Frontiers in Forests and Global Change

TYPE Perspective
PUBLISHED 27 October 2025
DOI 10.3389/ffgc.2025.1682353

OPEN ACCESS

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RECEIVED 08 August 2025
ACCEPTED 11 October 2025
PUBLISHED 27 October 2025

CITATION
Zhang W, Cheng Q, Li F, Kumar A, Qin G, Liu L, Hui D, Li H, Yuan X and Liu D (2025) Anthropogenic and climatic drivers of alpine wetland degradation: a multi-scale perspective.
Front. For. Glob. Change 8:1682353.
doi: 10.3389/ffgc.2025.1682353

Anthropogenic and climatic drivers of alpine wetland degradation: a multi-scale perspective

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Alpine wetlands play a vital role in water storage, ecosystem services, biodiversity conservation, material recycling, climate change mitigation, and environmental purification. At present, these high-elevation and high-latitude ecosystems are facing dual threats from the combined impacts of climate change and human activities. This perspective reveals that climate-related factors such as phenological changes and plant migrations, as well as human activities like agricultural reclamation, have significantly damaged these ecosystems. To address alpine wetland degradation, multiple strategies are proposed through integrated approaches. First, exploring the synergistic application of multiple restoration techniques, including ditch-filling, terrain-leveling, invasive species removal, and vegetation restoration. Second, establishing long-term ecological monitoring frameworks, including extreme climate and water level monitoring, vegetation and soil survey, among others. Third, sustained investments in scientific research and active public awareness and stakeholder engagement. Through these comprehensive efforts, integrating traditional ecological knowledge with modern restoration techniques, we can jointly safeguard biodiversity, maintain ecosystem services, mitigate the degradation of alpine wetlands and preserve these high-value ecological systems for future generations.

KEYWORDS

alpine ecosystems, climate and human disturbances, wetland conservation, ecological restoration, monitoring frameworks, sustained investments

1 Introduction

Alpine wetlands, which are typically distributed at mid- to low-latitude high mountain or mid- to high-latitude plateaus, such as the Tibetan Plateaus and Yunnan-Kweichow Plateau (Zhang et al., 2025), play an important role in water storage, ecosystem services, biodiversity conservation, material recycling and environmental purification (Kang et al., 2021; Vahsen et al., 2023). These ecosystems are renowned as biodiversity hotspots, sheltering numerous rare, endemic, and endangered plant and animal species. For instance, alpine wetlands are crucial habitats for migratory birds, providing abundant food resources, including insects, small fish, and aquatic plants, as well as safe resting and breeding sites (Ghimire and Regmi, 2024). In addition, alpine wetlands function as both "natural water towers" and "water purifiers," which can absorb and store large amounts of precipitation and glacial meltwater during rainy season and ensure a stable water supply for surrounding rivers and streams during dry season (Toetz, 1995; Acreman and Holden, 2013). Moreover, due to the accumulation of remnants of plant litter and animals and the suppressed microbial and enzyme activity under anaerobic conditions, wetlands store substantial quantities organic carbon and subsequently play an vital role in mitigation climate change (Temmink et al., 2022).

Alpine wetlands are complex ecosystems, that include water bodies, vegetation, soil, and the associated wildlife. These components interact to maintain the functions and stability of alpine wetlands (Xiong et al., 2023). For example, wetland vegetation plays an indispensable role in purifying waterbody, providing food sources for wild animals, maintaining biodiversity, conserving water sources, and enhancing the landscape (Cooper et al., 2017), while alpine wetland soil can regulate hydrology, degrade pollutants, store carbon, and provide ideal habitats for vegetation, soil animals, and microbes (Meng et al., 2020). These components should be considered jointly when facing external changes. Due to their lower temperature under high altitude or high latitude, alpine wetlands are sensitive to variations in temperature and precipitation patterns than other wetlands (Kuang and Jiao, 2016; Geppert et al., 2020). Climate change (e.g., increase of regional temperatures, frequent extreme droughts) and human activities (e.g., agricultural reclamation, overgrazing, tourism) have resulted in severe degradation, such as reduction of wetland area and loss of biodiversity (Miehe et al., 2019; Jiang et al., 2023; Xiong et al., 2023). Previous research has shown that the available water resource in alpine wetlands has been converted from natural to heavily modified water bodies, which severely hampered hydro-morphology, ecological functions, and the landscape of alpine wetlands (Kumar et al., 2024). Moreover, the degradation of alpine wetlands could lead to substantial carbon emissions to the atmosphere that is buried in anaerobic soils, which triggers a significant positive feedback to climate warming (Cheng et al., 2025; Li et al., 2019). Therefore, more research is necessary to characterize the problems of alpine wetland degradation and propose effective strategies for the conservation of alpine wetlands.

