ES), Trait-Based Ecology (TBE), and the Metabolic Theory of Ecology (MTE) to uncover causal relationships and trade-offs among traits and metabolic variables, providing insights into how organisms balance energy and nutrient use in the face of global change.

**Global change-driven water level fluctuations.** Mediterranean aquatic ecosystems are inherently subject to significant water level fluctuations driven by erratic precipitation patterns (Álvarez-Cobelas et al., 2005). However, global climate change is expected to exacerbate this natural variability, with shorter wet seasons and more frequent summer droughts (Coops et al., 2003), a trend already observed in Sierra Nevada lakes (Pérez-Martínez et al., 2020). Such fluctuations will amplify the significance of sediment-water interactions in nutrient cycling, particularly in vulnerable shallow lakes like those in Sierra Nevada. As precipitation patterns shift, larger areas of lakebed sediment become exposed to desiccation, altering key biogeochemical processes such as nutrient release and sequestration (de Vicente, 2021). Current literature on Mediterranean wetlands remains limited, with existing studies in analogous ecosystems reporting contradictory phosphorus (P) responses to hydrological shifts—varying from increased adsorption to post-flooding eutrophication (Barrow & Shaw, 1980, Baldwin, 1996). These inconsistencies reflect the intricate coupling of chemical, physical and biological mechanisms that regulate P cycling in hydrologically dynamic environments. Consequently, understanding the biogeochemical impacts of these phenomena is therefore critical for accurately predicting the future dynamics of these sensitive ecosystems.

**New frontiers in multi-stressor research.** Given the rapid evolution of environmental change, with both traditional and emerging human driven stressors increasingly affecting lake ecosystems worldwide—especially in high-mountain lakes—it is crucial to identify the main challenges in understanding and managing their combined impacts. In Sierra Nevada research remains limited due to the region’s inaccessibility and complex terrain compared to lowland lakes. Therefore, we highlight key challenges

for advancing multi-stressor studies in Sierra Nevada in the coming years:

1. Multiple stressors often interact non-additively, producing unexpected ecological surprises; therefore, studies on their combined effects in Sierra Nevada's high-mountain lakes are urgently needed. Given the prevalence of non-linear responses in nature, mechanistic models are needed to identify potential tipping points and irreversible ecological shifts.
2. The traditional focus on UV radiation and nutrients has overshadowed other stressors. However, the detection of emerging contaminants (e.g., pesticides, fungicides, hormones, pharmaceutical compounds), including microplastics and their derived compounds (Godoy et al., 2022) underscores the need for ongoing monitoring and for assessing their combined effects with conventional climatic stressors. Future research should incorporate high-order interactions to better understand synergistic and antagonistic responses at the community level and their effects on ecosystem metabolism.
3. Long-term and high-frequency monitoring in these remote ecosystems is vital to improve spatial and temporal resolution. Such efforts will clarify how acclimation and adaptation mechanisms within biological communities' shape stressor interactions across evolutionary timescales.

**Role of abiotic and biotic factors in shaping distinctive assemblages.** High-mountain habitats, at the extreme of altitudinal gradients, are defined by severe environmental conditions, including low temperatures, prolonged snow cover, short growing seasons, reduced oxygen availability, and high UV radiation. These constraints act as strong abiotic filters, giving rise to distinctive high-elevation assemblages composed of stress-tolerant species that differ markedly from those in lowland communities.