Despite the progress, key research gaps about wetland conservation still persist. Firstly, the interactive effects of climate change and human activities on wetland degradation remain poorly understood. Region-specific, cost-effective restoration strategies are limited, and long-term monitoring mechanisms are largely absent. Secondly, interdisciplinary collaboration across ecology, hydrology, climate science, and social science is insufficient, and public engagement in conservation efforts remains weak. Additionally, a disconnect between scientific evidence and policy implementation hampers effective protection. This perspective aims to address these gaps by advocating for integrated approaches that combine climate mitigation, ecological restoration, interdisciplinary cooperation, and public involvement. The goal is to inform decision-making and support the sustainable management of alpine wetland ecosystems.

2 Current challenges

Climate change poses severe threats to global ecosystems, with alpine regions being particularly vulnerable due to their unique physical and ecological characteristics (Zhang et al., 2025). Firstly, climate change can trigger phenological shifts in plants, which may lead to changes in community dynamics, population-pollinator interactions, plant reproduction, plant evolution and adaptation, and ultimately affect ecosystem functions and stability (Memmott et al., 2007; Cleland et al., 2012; Collins et al., 2021). Secondly, climate warming can cause upward shift in plant species, species accumulation at higher elevations, and contraction of alpine plants, which further promotes plant invasions and threatens native species (Lázaro-Lobo and Ervin, 2021; Iseli et al., 2023). The increasingly biological invasions could subsequently alter vegetation structure and lead to habitat fragmentation and loss at high-altitude and high-latitude ecosystems (Descombes et al., 2020; Iseli et al., 2023). Moreover, rising atmospheric carbon dioxide (CO_2) and melting permafrost under increasing global mean temperature enhanced nutrient (particularly carbon and nitrogen) availability, which has driven an unprecedented increase in tree growth and expansion of woody vegetation in these alpine areas (Silva et al., 2016; Lin et al., 2023; Zhao et al., 2023; Figure 1a). The expansion of this type of vegetation has further created favorable conditions for woody species to establish themselves in alpine wetland areas, which subsequently exacerbate alpine wetland degradation (Colautti and Barrett, 2013). In addition, a significant increase in temperature of alpine wetlands can stimulate the decomposition of soil organic carbon (Li et al., 2020), which weakens the carbon sink function of alpine wetlands, and subsequently goes against the carbon neutrality target. These effects can irreversibly change alpine ecosystems and result in biodiversity loss and carbon emissions.

Anthropogenic interventions such as agricultural reclamation, ditching, and channeling have altered the original terrain and hydrology, causing sustainable damage to these alpine wetlands (Kingsford et al., 2016; Qiu et al., 2024), which have decreased their area all around the world (Figure 1b). Concurrently, the human disturbance induced erosion of water networks, decline in water levels, drought, and invasion by non-native plants have led to increasingly severe wetland degradation (Sun et al., 2024; Xu et al., 2024). Moreover, dam construction and urbanization damaged the growth of alpine vegetation, altered the original landscape, and subsequently resulted in alterations in natural and regional water distribution patterns (Xiong et al., 2023; Figure 1c). The infrastructure associated with dam construction and urbanization, including the construction of electrical grid and access roads, further exacerbated exploitation and disturbance. In addition, overgrazing was another serious threat to alpine wetlands (Figure 1d). Excessive grazing can reduce vegetation through chewing and trampling of livestock, which affects the self-purification efficiency of the wetland and leads to the reduction in food supply and the loss of habitats for some wetland wildlife (Xiong et al., 2023). During recent years, with the development of tourism and agriculture, microplastics have become another important pollutant for alpine wetlands. The microplastics can disrupt the physical and chemical protection of soil organic carbon by minerals and aggregates, and stimulate soil organic carbon decomposition by increasing microbial activities, which leading to reduce of alpine wetland carbon sequestration capacity (Lan et al., 2025; Lin et al., 2025). These anthropogenic disturbances compromised ecosystem services of alpine wetlands, such as carbon sequestration and soil conservation. For example, the degradation of alpine wetland induced by drought resulted in significant loss of soil organic carbon and total

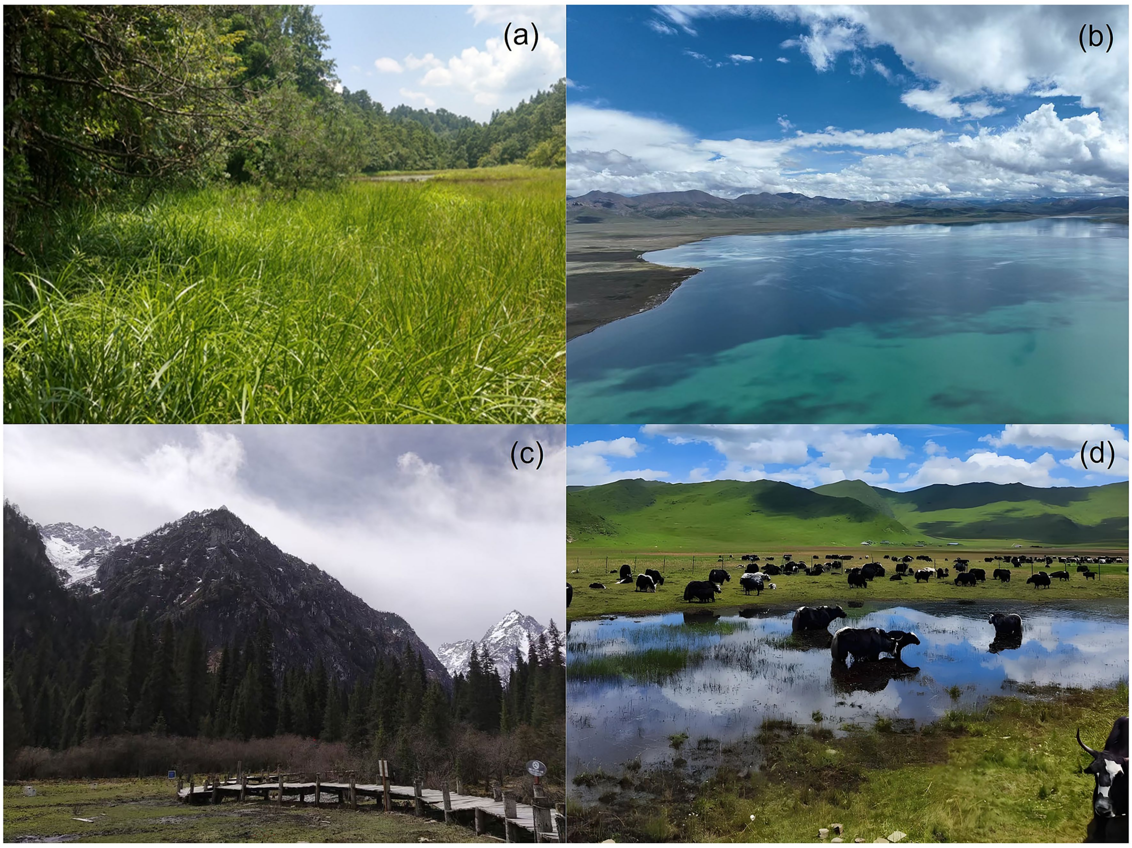

FIGURE 1
Different types of alpine wetland degradation. **(a)** Tree invasion of mountain pond photographed by H. Li in the Jingning Wangdongyang Wetland with an altitude of 1,300 m asl, in Lishui, Zhejiang, China. **(b)** Reduced area of alpine lake photographed by F. Li in Maduo County, Tibetan Plateau. **(c)** Humans' utilization of riparian wetland photographed by F. Li in the Wanglang Nature Reserve, Pingwu County, Sichuan Province, China. **(d)** Overgrazing of alpine swamp meadow photographed by F. Li in the Wayan mountain, Gangca County, Tibetan Plateau.

nitrogen, which reduced the carbon sink function of alpine wetlands (Li et al., 2021; Lin et al., 2021). Thus, the detrimental effects of human activities on alpine wetlands highlight the urgent need to take effective measures to protect these ecologically sensitive areas.