As climate change alters high-elevation water bodies through interacting drivers, predicting community responses requires moving beyond single-factor explanations towards a mechanistic understanding of how abiotic and biotic constraints jointly shape assemblage structure (Medina-Sánchez et al., 2022). Characterizing these interactions in alpine lakes and ponds is therefore essential to anticipate both long-term outcomes and the transient pathways of community reorganization under warming. Alpine organisms, similar to those in polar ecosystems, persist close to their physiological tolerance limits and are thus highly sensitive to even minor climatic shifts. As a result, even modest changes in temperature or exposure duration can translate into disproportionate ecological responses. Identifying the mechanisms underlying cold and heat tolerance in alpine aquatic species therefore remains a key research priority (Pallarés et al., 2020, Carbonell et al., 2024). Differences in thermal sensitivity can drive community reorganization through species loss, often favoring the replacement of cold-adapted or thermally specialized taxa by thermal generalists as warming increases (Peck et al., 2009). Yet, growing evidence indicates that fundamental thermal niches alone do not fully explain species segregation along elevational gradients (Carbonell et al., 2024), highlighting the need to consider additional thermal traits, other abiotic drivers, and biotic interactions. The effects of chronic and sublethal thermal stress on aquatic organisms in the Sierra Nevada remain poorly understood, despite their likely relationship with cumulative stress and survival. Moreover, although temperature is often considered the dominant environmental factor in alpine landscapes, variables such as oxygen availability, air density, humidity, and solar radiation may also shape high-altitude aquatic communities (Hodkinson, 2005) yet remain poorly integrated into predictive frameworks.

Addressing these knowledge gaps will require integrative theoretical and experimental approaches that explicitly incorporate multiple abiotic dimensions and species interactions. The colonization of high-mountain regions by lowland species represents an additional source of uncertainty, as it can alter food-web structure (Rosenblatt et al., 2019), modify interaction strength, and increase extinction risk for local species. In this context, understanding the biotic interactions between lowland and alpine organisms is essential for predicting the trajectories of high-elevation assemblages in the Sierra Nevada under ongoing climate warming.

**Collaborative open science.** It is increasingly evident that high mountain research should not only be shared with the scientific community but also reach and engage the broader public, fostering informed engagement and supporting conservation efforts. Therefore, scientific dissemination is a crucial tool for raising awareness about the uniqueness, fragility, and scientific value of the Sierra Nevada high mountain lakes and rivers.

1. For the past fifty years, we have worked individually to emphasize their scientific value to policymakers, land managers, and interest groups. However, it is only recently that we have managed to collectively communicate this message to the society (Villar-Argaiz et al., 2022). A pivotal step in this direction was the launch of a top-notch citizen science campaign “74 High Mountain Glacial-Lake Oases” in 2018 by the Department of Ecology, with support from the Sierra Nevada Global Change Observatory (OBSNEV) and the Sierra Nevada National Park (Villar-Argaiz et al., 2022, campaign website: <https://lagunasdesierranevada.es/>). Collaborative campaigns like this enhance spatial coverage and engage local communities in data collection, improving scalability of assessments (e.g., monitoring 50+ lakes). Many of their findings, yet to be published, will likely reveal numerous previously unknown aspects of these lakes—contributing both to our scientific understanding and the preservation of these natural treasures for future generations.
2. As a counterpart to initiatives focused on lentic systems, a group of professors from the University of Granada’s departments of Ecology, Zoology, Botany, and Didactics of Experimental Sciences launched in 2021 an educational project titled “Rivers of Life” (*Ríos de Vida*; <https://ecologia.ugr.es/informacion/presentacion/rios-vida>). Sponsored by the Spanish Foundation for Science and Technology (FECYT) and the OBSNEV, this initiative was introduced with the goal of fostering scientific vocations among high school students and raising awareness about the vulnerability and degradation of our rivers. Through this project, students are guided by researchers and educators in fieldwork to collect biological, physicochemical, and hydromorphological data from local rivers. These activities follow the official protocols of the European Union’s Water Framework Directive and aim to help students assess the ecological status of river ecosystems. All data, collected both in the field and through laboratory analysis, are compiled into a shared digital workbook (<https://digibug.ugr.es/handle/10481/72752>) and made accessible to the participating schools. In follow-up classroom sessions, students analyze the results with support from their teachers and project mentors, classifying the ecological health of the river as high, good, moderate, poor or bad. By involving students directly in the study and monitoring of river ecosystems, we aim to cultivate a sense of responsibility for environmental stewardship. The initiative’s broader goal is to raise societal awareness of the urgent need for sustainable water management policies to safeguard the ecosystems that support us all.