3 Conservation strategies

3.1 Ecological restoration

Various ecological restoration measures have been applied in alpine ecosystem restoration. Firstly, ditch-filling and terrain-leveling, which refer to filling the entire volume of the ditch with native wetland spoil material or natural non-wetland organic material, are the most common techniques for the restoration of the wetland hydrological system damaged by human activities such as ditch digging (Cooper et al., 2017; Chimner et al., 2018). The above techniques can promote surface hydrological connectivity, maintain hydrological balance and accelerate recolonization of plants, which further stabilize the area (Appels et al., 2016; Chimner et al., 2018). Secondly, the artificial barrier elimination, including fence, small earth dam, and simple bridge, helps restore the natural hydrology and terrain of alpine wetlands by removing the obstacles, and subsequently creates a favorable foundation for the healthy development of the alpine wetland ecosystem (Meng et al., 2020). Moreover, vegetation restoration is another important strategy for the conservation of alpine wetlands, which should be strengthened to recover the wetland landscape, enhance the carbon sink and partially offset greenhouse gases emissions (He et al., 2024). The specific measure includes manually removing invasive species, which can specifically expand the ecological space and support the self-renewal of original vegetation (Wang et al., 2016; Li et al., 2024). Although these ecological restoration measures are very effective for the conservation of alpine wetlands, they are partly hampered by their high construction and human resource costs, property rights disputes, and species rebounding (Bell-James et al., 2023; Kovaleva and Kovalev, 2023; Zachary, 2023). Therefore, agricultural reclamation, dam construction, and grazing must be regulated by strict planning and approval systems to protect wetlands from destruction (Zheng et al., 2024). The ecological impact assessment is recommended to be executed to avoid strengthened and illegal occupation and destruction of alpine wetlands (Ritika et al., 2024). In addition, an ecological compensation system should be established to provide financial support to stakeholders affected by wetland conservation measures, including nearby residents, local enterprises, and non-profit organizations engaged in wetland conservation (Zhang et al., 2024). This can encourage greater community participation and reduce the economic hardships of alpine wetlands and surrounding communities (Liu et al., 2025).

3.2 Strengthening monitoring

It is highly recommended to establish a comprehensive climate monitoring system in alpine regions. This can be achieved by integrating meteorological satellites, ground-based monitoring stations, and using big data analytics to track climate change trends in real-time (Montillet et al., 2024). To prevent and mitigate the potential damage of extreme climate events, accurate early warning mechanisms using AI-driven models should be adopted to protect wetland ecosystems from climate change impacts (Lu and Xiao, 2024). Otherwise, to accurately monitor the effectiveness of alpine wetlands restoration, water level, flow rate, and groundwater level can be measured using instruments like water-level gauges and piezometers. Vegetation can be surveyed through systematic vegetation surveys and by measuring plant growth parameters and biomass. Soil quality and erosion can be evaluated by analyzing soil samples and using erosion pins or sediment traps. Animal and microbial diversity can be monitored through trapping, surveys, sampling, and DNA sequencing. However, implementing a climate monitoring system in alpine regions faces challenges such as equipment setup and maintenance, technology integration, high costs, and data security concerns (Zandonai et al., 2024). Nevertheless, policy-making should support the quantification of wetlands' intangible value, the improvement of climate monitoring and early-warning systems.

3.3 Innovative strategies for alpine wetland protection

Sustained investments in scientific research are essential to drive innovation and optimize the current conservation strategies (Shen et al., 2023). This includes developing efficient, cost-effective ditch-filling, and terrain-leveling techniques for complex areas, as well as exploring water-storage technologies that can operate stably under extreme climates. Research should focus on effective invasive species removal and prevention to reduce manual intervention and improve long-term treatment results. Promoting cooperation and communication among multiple disciplines like ecology, geography, meteorology, and sociology is crucial for an in-depth understanding of the complex interactions between climate change and human activities affecting alpine wetlands (Lu and Xiao, 2024). Joint projects that integrate the expertise of multiple disciplines in alpine wetland restoration should be initiated, and cross-disciplinary training and education in relevant institutions should be strengthened. This collaboration can also foster innovative restoration technologies tailored to specific terrains and help understand the combined impacts of climate change and human activities on alpine wetlands, providing a theoretical basis for formulating more scientific and holistic protection strategies

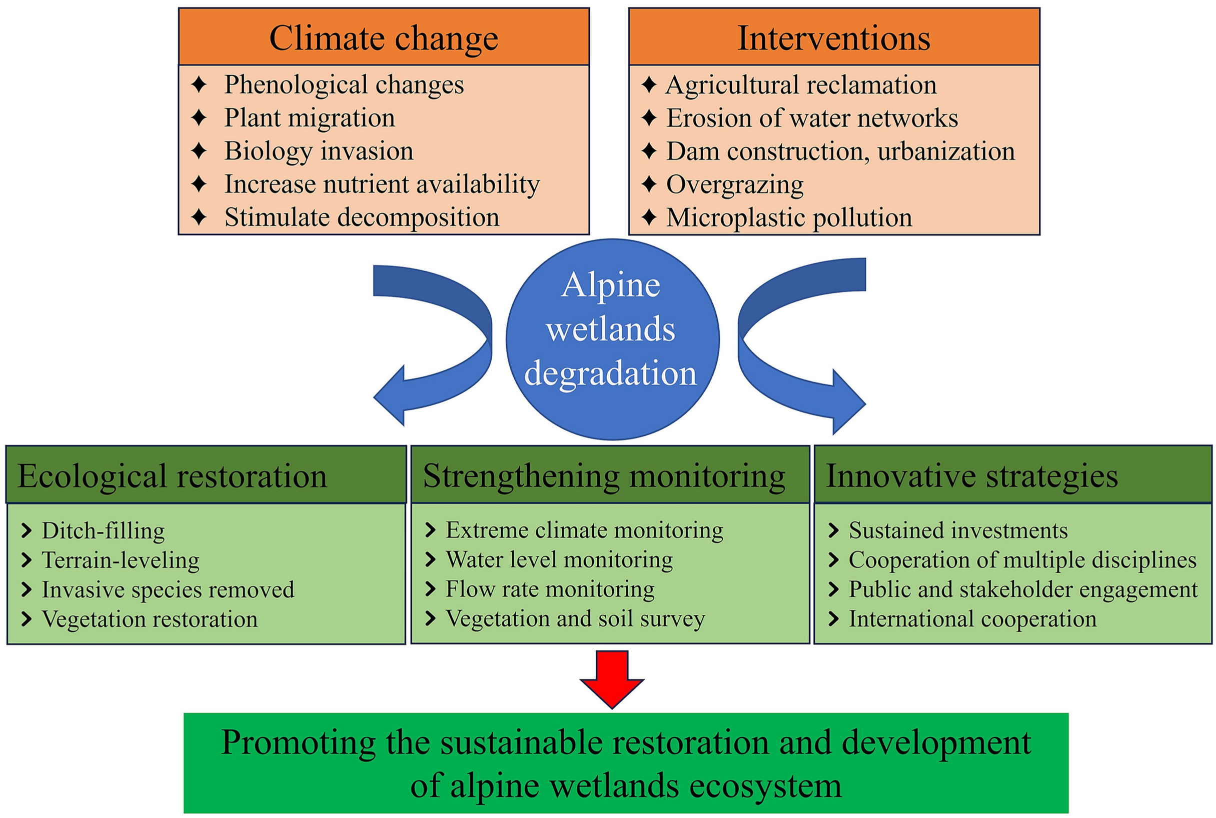

FIGURE 2
Conceptual framework of current challenges and conservation strategies under alpine wetland degradation.

(Adams et al., 2021). Environmental education for the public should be strengthened to enhance awareness of the importance of alpine wetlands (Bassi et al., 2019). Public outreach through science communication, awareness campaigns, and community engagement initiatives can foster a collective sense of responsibility and encourage active participation in wetland protection actions (Wang et al., 2018). For example, promoting the use of clean energy sources through public environmental education can reduce greenhouse gases emissions and contribute to global climate change mitigation. As climate change and wetland protection are global concerns, strengthening international cooperation and knowledge-sharing initiatives should be promoted. Sharing experiences and technologies in wetland protection among countries can jointly address global challenges and promote the sustainable development of alpine wetlands (Bibi et al., 2024).

4 Conclusion

Alpine wetlands are experiencing profound and often irreversible degradation due to the compounded effects of climate change and anthropogenic pressures. Climate-related factors such as shifts in phenology, species migrations, and woody plant expansion are exacerbating wetland degradation, while human interventions like agricultural reclamation, dam-building, and grazing have directly altered the terrain, hydrology, and productivity of these sensitive ecosystems (Figure 2). Conservation strategies face significant challenges due to the unique geographical characteristics of alpine wetlands, such as sloping terrains and soil erosion, and the need for cost-effective, long-term solutions. The future of alpine wetland conservation requires synergistic use of multiple restoration technologies, establishment of long-term ecological monitoring frameworks, sustained investments in scientific research and active public awareness and stakeholder engagement (Figure 2). Through these comprehensive efforts, integrating traditional ecological knowledge with modern restoration techniques, we can jointly safeguard biodiversity, maintain ecosystem services, and mitigate the degradation of alpine wetlands and preserve these precious ecological treasures for future generations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

WZ: Funding acquisition, Writing – original draft. QC: Writing – review & editing. FL: Writing – original draft, Conceptualization, Writing – review & editing. AK: Writing – review & editing. GQ: Funding acquisition, Writing – review & editing. LL: Writing – review & editing. DH: Writing – review & editing. HL: Writing – review & editing. XY: Writing – review & editing. DL: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was supported by the Science and Technology Research Program of Chongqing Municipal Education Commission (KJZD-K202503502, KJQN202303502), the Chongqing Science and Technology Commission (CSTB2023NSCQ-MSX0111) and the "Pioneer" and "Leading Goose" R&D Program of Zhejiang (2024C03226).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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