**The Global Change Observatory in Sierra Nevada (OBSNEV).** Long-term ecological studies are crucial for understanding global change impacts, detecting slow ecosystem shifts, and assessing extreme events as “natural experiments” (Hughes et al., 2017). The OBSNEV is a long-term ecological research initiative, launched through collaboration between the University of Granada and the Andalusian regional government. Initiated in 2008 and formally registered in 2011, it monitors Sierra Nevada-mountain ecosystems to assess global change impacts and support science-based management. OBSNEV plays a key role in understanding ecosystem dynamics through standardized, long-term monitoring across the region’s diverse habitats (<https://obsnev.es/en/investigacion/>) (Bonet et al., 2010). By integrating biophysical, ecological, and socioeconomic data, it enables assessment of ecological processes and the impacts of climate change and human activity. Working closely with researchers, land managers, and local communities, the observatory promotes adaptive management strategies that aim to reduce environmental degradation, restore landscapes, and enhance the resilience and biodiversity of Sierra Nevada (Zamora & Oliva, 2022 and references therein). Some of OBSNEV’s accomplishments

and ongoing research, grounded in its long-term monitoring programs ([https://obsnev.es/wp-content/uploads/2019/11/Dossier\\_Metodologias\\_OCGSN\\_2012.pdf](https://obsnev.es/wp-content/uploads/2019/11/Dossier_Metodologias_OCGSN_2012.pdf)), include studies on snow dynamics (<https://smartecomountains.lifewatch.dev/la-sierra-se-funde/>), vegetation productivity (<https://smartecomountains.lifewatch.dev/cambios-verdor-vegetacion-sierra-nevada/>), Saharan dust deposition (<https://smartecomountains.lifewatch.dev/aumento-concentracion-polvo-sahariano-sierra-nevada/>), and climate (<https://smartecomountains.lifewatch.dev/europa-se-ha-calentado-mas-rapidamente/>). In addition, OBSNEV has developed an integrated environmental information system using tools such as Biblio nevada (<https://biblionevada.obsnev.es/>), Climanevada (<https://climanevada.obsnev.es/>), Histonevada (<https://histonevada.obsnev.es/>), and MonitorEO (<https://ee-ugr-default-project.projects.earthengine.app/view/monitoreo-obsnev>), while also encouraging citizen participation in monitoring Sierra Nevada's lakes (<https://lagunasdesierranevada.es/>) and rivers (<https://ecologia.ugr.es/informacion/presentacion/rios-vida>). In summary, Global Change Observatories are crucial research infrastructures for predicting species' ecological and evolutionary responses to global change (Harold & Blanc, 2025), with OBSNEV serving as a key scientific resource for understanding and adapting to environmental change in Sierra Nevada and other Mediterranean mountain systems. However, these observatories face a major challenge in securing stable, long-term funding—a difficulty that OBSNEV also encounters. Reliance on short-term grants and shifting priorities threatens data continuity, staff retention, and consistent monitoring—undermining efforts to track and understand environmental change over time.

## CONCLUDING STATEMENT

We commemorate 50 years of limnological research in the Sierra Nevada, a milestone that also honors the scientific and educational legacy of the pioneering researchers—Drs. R. Martínez-Silvestre, Luis Cruz Pizarro, Rafael Morales Baquero, and Pedro Sánchez Castillo—who, guided by remarkable intuition, ventured into those once remote and little-known mountains. Half a century later, many researchers now find themselves drawn to the Sierra Nevada, viewing it not only as a natural wonder but as a vast landscape of opportunity—a mountain full of possibilities to explore. In the face of the accelerating global challenges confronting humanity, this unique ecosystem continues to inspire and drive scientific discovery.

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